

REAL TIME DEFECT DETECTION IN WELDS BY ULTRASONIC MEANS

In fulfilment of the requirements for the degree of Doctor of philosophy.

By

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To:

All those who helped or attempted to help me in the past.

ABSTRACT

A computer controlled weld quality assurance system has been developed to detect weld defects ultrasonically whilst welding is in progress. This system, including a flash analogue to digital converter and built-in memories to store sampled data, a peak characters extractor and a welding process controller, enabled welding processes to be controlled automatically and welding defects to be detected concurrently with welding. In this way, the weld quality could be satisfactorily assured if no defect was detected and the welding cost was minimised either through avoiding similar defects to occur or by stopping the welding process if repair was necessary.

This work demonstrated that the high temperature field around the weld pool was the major source of difficulties and unreliabilities in defect detection during welding and, had to be taken into account in welding control by ultrasonic means. The high temperatures not only influence ultrasonic characteristic parameters which are the defect judgement and assessment criterion, but also introduce noise into signals. The signal averaging technique and statistical analysis based on B-scan data have proved their feasibility to increase 'signal to noise ratio' effectively and to judge or assess weld defects.

The hardware and the software for the system is explained in this work. By using this system, real-time 'A-scan' signals on screen display, and, A-scan, B-scan or three dimensional results can be printed on paper, or stored on disks, and, as a result, weld quality could be fully computerized.

CONTENTS

1. INTRODUCTION	1
2. LITERATURE SURVEY	3
2.1 ARC WELDING QUALITY CONTROL.	3
2.1.1 Development of welding defects.	3
2.1.2 Automatic control of weld defects.	4
2.1.2.1 Seam tracking	5
2.1.2.2 Weld penetration and weld pool size control. ..	9
2.2 WELD INSPECTION.	11
2.2.1 General Survey	12
2.2.2 Ultrasonic inspection of welds	13
2.2.3 Austenitic weld inspection.	16
2.2.3.1 Difficulties in austenitic weld inspection.	16
2.2.3.2 Techniques to improve austenitic weld inspection.	17
2.3 AUTOMATIC WELD DEFECT DETECTION DURING WELDING.	21
2.3.1 Significance.	21
2.3.2 Difficulties of defect detection during welding.	22
2.3.2.1 Temperature.	22
2.3.2.2 Coupling problems in automatic scanning.	26
2.3.3 On-line weld inspection	28
2.4 APPLICATION OF MICRO-COMPUTER IN WELD DEFECT DETECTION	30
3. COMPUTER CONTROLLED EXPERIMENT SYSTEM	32
3.1 SYSTEM INTRODUCTION.	32
3.1.1 Ultrasonic system.	33
3.1.2 Welding system.	33

3.2 GENERAL CONSIDERATIONS.	34
3.2.1 Time and amplitude.	35
3.2.2 Time window.	39
3.2.3 Signal width	40
3.3 HARDWARE.	41
3.3.1 Interface.	41
3.3.2 Function control circuit.	42
3.3.2.1 Synchronous circuit.	42
3.3.2.2 Time gate circuit.	44
3.3.2.3 Peak detector.	45
3.3.3 Flash analogue to digital converter.	47
3.3.4 Welding system control circuit.	51
3.4 SOFTWARE.	53
3.4.1 Introduction.	53
3.4.2 Programming techniques.	57
3.4.3 Software functions.	62
4. EXPERIMENTAL TECHNIQUES AND RESULTS	64
4.1 SYSTEM TESTING.	64
4.1.1 Calibration	64
4.1.2 Amplitude versus signal width.	67
4.1.3 Datum point for measuring time.	69
4.2 EXPERIMENTAL SIMULATION.	70
4.3 HIGH TEMPERATURE EFFECTS ON RESULTS.	74
4.3.1 Arrangement.	75
4.3.2 Signal time change.	76
4.3.3 Signal amplitude change.	79
4.4 SIGNAL PROCESSING AND ANALYSING.	81
4.5 ON-LINE WELD DEFECT DETECTION.	86
4.5.1 Lack of fusion.	87
4.5.2 Porosity or inclusions.	88

4.5.3 Cracks.	90
4.5.4 Other defects.	91
5. DISCUSSION	92
5.1 DIFFICULTIES IN DEFECT DETECTION CAUSED BY THE HIGH TEMPERATURES OF WELDING.	92
5.1.1 Signal time.	92
5.1.2 Signal amplitude and gain control.	94
5.1.3 Grain growth and phase transformation.	97
5.2 NOISE AND NOISE REDUCTION.	100
5.2.1 Signal processing.	101
5.3 RELIABILITY OF DEFECT DETECTION DURING WELDING.	105
5.3.1 Restrictions caused by high welding temperatures.	106
5.3.2 Some limitations of contact coupling and the mechanical scan.	107
5.3.3 Some limitations of on-line defect detection.	108
5.3.4 The reliability of detecting defects during welding	109
5.4 STRATEGY LIMITATIONS.	112
6. CONCLUSIONS	114
7. FURTHER WORK RECOMMENDATIONS	117
8. ACKNOWLEDGEMENTS	119
REFERENCES	120
FIGURES	

APPENDICES:

Appendix A: Expression for the energy passed through the interface
in a perspex simulation block A1

Appendix B: Programs written for the system A3

Appendix C: Publication A52

1. INTRODUCTION

The application of ultrasonic sensors in welding process monitoring and control has become an important area and significant achievements have been made in ultrasonic seam tracking and penetration control^[1-10]. On the other hand, ultrasonic inspection of weld quality has long been employed as one of the most frequently used methods in industry, especially in the area of thick plate weld inspection and 'on-site' service inspection. However, the use of ultrasonic sensors to detect defects as they form in the interior of the weld pool whilst welding is in progress has received less attention^[11].

Some defects might occur during welding due to the complexities of the welding processes and the unpredictable factors. Therefore, welds must be inspected along the joint to be sure that the weld is free of defects and that the weld structure can still meet the demands of ultimate integrity and strength, even though some defects exist in the weld. If the defects could be detected as soon as they occur by on-line defect detection, then similar defects might be reduced or avoided thereafter if automatic welding parameters modification could be suitably found and applied immediately. In addition, if the defect is out of an acceptable region and a repair is necessary, then the weld process could be halted in order to carry out repairs. As a result, repair costs will be minimised, this could be very significant in many cases, especially when the defect is located in the root run of a thick plate weld^[12].

It is well known that conventional ultrasonic weld inspection is performed after the welding process is terminated, i.e., after the severe thermal gradients have given way to a lower and more equal background temperature and ultrasonic inspections are usually carried out manually^[13]. Thus the major difference between conventional ultrasonic inspection and the in-process defect detection is the existence of high welding temperatures with steep gradients and the impossibility of a repetitive test to increase signal to noise ratio in the 'in-process' defect detection. The high temperature could greatly influence signal time and severely

reduce signal amplitude, the two most important ultrasonic parameters in ultrasonic weld inspection. Therefore, temperature effects must be borne in mind in the development of welding defect detection ultrasonically. Furthermore, the existence of large austenite dendritic grains in the weld (before the phase transformation during cooling process) could, more or less, generate problems which were often encountered in the austenite weld inspection process. Austenite grains in welds could scatter ultrasound and produce the noise named "grass" and even skew the ultrasonic beam path^[14,15].

A principal objective of this work was the development of a computer controlled welding defect detection system and the demonstration of the feasibility to detect defects concurrent with welding by employing the system. Moreover, the overall effects of the high welding temperature and the possibility of the temperature effects compensation or reduction was investigated experimentally. To realize this successfully, computational algorithm was developed.

2. LITERATURE SURVEY

2.1 ARC WELDING QUALITY CONTROL.

Arc welding is a widely used method to join components permanently. Due to the complexities of welding processes and many unpredictable factors, such as incorrect selection of a welding parameter, an accidental malfunction of the equipment, interference from the surroundings or temporarily low spirits of the operator, welding defects are liable to occur during welding.

2.1.1 Development of welding defects.

There are many kinds of welding defects, but the most common defects about which welding scientists are concerned; are the following:

1. Cracks.

Cracks are the most serious defects because they can propagate when tensile stress is imposed on the structure and lead to service failure and thus result in disaster. Generally, there are two groups of cracks^[16]; hot cracks or solidification cracks which occur during the solidification of the weld metal, and, the second termed cold cracks, which initiate and propagate after welding in the weld, or in the parent metal or heat affected zone (HAZ) due to the embrittling effect of hydrogen (this defect, therefore, cannot be detected during welding and is not discussed here). Hot cracking occurs when the tensile stress developed during cooling contraction is larger than the strength of the weldment at that moment, or the deformation is greater than the ductility of the solidified metal, (which is usually caused by thin intergranular liquid films around the freshly solidified grain boundaries). All the factors which could increase the tensile stress during solidification (e.g. high welding current, high levels of restraint in welding plates) or factors which reduce the ductility of the solidified grains (such as high carbon content and substances which develop intergranular liquid films like sulphur phosphorus and copper)

increase the probability of hot cracking.

2. Lack of penetration or lack of root fusion.

Like cracks, lack of root fusion is one of the most serious defects because it can serve as a crack initiator and can also propagate during service which could result in structural damage. Unlike cracks, this defect is mainly caused by incorrect welding conditions, such as reduced current, unstable welding arcs or too long an arc length, or incorrect preparations, such as large root face, small gaps between plates, or both.

A similar defect to the lack of root fusion is lack of side wall fusion, which can be induced by inappropriate joint preparations, arc blow, or an inadequate distance between the welding head and the joint wall (which is usually the result of bad seam following).

3. Porosity and Inclusions.

These are usually less serious than the previous defects, because they are rarely prone to propagate during service (of course, big pores or inclusions, or too dense a level of porosity or inclusions can reduce the effective structure area and result in the structure failure). Their development often has some relationship with contamination of the weld zone.

2.1.2 Automatic control of weld defects.

From the previous statements, it is well known that some welding defects are welding process dominated, and could be reduced (or even eliminated) by welding process control. For instance, lack of side fusion can be controlled by an efficient joint tracking system and; lack of root fusion by penetration control. Great achievements have been made in the control of both of these areas^[1-10]. To meet ever increasing demands for welding quality control, great attention has been paid to welding quality control and this has produced a series of successful welding

process controllers.

2.1.2.1 Seam tracking

As can be seen above, lack of side fusion defects can be overcome or improved by accurate seam following and seam recognition. This is an extremely important task in automatic and robotic welding process. As reference [17] stated: "one of the greatest problems encountered in the robotic welding operation is that associated with weld joint alignment". In the field of tracking, most types have been tried at some time or other, including mechanical probes, inductive, capacitive, laser, photodiode array, optical fibre, television, arc parameter monitoring and ultrasonic systems. They can be roughly grouped under two types, contact or non-contact systems.

1. Contact Sensors.

Contact sensors (except for ultrasonic systems which are worth specific discussion later) utilise the joint preparation or part geometry as a mechanical guide^[18,19]. The sensor is kept in contact with the workpiece during operation and any deviation can be transformed into electric signals by changes of inductance, capacitance or any other electrical parameters. Their main advantages are their simplicity and reliability because of their relative stronger capability to resist the surrounding light or electric interferences. They are usually cheap to make or buy and environmentally friendly. Verdon believed: "the mechanical methods with their rugged simplicity will always be around to provide a cost-effective solution to a large number of welding problems."^[20] As a result, most of the earlier seam tracking systems belonged to this group and, actually, they were the most common methods used early in real welding production in industry. Additionally, Verdon predicted: "A mechanical probe combined with a computer might well be very popular for adaptive systems in the immediate future"^[20].

However, they have some inherent disadvantages. They will not fit all joint geometries, especially those joints with complex contours. In addition, because of the requirement of contact, welding or motion speed is limited and accuracy is affected by surface conditions and might be greatly reduced by 'weld spatters'. This was supported by the work which indicated that "they are somewhat limited in the joint geometry they can track, suffering inertia/speed problems"^[21]. Moreover, "the intrinsic difficulties associated with a contacting probe prohibit its use in many robotic welding applications."^[22] To eliminate the disadvantages of contact sensors, attention was transferred to non-contact sensing.

2. Non-contact sensors.

Non-contact sensors might be classified into two types, a) vision-based and b) non-vision-based sensors, though it is very difficult to group all non-contact sensors, simply due to their widely different functions.

A. Non-vision-based sensing

"Non-vision-based sensing techniques rely on the use of various sensors other than vision, for sensing variations in alignment between the actual weld joint location"^[17]. The sensors and sensing techniques employed electromagnetic sensors (including eddy current)^[23-25], arc sensing^[22,26-29] and other techniques^[30,31].

Inductive sensors can sense both horizontal and vertical deviation of the welding head at the same time^[24]. As a result, the welding process, mainly the arc voltage, can be kept stable as can the seam following process. If the preparation is good, accuracies can reach 0.2mm which is good enough for any 'gas metal arc welding' (GMAW), 'gas tungsten arc welding' (GTAW) and other welding processes.^[23] These techniques work independently of any welding process and can automatically find the seam before the welding starts, a very useful ability for welding robots.^[23] In addition, the technique only reacts on ferritic metals and is therefore

undisturbed by non-metallic materials such as paper, paint or oil etc..

Nevertheless, they can only be used for ferritic steel structures (not aluminium or stainless steel fabrications) and have the tendency to be affected by the structures variation, especially when there are any magnetic dipoles around. For instance, the output signal changes greatly when these sensors are passing over a tack weld. Additionally, a poor edge alignment in a butt-joint (edges not in the same vertical plane) will sometimes affect the sensors' horizontal ability^[23]. Finally, they have relatively weak ability to resist electrical interference due to the magnetic coils in the device, (such as the high frequency from arc ignition in 'tungsten inert gas' (TIG) arc welding).

Amongst non-vision based sensors, the "through-the-arc" sensing technique has recently been developed. "It is a natural extension of a well-established technology for tungsten-to-work control via automatic voltage control with the gas tungsten arc welding process."^[22] In operation, it produces signals by weaving the arc back and forth across the travel line in a V preparation joint. The oscillation of the arc causes changes in the arc voltage (or current) sensed at the joint walls (see figure 1). These changes are directly proportional to the fluctuations in distance between the surface of the joint and the welding electrode tip. Thus any asymmetry of the voltage waveform during a period of weaving indicates a deviation of welding head to the joint centre, which can be used to adjust the welding head until it re-locates to the central line.

The main advantages are:

- . Ability to track and weld simultaneously.
- . Ability to track joints with sharp changes in direction because no distance exists between a sensor and an arc.
- . Real-time compensation and correction for heat distortion during welding.
- . Not affected by smoke, welding spatters or arc light.
- . Ability to obtain the weld joint geometry if the distance of the

torch-to-workpiece is known.

- . Simplicity of the equipment and relative cost effectiveness.

The limitations are:

- . All joints must have a V preparation (or similar preparations) and the V shape should be symmetrical to the joint centre (which largely limits its use in thin materials).
- . Limitation of welding speed due to the requirement to oscillate the torch (or arc).
- . Tracking is dependent on the stable welding process especially the arc stability^[21].
- . Generally tracking is only possible when the arc is on, so it is impossible to find the correct start position, this being essential in some robotic welding systems.

B. Vision-based sensing.

The vision-based seam tracking systems which are commercially available, differ slightly in the manner in which they operate, due to proprietary differences. However, in principle, they usually employ normal light, infra-red or laser illumination techniques,^[32-40] and the employment of infra-red or laser illumination techniques can efficiently avoid any interference from the welding arc. The system uses these light sources to scan the weld joint, and senses the reflected two-dimensional information by a video camera or a photo-diode array, through an 'optical triangulation technique' to determine the joint centre line. In another words, projected planes of light produce illuminated co-ordinates of each point on the strip which can be calculated from the intersection of structured light illumination plane and the optical path along the camera axis, using optical triangulation techniques (see figure 2 and figure 3).

From this principle, it is known that these sensors usually obtain both positions

(horizontally and vertically) of the welding head relative to the joint. Besides, the technique has the ability to extract joint geometric profiles and weld fill situations which can be used as information for the process control, and it is obviously a prominent advantage. Moreover, they can be used on almost every kind of joint and joint preparation, they can track both before welding and during welding, and can locate the start point. They are suitable for application to welding robots and actually, many welding robots utilise this kind of technique.

However, the disadvantages of this system are also clear. Their effectiveness can be affected by the variations of the workpiece surface, smoke, welding spatters, whilst the cost of these systems is relatively much higher than other tracking techniques.

2.1.2.2 Weld penetration and weld pool size control.

It is very difficult to size weld pools, or more accurately, to control weld penetration because of the existence of the bright arc, the high temperature around the weld pool and sometimes severe smoke, the disturbance of the weld pool itself and the variation of the welding parameters. Even though, people have put much work into the investigation of welding penetration control (due to its great importance) and have made many advances.

Techniques normally employed in weld penetration and weld pool size control in arc welding mainly consist of three types, e.g. radiation sensing^[31,41-45], radiographic means^[46-50] and ultrasonic techniques^[1-10,51,52,53]. Here, weld penetration control or weld pool size control simply utilises feed back control of the pool size using specially designed sensors.

Radiation sensing techniques directly detect the radiation emission from the back face^[41] (sometime from the front face^[42,44]) of the workpieces. They discriminate between the temperature of weld pools and the temperature of the surrounding

metal by using a simple optical technique and a narrow band filter in conjunction with a suitable photodiode and an amplitude gate or a grey scale comparator. In this way, the technique uses this signal to control welding current and, in turn, control the weld penetration.

In a successful application, "the system was found to be successful in controlling bead penetration in mild steel and various types of stainless steel of thicknesses up to 6mm"^[45]. Besides, these systems were found to react very quickly to changes in weld pool size, for example, the measuring system can detect a change in less than 100 micro-seconds, faster than any weld pool can physically change its size^[43]. In addition, the system can be employed to follow the weld seam^[42] at the same time and the systems are relatively simple compared to other techniques. The technique is usually non-contactive (compared with the contacting measurement of ultrasonic techniques) and thus could be more efficient. Unlike radiographic systems, this technique is harmless to operators or the surroundings.

However, the technique suffers a lot in use because the detection had to be performed in the back side which is not possible in many real cases, while those able to detect signals from the front face do not provide close loop control of weld pool penetration because their performance relies on the validity of mathematical models and in establishing the correlation between the parameters being monitored (e.g. light intensity from the arc, or the weld pool width) and the parameters being controlled (the welding penetration). Practically, the predication of weld penetration by the measurement of weld pool length and width is vague except in very specific cases under closely controlled conditions.^[16,54] Consequently these systems cannot accommodate the penetration variations which may be caused by differences of the material composition^[45].

Radiographic techniques^[46-50] can solve the above problems. These techniques make use of the grey levels of the weld images and their histogram distribution and thus recognise the three-dimensional shape of a weld pool. The advantages are

that the method can detect weld defects during welding (which will be discussed in the section 2.2.1 later), but there can be a safety problem for operators and their surroundings, so the equipment and the welding system must be isolated, this limits their use in the welding industry. Besides relative high costs, the system basically responds more efficiently to bulk defects than to plane defects (like cracks which are more important to the structural service) if the defect plane is perpendicular to the X-ray, which produces very weak grey contrasts.

Ultrasonic techniques, the latest developed weld penetration control methods, have proved of great value in welding control^[1-9,51,52]. Although there are many aspects which need to be investigated in more detail, great achievements have been made in recent years. Now the technique can be used not only to measure and to control the weld penetration ^[1,4,6,9], but also to track weld seams simultaneously either for thick plates^[3,55] or thin materials^[56,57]. Compared with general sensors which are used solely either to control torch movement; as seam following or to control weld penetration, the advantages of ultrasonic sensing which combined the two requirements together are obvious. Additionally, the ultrasonic sensors have the tendency to detect weld defects at the same time when the sensor is fulfilling the above two functions. As a result, the technique has shown to have a bright future in automatic welding quality control.

2.2 WELD INSPECTION.

Though many achievements have been made (as stated previously), it is still impossible and impractical to expect that every weld can be guaranteed free of all defects (because of the complexities of welding processes and the many unpredictable factors in welding). It is for this reason that weld inspection has been given more attention with the development of welding quality control.

2.2.1 General Survey

For almost 25 years, the problem of non-destructive testing (NDT) of welds has been given prominent attention by IIW's Commission V, particularly in the areas of testing, measurement, and control of welds.^[58]

Current NDT methods can be subdivided into two major categories: 1) surface inspection and 2) volumetric inspection.

1. Surface inspection mainly includes visual, optical, dye-penetrant, magnetic particle and eddy current techniques. The importance and reliability of surface inspection is based on the supposition that most serious defects (cracks or fractures) initiate from the surface, whilst the possibility of inclusions buried inside welds are not as important structurally (although they may be a potential risk). To minimize this risk, surface crack detection methods have been increasingly refined.^[58] Amongst surface inspection methods, the dye-penetrant and the magnetic particle methods are regarded as the most economic and most frequently employed methods, both offer high degrees of sensitivity and dependable results.

Compared with volumetric testing, surface inspection is easier and cheaper. However, in the case of welds subjected to high demands (like pressurised and high stressed vessels), it is not sufficient to examine only the surface.^[58] Additionally, both surfaces of all welds can not always be accessed for surface inspection in many cases. This means that one of the most serious defects (lack of root fusion) may not be detected by this technique. Radiographic and ultrasonic testing, the classical methods of volumetric inspection, are therefore frequently used as indispensable NDT methods, of the two radiographic testing is the older.^[58]

Radiographic inspection gives a permanent record and a very clear and reliable result, especially when testing "volumetric" defects such as porosity and inclusions. It is thus natural that this method was, and still is, one of the most widely employed

methods.

Disadvantages of this technique are clear. The major drawback is that a narrow crack (which might cause a major service failure), which is regarded as more serious than the "volumetric" defects like inclusions, will not be detected unless it is parallel to the radiation beam. Even if a crack were detected, its depth within the component and its dimensions paralleled to the path of the radiation would remain unknown. These are essential pieces of information needed for a fracture mechanics assessment of the crack's significance. In addition, on one hand, the high level of radiation in nuclear reactors would rule out radiography as an in-service inspection tool, unless film protection methods could be devised. On the other hand, due to the limitation of radiographic energy, the testing cannot be performed on thick materials. Even when thick plate can be inspected, sensitivity reduces linearly with increasing plate thickness. Furthermore, "other impediments to the use of radiography are access difficulties and an inability to cope with complex weld geometries."^[59] As a result, a tendency to favour ultrasonic testing has developed. People are giving, and will give more attention to ultrasound inspection. "Ultrasonic techniques are probably receiving most attention at the present time"^[60] and "remain at present the most effective means of detecting physical discontinuities in the thickness of metals"^[61].

2.2.2 Ultrasonic inspection of welds.

Acoustic techniques can be used to detect all common weld defects like porosity, inclusions, cracks, lack of penetration, in any kind of elastic materials. Ultrasonic testing utilises a beam of short wavelength mechanical waves transmitted from a small probe and received by the same or another probe. Usually, when the waves enter the object, they "react" with the structures and flaws of the object, as such the received waves contain valuable information about the structure and flaws inside.

Waves propagate in elastic materials in a similar way to light in transparent

materials, because of their short wavelength. For example, ultrasound beams travel in a straight line in an isotropic homogeneous medium; reflect and refract when travelling across boundaries separating two media in which the velocities of the propagation are different. They also have similar behaviour for reflection and refraction as that for light. So, in many cases, when the behaviour of ultrasound is discussed, it could readily be considered as a beam of light which simplifies the analysis of ultrasound and serves to establish the relationship of ultrasound and the defects.

Most cracks and other defects are efficient reflectors and can be easily detected by the pulse-echo methods.^[62] When a short pulse of waves is projected into a test sample, some of the sound energy will be reflected back by the defect in the direction of the transducer, arriving at the probe after a time interval, which depends on the distance travelled to and from the defect. Thus the distance can be calculated by measuring the time interval (usually called the 'time of flight' (TOF)) with the known ultrasound velocity, it can also obtain the depth and location of the flaw, thus the defect position. Moving the transducer so that the beam scans across the defect, enables the defect dimensions to be estimated or calculated according to the 6 db technique or other defect dimension measurement techniques^[63].

The presentation of ultrasonic results (or data) depends on the equipment/system used. There are three ways of displaying presentations^[64].

1. A-scan.

The A-scan is a one dimensional presentation which shows the existence of flaws, their positions (according to the signal time), and gives an estimate of their sizes (based on the peak amplitude). This presentation mode gives the most essential and most detailed information of one point (stationary probe). By moving the probe (probe scan), the whole weld or whole area concerned may be inspected.

2. B-scan.

B-scan results show all reflections from all reflectors between the top and the bottom of the specimen (if a longitudinal wave probe is used) as the transducer moves along a line. Usually, a threshold or amplitude gate is employed, thus only those reflections whose amplitude are higher than the threshold will be displayed in the results. (In some systems, the amplitude could be represented by grey scale and no threshold level is used, like the ZIPSCAN system^[65]). In B-Scan the distinguishing feature is line presentation (shown in figure 4) (compared with one point presentation in A-scan). The advantage of B-scan is that both the length of the defects and their depth below the surface are revealed. If the peak amplitude or peak width is compacted in the presentation, the results will also show the reflector size. This has been demonstrated in a system where amplitude was represented as a grey scale with zero amplitude represented as mid grey, positive amplitude was represented as shades of grey to white and negative amplitude by darker grey shades through to black ^[65].

3. C-scan.

C-scan is a plane scan which produces a proportional image of the specimen and shows the position in a "plane view" of any internal flaws. In some cases, the amplitude of the detected signal can be quantified in colour levels (see figure 5). What is worth noticing is that the position between the front and the back surface echoes in A-scan trace is selected or gated and any signal exceeding a predetermined threshold causes the recording equipment to register.

Apart from the above three classical types of scans, another method of scanning, namely P-scan (Projection Image Scanning), was developed in 1981^[66]. This system has been defined thus: "The P-scan principle allows the formation of projection images of weld defects". Normally two projection planes are used, one plane parallel to the surface and another normal to the surface and parallel to the weld. In this way, a TOP VIEW and a SIDE VIEW are obtained respectively (see figure 6). From its principle, it is clear that the representation of the results is

similar to B-scan, while it scans a specimen from two directions (top and side) instead of only one direction in the normal B-scan, and the threshold can be selected at any time even after testing in the P-scan.

Many more advantages are claimed for the P-scan method than are with the more classical methods^[66].

1. A complete three-dimensional location of weld flaws can be obtained.
2. The display level can be selected at any time and the inspection sensitivity can thus be varied effectively for analysis without repeating the inspection.
3. Paper copies of P-scan image representation of any desired display level can be produced during the inspection or at any time later.
4. The technique is ideally suited for automatic weld inspection.

Actually, all the above advantages (except the first one) are the common advantages of any computerised digital ultrasonic systems. Many computer controlled systems besides the P-scan system (like ZIPSCAN, Micro Pulse) provide more or less similar advantages together with their own distinguishing features (see later sections).

2.2.3 Austenitic weld inspection.

2.2.3.1 Difficulties in austenitic weld inspection.

A frequently repeated adage may be quoted: "It has been accepted for many years that ultrasonic testing methods prove problematical when inspecting austenitic welds".^[14,59] On the other hand, austenitic stainless steel is a very important material in many industrial applications, such as in the structures for corrosive

environments, for high resistance to creep deformation in high operating temperatures (like reactor vessels and pipe lines in the chemical or nuclear industry). Therefore, many investigations in ultrasonic weld inspection on austenitic stainless steel weldments have been made.^[14,67-72]

There are two main reasons for the difficulties of ultrasonic austenitic weld inspection. 1) The coarse dendritic grain structure in the austenitic welds because no phase transformation occurs during whole welding process. 2) The segregation of impurities along the grain boundaries (due to the limited solubility of various impurities by the face-centred cubic (FCC) structure of austenite. Figure 7 is an example of an austenitic weld macrograph which shows the coarse dendritic grains. As a result, austenitic welds affect the ultrasonic inspection by reducing the signal strength due to the high level of scattering and by introducing higher noise levels (known as 'grass'). This not only reduces the signal to noise ratio but also produces many spurious echoes. In addition, the difficulty of ultrasonic inspection also stems from the elastic anisotropy^[14,69,70]. As a result, the simple laws of geometrical reflection no longer hold; and ultrasonic energy may be strongly reflected into unexpected directions which, therefore, makes the interpretation of ultrasonic results difficult even in a simple situation, and, sometimes gives false indications^[67,73]. The anisotropy of the welds, actually, can change the ultrasonic beam from a straight line to a curve (beam skewing) which makes the beam deviate from the expected propagation path and makes it very difficult to locate the weld defects correctly^[14,67,69-70,73-74]. Additionally, beam skewing also leads to a variation in beam width, which affects signal amplitude and, has a more significant influence than that of grain boundary scattering^[14,70,75].

2.2.3.2 Techniques to improve austenitic weld inspection.

Due to these peculiarities of ultrasonic inspection in austenitic welds, technologists have investigated several methods of improving their inspection results. Apart from the methods which optimise the welding process^[14,70], there are several ways which

are helpful in ultrasonic inspection of austenitic welds.^[14,62,68,70-76]

The theory of scattering from a spatially random distribution of small obstacles shows that most of the scattered energy occurs in the shear wave mode^[76], so that testing with compression waves in an austenitic material is subject to much less interference than would occur with shear wave testing^[14,62]. The largest angle of skewing from compression waves is much smaller than that from shear waves, therefore, using compression waves can produce less distorted results^[14,70]. However, some researchers preferred shear waves to compression waves because "simultaneously existing transverse waves make it difficult to interpret and discriminate between the echoes"^[69] if compression waves were used. Moreover, one researcher believed that transverse waves gave better results than longitudinal waves where the attenuation of ultrasound was not a major problem^[68].

As the preferred path of longitudinal wave beams is 45° to the grain axis, the beam angle and probe position have apparent influences on the results. Therefore, using a 45° angled probe can achieve better signal to noise ratio^[70] for thick materials, although other work^[68] indicated that the best beam angle for thin austenitic welds was 70° .

Even though different suggestions come from different researchers (due to the difference in the welding process, the welding parameters and the variations of austenitic micro-structures) most researchers suggested that using short initial pulse (broadband) narrow beam probe (focused probe if possible) should give better signal to noise ratios.^[14,15,59,68,70] As for frequency, using low frequency can obtain stronger reflection signals because the attenuation coefficient is proportional to the fourth power of ultrasonic frequency, but where attenuation is not the main problem; employing higher frequencies can give better results with higher sensitivity.^[68]

Apart from the previously discussed ultrasonic parametric methods, signal processing techniques can, sometimes significantly, improve the inspection results.^[15,77-83] Basically, there are two major groups of signal processing techniques; 1) processing signals in a time-domain or 2) transforming signals and processing them in a frequency domain.

1. Time domain processing.

The basic and simple technique is a 'signal averaging technique' (SAT)^[15,77-79] which can efficiently enhance the signal to noise ratio. When a probe is moving slightly to another position (a movement of the order of one grain diameter is sufficient^[77]) the noise (ultrasonic scattering) which randomly varies from place to place tends to be averaged to zero whilst the uniformly varying defect signals are augmented, and this, therefore, increases the signal to noise ratio greatly. A similar technique adopted; is the 'Boxcar Integration Technique',^[78-80] which works as follows: When moving the ultrasonic probe on the surface at a constant speed, the echo pattern from the grain which is a spatially random variation is converted into a temporally random signal and this signal can be averaged using a 'boxcar integrator'. Actually results can be simply explained as converting spatially random signals into random time signals and then averaging them to enhance the signal to noise ratio. This is possible because scattered noise is spatially random reflections; whereas the defect signal pattern is kept similar (only the signal time or amplitude or both change gradually, this could be compensated by delaying signal time when the probe movement speed is known).

Recently, a time-domain approach method was presented which was for improving the resolution of data^[81]. The technique was mainly used locally to separate those signals which could not be separated by conventional methods. A 'de-modulated auto-correlation' (DMAC) or pattern recognition function has been employed to increase sensitivity and to distinguish defects^[82,83]. It was claimed that this technique could detect 1% of a thickness notch in austenitic stainless weldments.^[82]

A further pattern-recognition methodology has been developed to distinguish defects and it has been claimed that the pattern-recognition algorithm yielded a better than 90% index of performance^[71,72]. However, the techniques, except for the signal averaging technique, are not suitable for on-line inspection at present due to the time consuming calculations involved. Furthermore, according to the respective principles adopted, it can be seen that the previously discussed techniques (except for the SAT and the boxcar techniques) are usually employed for defect discrimination rather than for enhancing signal to noise ratios (or detectability).

2. Frequency domain processing.

A technique using the scalar mean peak power and normalised mean deviation vector has been utilised, which transformed time-domain signals first (through Fast Fourier Transformer (FFT),) into frequency domain signals and then separated into several groups or clusters. By comparing clusters with defects to those without any defects, defects could be distinguished.^[82,84] Other researchers directly used signal spectra to discriminate defects and claimed that "it is shown that it is feasible to characterize a flaw by this technique in spite of its composition (i.e., crack, void, or inclusion) or shape and without the need for a calibration standard"^[83]. Not much practical inspection has been reported about adopting this technique. Clearly, these techniques were helpful where the spectrum of the signal from the defect is different from that of noise, otherwise it is unable to give results because the technique is based on the spectra.

2.3 AUTOMATIC WELD DEFECT DETECTION DURING WELDING.

2.3.1 Significance.

The importance of weld inspection for the purpose of ensuring quality (i.e. fitness-for-purpose inspection) is generally well accepted. However, the importance of inspection for an economical purpose or for welding quality control has been given less attention. Actually, the significance of weld inspection during welding is obvious.

Firstly, suppose a large cross-section weld was tested after the weld was completed. Any flaw found, located deep within the weld (for example, the lack of root fusion defect, which often happens in welding), meant that a large quantity of otherwise accepted weld metal had to be removed to eliminate the defect. Moreover, complete defect removal has never been assured. Following defect removal, the component must be re-welded and then re-inspected. If an unaccepted flaw still exists, or a new flaw occurred during the re-welding process, the repair has to be repeated. The costs associated with repairing welds in critical components are great. So, concurrent welding and non-destructive testing is economically very important. Reference [12] presented the result of an economic analysis of implementing the concurrent welding and non-destructive examination technique and indicated that a hypothetical welding program with concurrent non-destructive testing projected savings of \$73.26 per meter of weld for 2 inch thick plate with submerged arc welding.

Secondly, in a hypothetical real time system, when a defect is detected during welding, the information about the defect will be fed back to the control unit (e.g. computer). Measures to eliminate the defect or to stop the process for trouble-shooting will then be taken perhaps after some analysis or decision have been made. For example, if lack of penetration at the root was detected, the

system could either increase the welding current or decrease the welding speed immediately, or even stop moving the torch forward temporarily. In this way, the defect might be eliminated or alleviated, at least the same defect is avoided in further welding. Therefore, by this route welding quality can be well controlled and the process becomes a "multiple" or "overall" weld quality control compared with those control processes which only control a single parameter of welding quality e.g. for weld penetration.

2.3.2 Difficulties of defect detection during welding.

The significance of ultrasonic testing during welding may have been noticed, but little progress was made simply because of the great difficulties involved in the process.

2.3.2.1 Temperature.

As would be expected, elevated temperatures in and around the weld-pool were largely responsible for most of the problems encountered during the process^[85]. These problems are as follows:

1. High attenuation.

It has been established that the relationship of longitudinal ultrasonic attenuation with the sample temperature for carbon steel is not simple^[86] (see figure 8(a)). A broad peak at about 215°C (which is the Curie temperature of the cementite phase), after that the attenuation remains almost constant up to the A_1 temperature at which a sudden increase begins. During this period, body-centred cubic (BCC) ferrite changes gradually into the face-centred cubic austenite. Sound attenuations at high temperature (up to 1200°C^[87] and 1374°C^[88]) have been investigated and the relationship of the attenuation for longitudinal waves^[87,88] and shear waves^[87] with the temperatures obtained (see figure 8(b) and figure 9).

Results from different sources are clearly different from each other (those results in references [87,88] showed more detail) although their explanations are the same (some other work also gives the same explanation): i.e. interaction with the magnetization of the steel, the BCC/FCC phase transformation, the solubility of the carbides^[86-89]. After 900°C, grain scattering dominates the attenuation.^[86-89] The attenuation coefficients (α_l , α_s) can be expressed respectively as (from the reference [90]):

$$\alpha_l = \frac{4\pi^3 T f^4 \langle (\Delta C)^2 \rangle_{AV}}{5V_l^4 C_o^2} \left[1 + \frac{3}{2} \left(\frac{V_l}{V_s} \right)^5 \right] \quad (2.1)$$

$$\alpha_s = \frac{8\pi^3 T f^4 \langle (\Delta \mu)^2 \rangle_{AV}}{5V_s^4 \mu_o^2} \left[1 + \frac{3}{2} \left(\frac{V_s}{V_l} \right)^5 \right] \quad (2.2)$$

Where subscripts l and s imply respectively the longitudinal and shear waves, V the velocity of ultrasound, f the frequency, μ_o the elastic constant of the material, ΔC is a co-efficient and T the average grain volume. For equation (2.1) (for incident longitudinal waves), the first item in the square bracket is due to the scattered longitudinal waves and the second the scattered shear waves. Since $V_l \approx 2V_s$ in solid, the equation indicates that most of the scattered energy is as secondary shear waves (similar conclusion can be made from equation (2.2)). The equations show that two factors contribute to increase attenuation as the temperature rises; 1) the velocity decreases and 2) the grain grows (T increases). In a simple case the following expression has been arrived at from the equations (2.1) and (2.2):^[90,91]

$$\alpha_s/\alpha_l \sim (V_l/V_s)^3$$

This means that more energy will be scattered if using shear waves. Therefore, speaking of attenuation, using longitudinal waves should be possible to obtain stronger signals due to lower attenuation.

In shear wave inspection, due to the great attenuation caused by the high weld zone temperature, more ultrasound energy must be injected into the specimen to obtain a measurable returned signal, (which is also likely to increase the noise). On the other hand, if the signal strength becomes the main problem, using lower

frequency probes may improve the result because ultrasound attenuation is less severe at lower frequencies^[87].

2. Velocity change.

The velocity of both wave types decreases as the temperature increases, and has a steep drop during the solution of carbides between the A_{c1} and A_{c3} temperatures on heating. Above the A_{c3} the velocity decreases with temperature at a constant, moderate rate. During cooling the velocity follows this same slope well below the A_{c3} temperature and increases to the original curve near A_{c1} temperature (figure 10)^[87]. Similar result for longitudinal waves with a larger temperature range (20-1374°C) was obtained (see figure 11)^[88].

The velocity changing with temperature causes two main problems for defect detection during welding. Firstly, it increases the signal 'time of flight' due to the velocity reduction and, secondly, ultrasound refraction occurs due to the gradient of velocity, which will change the beam path from a straight line and increase the signal time too. It had been reported that the time increase due to this effect is not large if the beam is perpendicular or near perpendicular to the isotherms.^[92] As was predicted from theoretical assessment; the weld location error, caused by using the velocity in cold metal, was less than 0.5 mm (corresponding to about 0.3 μ s) for a 3.5 mm radius weld in pulse heating.^[92] At the same time, it was deduced that the error would increase if a steady continuous heat source was used as in a real welding process. On the other hand, according to the ultrasonic experimental results^[92], the error function was found to be:

$$\text{Error} = -1.01 + 0.497r$$

Here r is the weld radius. This meant that the error increment almost equals half of the weld radius as the weld pool expands. This work also showed that the experimental data fluctuated more severely for larger weld pools.^[92] As a result, the velocity change with temperature increased the difficulties to locate, to size, or to discriminate defects (even to say that it was not possible). This situation became

worse during welding because the variation of the temperature field was affected by several factors (e.g. welding parameters) and could not be simply determined. This, in turn, might be the explanation as to why the location errors from different sources had large deviations.^[6,51,85,92]

3. Phase transformation.

It is well known that phase transformations occur during welding if the material is ferritic steel. This can produce problems for ultrasonic defect detection because 1) the attenuation and velocity of the ultrasound will have severe changes when phase transformation occurs (see previous). 2) The large grains, especially the solidified large dendritic austenite grains in the weld, can influence the ultrasonic behaviour and make the inspection process more difficult. Actually, the large dendritic austenite grains in the weld before phase transformation, on cooling, could generate all the similar problems which existed in austenite weld inspection by the austenite coarse grains (see previous section) besides the difficulties related with high temperatures. However, these severe problems in defect detection during welding have not yet been carefully investigated and it thus becomes of great significance to explore them.

4. Problems associated with sonic coupling.

Due to the high temperatures around the weld pool, probes are likely to be damaged. This fact has been stated thus: "Several wedges become charred and distorted and needed replacement after short periods of continuous monitoring."^[85] In addition, the liquid couplant evaporated and formed gas-bulbs leading to lack of coupling. The piezo-electric sound generating element is sensitive to temperatures and the piezo-electric properties may change or even be lost if this element becomes too hot. To overcome these two problems in the ultrasonic inspection of hot samples, several methods have been tried, including the housing of the transducer inside a cooled roller at a high contact force^[93], momentary

contact between the probe and the sample at high pressure^[87,89]. These methods, though satisfactorily employed in hot specimen ultrasonic inspection, have not been reported of any use in the welding defect detection process. This might be due to their complexity of structure, or their inconvenience or lower efficiency for on-line detection and process control. Fortunately, the welding heating source (the welding arc) only heats the weld locally, this means that the probe could be protected from damage if it were a certain distance away from the welding arc, though it might affect the test sensitivity in some cases. Even then, the coupling problems still exist and could greatly affect the on-line defect detection in some cases.

2.3.2.2 Coupling problems in automatic scanning.

The probe might lose coupling during the auto-scan phase of on-line defect detection. This has been reported thus: "Loss of sonic coupling while dynamically monitoring weld formation was invariable, the direct result of irregularities on the surface of the parent material. The imperfections did not necessarily have to be very large, even the smallest surface marking was often sufficient to "kick-up" the modified acrylic wedge and thus cause momentary loss of signal."^[85] Since it is impossible to avoid such imperfections during welding, many kinds of transducers have been developed for these reasons.

Figure 12 (from reference [94]) showed a wheel shaped transducer filled with couplant. It rolls rather than slides on the sample under inspection, therefore, it moves more smoothly and lessens the problems previously mentioned. Also it reduces contact time and the heating of couplant and crystal.

In 1953 a transducer was designed which had a transit section with a water cushion to form a "local immersion" to the specimen and if water was fed in at sufficient pressure, a water cushion was obtained along which the probe could slide without being in mechanical contact with the surface (and thus generate a smooth scan)^[95].

This transducer could not only be used for flat specimens but also in the vertical position. The problem was that multiple reflections from the water gap could interfere with the examination of the signals. Water might also flow on to or near the weld area which must not be allowed during welding. Other liquid cushion probes have been made, two researchers designed a similar transducer which solved these shortcomings by reducing the gap thickness^[6,85]. In the probe a recess (about 0.25mm deep) was machined in the bottom of a normal probe shoe and a hole was drilled into the rear face to facilitate the formation of a thin film or reservoir of couplant between wedges and the specimen. Later, a "pseudo-immersion transducer" was developed. Both authors indicated that the transducers were reliable for ultrasonic coupling.

On the other hand, other researchers investigated the feasibility of using dry couplant for high temperature coupling and stated that this technique was effective, and thus the problems due to the use of couplant were avoided because this technique did not require any couplant^[96,97].

However, none of these improvements can change the nature of contact, therefore, the limitation or the problems associated with contact techniques, such as limitation of welding speed, high demands on the state of the material surface and access space, still exist.

Non-contact transducers are considered as a good way to solve the problems caused by the probe contact. Among them the laser induced ultrasound method and the electromagnetic induced ultrasound technique have been given great attention and might move in the right direction. However, as the ultrasound generated by laser is initiated by the mechanical stresses produced by the thermal expansion due to the short pulse laser surface heating,^[94,98,99] whilst "all thermal effects, due to their slow reaction, are unsuitable for receiving pulses"^[94]. Another kind of transducer is necessary to receive the signals from the sample being tested, which makes the system more complicated. In addition, the laser beam energy should be controlled

below the material ablation threshold to prevent any surface damage in many cases. In this situation, the amplitude of ultrasound generated is largely reduced and the waveforms are worsened. Moreover, the ultrasound in solid materials generated in this way consists of longitudinal, shear and surface waves, which makes the signal explanation much more complicated. Furthermore, the complexity, imperfections of the technique itself and the high cost limit their use in the welding area. Compared with ultrasound generation by laser, the electro-magnetic ultrasound generation technique is less expensive and, more importantly, the transmitter and the receiver are fundamentally the same. Nevertheless, if the ultrasound is transmitted and received by this kind of transducer, the signals are at least 50 db^[100] to 100 db^[101] below those obtained with conventional probes. This indicated that this kind of transducer was difficult to use in the weld inspection, especially for defect detection during welding where severe attenuation exists due to the high temperature of welding. Furthermore, there exists 'electro-magnetic' interaction with the welding arc because both are magnetic media and therefore should interact with each other.

Due to the many and various reasons related to non-contact transducers, successful application of these transducers in weld inspection has not been reported. All in all, it seems that the perfect answer to the ultrasonic coupling problems has not yet been perfected and; it deserves further investigation.

2.3.3 On-line weld inspection

The significance and the feasibility of on-line ultrasonic weld defect detection has long been recognised during the research of welding control by ultrasonic means at Brunel university. The idea of using ultrasound beam spread to investigate the weld quality was proposed.^[6,8,102] "The existence of the (sound envelope) trailing edge signal which interrogates the solid/solidifying weld bead, has potential as a final quality arbiter, but has not yet been developed."^[102] The feasibility was predicted: "Weld quality should also be able to be monitored by the trailing edge

signal"^[8] and the author indicated that "work begins immediately to employ this signal (the trailing edge signal) in a useful control situation"^[6]. At the same time, the investigation of on-line weld defect detection was performed in the Idaho National Laboratory, USA^[9,103] and National Non-destructive Testing Centre, Harwell Laboratory, U.K.^[104] and some progress was made. At Idaho, work was based on the simulation of machined samples with different weld pool geometries and using expert systems. It was reported that the system could discriminate between different weld pool geometries such as straight side-wall penetration, the unwelded bottom corner, and the single concave radius geometries (these three geometries were indicative of an unacceptable weld pool geometry) and, as a result, to close-loop control the weld quality. However, this system, in fact, was more weld pool geometry evaluation rather than the normal weld defect inspection. Later the same author improved the technique and concluded: "Discontinuities may be detected during GMAW using ultrasonic methods. The types of discontinuities detected in this work are incomplete sidewall fusion, gross porosity and undercut."^[103] Similarly, some later work investigated the feasibility of detecting weld defects in TIG welding processes^[104]. According to the author, the common weld defects, like porosity, inclusions and lack of side-wall fusion could be detected as they occurred. From the results, it was believed that "transmitted compression waves were effective at detecting all defects and distinguishing between them. Pulse-echo compression waves also detected lack of side-wall fusion with good sensitivity, porosity, and inclusions with rather less sensitivity. The only defect that could be detected by pulse-echo shear waves was gross lack of side-wall fusion"^[104]. On the other hand, other researchers seemed to favour more; the shear wave pulse-echo technique but also investigated compression waves^[9,103]. If consideration was taken into account of the conditions used experimentally in the work^[104] where the shear wave incidence angle was 60° and the distance was one and a half skips, the sensitivity to defects might be improved. This could be made possible by changing the angle to 45° and the distance to half a skip, because "the 45-deg refracted shear wave provides a favourable co-efficient of reflection at molten/solid interface"^[9]. A shorter distance also means less beam spread and

sharper signals, though the half skip distance was usually not practical for defect detection during welding due to the high temperature or the geometric relation of probe and weld region. Moreover, these results were obtained on the condition that the welding process was TIG and the current was only about 80A to 110A, which meant a relative small weld pool and heat affected zone^[104]. So, if a large current welding process, e.g. submerged arc welding, is to be investigated, more difficulties will be expected and the results will be vastly different.

2.4 APPLICATION OF MICRO-COMPUTER IN WELD DEFECT DETECTION

From the aforementioned literature, using computers in automatic weld inspection to acquire, to store and subsequently to analyze the signals is vital. Indeed, it has been shown that there is a large scope of microcomputer application in automatic weld inspection.^[1,4,6,9,55,56,66,104-108] In fact, almost all newly developed equipment for automatic ultrasonic weld inspection includes a micro-computer, because many computer accomplished functions could not be performed by any other devices. The apparent tendency exists to use computers more widely and more frequently due to the high quality; more and more complete functions and lower and lower prices have made computer application with this equipment natural, such as:

1. Data sample, data storage and testing process control^[65,66,103,107].

It is common to use microcomputers to sample data, actually almost all of the ultrasonic research systems developed in recent years employed computers to sample signals and to store data, such as the P-scan system^[66], ZIPSCAN system^[65]. It is usually the first choice, even the only choice, if people hope to get digital signals which are clearer and easier to compare and to analyze. For example, in the pulse-echo technique where the transit time is very important, by using a computer one can get the digital time directly (which can make time calibration unnecessary in ultrasonic testing) and control of the time gate very easy

and accurate^[55,56,65,66]. Moreover, as there is a large quantity of data needed for off-line analysis during weld auto-inspection, depending on computers to do this task is the only possible way to manipulate all the useful data and information. In developing the P-scan system it was found that using a computer to store all the A-scan data meant that one could select effectively the inspection sensitivity for analysis at any later time without repeating the testing^[66]. Similarly, other people have emphasized that "the major advantages of an ultrasonic digital recording system such as Zipscan are the permanent storage of all the A-scan records and the flexibility of computer based systems for analysis and display."^[65]

2. Data analysis and defect discrimination.

In automatic weld inspection, especially in defect detection during welding, the factors to be analyzed for defect discrimination or signal judgement are complicated. These factors are those ones such as the time of signals, the amplitude of the signals, the correlation of the signals, the history of the signals, etc.. It is therefore reasonable to depend upon a computer instead of any other devices to fulfil these demands. Actually, those digital ultrasonic systems (see above) are all capable of displaying and analysing the signals in this or that way. Due to the speed limitation, the on-line display and on-line analysis is relatively simple, especially when the process is performed during welding. Compared with the on-line processing technique, the off-line signal analysis and defect recognition could be much more complicated and more efficient and, offered better results.^[71,72,74,81,82,108,109]

In summary, as with the speedy development of micro-computer techniques, micro-computers will certainly be found in increasingly wider use in weld inspection. The function of the computer controlled ultrasonic system will thus be improved very quickly as will their capabilities.

3. COMPUTER CONTROLLED EXPERIMENT SYSTEM

3.1 SYSTEM INTRODUCTION.

It is known that a sound experiment system is very important, and even vital, to good quality experiment results in many cases. The experimental system developed during the course of this work is fully computer controlled, and composed of the following sub-systems.

1. Ultrasonic equipment including ultrasonic instrument and ultrasonic transducers. These are used to generate ultrasound beams, to receive signals, to amplify the received signals and to display the signal on the cathode ray tube (CRT).
2. A digital ultrasonic signal processing system which converts analogue ultrasonic signals into digital data, detects signal time, peak width and stores the data in a built in memory for later computer analysis.
3. A computer system is used to acquire and to process the data, save it, analyze it and to display signals on a screen or print them on paper, and most importantly, to control the whole system and processes.
4. A welding system, composed of a welding power supply, an interface linking the power supply to the control computer, welding table controller, welding parameter monitor and recorder.

Figure 13 is a schematic diagram of this experiment system.

3.1.1 Ultrasonic system.

The ultrasonic equipment employed in this work consists primarily of an ultrasonic pulse generator, an acoustic transmitter-receiver, an amplifier and a cathode-ray tube used to display signals.

When an short electric pulse is generated in the instrument, the pulse is then applied to a transmitter (or transducer) which transforms electric oscillations into mechanical vibration and generates a pulse of ultrasound. The ultrasound generated must be properly dampened to increase resolution while maintaining a good signal sensitivity. When the transmitter is placed firmly onto an elastic specimen, the ultrasound pulse can enter the specimen and propagate continuously inside the specimen. When the beam meets any discontinuity (like a defect), some of the energy will be reflected back and sensed by a receiver. In a pulse-echo mode, the transmitter and the receiver is the same quartz crystal (termed as transducer or probe), which means that this transducer must alternatively "sound" and then "listen".

Signals received by a probe are then amplified by a preset amplification to a given amplitude for outputting and for driving a CRT to display the signals.

The ultrasonic instrument used in this work can perform direct or immersion testing techniques and can be used for single or dual transducer testing (in the pulse-echo mode or transmitter-receiver mode).

3.1.2 Welding system.

The welding power supply employed is a three phase transformer rectifier and transistor controlled power source, the output of which is controlled by transistors using feedback to achieve output accuracy in the order of one percent with an output current maximum of 1000 amperes. The supply is based on the series

regulator principle, using a number of transistors connected in parallel and mounted on water cooled heat-sinks.

The control of output characteristics is achieved by using either current or voltage feedback or any combination of the two to achieve any intermediate slope. There are 11 output characteristics ranging from constant current to constant voltage and can be pre-selected from the front panel.

Welding parameters can be manually set from the front control panel or by the computer through an interface. Wire feed was provided by a capstan driven wire feed unit powered by a stepping motor, which meant that wire feed speed could be very accurately controlled. The stepping motor drive unit is mounted in the power supply itself, whilst control pulse series for wire feed speed can be provided from the computer system via an interface or the pulse generated inside the power supply. The power supply can be either used for tungsten inert gas arc welding or for any gas metal arc welding or submerged arc welding. Welding parameters (current, voltage, wire feed speed and welding time) were monitored and printed by a portable arc monitor system during welding.

3.2 GENERAL CONSIDERATIONS.

This work is one part of a series of researches on welding process control using ultrasonic sensors. Previous researchers have successfully proved that ultrasonic sensors are ideal for welding penetration control as well as welding seam following. During these applications of ultrasonic sensors in welding process control, the main ultrasonic parameter monitored during control was ultrasonic signal time. In another words, the control criterion was signal time. For example, for welding penetration control, a pulse of transverse wave ultrasound (called 'initial pulse') was generated in a probe and entered into a weld specimen, some of the energy could be reflected back from the interface between solid material and liquid weld pool. This reflected beam was received by the probe and displayed on the screen

of the ultrasonic instrument. For penetration control, the criterion was the time elapsed between the initial pulse and the reflected signal peak from the weld pool. This longer time represented a increased distance between probe and weld pool and meant a smaller weld pool size. In seam following, the situation is very similar: As signal time is proportional to the distance between the probe and the weld seam, the signal time could also be taken as a control criterion for seam following.

From this explanation, it is clear that the time between initial pulse and the peak of interest was the main parameter utilized by previous researchers. As a result, naturally, the previous systems were mainly for obtaining signal time. However, only obtaining the signal time is insufficient for welding defect detection. In another words, it was not possible only to utilize signal time for this research. A new ultrasonic signal acquisition system was indispensable for welding defect detection.

3.2.1 Time and amplitude.

Both signal time and amplitude are the two most important ultrasonic parameters for defect detection. The system must meet these two essential demands, i.e., to obtain signal time and signal amplitude. Here signal time, more accurately, peak time, is the time elapsed between the initial pulse of ultrasonic instrument and the peak detected. It is generally called transit time. For these purposes, it must be assumed that the zero point of time axis is the leading edge of initial pulses. However, because of the continuous repetition of initial pulses from any ultrasonic instrument and the similarity between initial pulses and signal peaks, it is very difficult to extract directly the leading edge of the initial pulses. Therefore, another signal must be sought to serve as a synchronous signal. Two demands generally need to be satisfied for these synchronous signals. First, the signal should be easily distinguished from returned signal peaks. Second, there must be a fixed time between synchronous signals and the initial pulse, that is, the relative time position of the synchronous signal to the initial pulse must not be affected by the signal

themselves, or by any parameter of the ultrasonic instrument. Fortunately, the synchronous output from the ultrasonic instrument (named sync signal) exactly meets the above two demands. It is a positive pulse, 20 microseconds earlier than the initial pulse (see figure 14).

There are two common methods to measure transit time. First, the integration method, in which the transit time is converted into a voltage by integration. During time measurement, the output voltage is produced by integrating from the time measurement start point to the stop point and thus it is proportional to the transit time if the integration is within the linear scope of the integrator. As a result, the method is an analogue method. The accuracy and measuring range of this method can be easily adjusted but digital output depends on other circuits like analogue to digital converters. Therefore, this type of output is not ideal for digital systems especially for a fast data acquisition system. The second is called "counting method" and is shown in figure 15. This is a purely digital method and was the one used in the designed system. As shown in figure 15, if the oscillator frequency is accurate and known, the cycle number in the counter represents the measured time. Clearly, the accuracy of the time measured depends on the oscillating frequency and is equal to a half period of an oscillation cycle. For example, if oscillation frequency is 50 megahertz (MHz), time accuracy will be 0.01 microseconds, this represents a distance of 0.0298 mm in a ferritic steel specimen (if using pulse echo mode with longitudinal waves) or a distance of 0.016 mm (with shear waves). This accuracy seems sufficiently high for locating defects in defect detection. So 50 MHz was chosen as an upper limit of frequency for the system, whilst an option remained to use 25, 12.5, 6.25 and 3.125MHz, or any other frequencies lower than 50MHz by changing a crystal.

The common way to obtain signal amplitude is to sample analogue signals using an analogue to digital (A/D) converter. There are three basic things to consider: conversion rate or conversion frequency, accuracy and range.

1. Conversion frequency.

According to the sample theorem, sampling frequency should be at least twice the signal frequency to be sampled to recover the signal uniquely. Generally, it needs 5-8 times the rate of signal frequency to restore the signals from digital data obtained after using a converter.

However, it is difficult to predict the upper frequency of ultrasonic signals before digital data are obtained because of the complexities and varieties of ultrasonic signals. Nevertheless, it is possible to make some estimation from some general ultrasonic test results. If it is supposed that the smallest peak width obtained from tests is about $0.5 \mu\text{s}$ (which represents a distance of 0.8 mm in steel when using shear waves, pulse echo mode). Actually, due to the width of initial pulse, the peak width of reflections smaller than $0.5 \mu\text{s}$ is unlikely to appear. It is acceptable to assume that the peak width is larger than $0.5 \mu\text{s}$. Using this assumption, 10 MHz conversion frequency can reasonably meet the sampling demands of restoring real signals because there are at least 5 sample points for each peak. Considering the varieties of ultrasonic signals, 25MHz as the upper limit of conversion frequency was chosen, which has a $0.02 \mu\text{s}$ time accuracy, and 12.5, 6.25, 3.125 and 1.5625 MHz was used as conversion frequency options. Similarly, any frequency lower than 25 MHz could be selected by changing the crystal and the suitable demultiplier in the system. Figure 16 shows some A-scan graphs obtained from different sampling frequencies.

After the A/D converter had been made, some typical ultrasonic signals were sampled. Ultrasonic signal spectra were obtained by Fast Fourier Transformer (FFT) to prove the reliability of the converter with a pre-chosen conversion frequency. Figures 17-19 are typical spectra of ultrasonic signals. They clearly show that the upper frequency of the signals is about 1 to 1.5 MHz. Beyond that frequency, only very small amplitude of spectrum exists which is mainly caused by the saturation of initial pulse or peaks. Figures 18 and 19 are two spectra from signals with the same condition except for the conversion frequency. Figure 18 is

a spectrum from a 10 MHz conversion frequency signal and figure 19 is from 20 MHz. That hardly any difference exists indicates that a 10 MHz conversion frequency is adequate for these signals.

These examples serve to prove that considering the varieties of ultrasonic signals, an upper frequency limit of 25 MHz or 20 MHz operated reliably and was suitable to restore real signal form.

2. Accuracy.

Accuracy here includes both time and amplitude accuracy. The time accuracy depends on the clock frequency controlling the conversion processes. For 25 MHz conversion frequency, the accuracy is 0.02 micro-seconds. There are two factors influencing the time accuracy, one is the digitization error which has been discussed previously. The other is the inaccuracy of the clock frequency itself. As the clock is generated by a quartz crystal, this accuracy does not need any special attention and, furthermore, any inaccuracy of the crystal can be corrected if necessary. The amplitude accuracy depends on the bit number of the conversion chip employed. Because the computer uses a 8-bit data bus, using 8-bit conversion chip is natural and acceptable, thus the amplitude accuracy is better than 0.2 percent which is good enough for any engineering application. Actually, 8-bit is the highest bit number practically available in high speed flash A/D chip group.

3. Range.

Range here means a period of time in which conversion continuously proceeds in a single sample time which produces a certain number of points for restoring original signals. Clearly, the longer the range, the larger the memory space is required to store the data from the converter; although a wider area signal can be obtained. Therefore, on one hand, range should be as small as possible to save memory space and to increase sampling speed, but on the other hand, range should be as large as possible to show wider range signals or even a whole beam trace. To account for both factors a suitable compromise was found to be 256 points for

each sample as an upper range limit, which covers a range of 12.8 micro-seconds if the conversion frequency is 20 MHz. Another reason to choose 256 points as an upper limit is that it can simplify circuit and increase speed. This is because the user input/output (I/O) port (the 1 MHz bus) of the computer has an 8-bit address bus, that is, it can only access 256 bytes of memory built in circuit each time. Using 256 points as an upper limit simplifies both hardware and software, as well as increases the speed of data transfer and analysis. Due to this range limit, the conversion rate should be selected with sampling range in mind. Higher rates mean narrower sampling range, which is not always recommended. For this reason, the conversion frequency used in this work was about 10 to 25 MHz to meet different experiment requirements.

Even using 10 MHz conversion frequency, 256 points only cover 25.6 micro-seconds, which still cannot cover all the time ranges in many cases. To cover this short fall, a time window needed to be introduced into the system.

3.2.2 Time window.

On one hand, as figure 14 shows, the time range of the ultrasonic instrument varies from 50 micro-seconds to about 1400 micro-seconds to meet different applications. On the other hand, the A/D conversion range selected is usually less than 25.6 micro-seconds. It is necessary to introduce a time window to ensure that the most important signal area is covered by the sampling range. That is, the most significant signals locate in the selected time window, thus to be obtained by the sampling process.

There are two major advantages in introducing a time window:

1. The most important signal(s) can be guaranteed to be sampled no matter where it exists on the whole time base.
2. Only those signal(s) concerned are sampled, thus it becomes possible to eliminate any distraction of noise or useless signals out of the window.

To realise the first advantage, the origin of the time window must be movable easily along the time axis, i.e., it should be possible to move the window easily from the initial pulse to any other place needed practically. For the second, the size of the window should be easily changeable as well. Reducing window size can not only get rid of noise or unwanted signals, but also reduces time for data analysis (in some cases it can be a great amount of time).

3.2.3 Signal width

Using a flash analogue to digital converter, a detailed signal can be obtained, which is helpful to analyze and identify defects from signals. However, on one hand, much more data needs be transferred, stored and analyzed every time, and this requires a longer time. On the other hand, only peak time and amplitude, in many cases, are needed rather than detailed signals. Therefore, it is useful to find a simple way to get these two above characteristic parameters of peaks, or similar parameters which can approximately represent characteristic parameters.

From the earlier discussion, it is apparent that signal time is not difficult to determine. Nevertheless, signal amplitude is much more difficult to obtain in comparison. Therefore, simplifying the way to obtain the characteristic parameters was potentially both beneficial and rewarding.

Fortunately, from some basic experiments performed previously (see chapter 4), it was found that signal width had some relationship with signal amplitude in many cases. Signal width in this work means peak width at a given amplitude. Signal width or peak width was used to express the meaning of signal width. That is, at a given amplitude gate level, the higher the amplitude, the wider the signal width. In contrast, signal width was much easier to capture than signal amplitude. Therefore, it is acceptable to use signal width as an amplitude substitution for simplification. For this purpose, an amplitude gate was necessary; to extract signal width and the gate should be adjustable to meet variable situations.

In a word, based on above discussion, signals were processed in the way explicitly shown in figure 20.

3.3 HARDWARE.

According to the requirements discussed in the above sections, hardware circuits were designed. The basic structure of circuits is shown in figure 21 and discussed in the following sections.

3.3.1 Interface.

An interface is a circuit which links a computer to circuits outside of the computer and gives the computer ability to control the outside circuits.

According to the diagrams in the BBC computer user guide,^[110] there are only two ports which could link this computer with outside circuits. One is an 8 bit user input/output port which could be connected to a wider range of external devices, the other being a 1 MHz bus connector which enables users to connect additional specialist hardware to the BBC computer. The first port can only connect with one particular address. If more than a one byte address needs connecting, an address latch is necessary. Using this method, the speed of reading data from several addresses or writing data to several addresses is slower and the outside circuits need be more complicated. For the second connector there are 512 byte addresses (&FC00 - &FDFE, here the symbol "&" means that the number followed "&" is a hex-number). That is, the computer can directly access to any one of 512 addresses which have been set aside in the computer. It is therefore an easier and faster connector to link the computer with outside circuits by a number of addresses and this is the connector employed in this interface.

Figure 22 shows a circuit diagram of the interface and it has the following main functions:

1. Buffering buses including data bus, address bus and control bus to increase the driven ability and to isolate outside circuits with the computer as long as the buffer is in a high resistance state. It means that when outside circuits are not selected, they are isolated from the computer. Thus, it can prevent the computer from being influenced by any design defect at the very beginning or by any natural chip failure during operation.
2. Assigning addresses to different circuits for various functions so that any circuit address can be accessed at any desired time and only one address can be accessed at any single moment.
3. Cleaning up page select pulse via 1 MHz bus. All 1 MHz peripherals were clocked by a 1 MHz 50% duty cycle square wave, while the computer control processing unit (CPU) was clocked at twice the speed of the peripherals^[110]. As a result, if the CPU needs to access any device on the 1 MHz bus, the processor had to be slowed down by the special circuit inside of the computer. When generating a valid 1 MHz address pulse, the slow down circuit produced an address decoding glitch even when the 1 MHz clock pulse was high and this could cause problems. Spurious pulses may therefore occur on the various chip select pins, leading to possible malfunction. It is necessary for the interface to clean up the spurious pulse appeared on decoding bus lines.

3.3.2 Function control circuit.

Function control circuit controls all circuits including 1) synchronous control, 2) time gate and amplitude gate, 3) time measurement and signal width extraction.

3.3.2.1 Synchronous circuit.

It is known that many chips, such as counters, memories, read/write control chips,

depend on clock pulses to realize their functions. In the circuits, a 50 MHz crystal was used to generate the clock pulses which controlled all circuits and served as a basic clock for signal time measurement as well. As discussed before, using a 50 MHz clock, the time measuring accuracy was 0.01 micro-second.

In addition, the time measurement circuit and the flash analogue to digital converter need a synchronous signal to start working; because both clock and ultrasonic output signals (sync and video) repeat continuously. As discussed before, the leading edge of the initial pulse from the ultrasonic instrument was the best signal for this purpose (as the time origin). However, because initial pulse repetition had a frequency of 0.7, 3.0 and 10.0 KHz, circuits were always "busy" with time measuring, data storing and analogue to digital converting if circuits were synchronized by the initial pulse itself. This meant that circuits were working all the time and would be out of the control of the computer or operators if the data acquisition circuit worked every time when the initial pulse appeared. Therefore, on one hand, another control signal was necessary to solve the above problem. That is, a signal from the computer, which is defined as a start signal, is required to initialize the synchronous circuit, this signal can be simply an address select signal. On the other hand, the start signal itself is not capable of realizing the function of process synchronization. It is only a signal informing synchronous circuit ready to start and is not a synchronous signal and cannot be taken as a time origin because of its time randomness relative to the ultrasonic instrument.

Therefore, an adequate control synchronous signal should be composed of a start signal from the computer and a synchronous signal from the ultrasonic instrument. The circuit for this role is shown in figure 23 and its time sequence is shown in figure 24. From this, it can be summarized as follows:

The start signal from the computer initializes the synchronous circuit and thus controls the process. After the start signal, the circuit waits for a sync pulse from the ultrasonic instrument and for detecting the leading edge of the initial pulse.

As the initial pulse is the first peak from the video output after the sync signal, it is easy to distinguish from other video peaks. After that, the initial pulse triggers the time measuring counters and the second sync pulse of the ultrasonic instrument locks circuits back into a wait state until another start signal is received from the computer. It thus prevents the circuit from being busy working all the time. In the wait period, circuits are "free" and can be accessed by the computer in any way at any time, such as reading, transferring data or sending another start signal to repeat the whole process. In this way, the circuit only works for a cycle of sync periods for each sampling period.

As a result, there exist two kinds of frequency relating to data sampling. The first is the frequency of analogue to digital conversion, which is hardware dependent, and controls the A/D converter. The data from each period represents a point of an A-scan signal. The second is the repeat frequency of the start signal, which is software dependent, and controls all the circuits including peak detector and flash analogue to digital converter. The data from each period are a group of A-scan signal data and represents a line in a B-scan graph. To distinguish these two kinds of frequencies, they are called respectively (the first frequency) conversion frequency and the second, sampling frequency.

3.3.2.2 Time gate circuit.

The Time gate circuit is shown in figure 25 and its time sequence diagram in figure 24.

In the circuit, a octal latch was used to store the gate value from the computer and two 4-bit magnitude comparators were used to compare the datum in the latch with the datum from the time measurement counters; which was equal to the time since time counting started. That is, datum from these counters increased with the signal time. When it was equal to, or larger than, the datum stored in the latch, the output state of the comparators changed, (as in figure 24) point G inverted from

high to low. As a result, if this change of state was used to control the acquisition circuit in such a way that it only worked when point G was low, it fulfilled the required function of a time gate circuit.

Furthermore, it was known from the circuit that port A of the comparators connected to the output lines T3 to T10 of the time counters respectively, which covered a range of 8 to 2048 cycles in steps of 8, whereas the datum range of port B is 0 to 255. As a result, when the datum in the latch varied from 0 to 255, the gate time varied from 0.2 to 51.2 micro-seconds accordingly, with a step of 0.2 micro-seconds (if a 40 MHz frequency clock is used). That meant that the time gate had a range of 0.2 to 51.2 micro-seconds, or 0.4 to 102.4 micro-seconds if using 20 MHz clock. Additionally, since the datum in the latch is software dependent, the gate time can be easily changed via programs at any time.

As a summary, this time gate enables that only those signals concerned were sampled, and thus it not only can get rid of any signals or noise outside of the time gate, it can also save time, a great amount of time in some cases, for transferring, storing and analysing data.

3.3.2.3 Peak detector.

The peak detector was a circuit to extract the peak time and width of every peak and temporarily to store them in the memory together with the relevant peak number. The circuit is shown in figure 26.

In the circuit, three synchronous binary counters were used. Amongst them, two were for measuring the signal width and one for counting peak numbers. Consequently, peak width had an upper limit of 255 cycles, which meant, it could measure peak width up to 12.75 micro-seconds if using a 20 MHz clock, or 6.375 micro-seconds if using a 40 MHz clock, a time large enough for realistic defect detection. As for peak numbers, up to 16 peaks could be detected for a single

sample cycle. Though this was sufficient for general use, it could be simply expanded to 256 peaks for each sample by adding another counter in series. In addition, a 3 to 8 line decoder was used for reading data from the data storage memory. Other chips were mainly for function control. Their time sequence diagram is shown in figure 27. It is clear from figure 27 that the process of peak detection was as follows:

Time gate signal F (as discussed in 3.3.2.2), changed state to low only when the signal time was equal to, or larger than, the selected gate time. As a result, function $(F+C)\bar{A}$ made it possible for the time gate circuit to control the peak detector. Only when F was low, could video signal C enter the peak detecting circuit. Combined with the clock pulse, to synchronize fully the process by leading edge of a clock pulse, $(F+C)\bar{A}$ signal generated signal CA, which controlled the peak detecting process. During this process, the signal CA, at point Pa, (see figure 27) triggered signal width counters to begin counting and at the same time, linked all counters including signal time measuring counters, with their respective memory, which then enabled it to store counter data into memory. By point Pb, three function were completed. Firstly, counting of signal width stopped, so the number kept in width counters was the signal width measured. At the same time, it disconnected all counters with their memory and, as a result, the data stored in memory was the correct data of peak time and peak width. Secondly, it increased the number in the peak number counter by one to make the next peak be stored in the next unit of memory; rather than flush the data in the current unit of memory. Thirdly, it cleared peak width counters for recounting when the next peak arrived.

Nevertheless, the above discussion neglected to take into account any time delay needed for correct function. For example, data bus and address bus must be kept stable as long as the write enable pin was active, otherwise the data saved into memory might not be correct. Moreover, the data in counters could be cleared only after the data were securely saved rather than at any earlier time.

Fortunately, simultaneous time delay made the above requirements readily possible. However, the delay time between each other must be suitably designed because too short a time delay may not allow correct function, while too long a delay may affect the next peak, especially, when the time gap between two peaks was very small.

3.3.3 Flash analogue to digital converter.

A schematic diagram of the flash analogue to digital converter circuit is shown in figure 28. The circuit had two main functions, the first to convert video signals from the ultrasonic instrument into digital data and then to store them correctly in memory. The second was to read digital signal data into the computer for performing signal averaging, display and analysis. The circuit was composed of an A/D converter, a memory array, an address decoder and a control circuit block.

1. A/D converter.

A commercial A/D converter chip (MC10319) was the nucleus of this circuit. It converted an analogue signal into an 8 bit digital datum. The range of input signals for this chip was 2 volts which could be any value between -2.0 and +2.0 volts, such as -2.0 to 0, -1 to +1 or 0 to 2.0 volts. So input signals had to be adjusted to the above range. As the ultrasonic instrument only output 'rectified signals', it was more convenient to choose 0 to 2 volts as an input signal range for the chip. Furthermore, because the output signal from the ultrasonic instrument was higher than 2 volts, it was necessary to attenuate, linearly, the input signal to within 2 volts. When a full scale voltage was input into the circuit, it would output a value of 255 with a digitization error of 0.5. This means that the accuracy of analogue to digital conversion is better than 0.2 percent.

The conversion chip used contained 256 parallel voltage comparators. During conversion, the chip compared input voltage with 256 evenly spaced voltages derived from the reference voltages and output digital datum; by encoding the

output states of the 256 comparators according to the relative position of the input signal and reference voltages. To maintain accuracy, the reference voltages had to be kept accurate and stable all the time because they represented the scale of conversion.

2. Memory array.

The reason that the memory was built inside of the A/D circuit was: firstly, the memory in the BBC computer was too small to hold all the data from the A/D converter. In the BBC computer, the memory having been set aside as input/output memory is only 512 bytes in size. Among them, some bytes must be kept aside as circuit control accessing addresses.

Secondly, even had the memory been large enough, the speed of the memory could not meet the demands of the fast analogue to digital conversion rate, because the memory itself operated at low speed, and still worse, "accessing memory through 1 MHz bus will generally be about twenty times slower than accessing memory directly."^[111]

Thirdly, transferring data in the A/D circuit to another location, and then using the memory again to store new data is also impossible because the only place available to store a large amount of data was a floppy disk, but the speed of the floppy disk driver was unacceptably slow and the capacity was not large enough. Consequently, building a large capacity fast access memory inside the A/D circuit became necessary. To simplify circuitry and to save board space, high capacity static random access memory (RAM) was selected. There were two conditions which had to be considered when choosing memories, the first was speed and the second, the size. When a 10 MHz conversion frequency was used, the cycle was of 100 nano-seconds (ns) duration, so the access time of memory must be 100 ns or less if data was to be stored in the memory directly. However, when 20 MHz or high frequency is to be selected, the memory access time must be less than 50 ns, it is

not readily available to purchase a large capacity static memory with this speed in a single chip. The alternative was to use a small capacity fast memory chip as a memory buffer to store the digital data temporarily from a single sample cycle. When the sampling period finished, the data in this memory could be transferred into a large capacity lower speed RAM by special circuit automatically or by computer programs. In this way, a relative low speed memory could be employed to keep large amounts of data.

The memory size required was estimated according to the sample frequency and the expected length of the sampling process, or welding time. Supposing that the highest sampling frequency was 20 Hz and the welding time 2 minutes (which represents an equivalent weld length of 600 millimetres if welding speed is 5 mm per second). Thus the size required to store all the data from whole process would be:

$$\text{Welding time} * \text{sample frequency} * \text{data number each sample}$$

That is:

$$2*60 * 20 * 256/1024 = 600 \text{ kilobytes}$$

In the circuit, 512 kilobytes (KB) were used, which could store all the data for 2048 times of sample with 256 bytes each sample.

3. Control block.

The control block was a block of circuits which controlled the whole process such as converting, writing and reading. It performed two main tasks: correctly to decode memory addresses, to save data and synchronously to time the converting process.

A. Memory decoding

As previously discussed, the size of the built in memory was 512 KB whereas the memory for input and output in the BBC computer was 512 bytes and the address bus had 8 lines, thus all memory can be accessed only

by 'paged mode'. That is, 512 KB was divided into 2048 pages and every page had 256 bytes. In any page, the 256 bytes were accessed directly and randomly by the computer, but to access any byte of 512 KB, the page in which the byte was located must be accessed first through page multiplexing, and then the byte could be accessed.

Furthermore, all the memory had to be accessible both by the A/D converter for writing (storing) or by the computer for reading or writing, but it had to be prevented from accessing by the two simultaneously. Another multiplexer was therefore required to connect the address decoder to the A/D converter or to the computer.

During data storage, (to store the data from the A/D converter into memory instead of writing), it was impossible for the process to be controlled by the computer, in another words, data must be able to be stored into the memory automatically. For the same reason, data should be stored in a sequential way, that is, current datum should be stored in a byte next to the byte with the preceding datum.

B. Process timing.

Process timing circuit controls signal digitizing and datum storage and keeps them working at the correct pace.

The signal voltage to be digitized was applied simultaneously and the data presented prior to the falling edge of the sample clock pulses was digitized and was available at the output 19 nano-seconds after that same falling edge. The datum was latched into the output latch at the same time and kept in the latch until the next datum was latched. After the datum was latched, it was ready to be stored into memory.

According to the timing diagram of the memory used, data write enable

pulse should start after address lines and data lines were stable and should end before address and data changed. The timing diagram of the circuit is shown in figure 29, which was an example in a 10 MHz conversion frequency with a condition that the chips used were low power Schottky (74LS) series TTL.

3.3.4 Welding system control circuit.

The welding system control circuit, see figure 30, was composed of three parts: process control, level control and wire feed control.

1. Process control.

The process control circuit was the circuit which controlled welding start, low speed wire feed and higher voltage for arc ignition, welding stop and so on. Figure 31 is a process sequential diagram for submerged arc welding (SAW).

For welding start, a start pulse was sent from the computer to the circuit by pressing either the welding start key or the remote control start button. This pulse triggered the welding power supply for starting, which turned on the cooling water valve and simultaneously started the process of arc ignition through slow wire feeding and higher voltage. Experimentation proved that arc ignition was more reliable by this method. Immediately after this process, the work table began to move at a preselected speed and wire feed speed and arc voltage returned to the normal values preselected in the program.

During welding, both wire feed speed and level (which determined the welding voltage in the constant voltage mode, see next section) could be adjusted manually or by any specially designed function. As a result, both welding current and welding voltage could be controlled in any desired form to meet different applications.

To stop the welding process, similarly, a stop pulse was sent from the computer. Besides manual stopping via the computer keyboard or remote control button, the computer could automatically sent a stop pulse as soon as the preset welding time elapsed. When the control circuit received a stop pulse, it followed the process indicated in figure 31 to stop the welding process.

2. Level control circuit.

The level control circuit controlled the output levels of the welding power supply. In a constant current mode, the value of the "level" proportionally controlled the welding current and in a constant voltage mode, the welding voltage. To the welding power supply, the level control actually was an input voltage. When the voltage varied in a range of 0 volts to 10 volts, the output current changed from 0 to 1000 amperes. Therefore, the task of the circuit was to generate a voltage ranging from 0 to 10 volts according to the preselected current. In this circuit, a circuit fundamentally similar to a switching power supply was employed. Compared with a digital to analogue converter, it was simpler and a little less linear at low values, but experimental results showed an adequate linearity for the level control (see chapter 4 and figure 35).

3. Wire feed control circuit.

As explained in section 3.1.2, the wire feed unit was driven by a stepping motor which was controlled by a series of pulses and the frequency of the pulse series determined the wire feed speed. Therefore, the purpose of this circuit was to generate the pulse series at any frequency demanded.

According to the manual of the power supply, the relationship between pulse frequency and the wire feed speed was 140 Hertz for one meter per minute (M/Min). Thus, the frequency should be ranged from 0 to 1400 Hz for a designed wire feed range of 0 to 9.99 M/Min. Wire feed speeds determines welding current

for submerged arc welding (SAW) and is one of the critical parameters, it needs to be kept as accurate as possible, which conversely depends upon an accurate pulse series. For this reason, a crystal timer was used because of its accurate and stable oscillating frequency. As the timer frequency was fixed, a frequency demultiplier with changeable division was therefore necessary to obtain different frequencies required.

In the circuit, a 6522 versatile interface adapter was used. The programmable internal timer inside this chip provided the ability to produce square waves on pin PB7 in the free running mode, whose frequency depends on the input frequency and the value latched in a 16 bit internal counter. More accurately, the relationship between input frequency (F_{in}) and output frequency (F_{out}) could be expressed as:

$$F_{out} = F_{in} / \text{value in counter}(V_c) / 2$$

In the circuit, the input frequency was the clock frequency of 1 MHz bus, so the equation became:

$$F_{out} = 500000 / V_c$$

Or in another way, the relationship between the wire feed speed (S_{wf}) and the counter value:

$$S_{wf} = 3571.43 / V_c$$

According to the above relationship, the values latched in the counter could be calculated directly from the required wire feed speed.

As the chip 6522 had two parallel ports, port A was used to store the data which controlled the "level" of the welding power supply.

3.4 SOFTWARE.

3.4.1 Introduction.

It is well known that software is indispensable for any flexible close loop control

system. Software not only makes function control possible by combining with hardware to fulfil all designed functions of hardware circuits, but also enhances the ability of the system. Actually, software and hardware are both supplementary and complementary to each other. For example, a given function may be achieved either by a hardware circuit or by a software program in many cases. Generally, software methods are cheaper and much more flexible whereas hardware methods can reach very high execution speeds. A perfect experimental system therefore; should be a combination of both hardware and software.

As stated in section 3.1, the computer used in the system was a BBC model B computer. This computer has two critical weaknesses: the first is the random access memory (RAM) size. There are only 32 KB altogether, more than 6 KB of which has been used by operating system and disk filing system (DFS). Several other kilobytes are used for display which depends on the mode selected. Using mode 0, 1 or 2, for instance, the computer uses 20 KB for screen display and thus, the memory left for any user program is less than 6 KB. Even though part of the operating system memory for DFS or displaying may be used by skilful arrangement, the memory size for user programs remains very small. The second is the program execution speed, the 2 MHz clock used in this computer is, itself, not fast and using a BASIC interpreter aggravates this problem.

To overcome the above two weaknesses, an effective and powerful method is to use the assembly language, despite the fact that programming in assembly is difficult and more time consuming to write. Therefore, a combination of the BASIC and assembly languages in writing programs is the effective way to avoid these disadvantages and to make full use of the advantages of the two languages.

System programs were written in the structure of a main program supported by procedures or subroutines. In this way, a large program for a big task was divided into several small named procedures and each procedure fulfilled a particular task. A procedure can be put into execution by the main program through calling its

exclusive name. This is a "calling" process, in which it tells the computer to go and to obey the procedure definition and to return when it finishes the procedure. Similarly a procedure can call another procedure and so on. It can even call itself (a system which is strictly forbidden in a standard BASIC program). This process is called recursion which makes some programs easier to write. Therefore, a large program can be written and tested separately and additional functions can easily be added into programs by adding the relative procedures. In addition, assembly language programs were inserted into programs in a similar way except that they were called by their addresses rather than their names. As a result, programs in this structure are easy written, debugged and understood.

Furthermore, to simplify the operation of programs, all programs were menu driven (see figure 32(a)). Command information and options were displayed on the visual display unit (VDU) screen and replies were selected using the keyboard. A man-machine interactive interface had been established to allow easy use with meaningful reports and a clear screen presentation. A program named "AUTO" may be taken as an example. When the program started execution, it separated the VDU screen into two areas (see figure 32(b)). The upper area was for command information, process options and parameters selection. Whilst the lower area was a high resolution graphic area for displaying digital data and A-scan signals in real-time. In the first area, two kinds of information was displayed, one for controlling actions, the other for setting up parameters. Keys to control actions were called action keys because actions were taken whenever they were pressed. For instance, when the welding start key (Ctrl-W) was pressed, the following actions were taken:

At first, the computer sent a welding start pulse to trigger the welding system control circuit, which immediately turned on the welding power supply. An arc ignition program via low wire feed speed and higher voltage was called to ignite an arc. During this program, parameters proven efficient by experimentation for arc ignition were used to enable successful arc ignition. After that, the work table was turned on and information "WELDING, TABLE ON" was displayed on the

screen to indicate the current state. Execution then passed to the main welding process control program.

In the welding process, a sampling start pulse, (see section 3.3.2.1) was repetitively sent to initialize the data acquisition circuit. Then the computer obtained data from the peak detector, compacted the data (to save memory space) and stored it in data memory inside the computer. During this process, if either the characteristic parameters of peaks or real A-scan signals, or both of them, were requested on screen display (and time allowed to ensure that sampling frequency was not influenced), the program would display them in a real-time. Otherwise, the computer would beep to inform operators and then ignore the display request.

Furthermore, during welding, parameters were controlled by the function defined by the operator, thus it was easier to perform some experiments about welding parameters effects on results. For instance, an experiment about the general effect of welding current on ultrasonic velocity was carried out using this facility. Finally, the welding time and the welding stop command were frequently checked to decide whether the welding process was to be continued. A welding stop command could be a stop key pressed or a remote control signal. As soon as a given welding time was reached or a stop command came, the welding process terminated immediately and whole welding time spent was displayed. After this, if the program was told to sample signal continually, which was the situation when sampling time preset was longer than the welding time, the process continued except that no welding current was available until the sampling time length was passed. Otherwise the program waited for another command from the operator such as displaying the signals stored in the memory individually, or saving the data onto disks.

Keys similar to action keys were those for setting up parameters and were called "setting up keys". Every time a setting up key was pressed, the program transferred to a procedure for operators to input selected parameters. After a new parameter was input, the program analyzed the parameter to check its feasibility and returned

to the main program.

3.4.2 Programming techniques.

As expressed previously, the main shortcomings of the BBC computer were, lack of memory and its slow speed. In order to compensate for these weaknesses, some special techniques were utilized.

1. Techniques to save memory space.

A) Overlapping programs.

As discussed before, programs were composed of a main program and some procedures. Among the procedures, some were fully "parallel", or in another words, these procedures never called each other. Therefore, these procedures could be arranged using the same memory space. This technique is termed "overlapping programs" in this work; and it is not a standard method in BBC BASIC and cannot be achieved by any standard BASIC function. It utilized a specially designed procedure. The procedure being overlapped was always kept on disks and was "loaded" by reading it like a data file and was appended to the end of the current program when it was being called. The execution was transferred to the procedure newly appended and the newly appended procedure was removed from the memory afterwards. In this way, all variables and input parameters in the program could be used for every procedure. However, every time the procedure was being called, it needed "loading", which reduced the execution speed. Therefore, the technique was specially useful when the procedure was not frequently called and whenever called, the speed was not critical. In the "AUTO" control program, the procedures kept in this way were the procedures for modifying input parameters and for saving data.

B) Using the system memory.

Firstly, according to reference [111], some of the operating system memory was

used as series input/output buffers, cassette input/output buffers, sound generating buffers and buffers for user defined keys. These memory areas could be utilized for programs if the series input/output, the cassette filing system and so on, were not used in these programmes. However, these memory areas could not be directly used for BASIC programs, because programs in BASIC had to be kept in a continuous area, whereas all these areas were separated from the standard program area. Even though, they were still able to be utilized for assembly language programmes or as data buffers (because assembly language programmes and data buffers can make full use of any RAM space available to them by correct arrangement). As a result, memory saving could be achieved by using assembly language programs.

Secondly, in the BBC model B computer with a disk filing system, the memory from &E00 to &18FF was used for the DFS work space, that is, the standard start address for BASIC programs was raised to &1900. This was the default "PAGE" address whenever the computer was reset. This meant that the DFS used 2816 bytes more than a tape filing system (TFS). Thus 2816 bytes can be saved if using a TFS, but losing all the advantages and facilities a DFS supplied, and this was not acceptable for the system. A better way was partially to use the DFS. For example, after a program was loaded from a disk using the DFS, the computer was changed to the TFS and left the memory used by the DFS for data buffers or for programmes by transferring programs to the memory before the program was executed. In this way, the memory for DFS work spaces could be fully utilized but all the disk operations during program execution were forbidden and program overlapping (discussed in the previous section) was not allowed either. Additionally, it was not convenient to use this method because programs can not be "chained" and executed continuously. So it was not adopted in these programs. The best way was partly to use the memory, with DFS being kept active all the time. According to reference [112], there are 5 files which can be allowed open at the same time and a certain memory was allocated to each opened file as an input/output buffer. Therefore, if the number of files opened simultaneously was

reduced, the buffers for opening files thus could be used for the program by simply changing the "page" address. Using this method, programs did not need modifying and were executed in the same way without any inconvenience and, the most significantly, it could fully make use of the advantages and facilities of the disk filing system supplied. This is the technique which was adopted in this work.

C) Compacting programs and data.

When a large program was being written or tested, spaces, meaningful variable names (which might be longer than necessary), variables after the keyword "NEXT" or even some remarks and so on were usually required. However, because BASIC is an interpreted language, all these occupied extra program spaces. Therefore, after a program was tested, it could be compacted by removing all spaces, remarks and variable names after "NEXT" as well as shortening variable names. By compacting, as much as 50 per cent of program space could be saved in some cases.^[113]

Similarly, data could be compacted using binary format rather than ASCII format, which can save a great amount of space. Furthermore, as previously indicated, the peak detector could extract the characteristic parameters of up to 16 peaks in a single sample. Each peak needed 3 bytes to store its data, one for signal width and two for signal time. In many cases, there were less than 16 peaks (or even no peaks at all). As a result, if data are compacted by neglecting all zero parameters and inserting a special symbol between each sample to distinguish data from different samples, some further spaces could be saved.

2. Techniques to increase speed.

Besides the general techniques recommended in reference [110] such as using integer variables (especially the resident integer variables), using procedures instead of subroutines, there were two other techniques which were utilized and developed in our programs.

A) Using assembly language.

It is well known that the best and most efficient way of maximising execution speed is by using assembly language. Though use of assembly language increases the difficulties of writing and debugging programmes, it enables increases in the execution speed by several tens to several hundreds of times and enables full use to be made of the facilities of the BBC computer. It makes it possible for the computer to perform multiple function controls or a large amount of data analysis in a real time. Without using assembly language it would be impossible.

B) Direct display memory accessing or direct screen accessing.

All on-screen displays depend on a cathode ray tube controller chip in the BBC computer. This chip converts the video data in the memory into signals to drive a CRT and displays them on the screen. There is a fully corresponding relationship between the display memory unit and the screen pixel. In another words, each pixel on the screen corresponds to a bit (or several bits) in the display memory according to the mode selected, except in the teletext mode. Generally, when data or video signals need displaying, a command or a function designed in the operating system or the BASIC interpreter, (such as print, draw, plot or a corresponding system call) can be used, which sends the data or the signals into the memory for display. In this way, programmers do not need to know any intermediate processes, such as where to put the data in the memory for displaying texts or signals, how to process the data for a selected mode and selected colour, and how to display them in the correct place, so it is easy and convenient to use. However, this simplicity and convenience has its price to pay; the relative low speed. If all the intermediate processes evolved in displaying commands or functions were avoided, the speed of display would increase accordingly. This advantage would be given full play when the signals to be displayed could be restricted with a fixed size in screen area and fixed colour framework. This was the situation in this system for display A-scan signals. This technique was termed 'direct display memory accessing technique' or 'direct screen accessing'. The results of using this technique proved that it could increase speed by as many as 5 to 10

times than those using assembly language programs which called for standard system display procedures.

Finally, as reference [110] stated: "sometimes there is a trade off between the size of a program and the speed". This means that saving space will usually reduce speed or vice-versa. However, the techniques discussed in this section are the exceptions to this statement. Both using assembly language and compacting programs make it possible to save space and to increase speed simultaneously, whilst using the system memory and direct display memory accessing can save space or increase speed with no side effects to the other side. The overlapping program technique reduces speed but it was only used at the time when execution speed was not critical.

3. Techniques to print signal graphics on paper.

Printing signal graphics on paper was more difficult than printing text or displaying signal graphs on a VDU screen, because there was no standard function or command which could be utilized in the computer. Therefore, a specially designed program was required to print graphs on paper. For a dot matrix printer, the smallest printing unit is a dot. The task of a graphic print program was to control each dot so that it printed in the desired place. In other words, two things needed to be controlled during printing, one was the movement of the printer head to the correct place, the other was to chose the correct pin or pins to print. There were two methods used in these programs.

The first method was 'direct printing', which was used to print graphs composed of (or possibly to be expressed in) straight lines, such as A-scan signals and B-scan graphics. During printing, the program calculated the distance in dot units relative to the previous position and moved the head to the new position by inserting "blank dots" and then controlled the corresponding pin or pins to print a dot (or dots) using the bit image mode of the printer. By repeating the above process, a whole

graph could be printed. By this method, a program printed a graph directly from the data without converting the data into an image, thus the printing speed was quicker than the indirect method about to be discussed.

The indirect (or 'screen printing') method was designed to print a 3 dimensional graph composed of a group of A-scan signals or any other kinds of pictures. When using the direct printing method to print this kind of picture, the program needed many calculations for each line of printing because each line intersected a group of A-scan signals. As a result, the program would be very complicated and the printing speed would be very slow. Fortunately, as indicated before, there are ready functions and system calls in the computer for displaying signals or drawing pictures on the screen. If a fixed relationship could be found or decided in a given mode between each pixel on the screen and a dot on printed paper, it is possible to move the picture on the screen onto paper by copying each pixel of the screen respectively. That is, by turning pins on or off according to the contents of the displaying memory, the graph on the screen could be printed onto paper. This is usually called 'screen printing'. In addition, due to the large differences between the total number of pixels on screen and that on paper, it is possible to print several screens on to a piece of paper to generate a large picture or print a graph in different greys to represent different colours on the screen. Similarly, it is also possible to enlarge or to shrink graphs by copying a pixel to several dots or vice versa.

3.4.3 Software functions.

Figure 33 shows a schematic diagram of the programs designed for this work which could be classified into three major groups:

The first group consists of only one program named "AUTO" which was an on-line controlling program. Its main functions were:

A) to control data acquisition, for which conversion frequency, sample

frequency, time window and amplitude gate can be selected or modified by operators to obtain desired results.

- B) to perform A-scan data averaging and to analyze B-scan data statistically. Both of them were for increasing signal to noise ratio and producing stable and reliable results.
- C) to compact and to analyze B-scan data, to extract signals from original data and to store them in the data memory. In addition, it can save data stored in the built in memory onto several disks at any one time continuously.
- D) to display real time A-scan signals on a screen window, which served as a digital signal scope. This was useful when setting ultrasonic parameters and testing circuits.
- E) to control the whole welding process and welding parameters according to any preset function. It was extremely helpful when performing experiments for the effects of welding parameters.

The second group of programs were mainly for displaying and printing signal graphs including A-scan, B-scan and 3 dimensional graphs. During display, it selected scales according the signal data automatically or manually. Furthermore, graphs could be "zoomed in" or "out" manually by setting scales.

The third group of programs consisted of two set of programs. One was a data conversion program which converted a group of A-scan digital data into a group of B-scan data according to a selected amplitude gate. Besides obtaining B-scan data, this program could be used for performing amplitude gate simulation. The other programs were utilities such as assembly debugging and program compacting. The assembly debugging program was essential for writing and testing assembly language programs, such as de-assembling a machine code language program back into assembly for testing, monitoring and controlling the running process of a program, monitoring and modifying the contents of registers of CPU or any byte of RAM.

4. EXPERIMENTAL TECHNIQUES AND RESULTS

4.1 SYSTEM TESTING.

Some basic calibration tests were carried out to ensure the quality of the designed system and, after calibration the system was utilized to perform some essential tests for optimizing ultrasonic parameters.

4.1.1 Calibration

As an ultrasonic system for defect detection, the most important qualities are linearity, accuracy, sensitivity and resolution.

A. Linearity and accuracy

Linearity and accuracy includes three aspects: a) time linearity and accuracy, b) amplitude linearity and accuracy, and c) welding parameters linearity and accuracy.

The first is the time linearity and the time accuracy which depend on frequency stability and the accuracy of the clock pulse which is generated by a quartz crystal. It is known that the frequency of quartz crystals is very stable and the time linearity is excellent so that no calibration is actually needed. In addition, the system digitized signal time and output digital time directly, so standard calibration before inspection which was necessary if using an analogue ultrasonic instrument was not required when using this system to perform defect detection. The advantages therefore were obvious: firstly, operators could get rid of the time consuming calibration process during which a standard calibration block made of the same material as the test specimen and with an accurate thickness was necessary to obtain the signal time or defect distance from the probe. During the calibration process for an analogue instrument, repetitively adjusting "DELAY", "RANGE" and "MATERIAL CALIBRATION" was essential to establish a simple relationship

between the position on the screen and the distance in the material, which was time consuming to achieve accurate results. Secondly, the results from the digital system were more stable and reproducible because the calibration process for the analogue ultrasonic instrument could be affected by the operators' experience and their mood at that moment.

Time accuracy depends on the accuracy of the clock frequency itself and the digitization error. A clock frequency test by using an RS calibrated frequency meter (which was claimed to have a accuracy of 0.3 parts per million (PPM)) showed that the accuracy of the clock pulse was 12.9 PPM. Whereas the digitization error was half a cycle of the pulse, that is, 0.025 micro-seconds for 20 MHz clock.

Second is amplitude linearity and amplitude accuracy which depend on the A/D conversion circuit. Figure 34 is the result from the linear test. It is clear from the results that linearity is excellent. As for the accuracy which was dictated by the accuracy of the A/D chip itself, it was claimed by the manufacturers to be 1/2 least significant bit (LSB), i.e., better than 2 per thousand.

Third is the accuracy and the linearity of the welding parameters, including wire feed speeds and level output (for controlling welding current and voltage). As wire feed speed was controlled by a stepper motor via a frequency de-multiplier from the crystal pulses, the wire feed speed was as accurate as the clock frequency itself. This meant that the wire feed speed could be very precisely controlled, which was significant for accurately controlling welding current of SAW processes. Figure 35 is the results of linearity and accuracy from level output tests. From the results, the linearity was fairly good between the output scope of 0.3 to 9.5 volts, which corresponded to the range of the welding current of 30 to 950 amperes or voltage of 3 to 50 volts. This range covered the full range of welding experiments. In other words, welding application ranges were within the linear scope of the system level output. Similarly the digitization error was 1/2 LSB, so the relative error was

better than 3 per thousand.

B) Sensitivity and resolution.

Figure 36 shows the sample used for sensitivity tests and the results. The test was performed by using the designed digital ultrasonic system introduced previously, and, a 1/4 inch 5 MHz longitudinal wave probe on a mild steel block with a one millimetre flat bottomed hole drilled at the underside. The arrangement is shown in figure 36(a). The result (figure 36(b)) shows clearly that the one millimetre hole was easily detected.

Figure 37 shows a sample and results of a resolution test. A one millimetre wide 2 mm deep slot was cut at the bottom of a mild steel block. The arrangement is shown in figure 37(a) and the equipment and the probe used were the same as those used in the sensitivity test. The reflections from that slot were separated clearly in the A-scan graph (figure 37(b)). Actually, the standard calibration block for welding defects inspection (the "V1 block", see figure 38(a)) designed by the International Institute of Welding has a 2 mm wide 6 mm deep slot cut at the bottom. Figure 38(b) is the result from this block in which three peaks were widely separated from each other.

It is known that there are a lot of things which can affect the sensitivity and the resolution of an ultrasonic system. As for the system designed, the resolution and the sensitivity practically depend on the probe and the ultrasonic instrument rather than the computer controlled digital system. The reason is that the digital system has a time resolution of 0.02 micro-seconds which is equal to a distance of 0.12 millimetre in mild steel for a longitudinal wave. This resolution is much higher than the possible resolution an analogue ultrasonic instrument can reach. It is also true for the sensitivity, that is, the sensitivity of the digital system depends on the ultrasonic instrument rather than the computer controlled digital system.

4.1.2 Amplitude versus signal width.

As indicated before, peak width was easier and quicker to obtain than peak amplitude because the former could be directly obtained from a simple hardware circuit, whereas the latter usually relies on complicated combination of hardware and software to extract. Therefore, it is desirable to replace signal amplitude with peak width, if the replacement has an acceptable reliability. For this purpose, several experiments were performed.

When a probe was firmly applied on a sample, the initial pulse left the transducer and passed through the couplant and then entered into the sample. After the sound pulse was reflected from the back wall and reached the front of the wall, part of it left the wall and the first back wall reflection was received by the probe. The rest was reflected and passed through the wall a second time until a second back wall echo was received, and so on. If the wall surfaces were sufficiently flat and parallel to each other, a clear back wall reflection sequence could be obtained. It could be deduced that for multiple reflections the amplitude ratio of the current peak to the previous peak met an exponential relation. Figure 39 shows some A-scan graphs with multiple reflections. The test conditions are, besides those indicated in the figure, 2.25 MHz longitudinal wave probe, 20 mm thick mild steel block. The frequencies used were 2, 5, 10 MHz and broad band respectively.

Figure 40 shows the peak width and amplitude of each peak from multiple reflections tests. The results indicated that the amplitude of both groups decreased exponentially with the peak number, which was fully coherent with the theoretical prediction made before. Furthermore, because of the saturation of the peak amplitude, the exponential relationship only matched for several peaks. This meant that the exponential relation of peak amplitude could be utilized as a criterion for only several peaks but not for all peaks. In contrast, the peak width could be used for all peaks because it never saturates despite the fact that the linear relationship between the peak width and the peak number (or peak energy) is not versatile

enough to be accurate for all the range of multiple reflections. In addition, from figure 40, the linear relationship worked well except for the first peak and the last peak in group A. The deviation from the linear relationship was mainly caused by the trailing edge shape of the peaks. Compared with peaks in group A, peaks in group B had "better" trailing edges and, as a result, the peak width was coherent better with the linear relationship.

Similar results were obtained from tests on the relationship between change of gain and change of amplitude as well as peak width. Figure 41 shows these results. In the tests, all parameters were kept constant except for the gain which was adjusted through both the coarse and the fine gain controlling knobs of the ultrasonic equipment. Because the rated scale of the coarse knob did not match accurately with the fine adjusting knob, the results in the figure had steps whenever a coarse knob was adjusted. However, the results showed a similar regulation and relationship as in the situation of multiple reflections.

To prove the versatility of the above regulation, tests on different defect sizes and on different defect distances were performed. Figure 42 is the results of signal amplitude and peak width with the change of defect distances. The tests used a mild steel block which had a group of side drilled holes as defects, of the same size but at different distances. Figure 43 shows the results from different defect sizes. This test was performed by utilizing a perspex block which had a set of different radii flat bottomed holes drilled in the underside of the block to simulate different sized defects at a constant distance. Both figures suggested that a versatile existence for the above illustrated phenomena of signal amplitude and peak width.

All in all, from the results in the above figures, peak width can serve as a criterion for defect detection though it exists as a deviation to linear relationship in some cases, such as the results in defect distance or defect size tests. However, the conclusion is always true that a wider peak represents a larger signal peak when the amplitude gate is fixed. In other words, a wider peak always corresponds to a

larger or a closer defect. Moreover, compared with the signal amplitude, peak width has a much larger measurement range because they never saturate. Therefore, peak width can be used as a replacement of peak amplitude in quick and preliminary defect detection when using a digital ultrasonic system.

4.1.3 Datum point for measuring time.

It is well known that the signal time is a very important ultrasonic parameter. However, due to the fact of non-zero peak width, its measuring accuracy is affected by a standard measuring point (termed the datum point in this work) which is selected as the base for time measurement. As shown in figure 44, the datum point can be the leading edge labelled A, trailing edge B, geometrical centre C, apex or the end of leading edge D or some other points between A and B. Obviously, different points will produce different time results. Which point is more accurate for measuring ultrasonic signal time?

It is known that the measured time of back wall echoes from the same specimen should be kept constant if the thickness of the plate is fixed, regardless of the difference of the ultrasonic parameters (like amplification or gain). In other words, the datum point is such a point that the time measured based on this point is kept constant and is not affected by ultrasonic parameters. It is also true that the time between multiple reflections should be kept the same if the measurement is based on the datum point. This indicated to us that the datum point could be obtained through comparing the data based on different points under a continuous change of parameters. Figure 45 is a B-scan graph from a multi-reflection test in which all conditions were fixed except for the equipment gain. The figure clearly showed that the signal time based on point A, i.e. the leading edge of peaks, was more accurate than the time on the trailing edge. The reason is that the time on point A hardly decreases with the increase of gain while the time on point B increases more severely. This phenomena could be explained simply as follows: as gain increases, peaks became larger, which moved the leading edge slightly left and the

trailing edge a great deal to the right, especially when the peak was large (see also in figure 46). This implies that there must exist a point between A and B which does not move when the gain changes and this point can be named the "real centre" and is the point being sought for. However, it is practically very difficult to find an accurate equation suitable for all conditions to calculate this point, nor is it necessary for general defect detection. A simple empiric expression from experiments for approaching the real centre can be expressed as:

$$A + 1/8 * (B - A)$$

Or in words, a more accurate signal time could be obtained from the time on the leading edge plus one eighth of the peak width. The time calculated according to this expression is labelled E in the figure 44. That the linear regression from data on point E resulted in a horizontal line indicated that point E was the "real centre" (see figure 46).

Although fluctuations of measured time existed in the above results, which was mainly caused by the digitization error, the phase conversion of the received ultrasonic pulses and so on, the results showed a consistent regularity: The leading edge of a peak is a more accurate point for measuring time than the trailing edge or the geometric centre of the peak, and the leading edge is acceptable for time measurement in general engineering experimentation. In this work, signal time was measured based on this point except for those specially indicated. In addition, if more accurate timing is required, then point E, simply calculated from the time on the leading edge and the peak width, should be utilized.

4.2 EXPERIMENTAL SIMULATION.

Only a system which is capable of detecting weld defects, on line, at room temperature can be possible to detect weld defects during welding. In other words, room temperature weld defect detection is the first step towards on line defect detection during welding. In addition, because of the complexities and the time consuming preparations needed for defect detection during welding, it is helpful to

perform some basic experiments at room temperature first so as to substitute the experiments during welding; if the regularity from room temperature experiments is also true for the experiment during welding. However, specimens with different defects and different sizes are not easy to produce, and actually, welds with defects of given sizes and fixed locations are practically impossible to produce. For this reason, some perspex blocks with designed "defect" types, sizes and positions were made to simulate various defects. Figure 47 is a schematic structure diagram of the simulation test block. The block was made in two steps:

1. Cut grooves and holes with designed shapes, sizes and positions in the side edge of a perspex plate.
2. Fasten this plate to another plate by adhesion with solvent.

The advantages of using this kind of perspex block were obvious:

1. It could produce any desired "defects" with any practical sizes and positions because the "defects" were machined on the plates. This enabled us to simulate any defect with any size and location.
2. It produced an air/solid interface in the place of "defects", which gave the same situation as most real weld defects such as lack of root fusion, cracks and porosity. This made the simulation results and regularity obtained from the simulation more accurate to those from real weld defect detection.
3. It eliminated the interface between two plates where no "defect" existed. This was an essential requirement for the block to function. As a result, the block could be used both in the pulse-echo mode or the through-transmission mode, which could not be performed accurately with other kinds of blocks.

Strictly speaking, the interface between two plates by this joining method could not be totally obviated because the layer dissolved by solvent had some slight changes in surface conditions, and, as a result, some ultrasonic energy

could be reflected back when most of the energy passed through the layer. It was demonstrated by experiments that about 92% to 96% of the energy passed through the interface and only about 4 to 8 per cent of the beam energy was reflected back. This made a great difference to those "defect" areas where a 100 per cent of the energy is reflected back and made it easy to detect these "defects".

The process used to demonstrate the above solution was as follows: preparing two samples and taking the gain values for a half screen high of first back wall echo before and after the joining of plates as G_1 and G_2 respectively. For this process, all the ultrasonic parameters except for gain, as well as experimental conditions were kept fixed, such as, frequency, damping, probe position and coupling state. The readings from two samples were: G_1 : 73, 73; G_2 : 84, 87.

Apart from the results, it was supposed that the material was inhomogeneous and the coupling difference for experiments before and after link was negligible. Based on these assumptions, it proved that the factor (K) of the beam energy passed through the interface could be expressed as (see appendix A for detail):

$$K = 1 - 10^{(G_1 - G_2)/10}$$

Replacing G_1 , G_2 with the experiment readings to obtain the solution that the energy passed through the interface was 92.06 and 96.02 per cent respectively.

Several experiments were performed through using this kind of simulation block and some typical results are shown in figure 48 which also shows a schematic diagram of defects in the block and the X-ray test result. This figure clearly shows the following:

1. All defects could be detected at a single run. The probe used was 1/2 inch in diameter and 45° shear wave for ferritic steel, this generated a 36.7° longitudinal wave and an 18.24° shear wave in the simulation block. The reflections in the figure were from a longitudinal wave beam. The longitudinal beam from this probe could "illuminate" a area vertically larger

than 20 mm in diameter even when the beam spread was neglected. This meant that the beam covered all defects areas if the beam was focused on the centre of the plate side edge. The reflections in the figure were obtained when the beam centre was focused on a position of 8 mm from the bottom of the plate, and even so, all defects were exposed, this indicated that the system designed could detect defects reliably on line.

2. The peak width of reflections from defects corresponded to the defect size when the distance of defect to probe was the same. The defects labelled C and D in the figure changed their sizes gradually and produced the reflections whose peak width varied accordingly. However, it seemed that large deviations existed for defect D which generated even a bigger peak width at the smaller end of the defect. Careful inspection revealed that the large peak width at the end was generated by a fault in the block manufacturing. When producing samples, the surfaces were manually polished by using emery paper and this made the surface bevelled slightly rather than flat and, as a result, a very thin gap labelled E in the figure was actually produced at the end when the two plates were joined together, which generated the larger peak width at the end of the sample. This was proved by the X-ray results in the same figure which clearly showed this gap in the corresponding position. Here, the results demonstrated again that the peak width could serve as a criterion for sizing defects.
3. The reflections from plane defects (labelled B, C or D in the figure) had large differences to those from bulk defects like porosity (labelled A). Firstly, plane defects produced reflections whose peak width changed gradually and continuously, whilst the reflections from porosity were very "unstable", both peak width and peak time changed quickly and even disappeared suddenly. Secondly, plane defects usually produced a single peak whilst the porosity generated multi-peak reflections. some A-scan graphs (see figure 49) showed this regulation more clearly than the B-scan

graph did. This regulation enabled bulk defects and plane defects to be distinguished on-line.

In summation, simulation results discussed above indicated that the system designed could be well used to detect weld defects at room temperature or used for weld inspection after welding. Moreover, the room temperature simulation provided some helpful information and regulation which could be employed to judge and to assess different defects in welds during welding.

4.3 HIGH TEMPERATURE EFFECTS ON RESULTS.

The main and the most important difference in defect detection between the defect detection at room temperature and the detection during welding is temperature. As it is well known that the high temperature of a welding arc can influence ultrasound velocity and attenuation and, in turn, affect signal time and signal amplitude. This will increase the difficulty to locate and also to size weld defects, even to determine whether there is any defect inside the weld. Therefore, it is necessary to investigate the influences of high temperatures on signal time and amplitude.

Static relationship of ultrasound velocity and attenuation with specimen temperature were well established^[87,88]. This made it possible to calculate the change of velocity and attenuation at each point along an ultrasound beam and to obtain overall effects of welding temperature on ultrasonic signal time and signal amplitude provided that the temperature field along the ultrasound beam line was accurately known. However, the temperature field surrounding a weld pool changes abruptly and the temperature gradient near the weld pool is so steep that it is very difficult to measure accurately. Moreover, the temperature field has much variation between different welding preparations, different welding parameters and even greater variations between different welding techniques. Therefore, an accurate calculation of welding temperature effects on ultrasonic

signal time and amplitude is very difficult and practically undeserving if the calculation is for weld defect detection.

4.3.1 Arrangement.

Although it is very difficult to measure accurately the effects of the high temperature on ultrasound because of those factors indicated previously, it is possible to make some estimation through experimental testing. For the purpose of weld defect detection, the important aspect of testing is not to measure the values of velocity or attenuation at each point along the ultrasound beam (which is very difficult to obtain), instead, the significant result is the overall effect or integrated change of signal time and signal amplitude caused by the high welding temperature field. This means that the task is to find the differences of signal time and signal amplitude (or peak energy) between the results at room temperature and those during welding. For this purpose, the ultrasound beam should be focused on a point which is very close to the weld pool to produce satisfactory experiment results. On the other hand, this point should not be too close to the weld pool to prevent it from melting so that the probe could receive the reflection from the same point during the whole experiment process. In addition, the arrangement should be designed as close as possible to the situation in real weld defect detection to obtain the results suitable for real defect detection. Figure 50 is a schematic diagram of experiment arrangements. Figure 50(a) is for the situation of welding root pass (arrangement (a) for short) which is the same as the experimental arrangement for defect detection during welding except for root openings and root faces. Whilst figure 50(b) is for the top pass of welding (arrangement (b) for short). During the experiment, the ultrasound beam was always focused on the measure points i.e. the root corner or the bottom of the hole respectively.

4.3.2 Signal time change.

Figures 51 to 55 are the experimental results of temperature effects on the signal time under different conditions. Figure 51 shows the results from TIG welding experiments with the arrangement (a), during which the arc and the probe position were fixed. Figure 52 is the results from the arrangement (b) with all other conditions kept the same. Figure 53 is a comparison of results between a constant current and the gradual increase of the welding current. Figure 54 is the results from SAW processes in the arrangement (b) with different hole depths. Figure 55 is the results from SAW process in the arrangements (b) and (a) respectively. During SAW welding experiments, the electrode was moving over the probe beam centre at a given speed and this is a closer situation to a real SAW process. The figures indicated the following:

1. In comparison of figures 51 (a) to (d), the indication is that signal time increases with welding current. For example, at the 20th second after arc ignition, the relative increases of the signal time were 0.65, 0.85, 1.55 and 1.8 micro-seconds. Similarly, the relative time increase from SAW processes was larger (much larger) than the TIG experiments due to their high welding current (see figures 51 and 55). It was apparently caused by a higher temperature and a larger high temperature field which reduced the ultrasound velocity.
2. Four groups of data in figure 52 were from the same experimental conditions except for the arc time (or the welding time). Apparently, the longer time of arc heating meant the more heat input and the larger high temperature field, which, in turn, caused the greater time increases. This figure also shows the good reproducibility of the experiment.
3. The rate of signal time increase levelled off under the condition of constant welding current as the welding time increased (see figures 51-53). It is

possible to believe that signal time would approach its limit under a given condition if welding time was sufficiently long. This was because a balanced temperature field could be gradually established when the heat input from the welding arc and the heat losses from the work plate were equal. This meant that there existed an upper limit of the signal time increase as a balanced temperature field was established.

4. The largest signal time increase in figure 51 reached $3.0 \mu\text{s}$ at 35 seconds after arc ignition when the welding current was 273 amperes. It could be deduced from the results that the largest signal time increase could be more than $3.0 \mu\text{s}$ if either the welding current or welding time increased. In contrast, the maximum time increase in figure 52 was less than $1.7 \mu\text{s}$, much smaller than the above value from the arrangement (a). This phenomena was more clearly demonstrated in the SAW process (see figure 55). The maximum time increase from SAW experiment in arrangement (a) was larger than $4.5 \mu\text{s}$ (which represented a distance of about 14mm at room temperature or a 7mm return distance) whilst the maximum increase in arrangement (b) was less than $2 \mu\text{s}$.
5. Figure 53 compares the signal time change between constant current and the gradually increased current. It is clear, from the figure, that the rate of signal time increase went up with the welding time; when the welding current increased gradually during the experiments. In contrast, the rate went down during constant current experiment. This regularity is shown clearer in figure 53(b) which displays the differentiation of the signal time with respect to welding time. With a constant current experiment, the value of differentiation becomes smaller as the welding time increases, whilst the value became greater for gradual current increase.
6. Figure 54 shows the signal time recovery process. A short time after the welding current had stopped (about 2 to 3 seconds which depended on the

welding parameters), signal time reached their maximum and then reduced very quickly. The "recovery" speed of the signal time slowed down with the welding time increase. The signal time did not return to its start value until the work plate was fully cooled down to room temperature, this process could vary from about several minutes to several hours depending on the welding parameters.

7. The signal time had large deviations at larger welding current results. Signals became weak at larger welding currents due to heavier attenuation, which could make signals less stable. Additionally, when the welding current was high, the temperature gradient increased, which could result in ultrasound beam skewing. This, on one hand, could further weaken the signals and, on the other hand, aggravated the signal time increase. The results from SAW processes showed their support since the results from the arrangement (a) produced larger deviations than those from arrangement (b) (see figure 55).

It can be concluded from the above figures that two factors affect ultrasonic signal time during the welding process: the welding current, (more accurately the welding parameters) and the welding time. The former directly determines the heat input which controls the overall degree and the size of the high temperature field. The latter regulates the heat transfer which affects the temperature field at any particular moment.

There are two points which need underlining here: firstly, there were several factors which influenced the result reproductivity and stability. All factors (such as plate dimensions, weld pool surrounding conditions) which affected heat transfer

and heat losses could affect the heat balance and, thus, the results obtained. Therefore the results from different experiments were not fully comparable unless all the experiment conditions were kept the same. Secondly, all the signal time shown in this section was measured according to the leading edge of peaks. According to the previous discussion, it gave smaller values as the peak width increased, this meant that the actual signal time increase was a little bit smaller than the value indicated in the figures. Figure 56 shows the experiment results which were obtained at room temperature by adjusting the gain to increase peak width for quantifying the difference. From this figure, it was known that the signal time would decrease by about $0.75\mu\text{s}$ when the peak width increased by $4.5\mu\text{s}$. (This further proved the previous solution that the real peak centre was approximately equal to the sum of the value from the leading edge and one eighth of the peak width). Based on this compensation, the real signal time increase for SAW with about 300 amperes of welding current was about $3.0\mu\text{s}$. Therefore, this must be taken into consideration when trying to locate or to size defects and this is also very significant for welding penetration control or for any welding process control using an ultrasonic sensor.

4.3.3 Signal amplitude change.

Apart from great effects on the ultrasonic signal time, high temperatures surrounding the weld pool had severe influences on ultrasonic signal amplitude due to the heavy attenuation at high temperature. Figure 57 shows the results of general temperature effects on signal peak width (the same experiments for figure 51). These results expressed the following features;

1. Comparison of graphs (a) to (d) in figure 57 indicated that the peak width was reduced to a great extent and, reduced more quickly at higher welding currents.
2. Peak width reached their minimum shortly after the welding current was

stopped. After that, the peak width increased very quickly and then levelled off slowly.

3. The peak width had much greater fluctuation, especially when the welding current was high. There were several reasons for this fluctuation: the shape and the distribution of isotherms of the high temperature field could affect the reflection or refraction path and, as a result, could influence the received ultrasound beam intensity (or the amplitude). The instability of grains in HAZ (either due to boundary moving or grain growing) could result in signal amplitude change (i.e. the signal width change in a B-scan graph). This was more clearly demonstrated after the welding current was stopped (see also figures 58 and 59).

All in all, the peak width had a corresponding response to the welding current as the signal time did. However, compared with the signal time, the peak width results had their own features. First, peak width could "recover" more quickly and even could surpass its start value (see figure 57(a)), which was impossible for the signal time. It seemed difficult to accept this fact because the attenuation could not be less than its start value obtained at the room temperature. Detailed experimentation (see next section) proved that the large peak width was mainly caused by large grains which reflected some energy back to the probe. As a result, reflected peak shapes were altered and became less sharp and, made peaks "wider". In fact, after stopping the welding current, there existed two complementary factors, the temperature induced attenuation and the large grain reflector, they decided the peak width together. The former delayed its width recovery whilst the latter made peaks wider. The real peak width, therefore, depended on these two sides. Secondly, peak width had more severe fluctuation than the signal time, especially when a high welding current was used. Besides the fact that great attenuation caused by a high welding current produced weak signals which could generate large signal deviations, phase transformation and grain growth could influence the stability of peak width because the large unstable grains could effectively reflect

ultrasound and made their contribution in peak width. Figures 58 and 59 are two examples of experimental results in B-scan graph.

4.4 SIGNAL PROCESSING AND ANALYSING.

Signals from weld pools or near these areas are very weak because of the severe attenuation caused by the high temperature field of the welding arc. To detect signals, it is necessary to raise the amplification of received reflections. However, the amplifier of the ultrasonic instrument not only amplifies signals but also increases noise amplitude. When the gain of the ultrasonic instrument was raised to 100 db (which represents a amplification of 100,000 times), even a very very weak noise reflection can be amplified into a large peak and appear on the ultrasonic instrument screen, figure 60 is an example of B-scan results with much noise. To extract the defect signals from the results with much noise, the signals need to be analyzed to remove this noise. On the other hand, real signals can be lost temporarily due to the momentary loss of coupling or any other reasons. Therefore, the purpose of analysis, firstly, is to remove as much noise as possible and to recover as many signals as possible simultaneously.

Figure 61 shows 4 frames of A-scan signals with noise. The noise peaks in the figure randomly varied their sizes and locations, so they could not be filtered by digital filters (in fact, even though they can be filtered in some scales through digital filtering, the speed of digital filters using the BBC computer is far too slow than the demand of on-line analysis) or common analogue filters without severe alteration of the real defect signals.

However, on one hand, it is well known that the signal averaging technique is useful to enhance the signal to noise ratio, especially to reduce those time randomly distributed noises, such as electric noise or heat noise. Figure 62 shows this feasibility to reduce noise amplitude effectively by the data averaging technique. The results were obtained through increasing the averaging times step

by step from 1 to 128 respectively. This figure clearly showed that the more average the times, the better results could be produced. Additionally, the averaging technique became the box-car technique by moving the probe, which was helpful to enhance further the signal to noise ratio (especially to reduce the noise from large dendritic grains in welds). Therefore, this averaging technique was employed in most of the experiments.

On the other hand, real signals could be recognised from B-scan graphs. This indicated that the signals could be separated from noise, based on the B-scan graph. In other words, reflections could be judged and recognised according to their previous responses at the same time range. If the sample frequency was sufficiently high, signals between adjacent samples could not change abruptly. This implied that if several previous samples did not have any signal at the time range, they were unlikely to appear as signals in the current sample. That is to say, even a peak was detected in the current sample, the reflection was most likely to be a noise peak rather than a real signal. In this way, it could be decided whether they were real peak signals by comparing current sample data to the previous records in their relative segment. The corresponding methodology is explicitly shown in figure 63 and is discussed in detail as follows:

An A-scan signal time axis located in the time window was divided into several time segments ($S_1 \dots S_r$), each had its separate width and signal number history which recorded the peak number for the current sample and the previous $N-1$ samples. This number (notated as M_j in the figure 63) ranged between 0 to N and represented peak repetitive frequency at that time range. Based on the above discussed signal continuity principle, if M_j were smaller than G_l (the low gate in the figure 63), i.e. signal repetitive frequency was very low, peaks which appeared in this segment were most likely to be noise reflections and, therefore, should be removed. In contrast, if M_j were larger than G_u (the upper gate) and no peaks were detected in this segment, signals were likely to be lost. The "lost" signal should be "recovered" by adding a signal which was supposed to be the same as the

previous signal in the segment. In this way, all peaks obtained from the peak detector were first analyzed to distinguish between signals with noise peaks and to decide whether there were any "lost" signals to be recovered. The results produced through using this method depended on several parameters:

1. The segment width (or segment number).

A small segment width represents a more detailed analysis and can remove noise peaks more efficiently. As noise peaks are randomly distributed in the time axis, a small segment width corresponds to a low appearing frequency of noise peaks for each segment and thus noises are easier to remove. On the other hand, too small a segment width not only increases data processing time but also increases the probability of interrupting the continuity of real signals when a signal is switching from one segment to another, which will result in less efficient recovery of lost signals or, there is even the risk of deleting the useful signals.

2. Counting range N .

It is clear that counting range N directly represents the continuity extent, large values mean that the current results depend more strongly on previous results, that is, they are affected more by previous status. Therefore using a larger counting range N , noise removing and signal recovery are more efficient without increasing data analysing time. However, the side effect is clear, too large a range might involve the risk of removing real signals or inserting "false" signals. On the other hand, of course, too small a range cannot maintain the signal continuity and also reduces the efficiency of signal processing.

3. Gate values G_u and G_l .

These two values are the gates for control and they serve as criteria. In processing the signals, only when the recorded peak number for the segment located between the gates, were signals in that segment kept unchanged. In

all other situations signals might either be removed or added. Thus, it is easy to accept the fact that the gates have most important and direct effect on data analysis results. Apparently, G_1 dominates the capability of removing noise peaks whilst G_u (or more strictly $N-G_u$) of recovering signal peaks (actually, they decide respectively the maximum peaks which could be continuously removed or recovered). Therefore by pre-selecting G_u , G_1 for each segment, the reflections in different segments could have different influences, for example, "magnification" or "reduction". If it were known that the real signal probability was low at a time segment from previous experiments or from theoretical analysis, the gates for this segment could be increased so as to improve the capability of removing noise reflections and to decrease the chance of inserting signals. In an extreme situation, when G_1 and G_u were increased up to the limit N (i.e. $G_1 = G_u = N$), almost all reflections in the segment could be removed and this kept the segment "clear". Similarly it could generate an opposite influence when gates were moved downwards. In this way, the original one time window (the computer controlled ultrasonic system only had one time window) could be separated into several "windows".

4. The initial value of peak number (M_{j0}).
This initial value can only affect the analyzed results of the first N samples. They are usually set to the middle of the gates.
5. Original peak probability (notated as P_j) in a segment.
Unlike previous discussed parameters, peak probability influences data processing results in a less direct way and it decides the probability of peak number M_j which is smaller than G_1 or larger than G_u or, in other words, it decides the probability distribution of M_j .

If the following suppositions are met:

1. The counting range N is fixed.

2. The peak probability remains constant for all the samples.

The probability of peak number M_j being equal to any value (x) between 0 to N meets the binomial distribution^[114] with the formula below:

$$P(x) = \frac{N!}{(N-x)!x!} P_j^x (1-P_j)^{N-x}$$

$$\sigma = \sqrt{NP_j(1-P_j)}$$

$$\mu = \sum xP(x) = N P_j$$

Here σ is the standard deviation and μ the mean.

Figure 64 explicitly shows some examples of $P(x)$ with different peak probabilities P_j (0.01, 0.1, 0.3 and 0.5) and their effects on results of data analysis. It clearly showed that the lower the peak probability, the higher the chance at which the reflections to be removed, or vice versa. According to the previous continuity principle, the area below G_l represented the percentage of reflections to be removed and the area above G_u the percentage to be inserted. So the overall effects on original reflections depended on the differences of the above two opposite effects. For example, when G_l , G_u and N were equal to 5, 15 and 20 respectively (i.e. G_l and G_u are symmetric to the range centre), peak probability P_j being 0.5 generated a "null" effect on original reflections (number of reflections to be removed equalled to that of those to be inserted). Whereas when P_j was equal to 0.01 with all other parameters unchanged, all reflections could be removed but no signal peak would be inserted, this meant that all reflections would be deleted. (Overall effects for P_j equalling to 0.1 and 0.3 are also shown in figure 64). The above examples explained the effects of original reflection probability on data analysing results. As a general rule, when the gates symmetrically locate in the counting range, the original reflection probability below 0.5 produces a "reduction" effect, that is, more reflections to be removed than that to be inserted,

and vice versa.

The feasibility of this data analysing method have been proven by a simulation process performed for a segment (see figure 65). Finally, based on the above discussion, a program (the major part was written in assembly language) was designed for analysing data on-line or afterwards. The parameters could be pre-selected and the ranges proven were as follows:

Counting range (N): 10 to 20 (no upper limit)

Segment number (r): 4 to 10 (upper limit was 16)

Gates value (G_l & G_u): 0 to $N/2$ & $N/2$ to N ,

(requirement: $0 \leq G_l \leq G_u \leq N$)

The time needed for analysing a group of data from a single sample depended on the above listed parameters and the reflection number (usually 5 to 50 milliseconds). Figure 66 shows the results after analysing the data of figure 60 by using this method. By comparing figure 66 with figure 60, the efficiency of this method was convincingly proven.

Though the statistical method discussed previously only modified the peaks in total (removal or insertion), this method could be extended to modify the peak width or peak amplitude concurrent with the analysis stated in the above sections and thus produce better and smoother results.

4.5 ON-LINE WELD DEFECT DETECTION.

There are four kinds of commonly existing defects found in fusion welding: lack of fusion (a more common defect in welds is the lack of root fusion), blow holes and undercuts, porosity and inclusions, and cracks.

4.5.1 Lack of fusion.

The experimental arrangement for detecting lack of root fusion is shown in figure 67. The plates used were 20 mm thick mild steel with a 60° included angle and a root face of approximately 3 mm and a 2 mm opening gap. One 45 degree shear wave probe working in a pulse-echo mode was placed on one side of the plate. The probe was spring loaded with adjustable pressure to keep-up constant contact to the plates and moved with the welding head to monitor the process on-line. The probe was coupled with commercial medical glycerine.

It is well known that both weld pools and lack of root fusion defects can fully reflect shear wave ultrasonic beams and the differences between their spatial locations are small or even zero. This means that the reflection time from a fully penetrated weld pool or from an unmelted root face (the lack of root fusion defect) can be of the same value at different welding time. Additionally, the relative signal time change caused by high temperature fields of SAW could be as large as $4 \mu\text{s}$. As a result, it is almost impossible to distinguish weld pool signals from the lack of root fusion defect signals by the signal time only. This is to say that the probe should be arranged to avoid receiving reflections from the weld pool or the probe should be focused at some distance back from the weld pool. The interception point between the weld and the ultrasonic beam centre (the interception is termed "beam centre" for short from now on) to electrode distance is named the beam centre to electrode distance (**BCED**). This was usually arranged to about 15 mm for submerged arc welding.

The lack of root fusion defect could be produced by incorrect preparation such as too large a root face or too small a gap. Therefore, if the root face was locally increased to generate "shoulder" which prevented the weld from fully penetrating, whilst all other places were fully penetrated, as a result, the lack of root fusion defect at the shoulder was produced. Figure 68 shows the B-scan results from this kind of defect, the welding parameters and ultrasonic parameters, and figure 69 the

three dimensional results, whilst the specimen photo and X-ray results are in figure 70. The ultrasonic results clearly showed the lack of root fusion. According to the B-scan result, the defect length was about 20.45 mm by calculating from the corresponding sample number 160 to 205. It was in accord with the shoulder length (20 mm).

The lack of root fusion defect might be produced by inadequate welding parameters such as a small welding current or a high welding speed or both. Figure 71 is the B-scan results which showed the defect (the lack of root fusion) by temporarily reducing the welding current. Additionally, the lack of root fusion could be generated by several incorrect procedure factors acting together. In this case, lack of root fusion might be produced in some unpredicted region, or, in other words, lack of root fusion might be produced irregularly in welding length. Figure 72 is the X-ray results and the ultrasonic B-scan results which showed these kinds of defects. The X-ray results and the B-scan graph were in good accord with each other, which proved the efficiency of detecting the lack of root fusion defects. Similarly results could be confidently expected; for detecting lack of side wall fusion.

4.5.2 Porosity or inclusions.

To simplify the welding preparation, experiments for detecting porosity or inclusions were arranged in the form of 'bead on plate'. This arrangement also reduced the probe to weld distance from one and a half skips to one skip, which could reduce signal attenuation and beam spreading. This was helpful in detecting porosity or inclusions.

Porosity could be introduced into welds by adding water or oil etc. which could produce gases during welding. However, porosity was not easy to generate in SAW due to too "good" the flux and the large weld pool which allowed gases to exit before weld solidification. Whereas adding too much water could severely interfere

with the arc stability and the welding process. In contrast, porosity was easy to produce in GTAW welds by adding nitrogen into the shielding gas or reducing the shielding gas flow rate. Porosity appeared just after solidification, and thus the reflections from porosity often mixed with those reflections from large dendritic grains in the weld. A-scan results indicated that the reflections from porosity did not have apparent discrimination with those reflections from large grains.

Figure 73 shows two sets of B-scan results from welds with and without porosity respectively. The results were obtained from static probe experiments and the porosity was produced by reducing the shielding gas flow rate. Figure 73(b) shows that there was a zone where large reflections (noise) appeared in the signal some time after the weld pool was solidified and before the phase transformation finished. This area was 17.65mm in length for the experiment. This meant that reflections could be received no matter whether there was a defect if the ultrasound beam was focused on this area. However, this noise area depended on welding parameters. For SAW process, it became as long as 95.68mm (see figure 74). In this situation, to avoid this area totally seemed impossible or impracticable. Fortunately, there existed a "quiet zone" in which porosity or other defects could be detected. On the other hand, comparing graphs (a) and (b) in figure 73, it was clear that the reflections from the noise area with porosity were bigger, much bigger than the one without porosity (in fact this is also always true for other defects).

Regarding the above stated facts, there were two ways to detect defects: (a) to avoid the noise area (such as in the situation in TIG welding), (b) by comparing the reflection amplitude or, in a more convenient and more efficient way, the mean amplitude from a whole sample (which is corresponding to the total reflection energy). Figure 75 is the results when BCED is 20 mm. In this figure, the grain noise was effectively reduced and porosity was clearly shown. In the experiment, the shielding gas was reduced from the middle part of the weld so as to generate porosity. The B-scan graph shows that porosity existed in the end period of weld.

Figure 76 was obtained from the results where BCED was 7.5mm. The porosity in the weld could be clearly distinguished based on the mean amplitude from the B-scan data.

4.5.3 Cracks.

The arrangement for detecting cracks was the same as the experiment for detecting porosity. That is, weld beads were deposited on to a plate surface and a 45 degree shear wave probe was placed on the plate and the probe to weld bead distance was one skip. Cracks were introduced into the weld by adding copper powder or iron sulphide (FeS). Both were very effective for initializing cracks in TIG welding processes. Figure 77 shows the cracks initiated by adding FeS and copper respectively. From this result, it could be seen that sulphide cracks appeared immediately after solidification, whilst copper cracks needed a longer time to appear. Apparently, if cracks were generated before ultrasound beam centre, they could be detected otherwise they might not. In this case, increasing BCED was helpful in TIG welding. There are two similar ways to detect cracks as in the situation to detect porosity. Cracks could be detected by analysing the mean amplitude and signal width (see figure 78 which also shows the dye-penetrant results, the cracks were too fine to be exposed by X-ray methods because of the thickness of the plate). In this method, if the BCED was not long enough, the copper cracks might not be detected reliably; because the cracks may not have been initiated when the ultrasound beam reached the area. In the other way, both cracks (sulphide or copper initiated cracks) could be reliably detected if the BCED was increased to about 20mm for the given condition. Figures 79 and 80 are the results with cracks generated by adding copper and the results were obtained by testing during welding and after welding respectively; and figure 80 also shows the corresponding dye-penetrant result. The on-line results, off-line results and the dye-penetrant results were in good agreement and they convincingly proved the effectiveness of on-line crack detection.

4.5.4 Other defects.

In TIG processes, other defects likely to occur were undercuts and blowholes. The arrangement for the experiment was the same as for the previous ones. Figure 81 are the results showing several undercuts and one blowhole. In the figure, the signal time of the blowhole was about $3.55 \mu\text{s}$ shorter than that of the undercut. This meant that the bottom surface of the blow hole was about 5.74mm deep if the heat effect on the ultrasound velocity was neglected. The blow hole was cut and measured afterwards. The depth was 5.5mm which was in good agreement with the value from the ultrasonic results. In addition, from the figure, it could be seen that the undercut was located in the middle part of the weld, which was coherent with the photo (see figure 81(b)).

All in all, all the above results demonstrated that all common weld defects could be effectively detected during welding though the BCED should be maintained longer in order to detect copper cracks reliably. For TIG processes, there were two ways of detecting welding defects, whereas for SAW processes, the best way was to focus the ultrasound beam on the "quiet zone" and to analyze the mean amplitude simultaneously in order to determine defects. In this way, common weld defects could be successfully detected.

5. DISCUSSION

5.1 DIFFICULTIES IN DEFECT DETECTION CAUSED BY THE HIGH TEMPERATURES OF WELDING.

As stated in chapter 4, the main and the most important problems encountered in defect detection concurrent with welding, were the high temperature of welding, which reduced ultrasound velocity and increased attenuation. The former made it difficult to locate defects accurately, whereas the latter, made it difficult or almost impossible to size weld defects accurately. On the other hand, it was well known that signal time and signal amplitude are the two most important ultrasonic parameters, in fact, they are the two basic parameters employed for common ultrasonic weld inspection.

5.1.1 Signal time.

Signal time change (ΔT) caused by high welding temperatures was investigated by several investigators because of its great importance. However, the results from different sources had great deviations.^[6,51,85,92] The results in chapter 4 showed the largest ΔT than all other results from other references. In figure 55, the ΔT for SAW was greater than $4.0\mu s$ which represented a radius reduction (ΔR) of 6.46mm, or $3.0\mu s$ ΔT (4.85mm ΔR) for the TIG process (figure 51). There may be many reasons for this big time difference (ΔT) in the results, but the major reason could be the different experimental arrangements in which the measurement point (the reflecting point for the ultrasonic beams) was different. For example, all the results showed above were obtained when the probe was focused on the bottom corner of the sample (the arrangement (a)). This arrangement had two apparent influences on the results (ΔT) obtained.

1. It can be accepted that the high temperature field around weld pools depended on heat conduction to the surrounding areas. Figure 50 is the schematic

diagram showing two different experimental arrangements, a) the same arrangement as for the experiment in figure 51, b) the arrangement similar to the one in reference [92]. Figure 82 shows heat conducting angles for the two arrangements and the figure clearly shows that the included heat conducting angles were 60° and 90° respectively, so that the arrangement (a) had worse heat conducting properties. It required a steeper temperature gradient to conduct the same amount of heat from the weld pool and, in turn, produced a larger high temperature field. As a result, the arrangement (a) would produce a larger signal time increase ΔT or a larger radius variation ΔR . Besides, due to the poorer heat conduction of the bottom corner in arrangement (a), a very high temperature area would be generated in that corner, which also gave rise to a high ΔT .

2. Figure 83 qualitatively shows the beam path direction relative to isotherms. In arrangement (a), the beam cut isotherms at a slight angle rather than the perpendicular or nearly perpendicular angle to the isotherm in arrangement (b) and, as a result, the beam path could greatly 'skew' and become longer.

In contrast, it could be deduced that the experiment with arrangement (b) could produce similar results if using TIG processes. As the hole bottom in the arrangement (b) could be very close to the weld pool boundary, the results obtained from this arrangement could be taken as an acceptable approximation for similar experiments.

From the above discussion, it could be concluded that the experimental arrangement had great effects on the signal time change (ΔT), and the arrangement (a) could produce larger signal time increase than the arrangement (b) did (see figure 55). In fact, not only the parameters determining heat input (such as the welding process or the welding current) but also the conditions which influenced heat losses could affect the ultrasonic signal time. Therefore, it could be predicted that the ultrasonic beam angle (45° , 60°) could also influence the signal time obtained. To compensate the ΔT reliably, (for example, in the situation to

determine the weld pool quantitatively rather than to control an even weld penetration only), a series of experiments with the same as, or similar to a real situation were helpful to establish the necessary relative data base. By using this data base, an expert system could automatically compensate for the high temperature influences on the signal time. As for the signal time in on-line welding defect detection, especially the detection as a quality control method rather than an inspection process, the interesting area is the weld bead just welded. In this case, the accuracy of ΔT is less critical though ΔT must be taken into account in detecting weld defects. However, signal time, although not necessary the absolute signal time (the comparison of the signal time from different defects), is helpful to determine defect types. For example, lack of fusion generally produces a smaller signal time than those defects inside welds such as porosity, and surface defects (such as undercuts) which might produce the longest signal time.

5.1.2 Signal amplitude and gain control.

It is well known that signal amplitude is also severely influenced by high temperatures. In the pulse-echo mode of ultrasonic defect detection, the size or the dimension of a defect is determined by comparing the amplitude of the echoes given by an unknown defect with that given by a reference defect. "At present, it is difficult to avoid a method which uses the comparison of the amplitude of the defect echo with that of a reference echo"^[102]. However, the reference echo, in an on-line welding defect detection process, is very difficult (or even impossible) to obtain due to the high temperature.

To demonstrate this statement, a simplified schematic diagram of the ultrasound transfer process from the transmitter to the output is shown in figure 84. According to the figure, the output signal or the signal amplitude V (which is used to determine defect size) could be symbolized as a function of three factors:

$$V_o = V_i f(G, D, A) \quad (5.1)$$

Where G stands for the gain of the amplifier of an ultrasonic instrument, D for all effects of the defect on the ultrasonic signal, A for the ultrasound attenuation, and, the subscript o for output, i for input. Based on the gain definition and figure 84:

$$G = 20 \log(V_o/V_{io})$$

or;

$$V_o = V_{io} e^{G/20}$$

Thus, the equation (5.1) could be written as:

$$V_{o,s} = V_i e^{G/20} f_0(D_s, A_s) \quad (5.2)$$

Here subscript s stands for the signal from a real time experimental result. As attenuation depends on temperature (T) and beam path length (L), in expression:

$$A = f_1(L, T)$$

Thus (5.2) could be re-written as:

$$V_{o,s} = V_i e^{G/20} f_2(D_s, L_s, T_s) \quad (5.3)$$

Also, for a reference echo,

$$V_{o,r} = V_i e^{G/20} f_2(D_r, L_r, T_r) \quad (5.4)$$

If temperature (T) and beam path length (L) are the same in experiments for the reference defect and for the real defect, then T and L become constants. Dividing (5.4) by (5.3) yields:

$$V_s / V_r = f_3(D_s) / f_3(D_r)$$

or;

$$D_s = D_r f_4(V_s/V_r) \quad (5.5)$$

This means that the defect dimension could be determined by comparing the output (the signal amplitude) from the given reference defect with that from the real defect detection experiment at room temperature. Conversely, the reference echo from the given defect is necessary to size the defect in a real experiment.

During the above discussion, the gain (G) was supposed to be kept constant in both the reference experiment and the real experiment. In fact, even the gain was not the same, the above solution was still feasible because the gain effect could be easily compensated by using the gain definition. Furthermore, even the beam path length was not the same in both experiments, the size of the unknown defect could be determined through employing the "distance amplitude correction" (DAC). However, in the ultrasonic testing process of welding, since the temperature in the

defect detection experiments for obtaining the reference amplitude is different from that in a real test, equation (5.5) no longer holds. In another words, D_s cannot be obtained by simply comparing the signal amplitude from the reference defect with that from the real defect. This is because an accurate reference echo with the same temperature effects could not be obtained.

Another problem related to the signal amplitude in the real-time defect detection process is the pre-selection of gains. Generally, for a real-time ultrasonic testing experiment, the temperature effect on attenuation is not known before the experiment is actually performed. This means that a preset gain is just a estimated value (because no "hot state calibration" was carried out). Too large or too small a preset value severely influenced the ultrasonic results. For example, if the gain had been too small, no defect signal could be detected even though some defects existed in the weld. Whereas too large a gain not only produced too much noise but also hindered the correct judgement of defect existence or the correct assessment of defect size due to the deep saturation of the real signal output.

To preset a suitable gain, several experiments with the same conditions as the real tests were required. During this process, the gain needed adjusting gradually and the results were compared and appraised accordingly. In this way, a suitable gain for that experimental condition could be approached by this "trial and error" process. Actually, by employing this process, not only could correct gain be decided but "empirical" reference echoes were also established by recording every experimental condition, ultrasonic results (such as echo amplitude and echo patterns) and those related to the defects. The defects should be inspected by approved conventional methods like the room temperature ultrasonic inspection, the X-ray technique or even the destructive testing. This process was, in fact, a learning process for an expert system. In this way, a reference echo data base was established. As a result, defects could be detected and estimated in size by comparing the signal echo received with the reference echo in the reference data base. Of course, the establishment of a reference data base for different welding

conditions and different welding processes is very time consuming. Even so, an accurate sizing defect method is still far from being perfect without real "hot state calibration".

5.1.3 Grain growth and phase transformation.

It is well known that metal grains grow quickly and that ferrite metal undergoes phase transformations at high temperature during welding. In addition, both large grains in heat affected zones and large dendritic grains in welds scatter ultrasound severely which could result in much higher attenuation and much noise, and can even alter the beam path from the direct line. This, therefore, aggravates the difficulties to detect defects during the welding processes. However, this problem has not yet been paid proper attention in previous researches in using ultrasonic sensors for a welding process or welding quality control.

At first thought, it seemed that the beam centre to electrode distance should be kept as large as possible to avoid; or to reduce the high temperature effects during welding and to avoid any signal confusion from weld pool reflections, but in fact, experimental results proved that this was not always true. Actually when BCED was in a certain range, the noise was so large that it drowned all real signals. To find a position which avoids the noise, a group of experiments were carried out and an instinctive method was to keep conditions constant except for the BCED, that is, to keep the probe fixed to the work plate when carrying out welding.

Figure 85 is one of the results from this kind of experiment in which a welding bead was deposited on a plate surface with the SAW process (similar results were obtained from the TIG process). The results of figure 85 could be divided into four periods. Period 1 was from sample number 1 to about 44 during which there were no signals because the electrode or the weld pool had not reached ultrasound beam level. Period 2 (from 45 to 113) showed signals from the weld pool during which the signal time decreased as the weld pool size increased. Period 3 (from

114 to 200) was another "quiet" period as no signals were detected. Period 4 (after 200) was a noise dominated period during which very large noisy signals existed. As there were no defects in the weld bead according to the X-ray results (and the disappearance of the reflections; the results after sample number 550 also proved this), the signals (more accurately speaking, the reflections) must be generated from some reflecting sources rather than defects. The possible reflecting source might be large austenite grains. If large grain boundaries were the signal reflecting source, reflections from them should have multiple peaks and this was seen by the results in the figure. Furthermore, reflections from large austenite grains should gradually become smaller and eventually disappear as the coarse austenite grains phase-transformed into fine ferrite grains during the cooling process, this was also proven by the results in figure 85. On the other hand, if the work plate was austenitic steel which has no transformation during welding, the large and noisy reflections from large austenitic grains should not reduce or disappear during the cooling process. Figure 86 is the result from a TIG process with spot heating on an austenitic steel plate, which was in good accord with the above mentioned assumption that large reflections were from large austenitic grains. Similarly, if large austenitic grains were the noise source and served as ultrasound reflectors, they should similarly produce large reflections when ferritic steel plates were heated to a sufficiently high temperature and transformed and grew into large austenite grains; though the grains were smaller than the austenite grains in welds. To prove this, a mild steel plate was heated on a spot by an oxygen/acetylene flame and was prevented from melting to eliminate reflections from the solid/liquid interface. In this way, if there were any reflections from the heated zone, they must be reflected from the large grains. Figure 87 is the result from this experiment and clearly shows that after a period of heating on the plate, the heated zone reflected ultrasound and produced signals. After the heating was stopped at sample number 500, the reflections disappeared quickly as the temperature went down and the large austenitic grains transformed back into fine ferrite grains due to transformation.

All in all, it could convincingly be accepted that large grains, especially large dendritic austenitic grains in the welds, were the reflectors which generated large noisy reflections in ultrasonic results. Additionally, as grain boundaries were not stable and they were always "moving" and "shifting" due to grain growth or phase transformation, the reflections from the large grains were changing accordingly and produced unstable "signals" with multiple peaks. These reflections from large grains were noise (or "grass") from the view of ultrasonic defect detection and this noise was nominated as grain noise in this work. This grain noise could confuse the interpretation of received signals. In fact, this noise might either submerge real signals from defects or produce false indications of defects. To detect defects reliably, it is necessary to avoid or to eliminate this grain noise.

Apart from all the difficulties discussed above, the ultrasound coupling was also proven to be problematic in defect detection during welding. Firstly, the thickness of the couplant and the mechanical pressure applied on the probe might not always be kept constant and the movement might not always be smooth due to variations of plate surface and couplant feeding. With ultrasound coupling efficiency, even very small changes of the couplant thickness could greatly alter the ultrasound signal amplitude which in turn would influence the signal analysis and judgement. Secondly, the probe had to be kept sufficiently far away from the weld pool to prevent the probe (or probe shoe) from becoming damaged, because of the high temperature around the weld pool. Compared with the room temperature ultrasonic inspection (in which half a skip to one skip distance was usually used), the distance should be raised to one skip to one and half skips or even longer (suppose the plate thickness was about 10 to 25mm). This would mean an increase of the beam path length which would broaden the beam section and reduce the ultrasound beam centre pressure. As a result, it not only weakens the reflections from defects ("blur" reflections) but also generates some "false" ultrasound peaks, which accordingly decreases the 'signal to noise ratio' and increases the difficulties in analysing and judging signals.

5.2 NOISE AND NOISE REDUCTION.

As indicated previously, there existed much noise in the received signals due to high gains (high amplification) which produced 'white noise' and reflections from large grains (the 'grain noise'). It is necessary to avoid or reduce these noises in order to detect defects in welds reliably. Several methods have been tested and each had its suitable range and inadequacy or even side effects. It should be decided according to the relevant situation.

1. To avoid grain noise dominated areas.

As shown in figure 85, there existed a quiet area between the weld pool and the grain noise, so focusing a beam on this area effectively obviated the grain noise. However, the length and the accurate location of the quiet zone depended on welding processes and welding parameters. For TIG processes, experimental results indicated that the quiet zone was very narrow and in order to avoid the grain noise area thoroughly was not always feasible (see figure 88). Fortunately, the grain noise zone is not very large in the TIG processes. Increasing BCED to about 15-20 mm for a similar experimental condition enabled the observers to obviate the majority of the grain noise (in some cases all the grain noise could be avoided).

2. To reduce ultrasound frequency.

It is well known that the sensitivity of an ultrasonic system is proportional to the frequency used. Thus, reducing the frequency means reducing the sensitivity. In this case, only those discontinuities whose dimensions are larger than one quarter of the wave length might respond to the ultrasound. As a result, noise reflections could be successfully reduced or even eliminated. Figure 89 shows an example tested with 1 MHz frequency ultrasound. The result convincingly proved that the noise reflection was fully eliminated and only those signals from the weld pool were left. Furthermore, the signal from the weld pool was greatly enhanced due to low

attenuation at a low frequency. Of course, this technique of avoiding grain noise was always accompanied by a reduction of the 'system sensitivity'. Therefore, correct frequency selection is important with an overall balance of sensitivity and noise reduction. It is suggestible to use the lowest frequency which would meet the required sensitivity.

3. Use signal processing techniques.

The method has the potential to reduce both white noise and grain noise. However, different signal processing techniques have different capabilities which require discussion in more detail.

5.2.1 Signal processing.

1. Power means and amplitude means.

Assume the total ultrasound power of grain noise in a given time range as noise power (P_n) and total signal power in the same range as P_s . Due to the reiteration of power, the total power (P_r) received should be:

$$P_r = P_n + P_s$$

or;

$$P_s = P_r - P_n$$

This indicated that the received total power could serve as a measure of a real signal from any defect if the grain noise power would remain unchanged in different probe positions. In other words, P_r could be employed to judge the existence of defects and to estimate approximately the defect size.

According to reference [115], P_r could be obtained from the digitised ultrasound pressure (or ultrasound signal amplitude) S_i :

$$P_r = \sum_{i=1}^N S_i^2 \quad i=1,2,\dots,N$$

Where i is the i th datum in a given sample and N the total number. Average

power (P_{av}) will be:

$$P_{av} = P_r / N$$

As there is no multiplication instructions in the BBC computer processor, multiplication could only be realized by shift and addition, which needs a relative long time calculation even using the assembly language. In this case, using an average amplitude (amplitude mean or signal mean) S_{av} could simplify calculation and, more importantly, save time to meet the demand of real-time analysis for defect detection during welding. The amplitude mean is expressed as:

$$S_{av} = \frac{1}{N} \sum_{i=1}^N S_i$$

The feasibility of using S_{av} to replace P_{av} , apparently, depends on the difference between S_{av} and P_{av} . In other words, whether the S_{av} could be used as an approximation for determining defects. Figure 90 is a result showing a comparison which was obtained by randomly adjusting gains to simulate various signals. From the figure, it could be seen that both P_{av} and S_{av} were coherent in all ranges though some differences existed. In general, P_{av} had a stronger ability to restrain small reflections and to enhance large signals which was very helpful to enlarge the difference between pure noise reflections and the signals with noise and defect reflections. (This may be clear from the curves of $y=x$ and $y=x^2$ in the up right corner of the figure 90(b)). Therefore, if the calculation speed is permitted, using P_{av} enabled the system to produce more effective results, otherwise the signal mean S_{av} could be used as an acceptable approximation in most cases.

2 Signal averaging.

As is well known, A/D conversion (only by means of A/D conversion) makes it possible to average several frames of A-scan signals. Fundamentally, this method permits the enhancement of the signal due to its fixed time position and the

elimination of the noise due to its time randomness simultaneously. As a result, this technique has the potential ability to reduce or eliminate both 'white noise' and 'grain noise'. As showed in chapter 4, the method effectively reduced white noise amplitude because the noise was the 'random time signal'. However, for the grain noise (the spatial random signal), the averaging method itself did not come into effect. It must be combined with the so called 'box-car technique'. When a probe was moving, the spatially scattered signals would be transferred into random time signals which could be effectively averaged off. Therefore, to generate full capacity of the technique, on one hand, every adjacent A-scan frame should be sampled from an adequately separated probe position so as to vary those spatially random signals sufficiently in time base. On the other hand, the two probe position should not be separated too much so as to retain the continuity of those real signals from defects, otherwise the real signals might be largely reduced or destroyed at the same time that the noise was eliminated. Furthermore, the averaging times should be properly selected. The more the averaging times, the stronger the ability to diminish noise amplitude. However, the averaging times were, seemingly, restricted by the computer speed to keep in step with the welding speed. This is not always the situation. In fact, increasing averaging times could be realized through employing special programming methodology rather than repetitive addition. Taking N times averaging as an example to explain this method:

If all previous N times of A-scan data are stored in the temporarily memory (or buffer), the current averaging results could be calculated using the expression below:

$$R_i = (A_i + R_{i-1} - A_{i-N})/N \quad i > N$$

Where i stands for the ith sample, N for the averaging times, A for a group of A-scan data and R for the averaged results (see figure 91). From this expression, it could be clearly found that calculation work was independent of the averaging times (N) and, in fact, the calculation amount was fixed no matter how many groups of A-scan data were averaged. In this way, large averaging times could be selected to enhance the 'signal to noise ratio'. However, the first N group of

results should be calculated in another way. Either by directly sampling the N time to start the first average calculation or by using the first i groups of data to average, this method should be employed for the first N groups of samples.

Even though great averaging times did not slow the calculation speed, it would generate some side effects if the averaging times were too high. Large averaging times corresponded to a longer distance between the position for A_{i-N+1} and the position for A_i at a given welding speed. As indicated previously, this would worsen the real signal through reducing the signal amplitude. More importantly, too large a distance range in the average period might cancel out each other in different A-scan signals from those small dimensional defects like small pores. In fact, data averaging over a long distance between probe positions always decreases the testing resolution.

In summation, the parameters, mainly the averaging times and the averaging period, should be adequately selected according to the calculation speed, the welding speed and the noise source so as to produce the best noise reduction results.

3. The FFT method.

FFT techniques were proved to increase signal to noise ratio in austenitic steel weld inspection in some cases, but it did not seem so positive in defect detection during welding. Figure 92 shows several spectra from A-scan results in different situations. Figure 92 (a)-(c) are the spectra from the weld pool signals, crack signals mixed with grain noise, and crack signals only respectively. These figures showed some differences between each other. In comparison, each figure used two sets of A-scan data from the same situation. The full coherence of any two spectrums in each figure indicated that the differences between figures were generated by different signal sources rather than signal fluctuations. Figure 91(d) directly compared two spectra from the weld pool and from the copper crack

respectively. All results indicated the existence of spectrum differences from different sources of signals. Nevertheless, the comparison between figure 92 (b), (c) & (d) could be the answer that there is no simple direct corresponding relationship between the defect type and the spectrum because large differences existed even though the signals were all copper induced cracks. This meant that the differences between spectra were not ready to be simply employed to judge the existence of certain defects or to estimate defect sizes. Additionally, even FFT techniques could be potentially employed in some way or the other in order to increase signal to noise ratio, the calculation speed was usually not satisfied (if using software FFT) for the real-time defect detection during welding.

Apart from all the difficulties stated above, the ultrasonic coupling also caused problems in defect detection during welding. Due to the high temperatures around the weld pool, the probe should be far enough away from the weld pool to prevent the probe (or probe shoe) from being damaged and; to prevent the couplant from vapourisation. In addition, the broad ultrasound beam section due to the beam spreading, not only greatly reduces the ultrasound pressure at the beam centre but also increases the tendency of introducing unwanted reflections, and both of them decrease the signal to noise ratio.

5.3 RELIABILITY OF DEFECT DETECTION DURING WELDING.

Like any other NDT methods, ultrasonic weld inspection has its suitability and limitation even when it is used at room temperature for inspection, especially, when attempts are made to size defects quantitatively.

Generally, defect sizes are estimated from amplitude data, either directly or through a defined decibel/amplitude criterion as the scan proceeds. "Transducer/specimen coupling changes, or defect transparency, orientation and roughness variations, may combine to make the correlation between reflected pulse amplitude and defect size very weak. This is an inherent weakness with reflected

amplitude approaches to quantitative defect assessment."^[13] Usually, the testing sensitivity, resolution and reproducibility etc, depend on the nature of the defect, the ultrasonic system, ultrasonic parameters and the inspector. Apart from all those conventional factors at room temperature testing, there are some special factors which could seriously affect the reliability of on-line defect detection during welding.

5.3.1 Restrictions caused by high welding temperatures.

It is well known that, in ultrasonic defect testing, the judgement of defect existence and the estimation of defect dimensions are based on signal amplitude, whilst the signal amplitude itself is severely affected by high welding temperatures. The overall temperature effects on amplitude might be compensated for by "temperature amplitude correction relationship" (TAC), or more realistically, the "welding parameter amplitude correction relationship" (WPAC) which could be statistically established through a sufficient number of experiments on a welding parameter and signal amplitude in a given welding process with all other conditions fixed. However, even this relationship was reasonably accepted in accuracy, any amplitude fluctuation caused by the variation of heat balance or a temperature field affected by factors rather than welding parameters. For example, gas fluctuation or welding structure changes at certain places, could alter the signal amplitude and, in turn, affect the result obtained based on the established relationship. Even though, the problem can be reduced or eradicated by statistical analysis (like the averaging technique and the statistical data filter based on the B-scan data). In this way, if the sampling frequency and computer application calculation speed is permitted, the temperature effect on amplitude may be compensated by the established relationship of welding parameters and amplitude. In that case, a fairly reasonable result could be obtained. Nevertheless, the establishment of accurate WPAC relationships for all different defects is not a simple task and needs a lot of experiments. Actually, the establishment of a complete data base for all the different welding parameters and all the possible

defects (even for only a given welding process), although not impossible, is practically undeserving for the time being. This means that defect detection during welding, especially the accurate assessment of defect sizes, is not always reliable. In fact, defect detection techniques during welding were developed as a welding quality control method rather than a replacement of conventional NDT.

On the other hand, the signal amplitude range for assessing defect dimensions reliably is from about 0.1 (or 0.2) full screen to a full screen which represents a range of 14 (or 20 db). In contrast, the attenuation range caused by high welding temperatures could reach as high as 20 to 50 db in different welding processes using different parameters. This means that the range for assessing defects based on the signal amplitude is only part of the full attenuation range and this, in turn, would cause the signal amplitude to go out of its measuring range unless the gain was preset correctly not only according to the room temperature state; but also the welding process and parameters. In fact, it was the latter (the welding process and welding parameters) which played a more important role. This made it very difficult to employ signal amplitude for estimating defect dimensions and this is one of the reasons why signal width rather than signal amplitude was employed in the peak detector.

5.3.2 Some limitations of contact coupling and the mechanical scan.

"The most common method of producing ultrasonic waves is by the use of a 'piezo-electric transducer'."^[13] For this kind transducer, the probe had to be well contacted to the specimen via a coupling fluid in order to transfer the ultrasonic energy to the specimen. A major problem associated with this contact coupling is that the efficiency of the coupling is influenced by the state of the specimen surface. Any pit or spatter from welding could reduce the coupling effect or even totally lose the coupling. Generally, trivial variations of couplant thickness between the probe and the specimen could severely change signal amplitude and thus affect the defect judgement or assessment based on the signal amplitude. Furthermore,

the need of physical contact between the probe and the welding plate indicated some limitations of ultrasonic testing in structural configurations which possess geometries with difficult-to-reach areas. Limitations are also caused by elevated surface temperatures, such as the situation in a very high welding current processes or the last few runs in a 'multiple run' welding process.

Additionally, the scan speed is usually constant in a fixed process. That is to say that even when the assessment is in doubt due to unexpected reasons, such as temporarily loss of coupling, too wide welding parameter fluctuations, the probe cannot scan back for a short distance to perform a repetitive scan. Even if the probe could move back and re-scan for the suspicious area, all signals obtained thereafter could not be employed directly because the conditions would have changed, for example, the probe to welding arc distance had changed. In contrast, re-scan or repetitive scan locally, which is very helpful in estimating defects correctly, is the most common method used in manual ultrasonic inspection processes. This means that the automatic scan might reduce reliability in some situations.

5.3.3 Some limitations of on-line defect detection.

Due to the limitation of the computer speed and the requirement of on-line tests, the selection of signal processing techniques is restricted. Those signal processing techniques proven by off-line ultrasonic inspection processes might not be adopted or the advantages may not be fully taken due to the time limitation. For example, spectrum analysis, signal de-convolution and pattern recognition techniques have demonstrated their ability to increase signal to noise ratio, to characterise defects or to enhance system resolution. However, these techniques could not meet the general time demands of on-line defect detection at the current micro-computer application speed. On the other hand, even those techniques might be adopted and were indeed employed to process signals on-line (such as the signal averaging and the statistical analysis discussed in the previous chapters), the extent and scope of

using these techniques was limited to some degree by the computer speed.

As a result, the signal processing techniques for on-line defect detection during welding should be selected according to the practical multiple conditions. Among all those methods adopted in the test process, both the signal averaging and the statistical analysis based on B-scan data proved their ability to increase the signal to noise ratio, especially to reduce or eliminate the 'white noise' and the 'grain noise'. In addition, the averaging technique should be given priority in the selection of signal processing methods if the special methodology (see previous sections) is employed. As this method made it possible to perform signal averaging with large averaging times without increasing calculation time, selection of this method enabled the researchers to take full advantages of the technique, even at a lower computer speed.

5.3.4 The reliability of detecting defects during welding

There are several kinds of defects prone to occur during welding, but the reliability of detecting them is not always the same.

1. Lack of fusion:

Compared with all other defects, lack of fusion is the easiest defect to be reliably detected during welding. Generally, lack of fusion is produced by either low heat input, inappropriate preparation or; unsuccessful seam following or all of these and, the direct result is inadequate melt of the welding plate. Thus the lack of fusion defect almost always locates outside of the weld bead. Alongside these reasons, there exist several characteristics which could be employed to detect this kind of defect. Firstly, due to low heat input or its location outside of the weld or both, ultrasonic attenuation is relatively low which, in turn, will produce high amplitude signals. So these signals are easy to detect. Secondly, the signal time from this kind of defect is different from those signals from the defect inside the weld bead

or the grain noise. This is helpful in distinguishing this defect from all others. Thirdly, this kind of defect is usually, not necessarily, large in dimension and often distributes continuously or repeatedly. This feature can also be used to decide its existence based on B-scan data.

2. Cracks:

It is well known that welding cracks could be classified into two groups: hot cracks and cold cracks. Cold cracking, as the name implies, is generated in a cold or near cold state (not in the solidification process). As a result, this kind of defect could not be detected during welding since the probe was aimed at those solidifying or just solidified areas in the weld in this work.

Hot cracking is mainly associated with low melting point constituents in the weld metal and, therefore, it occurs in the weld bead being solidifying or the just solidified weld bead. The existence of this low melting point liquid film usually depends on the weld ingredients or the quantity of the liquid. Whereas the very thin liquid film around the metal grains can partly transfer ultrasonic energy, and its transfer ability is much higher than that of an air film. Before the cracking actually occurs, the grains are linked by those liquid films which can partly transfer ultrasound energy, after the cracking has occurred, the place of the thin liquid film is replaced by air gaps which barely transfer ultrasound energy. This means that hot cracks can more efficiently reflect ultrasound after actually cracked than that during cracking. Consequently, if the BCED is not large enough, i.e. the probe was focused on the area where hot cracking was being generated, the amplitude of the received signals could be affected by the quantity of the low melting point substance. In the real experiment, it was found that the time between weld pool signal disappearance and crack signal appearance was not constant but varied from experiment to experiment. This might be caused by the quantity and distribution of the liquid films. Therefore, to avoid this uncertainty in detecting hot cracks, the BCED should be adequately arranged. Too small a

BECD might cause unstable crack signals. It could be recommended that the probe focused on the area fully solidified (thorough disappearance of liquid) for TIG welding processes. In that case, the grain noise was greatly reduced or even faded. Thus hot cracks could be properly detected. Nevertheless, the BCED should be selected according to the welding parameters (the attempt to avoid grain noise fully; might not be always recommendable).

3. Porosity or inclusions:

Compared with the afore mentioned defects, porosity or inclusions are the least important defects to welding structures provided that the overall size is not too big. Porosity and inclusions are ultrasonically similar to each other and any discussion about them could be extended to the other. In the following discussion, porosity is taken as an example. Generally, porosity is a good ultrasound reflector even though those very small size high density pores could scatter or absorb ultrasound severely. As a result, porosity produces fairly large signals. In addition, due to their size and discontinuous distribution, signals change greatly with probe movement, this can be employed to distinguish porosity from other plane defects. Of course, some cracks, like copper initiated cracks, have similar features and are very difficult to discriminate against each other reliably in the on-line test during welding. Besides, due to its signal characteristics, the averaging range for the data averaging method and the counting range for the statistical analysis based on B-scan data should be adequately selected. Otherwise, the signals could be severely distorted if the averaging times or the counting range selected are too large, because this would "smooth" the signals or even "filter" out the real signals from porosity. As a result, the feature of great change in signal amplitude might not remain and, this makes it difficult to classify the defect detected. It is for this reason that the averaging times should be suitably decided; though large averaging times are helpful in increasing the signal to noise ratio.

5.4 STRATEGY LIMITATIONS.

As was stated previously, the system was not developed to replace a conventional room temperature NDT, but as an auxiliary welding quality control device. The question was how and to what extent the system could control or improve welding quality. From an economical point of view, the significance of this system is fully proven (see chapter 2). Nevertheless, as a control device, there is a philosophical problem: the strategy of feed back control. Unlike the penetration control (which could be controlled by either adjusting the welding current or the welding speed or both), and seam tracking (by physically moving the welding head position), defect detection is not adequate as a simple and direct control of welding quality. In another words, how could the defects found in the weld be corrected or prevented.

Two methods were considered for making use of the results from the defect detection system. Firstly, the attempt to correct or to eradicate the existing defects. According to reference [7], it might be possible to remelt the just solidified area around the weld pool or locally 'melt back'. In this way, those just generated defects very close to the weld pool might be corrected. Nevertheless, it is practically very difficult to achieve good results, because the BCED had to be very small (which does not produce favourable results in some case) and the welding power source must respond very quickly (which is not easy, especially in the situation of high welding currents). Secondly, more importantly and more realistically, the attempt to prevent the same defects from developing or to warn the operator or even totally shut down the welding system. To accomplish these functions properly, an expert system is desirable. During the process, the computer system can access relative standards stored in the computer and make decisions according to the defects having been detected and analyzed. If the defect is within acceptable limitations then the computer displays the defect information in order to remind the operator and, at the same time, adjusts the welding parameters accordingly to prevent this same defect from occurring at a later time. For

example, if any lack of root fusion was found and the size was within the acceptable region, the computer could alert the operator by displaying the relative information and increases the welding current immediately. As a result, the same defect could be avoided in a later welding operation. On the other hand, if the defect is unacceptably large, then some action should be initiated. It could be either an alarm to the operator by displaying the relative information about this defect which would allow the operator to make the final decision whether to stop or to continue the process. It is also possible to shut down the system automatically and thus leave time for repairing the defect.

For a system which will combine a defect detection system (including process control, signal sampling, digital signal processing) and an expert system (including defect judgement and assessment, decision making), the use of one slow speed computer might not fully meet the demands of this multi-function. Two computers (e.g. one for defect detection and the other for decision making) working parallel could be necessary. These two computers could be linked to each other by the large capacity built-in memory for data storage (see figure 93). In this way, a more powerful defect detection system which controls the welding quality intelligently during welding could be put into practice besides the ability to detect weld defects more reliably.

6. CONCLUSIONS

Present research enabled the development of on-line welding defect detection concurrent with welding. The following conclusions have been made on the basis of the work presented in this thesis, and these are:

1. A welding defect detection system including all hardware circuits and all software programs was designed and constructed which comprised of a flash analogue to digital converter, a high speed peak characteristics extractor and a process controller. The conversion rate could reach as high as 25 MHz which corresponded to a time accuracy of 0.02 microseconds or about 0.032 millimetres in defect location. The clock frequency employed in the peak detector was 50 MHz and this doubled the above accuracy of signal time measurement and the defect location.
2. By employing the system and the techniques to overcome the problems caused by high welding temperature, the feasibility of on-line weld defect detection concurrent with welding was successfully demonstrated. Lack of fusion, hot cracks, porosity, inclusions, undercuts and blowholes could be detected during their creation if ultrasonic parameters were properly selected.
3. The high temperature in the welding process was the main cause to all major problems met in the defect detection process during welding. The high temperatures could change signal time to as much as approximate $4 \mu\text{s}$, which varied with welding processes and welding parameters, and generated inaccuracies in locating defects. The high temperatures also severely affected the signal amplitude and produced inaccuracies of defect assessment.
4. Large grains, especially the large dendritic grains solidified in welds, were

able to reflect ultrasound efficiently and generated heavy noise, the "grass". This noise could submerge all real signals from weld defects in some cases, especially when the real signal was severely attenuated in a high welding current process.

5. The 'digital signal averaging' technique and the 'statistical analysis' based on B-scan data could effectively reduce or remove both 'white noise' and 'grain noise' and enhance the signal to noise ratio accordingly.
6. The large capacity memory built into the system could store 2048 frames of A-scan data with 256 points for each sample, which enabled all A-scan data to be saved into floppy disks at any later time, results to be displayed on screen and to be printed on paper in the form of A-scan, B-scan or 3-dimensional graphics. As a result, a complete documentation on weld quality and welding process was enabled to be established during the welding process. Furthermore, by using this system, a simulation of amplitude gate effects on B-scan results could be easily performed, which is helpful in a correct selection of ultrasonic parameters.
7. Written in BASIC and assembly languages, the programs made it possible for quick responses to welding defects in about 50 milliseconds, which was the time of one cycle of operation and control software to be executed.
8. Using perspex blocks, all kinds of common weld defects with any desired size and location could be easily produced, which enabled room temperature defect simulation to be performed. The results from the simulation experiment provided some very useful information and regulation which could be employed to judge and to assess different defects in welds during on-line experiments.
9. As no reference block existed for calibration, the assessment of weld defects

was not always reliable. As a result, this method was developed mainly as a welding quality control means, but not to fully replace conventional ultrasonic weld inspection systems.

7. FURTHER WORK RECOMMENDATIONS

1. Employing parallel computer systems.

To meet the demands fully of signal analysis and weld defects classification and assessment, and more importantly, the intelligent reaction to defects detected, another quicker computer (such as the IBM 486) could be added parallel to the system. This second computer is exclusively used for complicated data analysis and as an expert system. In this way, those complicated signal processing techniques could be fully employed 'on-line' to improve the system ability for classifying and assessing weld defects during welding and to respond to the results obtained intelligently.

2. The establishment of a defect data base.

It is well known that it is necessary to obtain the reference peak amplitude, which should be calibrated from the same conditions as the real weld defect detection during welding, for quantitative assessment of the defects. On the other hand, real hot state calibration is very difficult to perform at the moment. However, the reference amplitude could be obtained from those defects in the real experiments during welding and the defects could be assessed by other NDT techniques at room temperature. By employing this method combined with statistical analysis, a one-to-one relationship (defect size and signal amplitude in a certain experimental condition) could be established and thus a data base for a given welding process.

3. Auto gain control (AGC) circuit.

Since the signal amplitude is affected by the welding temperature, which influences the defect judgement and size assessment. If a reference signal existed (for example, the weld pool signal), an AGC circuit could be designed which would enable an automatic compensation for high temperature influences at a certain range and, as a result, the defect classification and assessment would be easier and more reliable.

4. Contactless ultrasonic generator and receiver.

One of the inherent weaknesses of the system as an on-line method for use in practical welding processes is the requirement for using a contact probe and constant coupling. Using a laser to generate ultrasound and using an electromagnetic ultrasound receiver to accept signals might be a possible substitute for the conventional 'piezo' ultrasonic probes, this would obviate the problems of probe contact.

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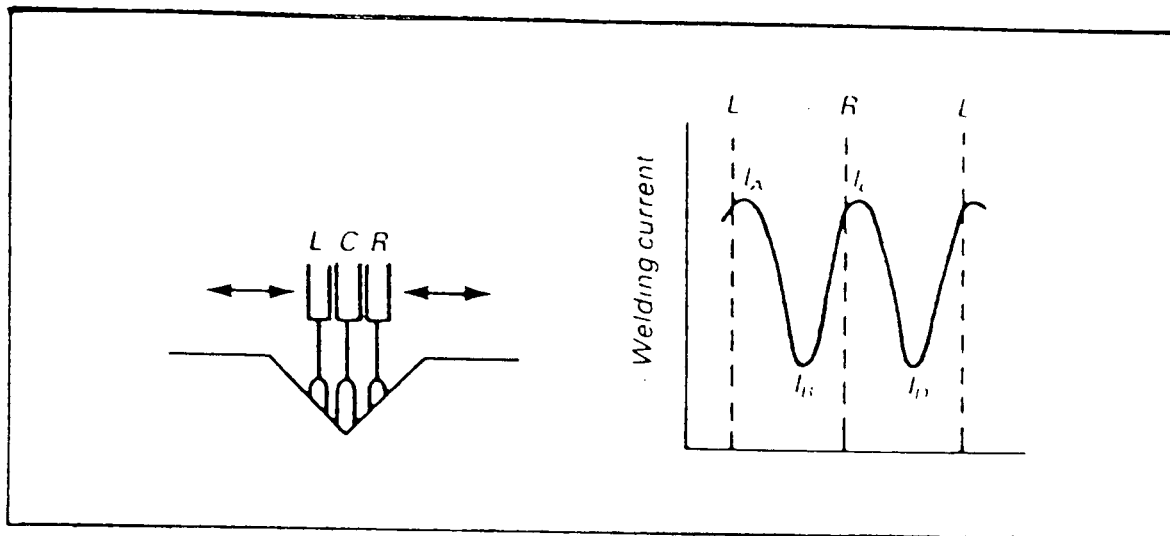


Figure 1 Tracking principle of arc sensing technique

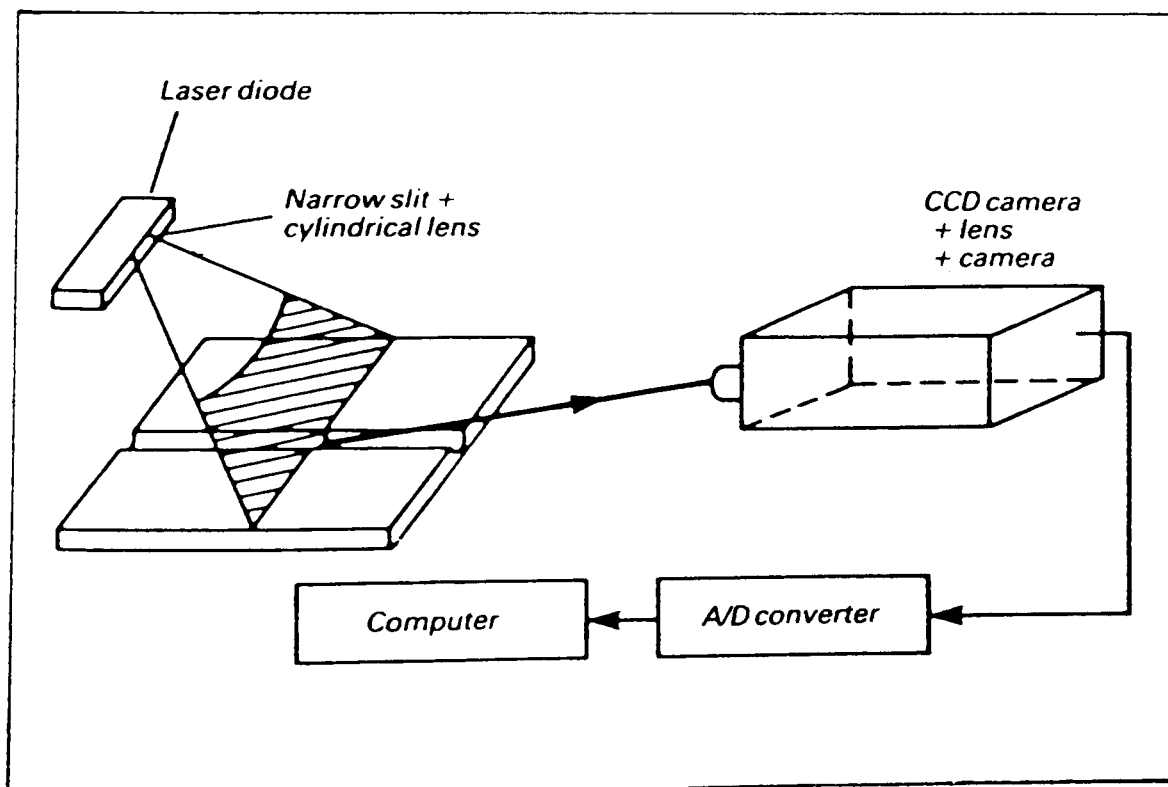


Figure 2 Principle of the shadow-cast technique

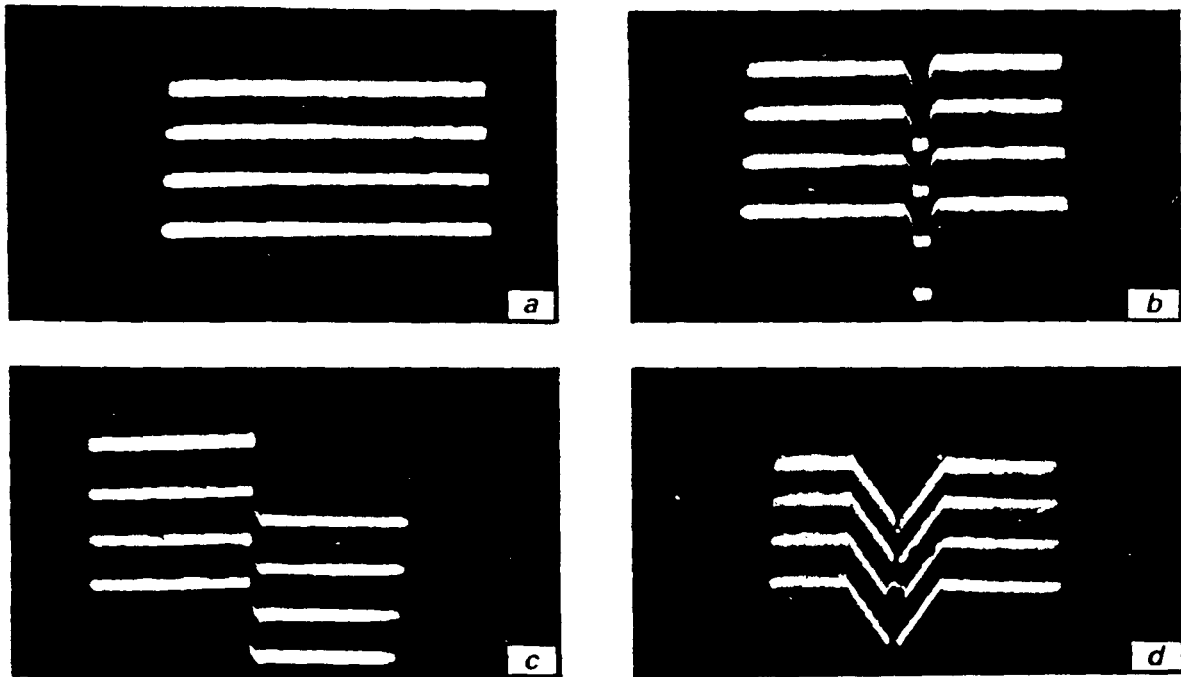


Figure 3 Original camera images showing seam lines illuminated by structured light: (a) flat workpiece surface; (b) butt seam; (c) overlapping seam; (d) V-shaped seam

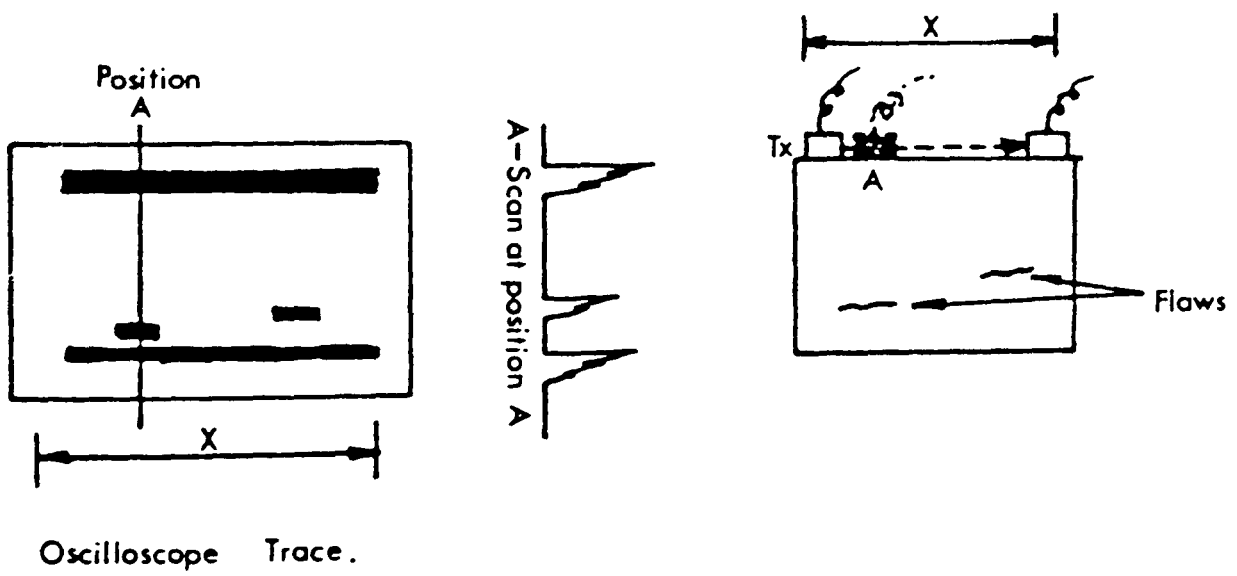
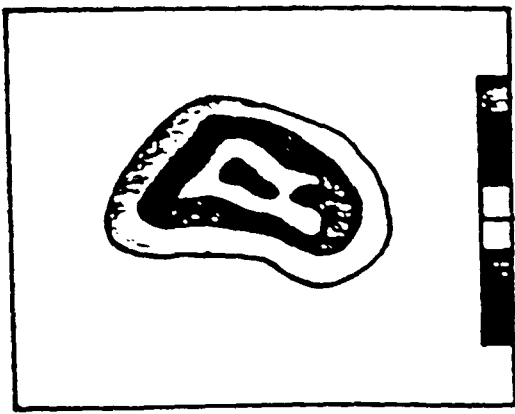
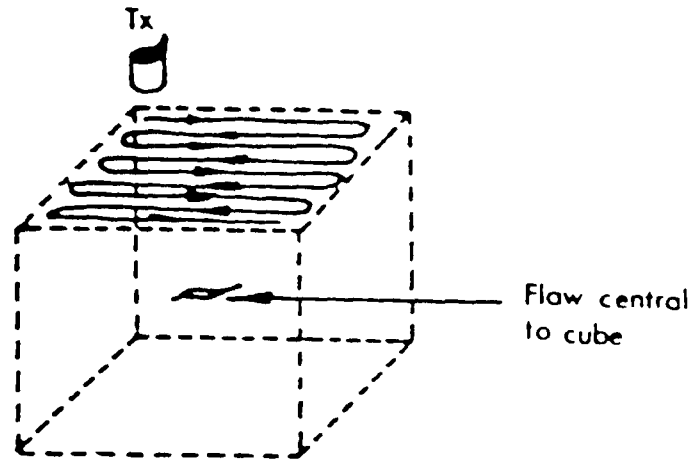


Figure 4 B-Scan presentation



C-Scan image of cube.



Gate position

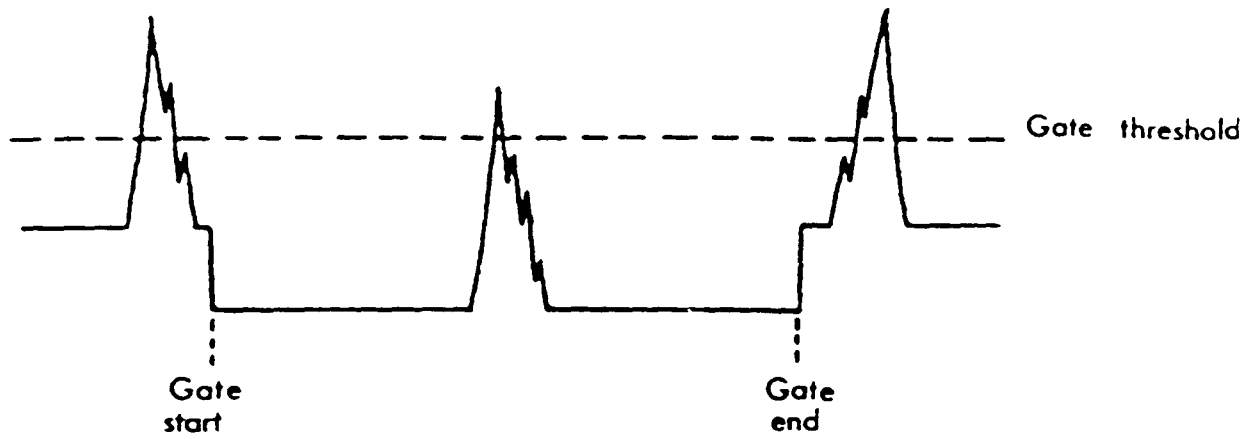


Figure 5 C-Scan presentation

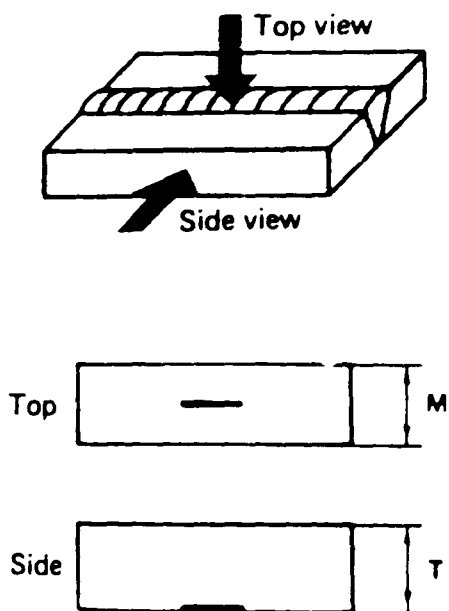
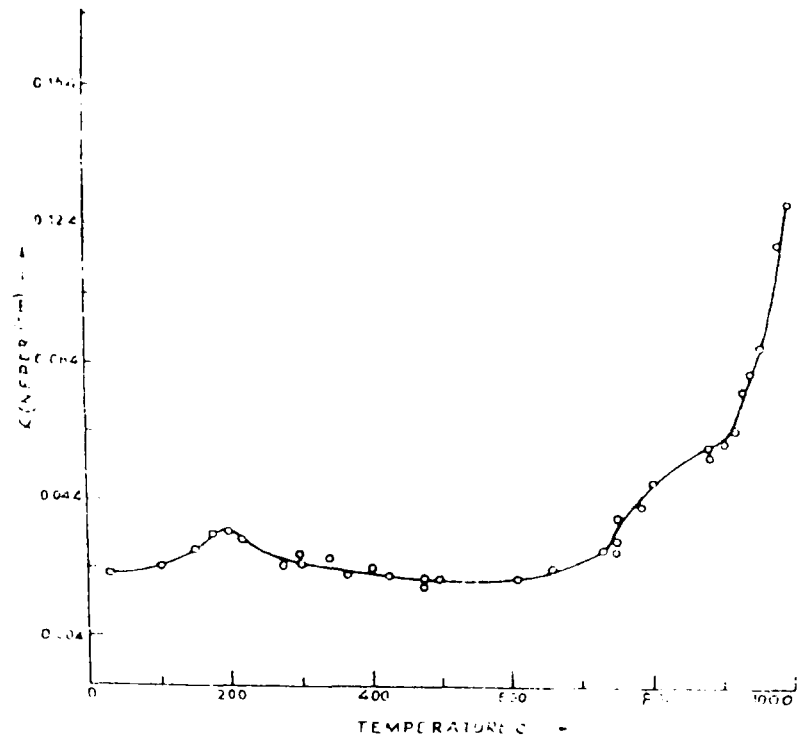


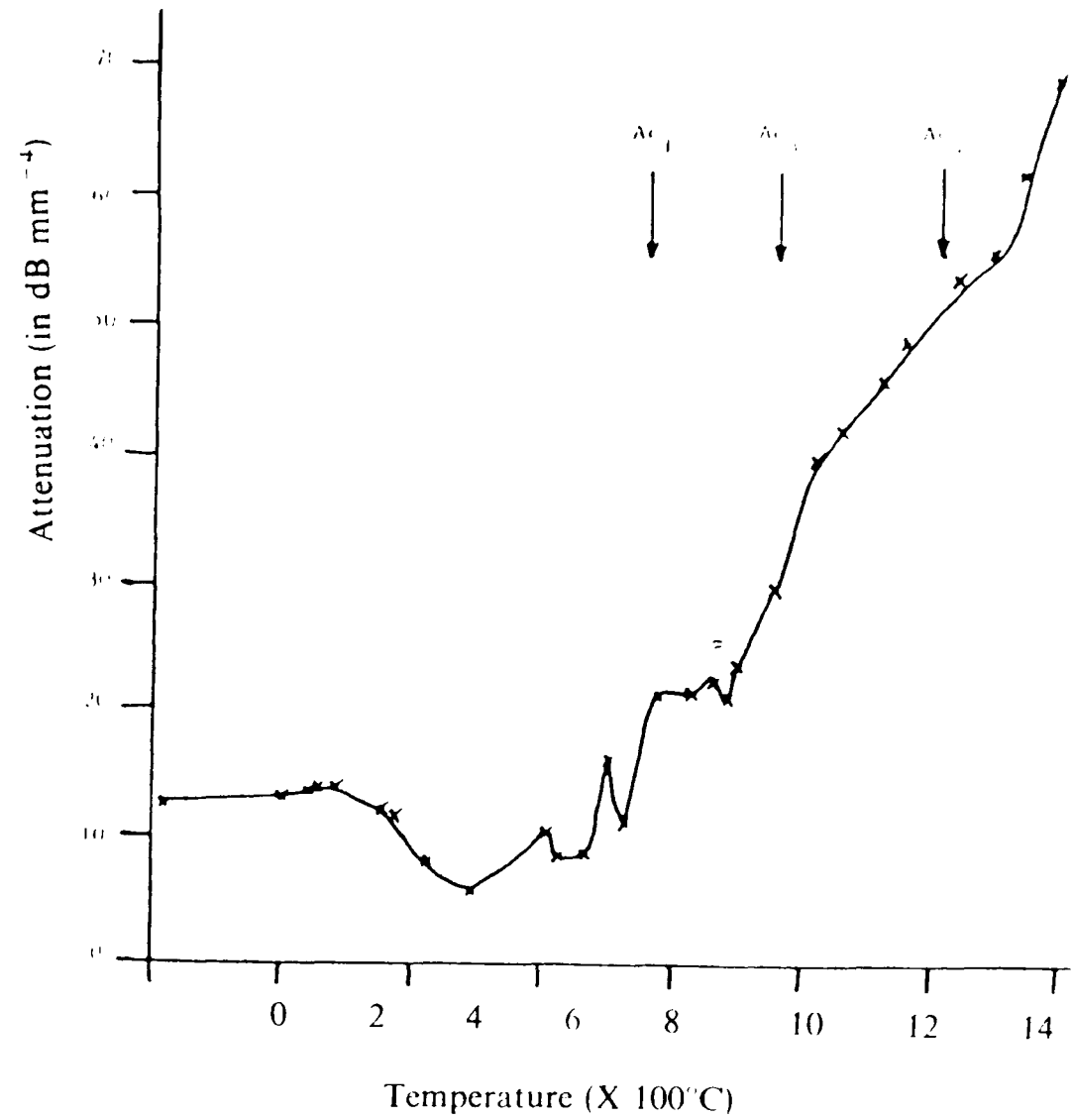
Figure 6 P-Scan principle



Figure 7 Macrograph of austenite weld showing large grains (from reference [70])



(a)



(b)

Figure 8 Relationship of ultrasonic attenuation and temperature: a) from reference [86]; b) from reference [88]

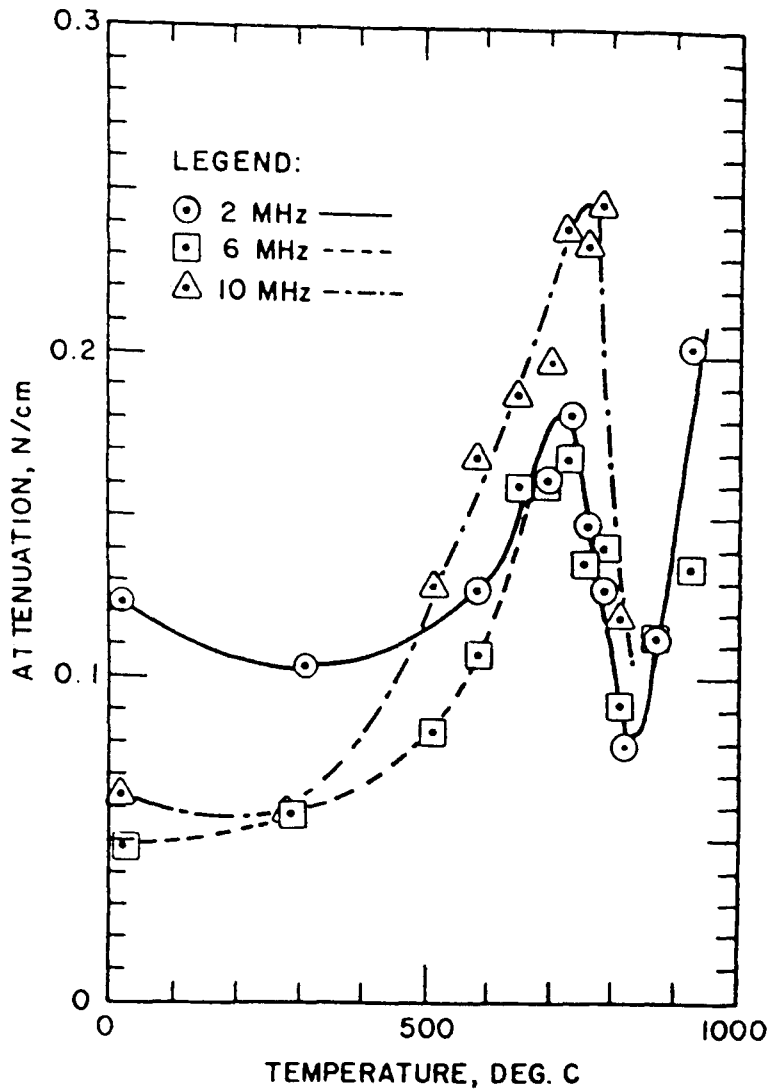
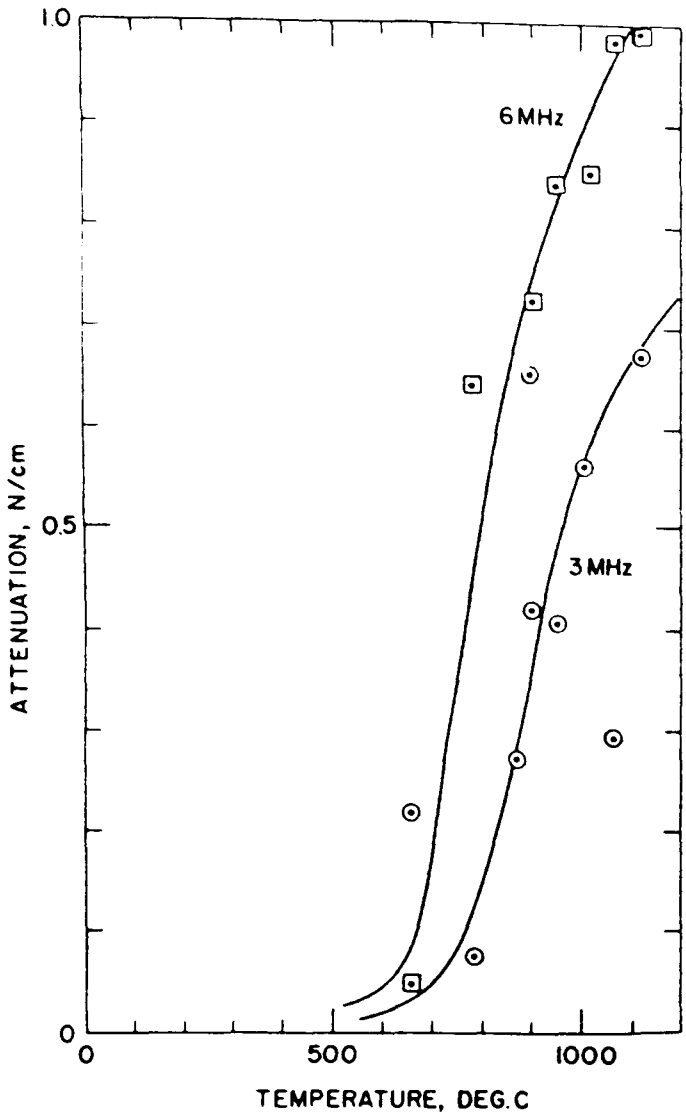


Figure 9 Relationship of ultrasonic attenuation and temperature:(from reference [87]) (a) Shear wave; (b) longitudinal wave

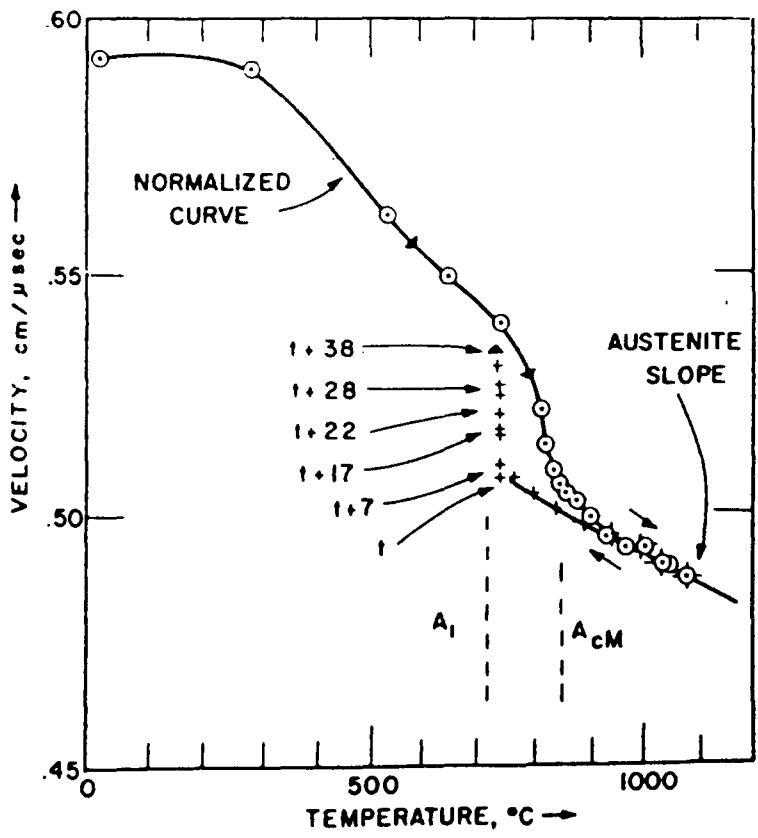
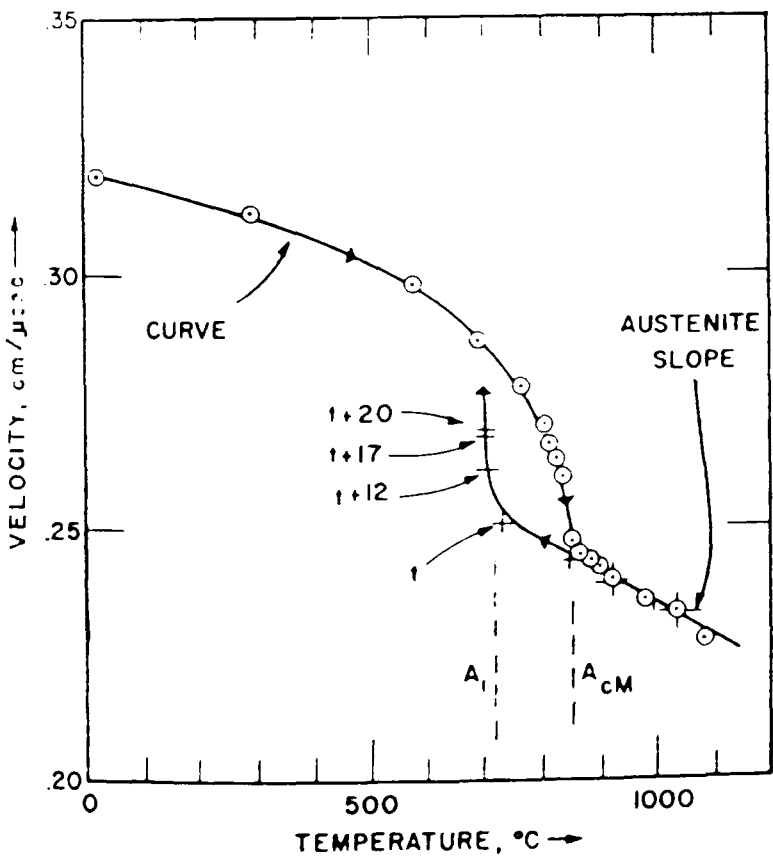


Figure 10 Relationship of ultrasonic velocity with temperature:(from reference [87]) (a) Shear wave; (b) Longitudinal wave

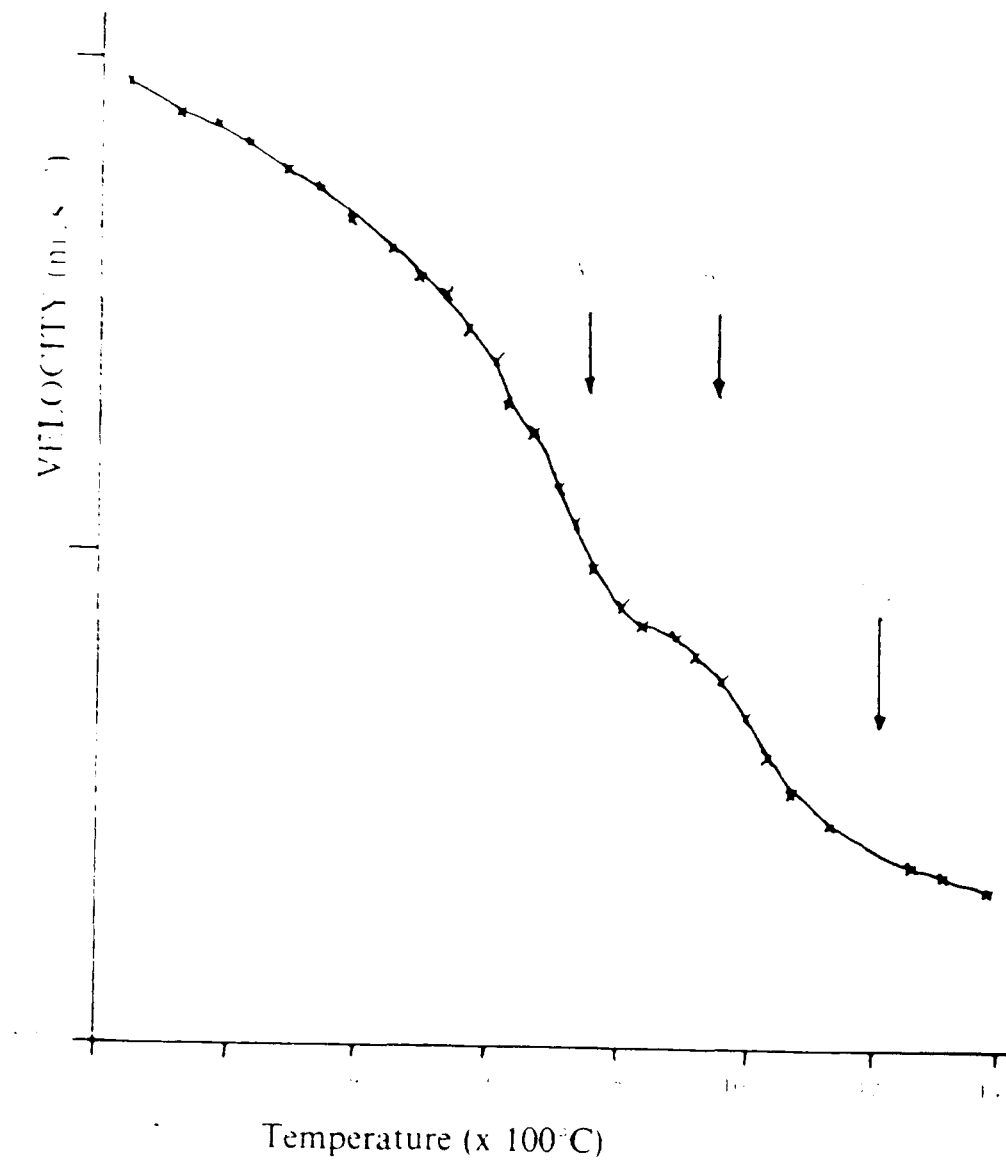


Figure 11 Variation of ultrasonic velocity with temperature(from ref.[88])

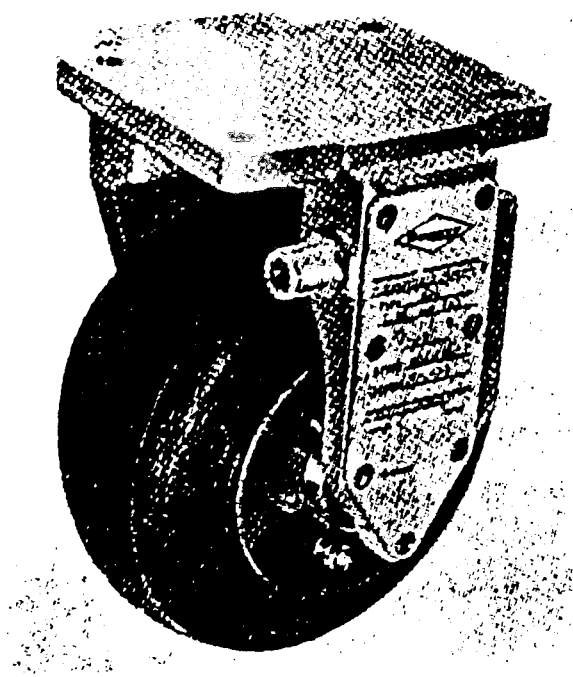


Figure 12 Sperry wheel ultrasonic transducer (from reference [94])

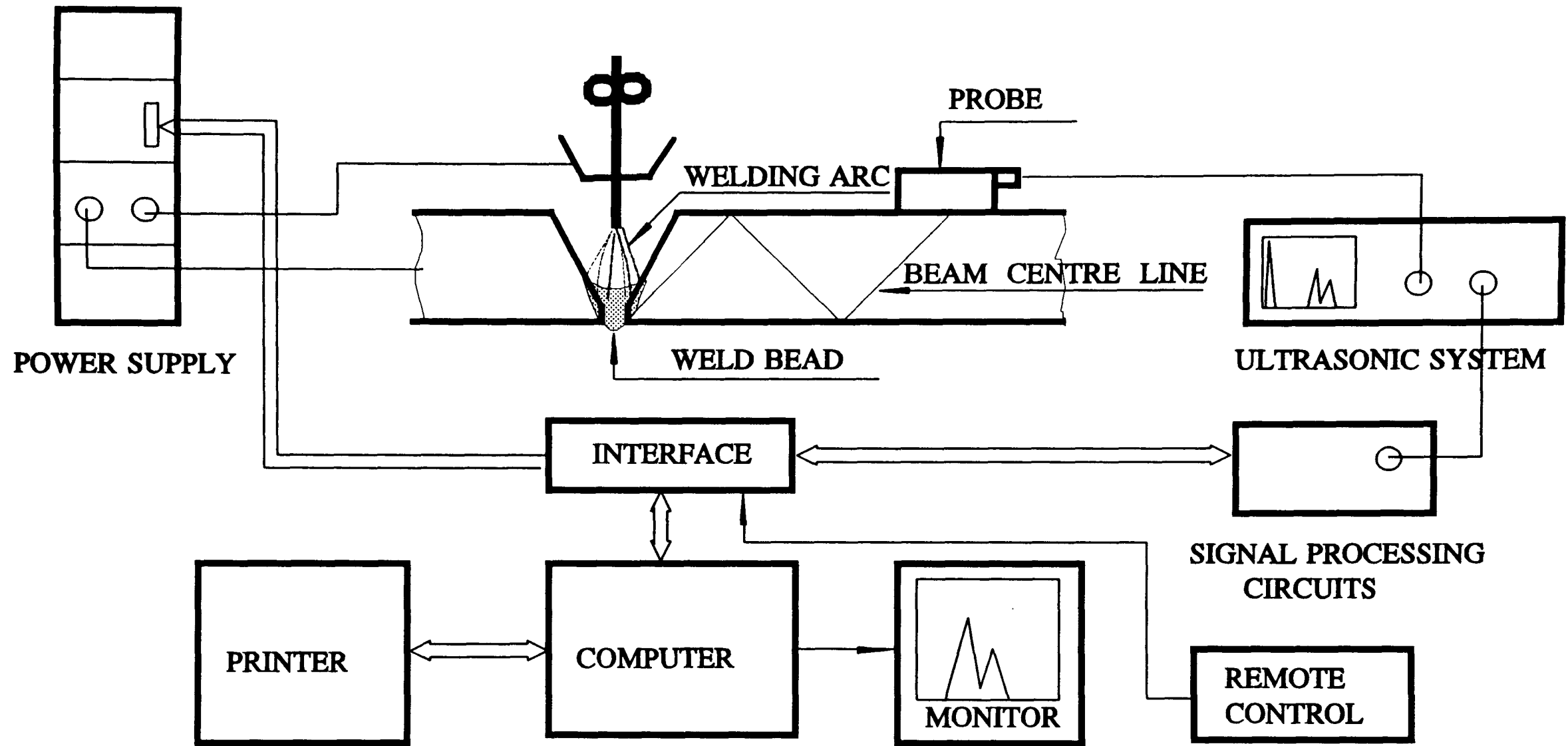


Figure 13 Schematic diagram of computer controlled experiment system

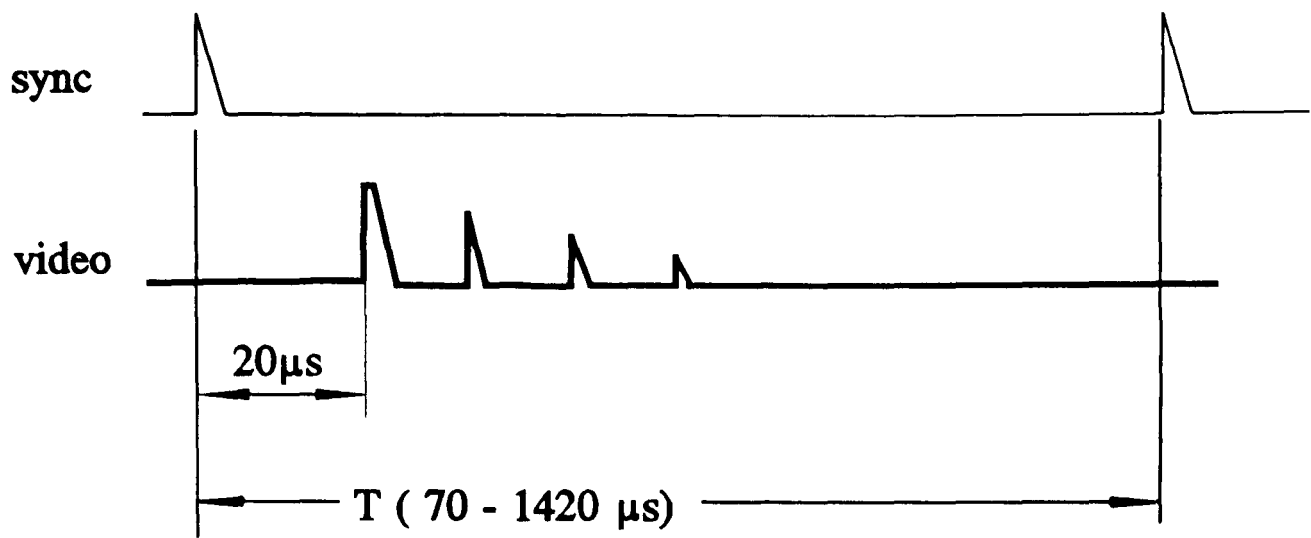


Figure 14 Sync & video signals from ultrasonic instrument

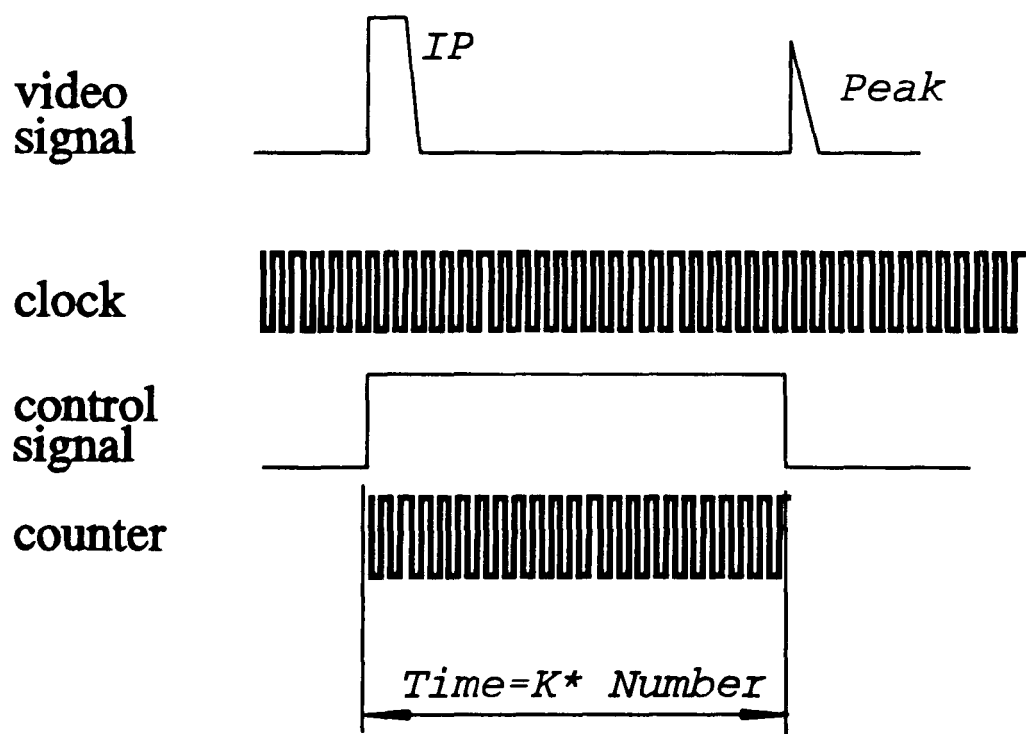
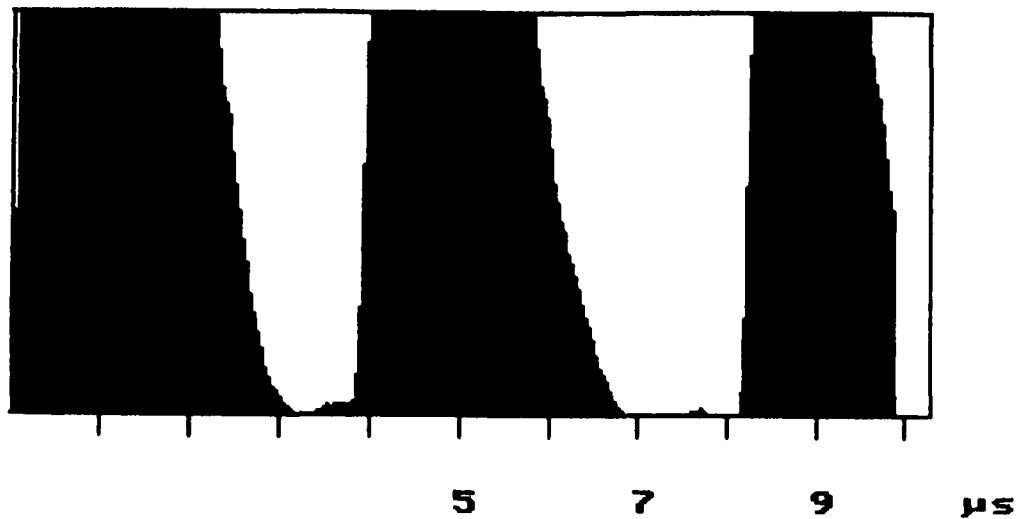
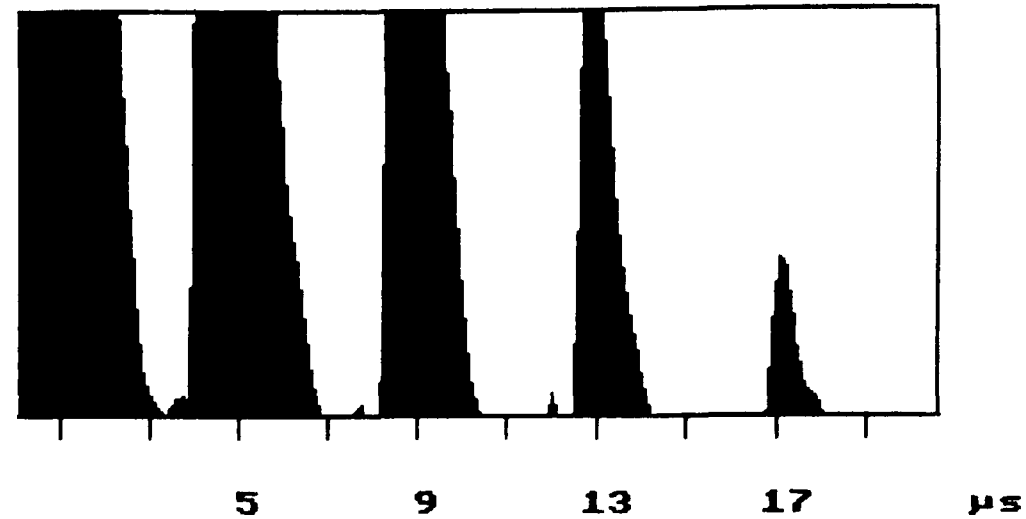


Figure 15 Counting method of time measurement

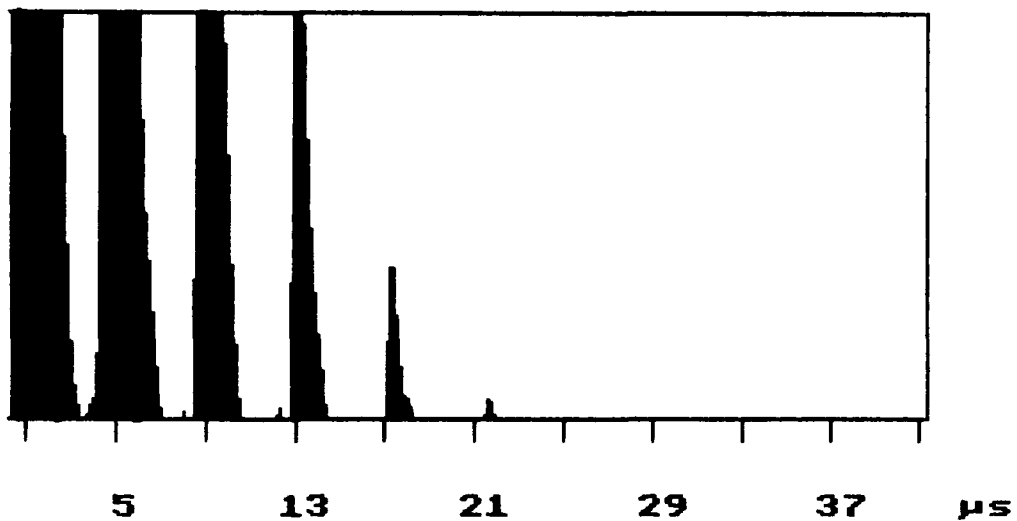
25MHz conversion frequency



12.5MHz conversion frequency



6.25MHz conversion frequency



3.125MHz conversion frequency

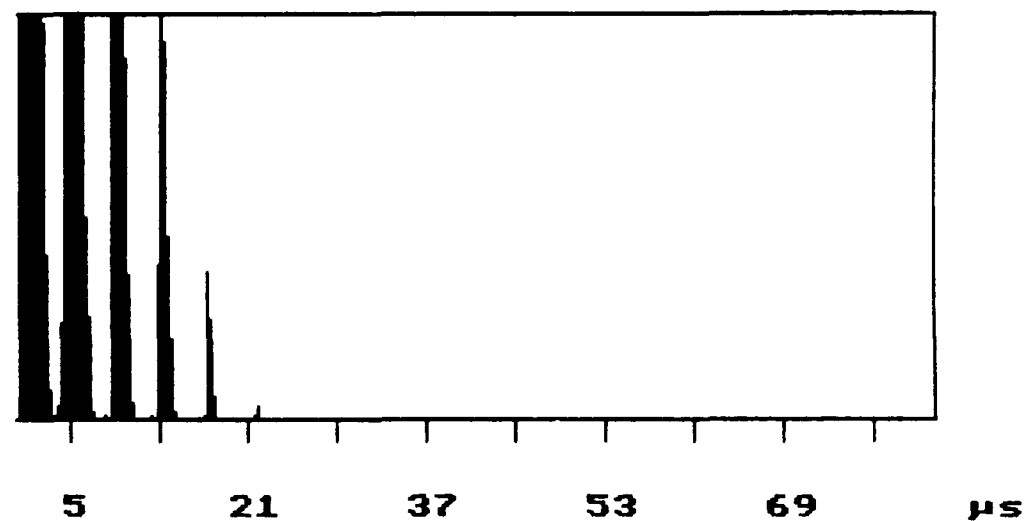


Figure 16 A-scan graph examples with different conversion frequencies
(Condition: 1/2" steel calibration block; 2.25MHz longitudinal wave probe; Pulse-echo mode)

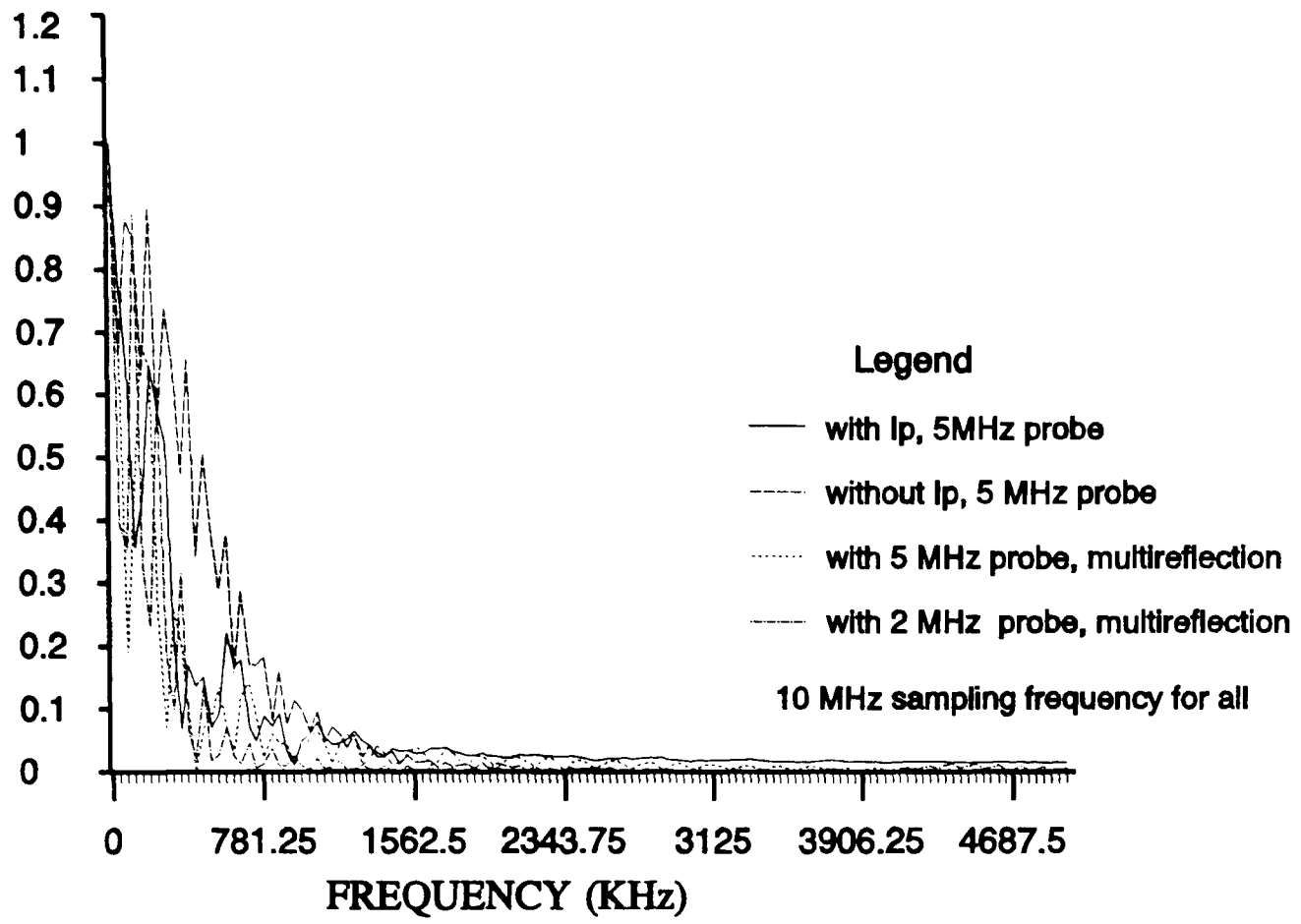


Figure 17 Some ultrasonic signal spectra

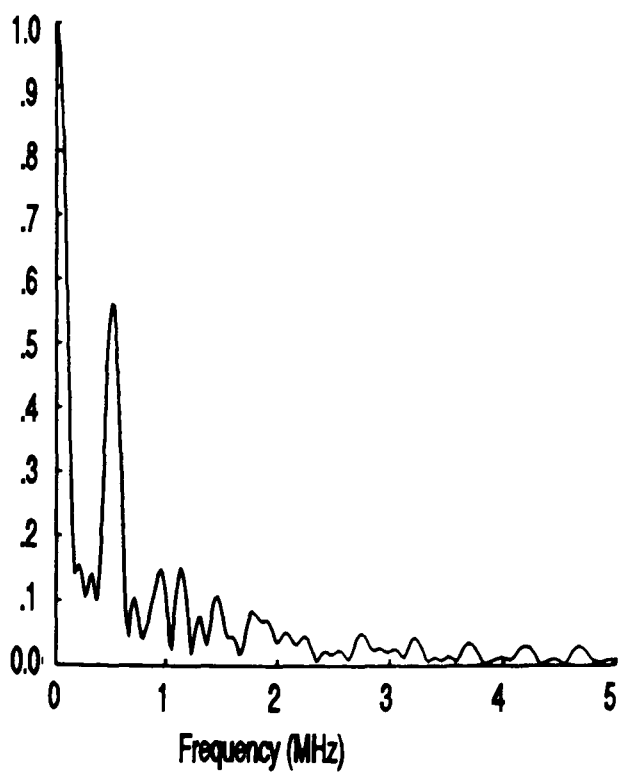


Figure 18 Signal spectrum from 10 MHz sampling frequency

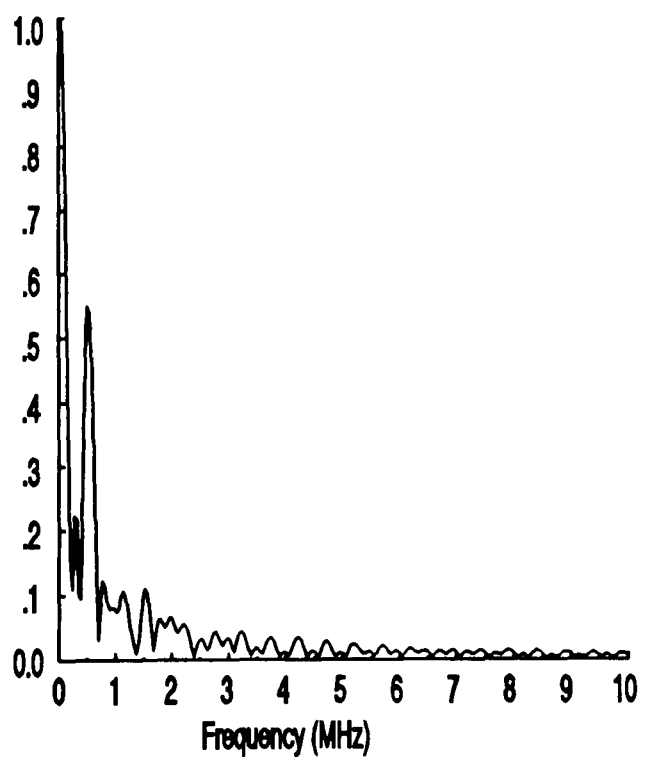


Figure 19 Signal spectrum from 20 MHz sampling frequency

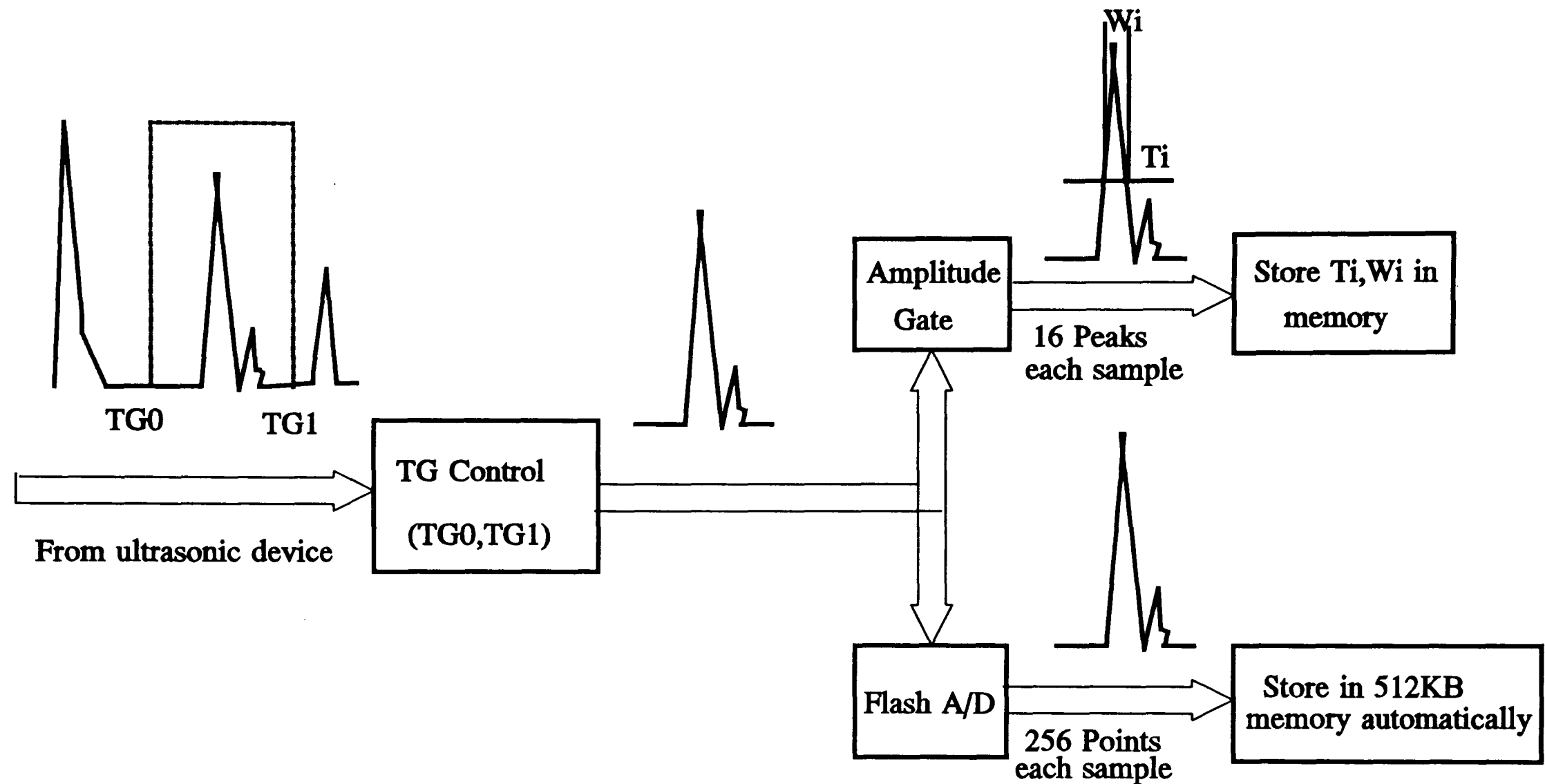


Figure 20 Schematic diagram of data acquisition process

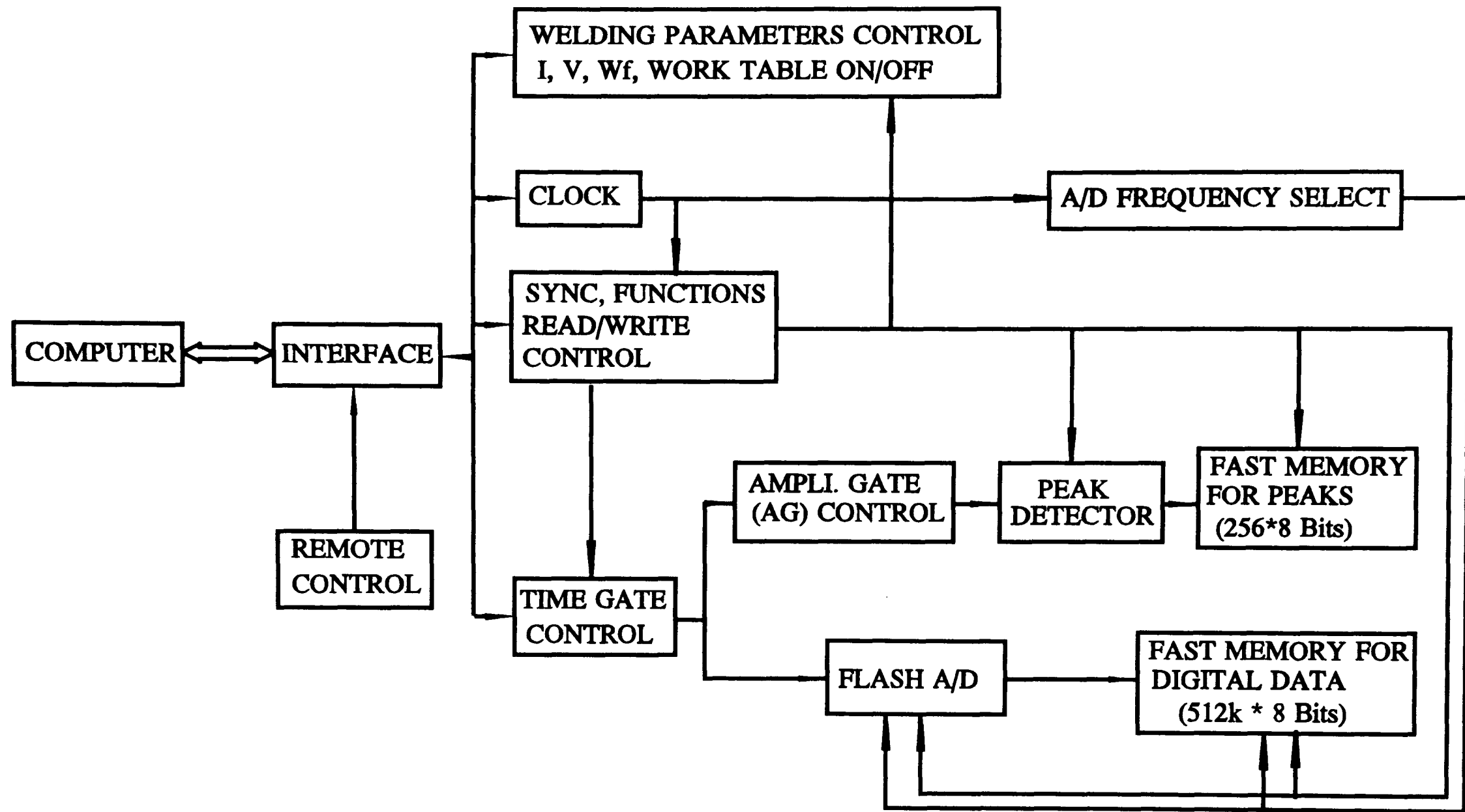


Figure 21 Schematic diagram of circuits

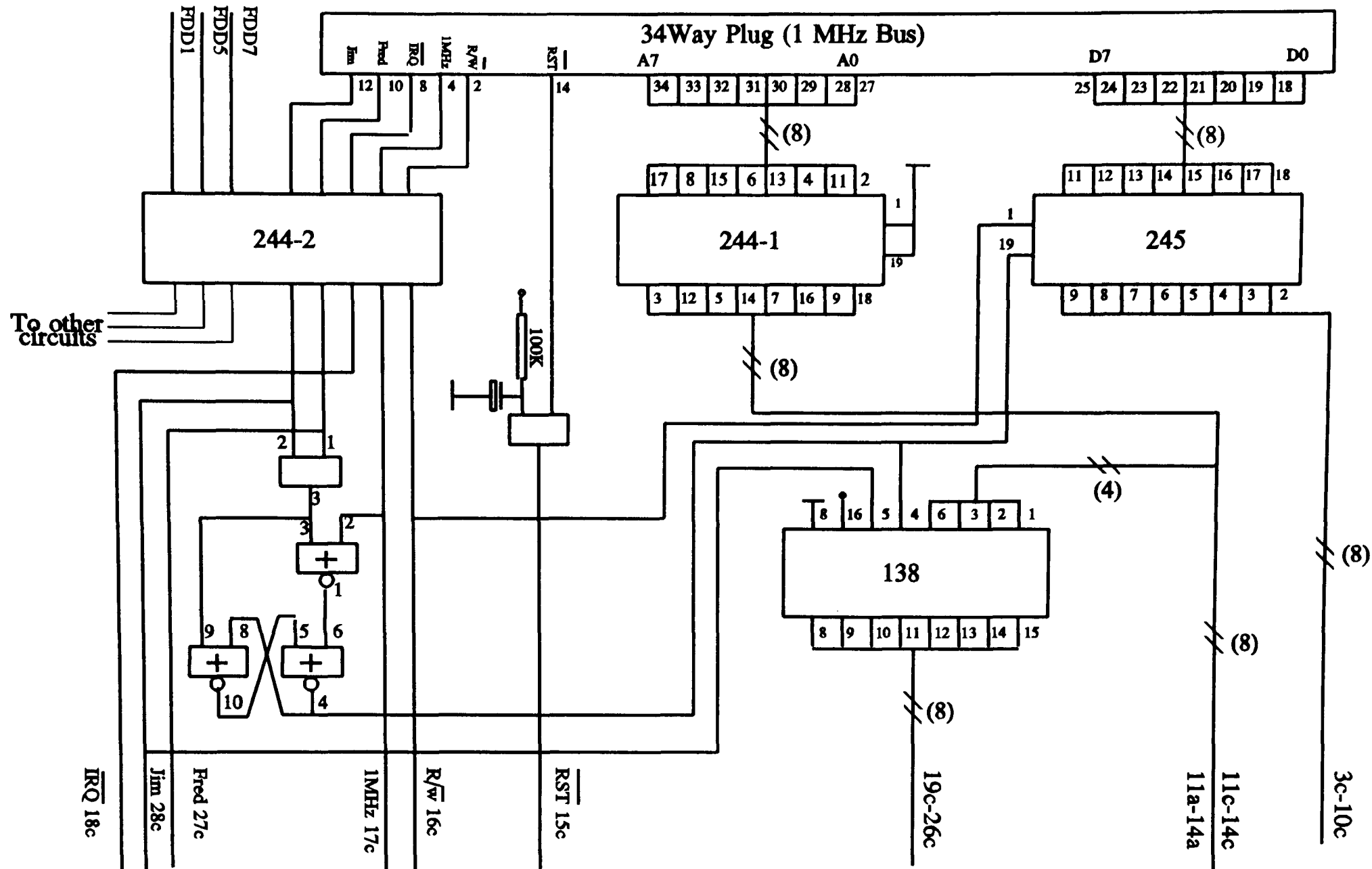


Figure 22 Diagram of interface circuit

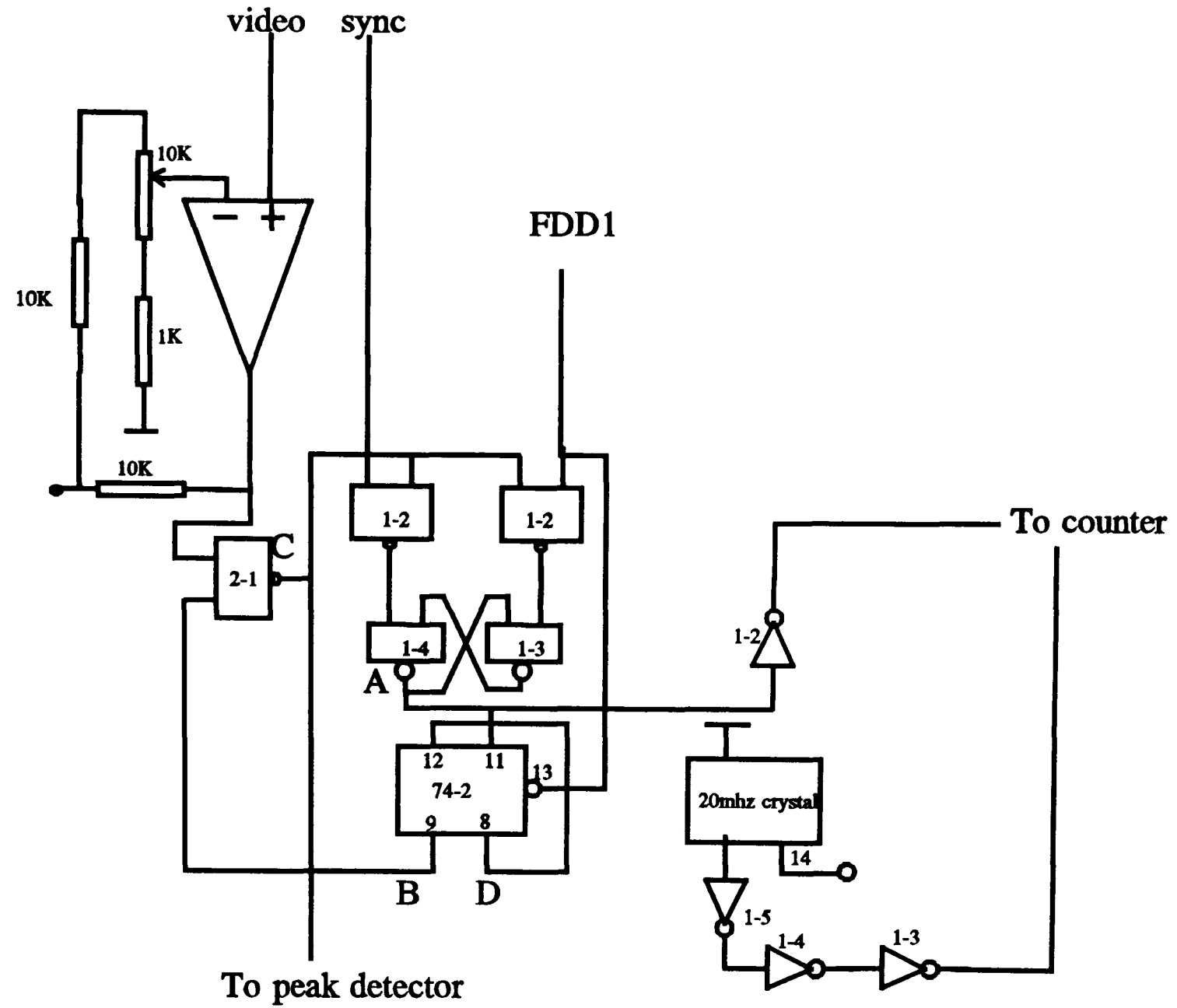


Figure 23 Diagram of synchronetic circuit



Figure 24 Diagram of control sequence

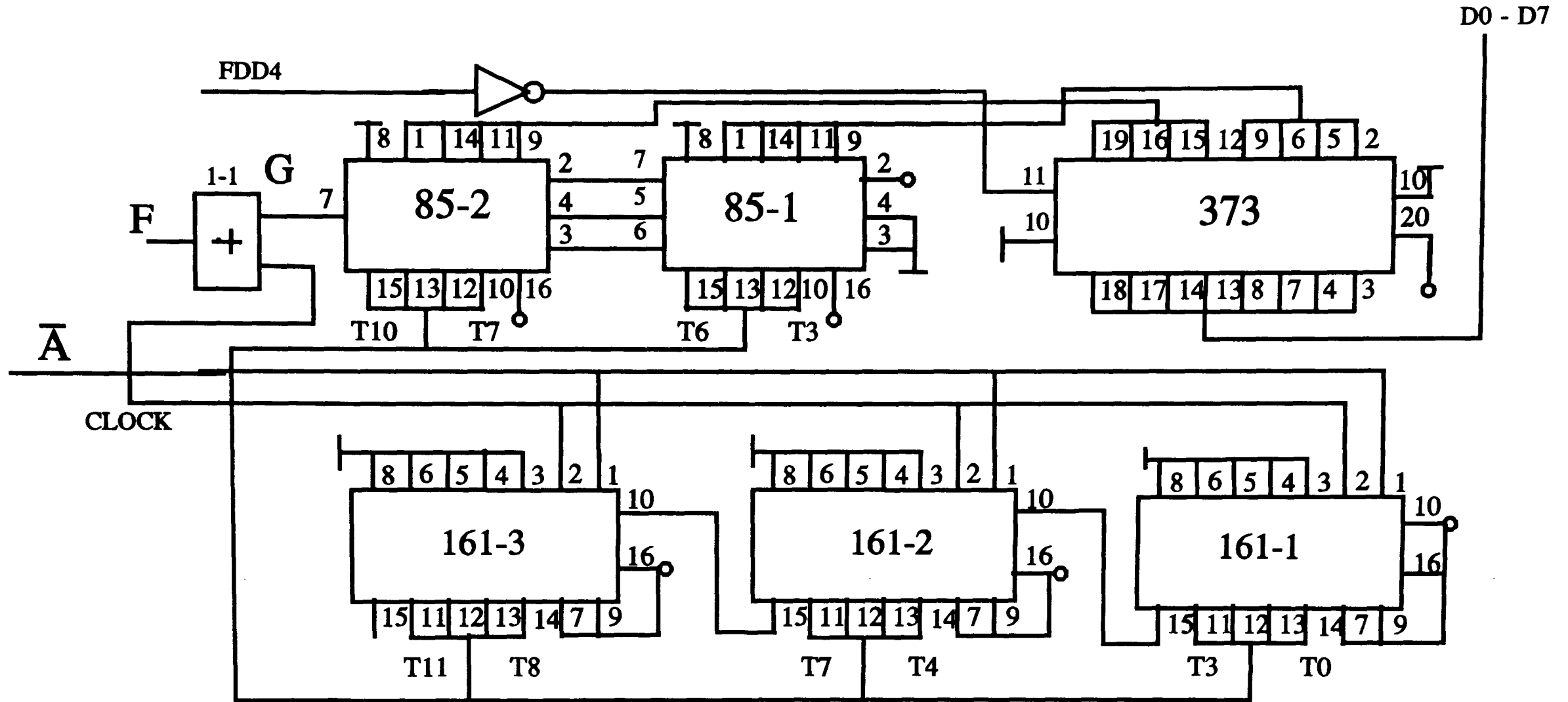


Figure 25 Time gate control circuit

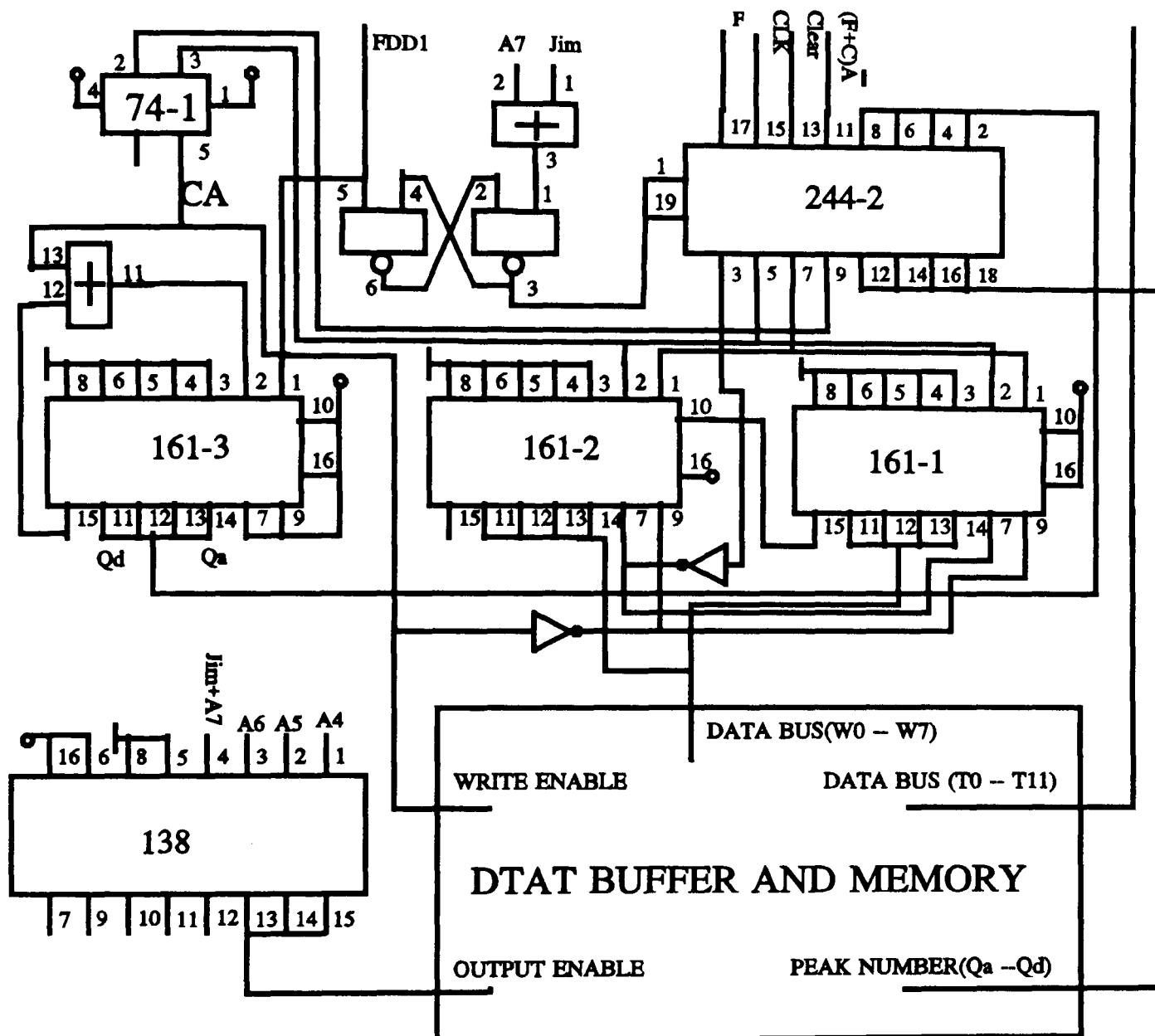
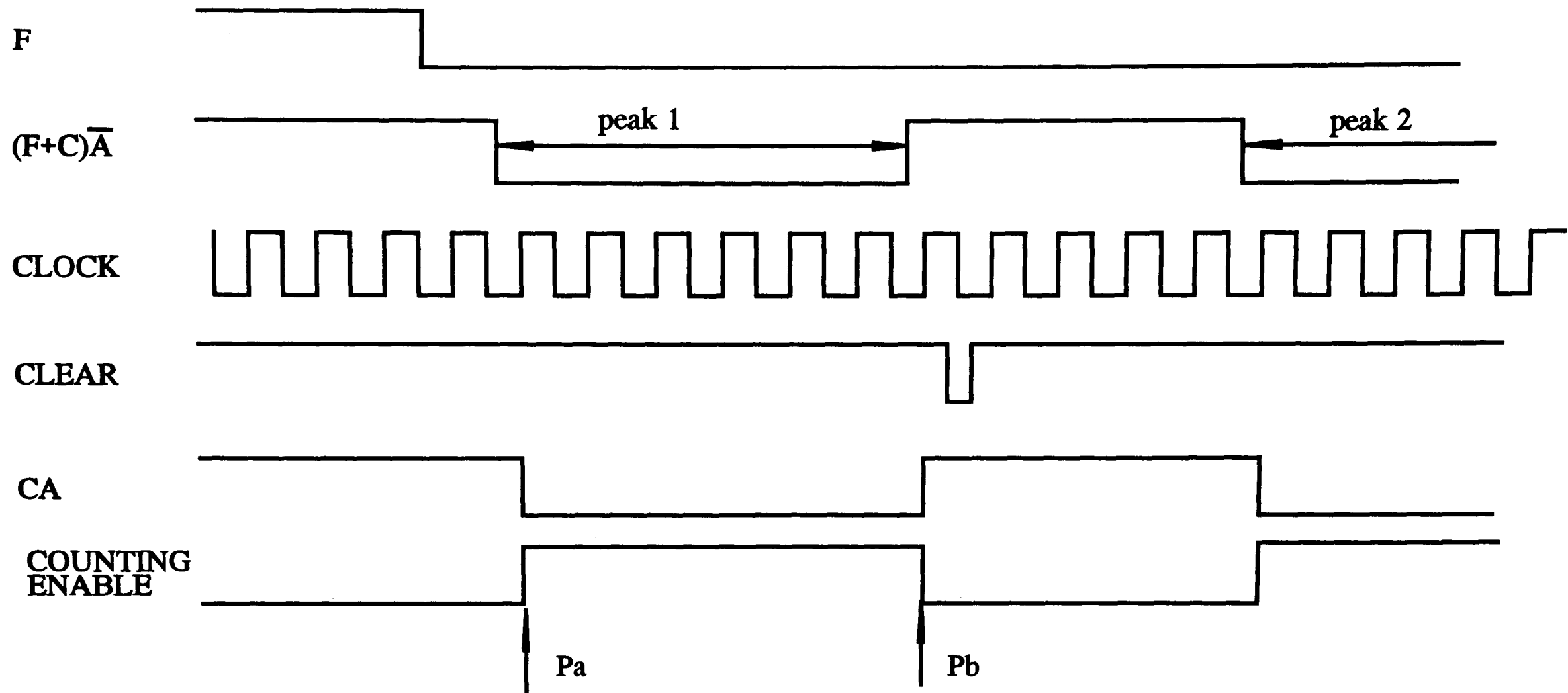


Figure 26 Schematic diagram of peak detector



Pa: start counting for signal width, connect counters with memory

Pb: writing data of time and width; increasing peak number counter by 1; clearing width counters

Figure 27 Time sequence of peak detector

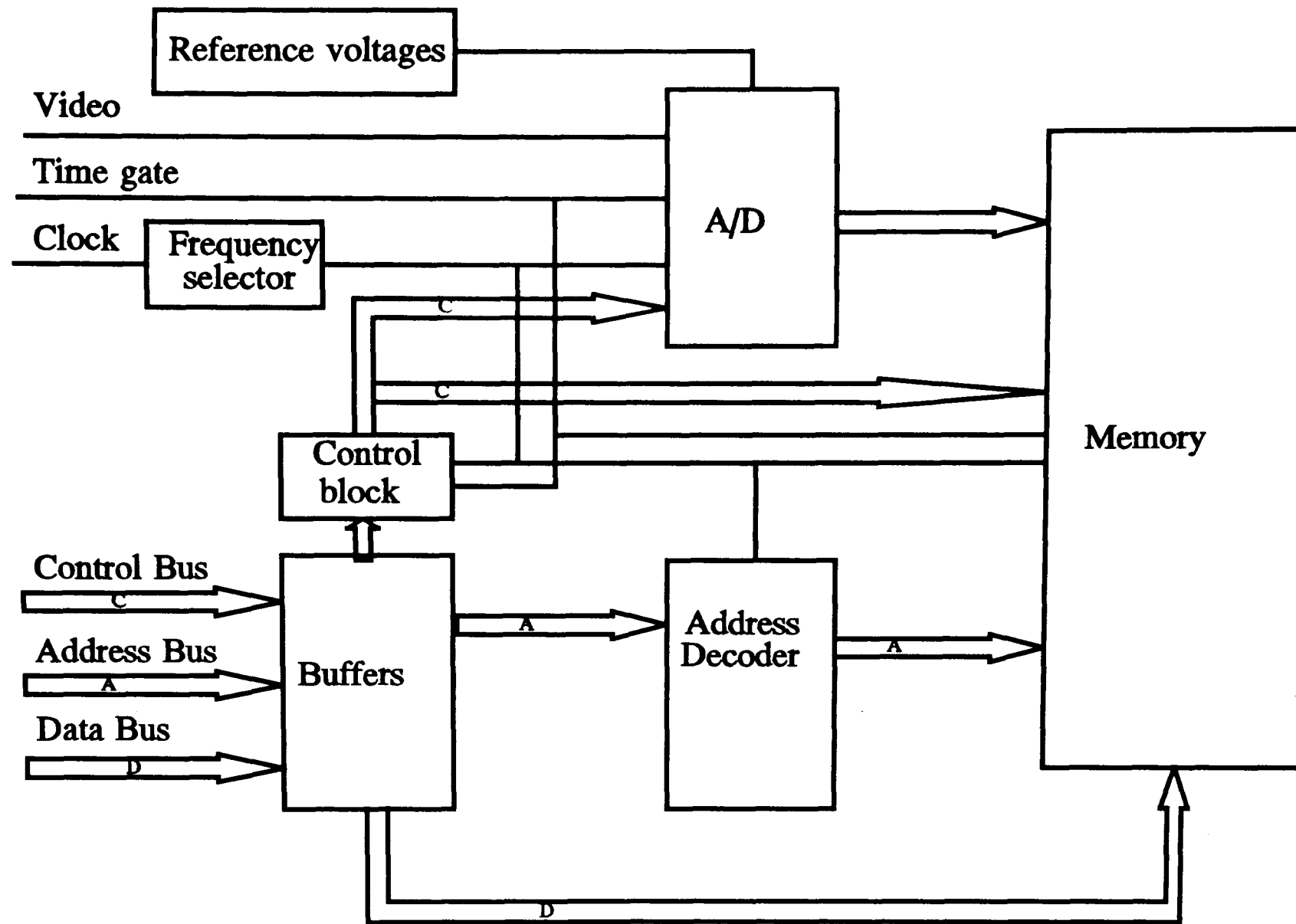


Figure 28 Schematic diagram of flash A/D

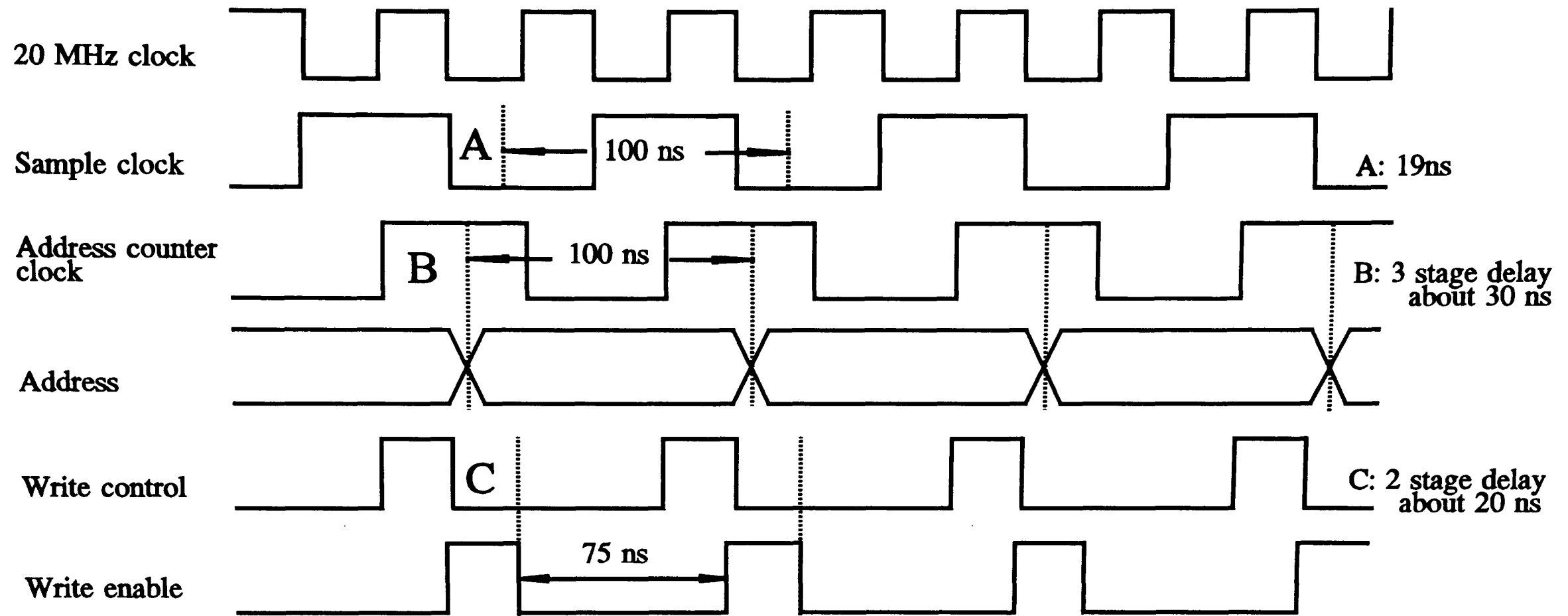


Figure 29 Timing diagram of flash A/D

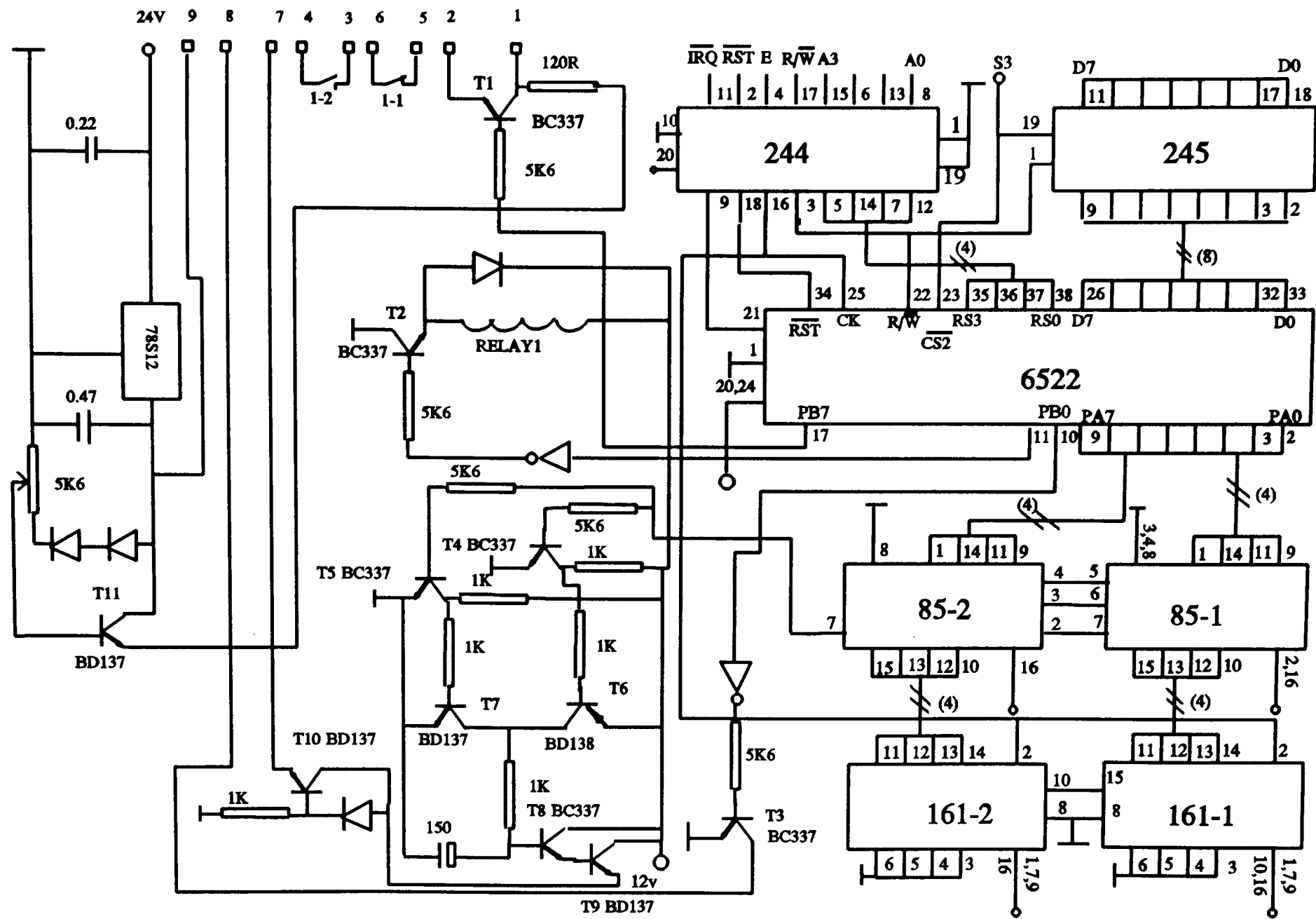


Figure 30 Welding power supply control circuit

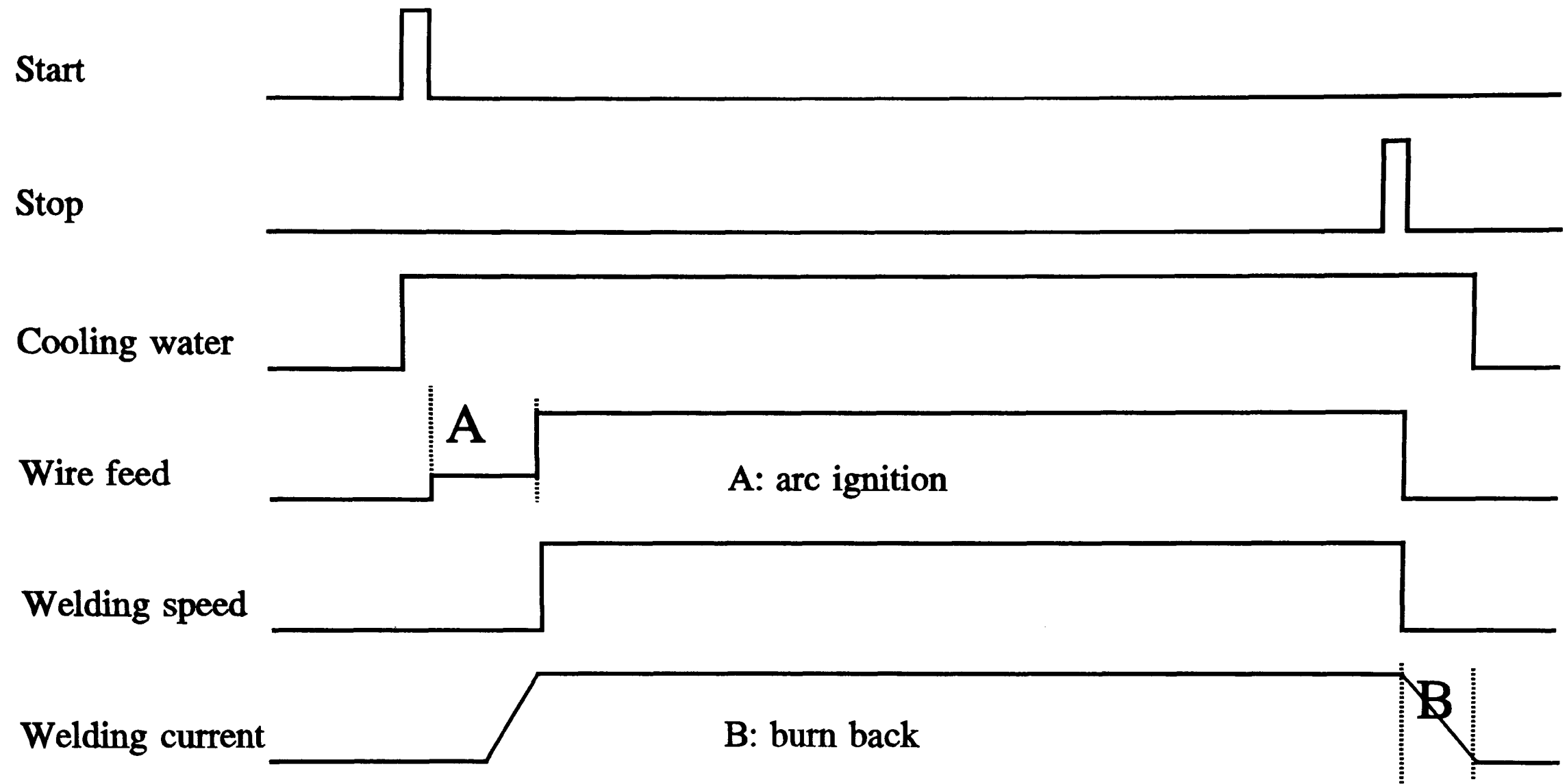
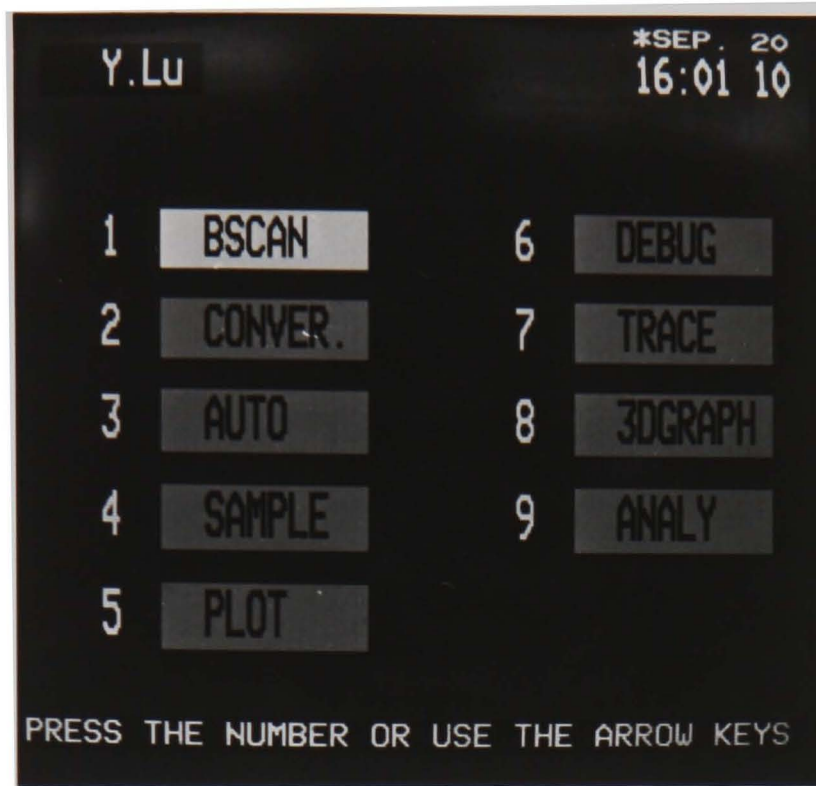
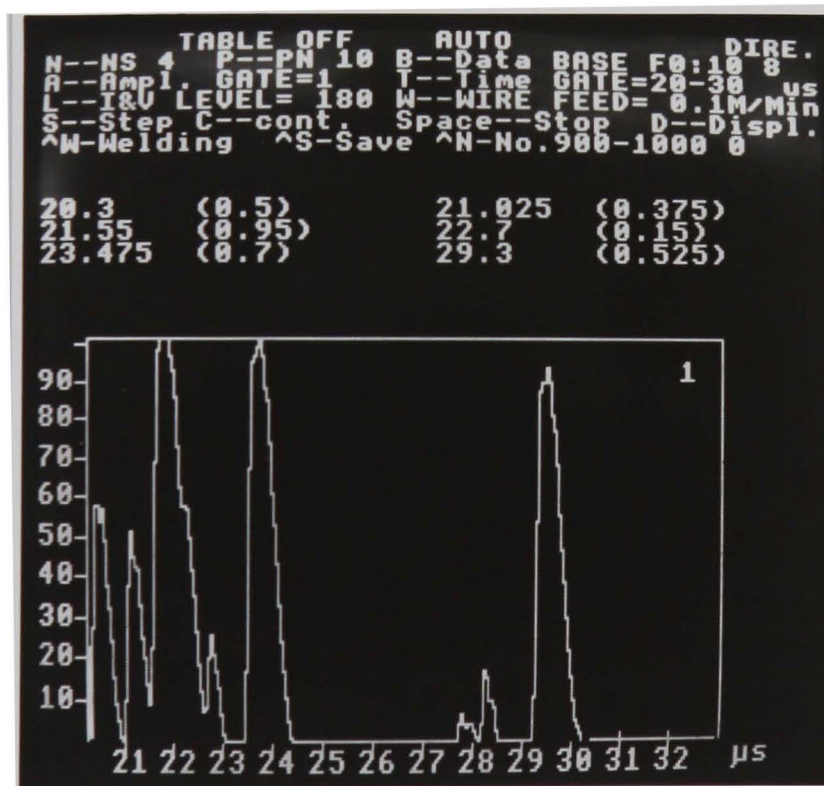


Figure 31 Schematic diagram of welding process



(a) Main menu



(b) Menu for program "AUTO"

Figure 32 Main menu & Program "AUTO"

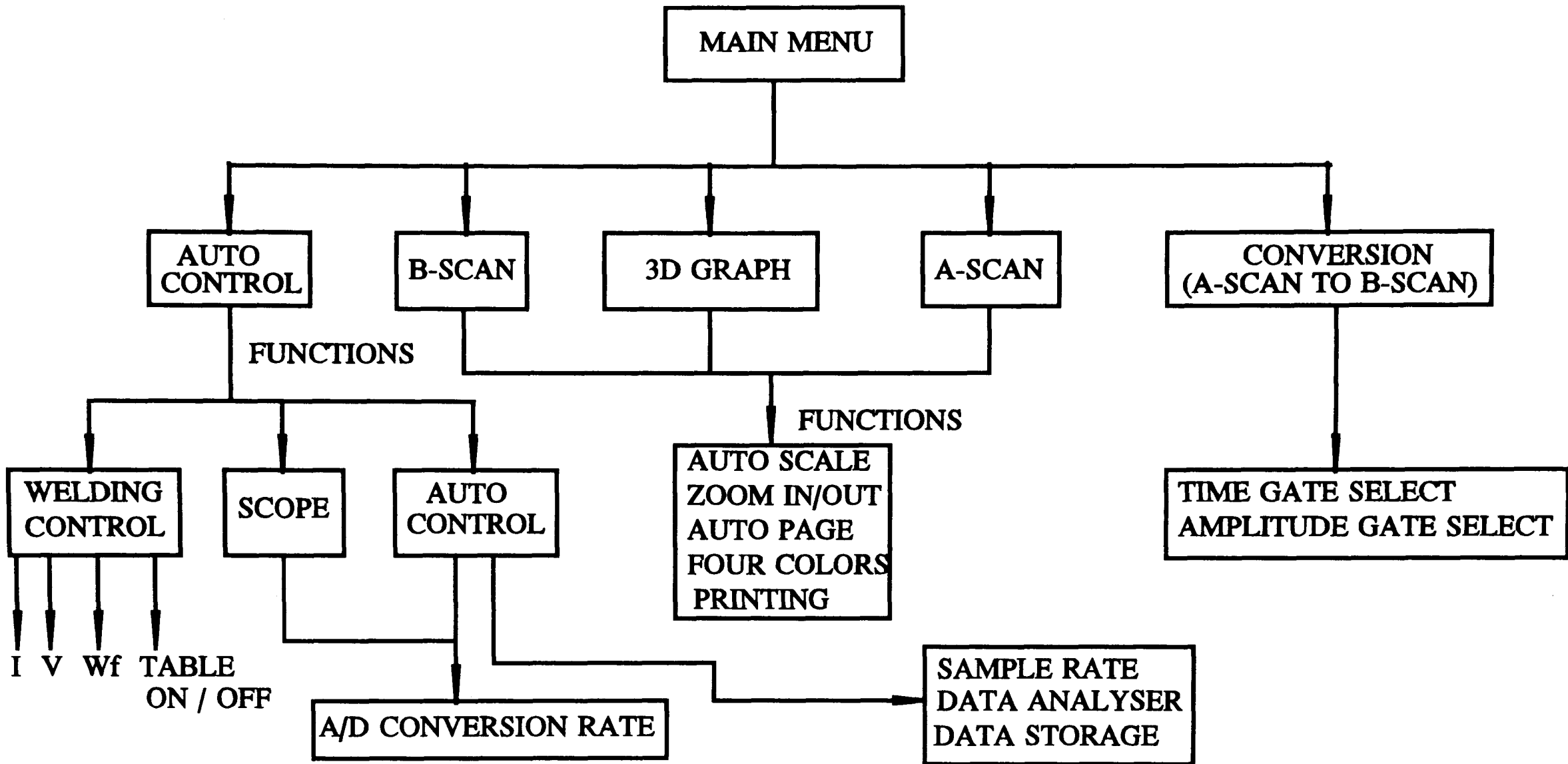


Figure 33 Schematic diagram of programs

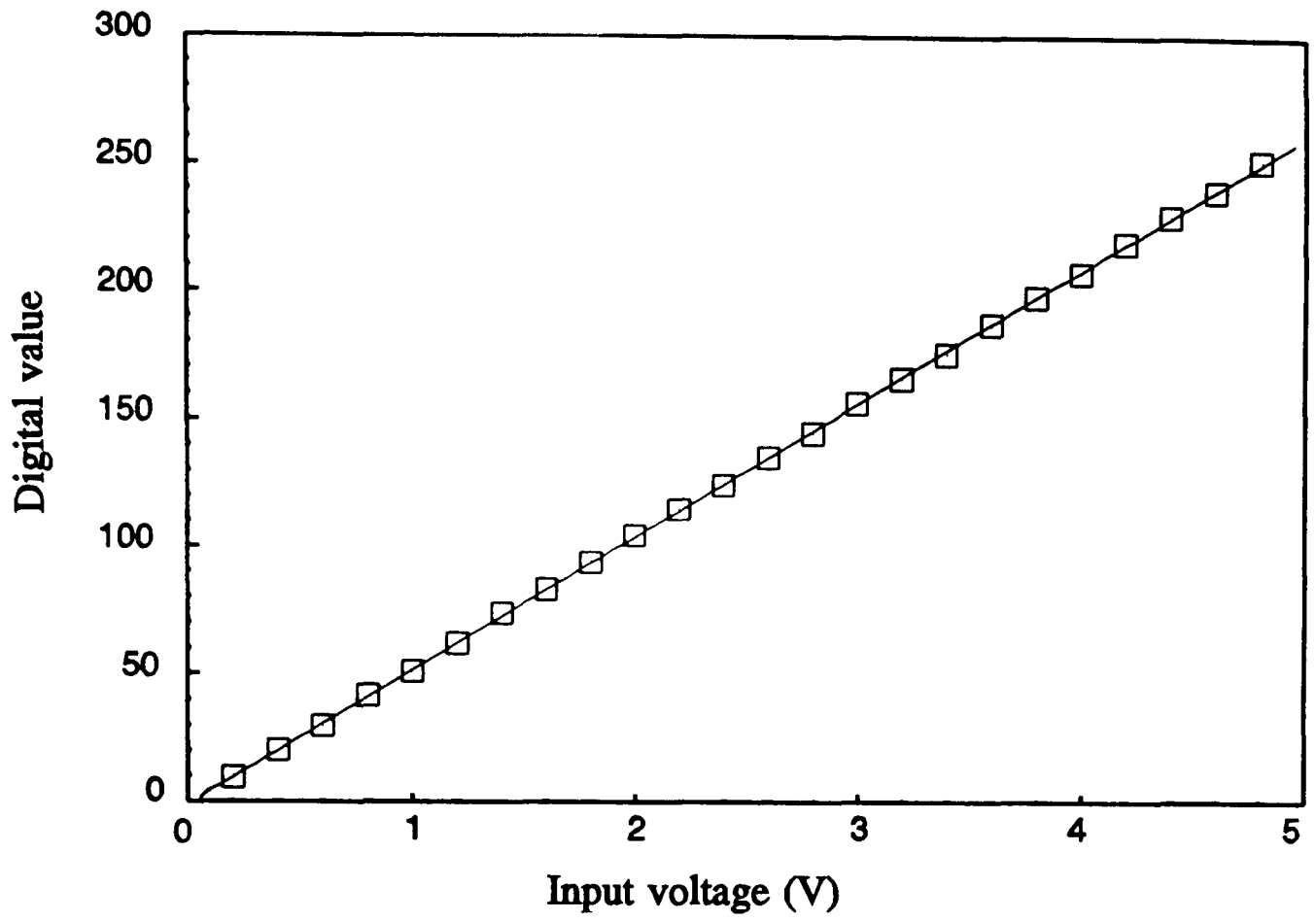


Figure 34 A/D Linearity test result

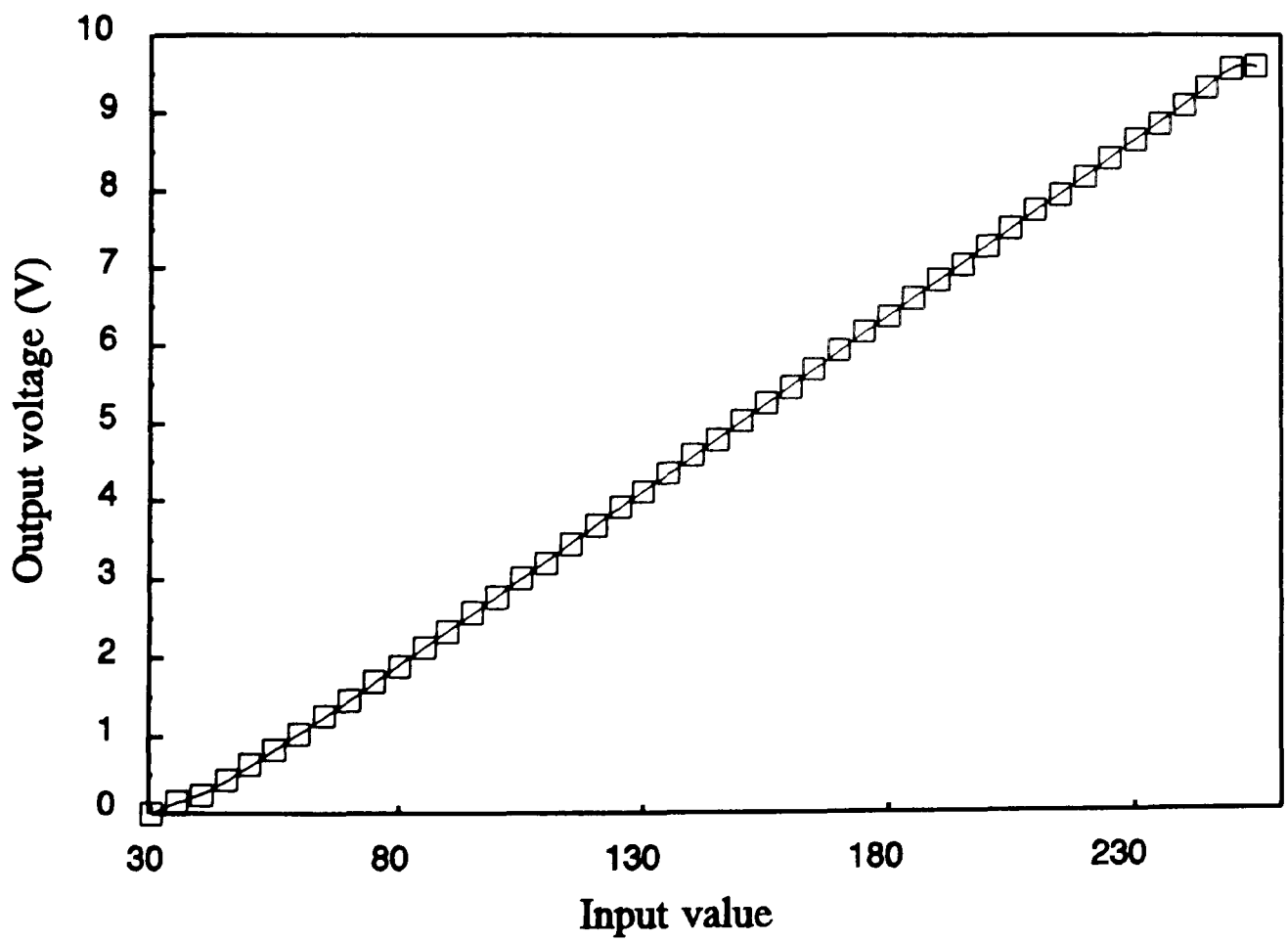
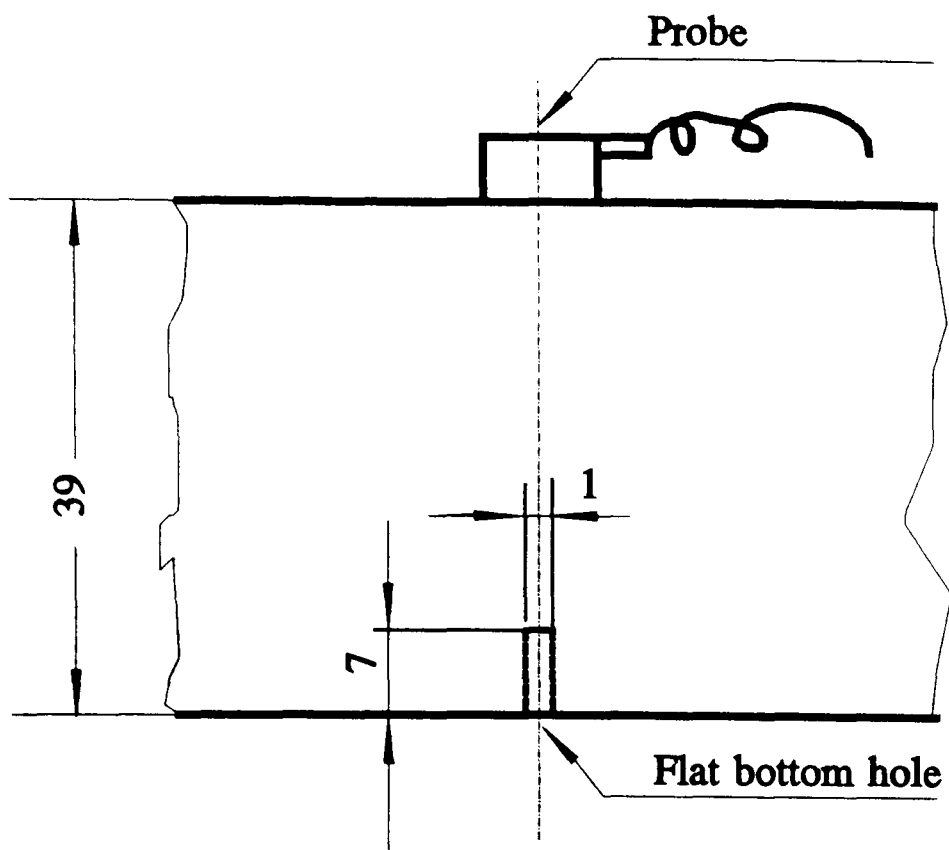
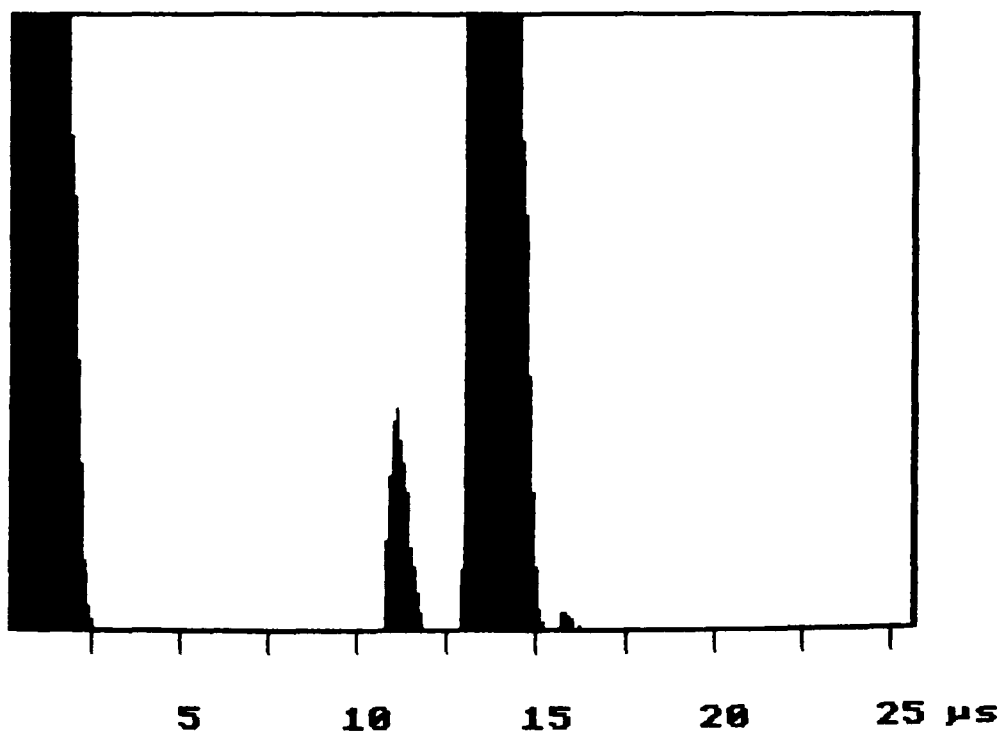


Figure 35 Linearity of level output for welding power source



a) Sensitivity test sample



Gain=41

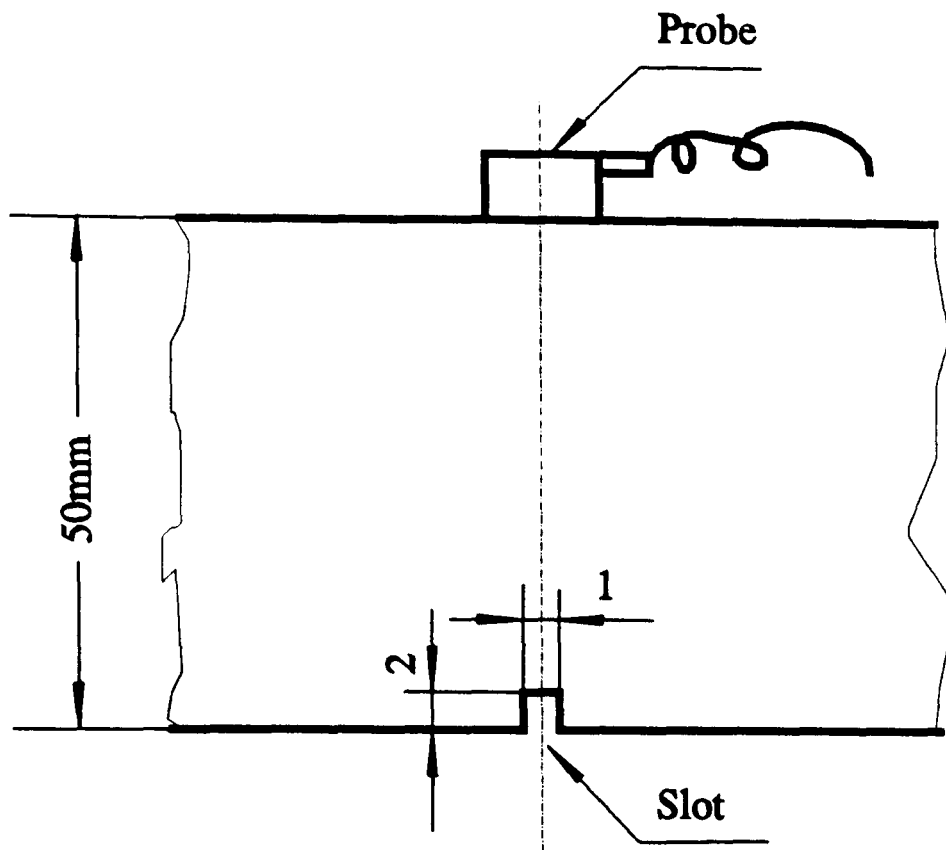
Time gate(μs): 0.4

Sample date:17/5/91

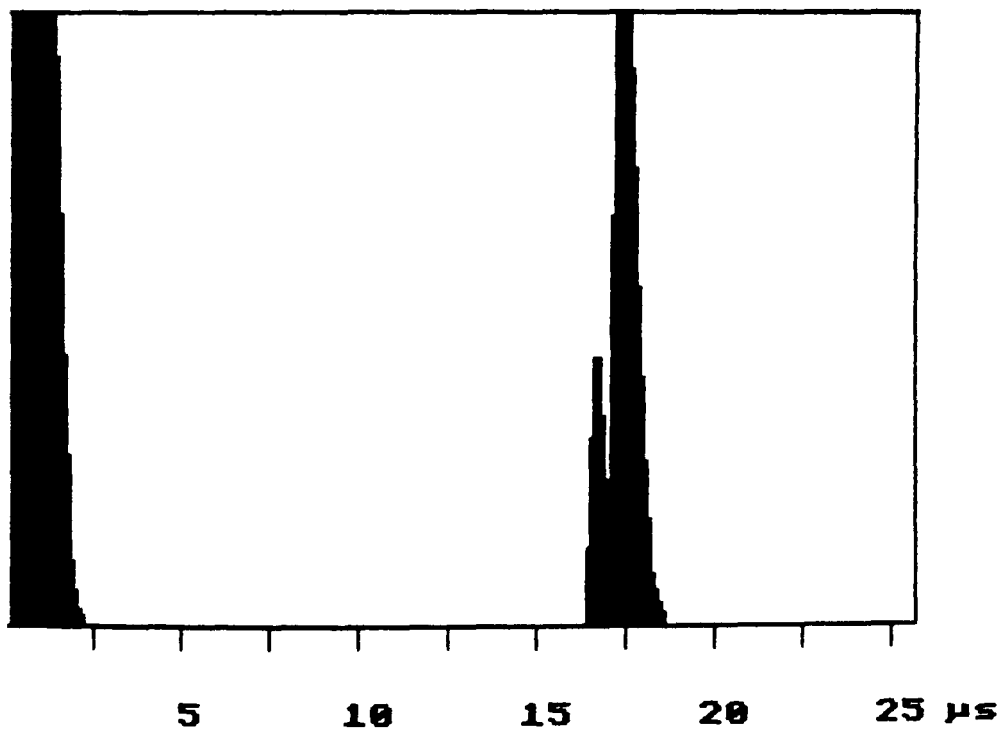
Sample time: 11:44

b) Sensitivity test result

Figure 36 Sensitivity test



a) Resolution test sample



Gain=32;Freq.=5MHz

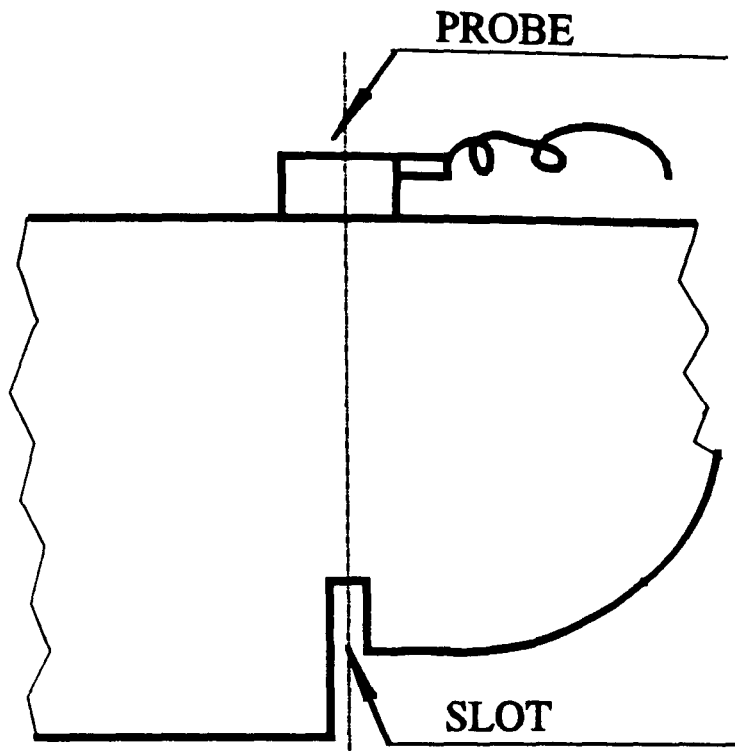
Time gate(μ s): 0.4

Sample date: 16/5/91

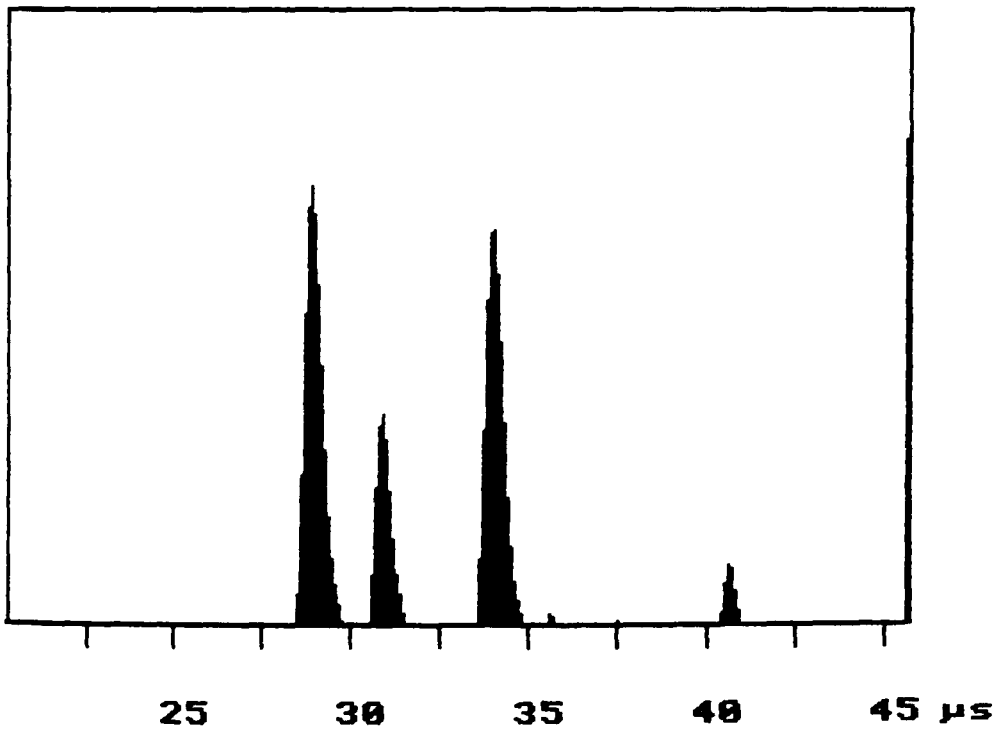
Sample time: 17:34

b) Resolution test result

Figure 37 Resolution test



a) Sample (V1 Block)

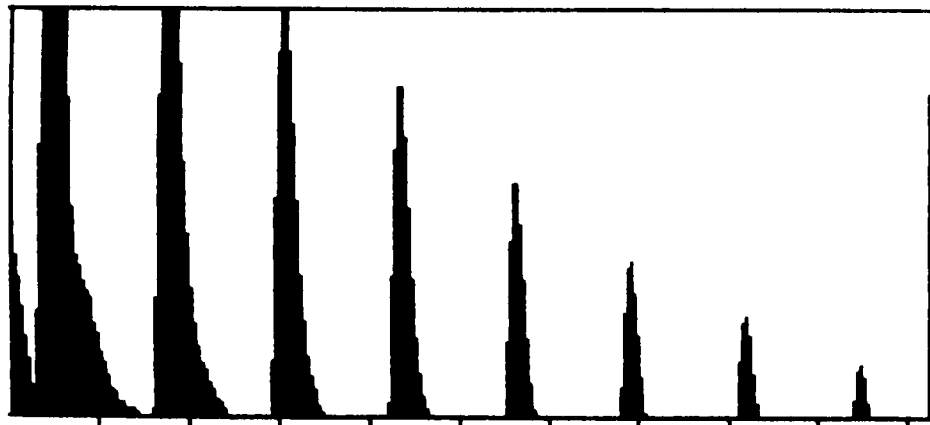


Probe: 5 MHz; 1/4 inch
Damping: 0; Gain: 55db
Time gate (μs): 20
Date:17/5; Time: 10:20

b) A-Scan result

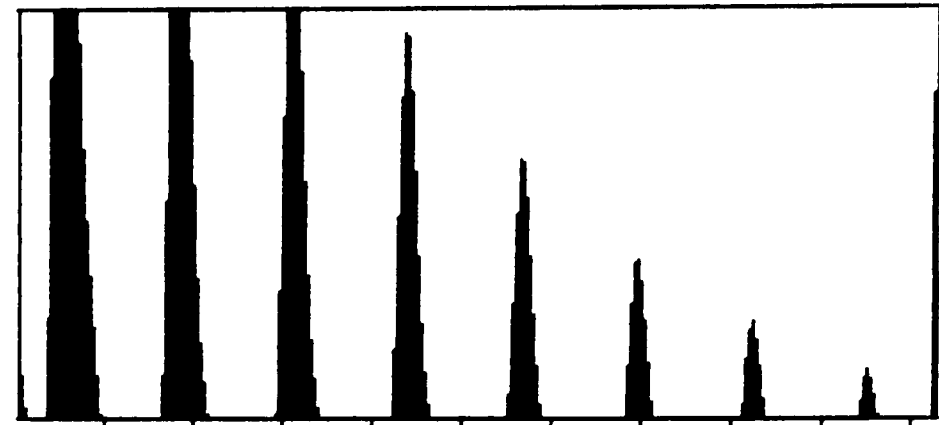
Figure 38 Resolution test with V1 block

Frequency: 5MHz; Gain: 52db



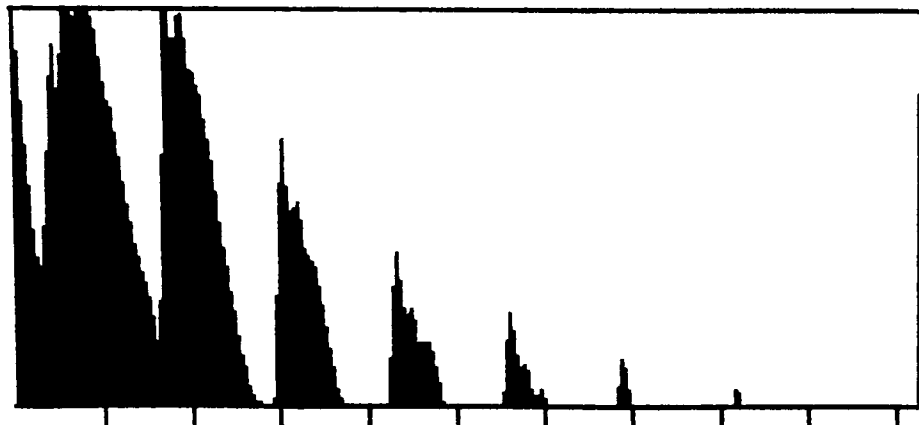
10 20 30 40 50 μ s

Frequency: 10MHz; Gain: 55db



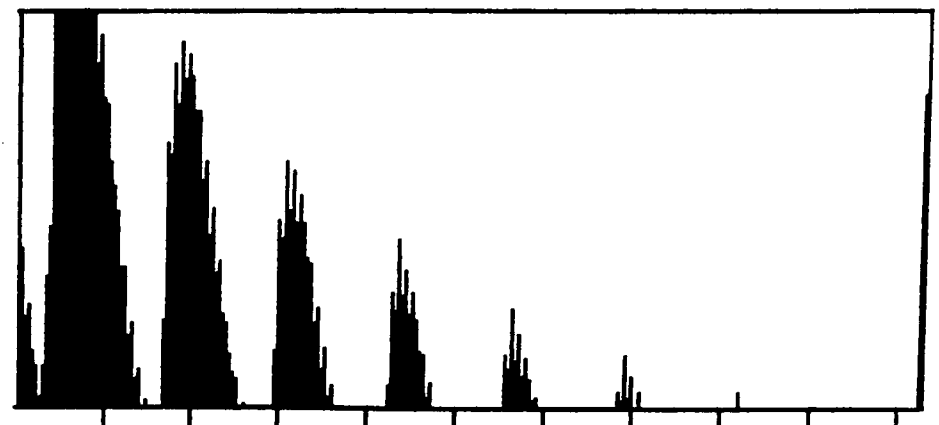
10 20 30 40 50 μ s

Frequency: 2MHz; Gain: 40db



10 20 30 40 50 μ s

Frequency: broad; Gain: 40db



10 20 30 40 50 μ s

Figure 39 A-Scan graphs with different ultrasonic frequency

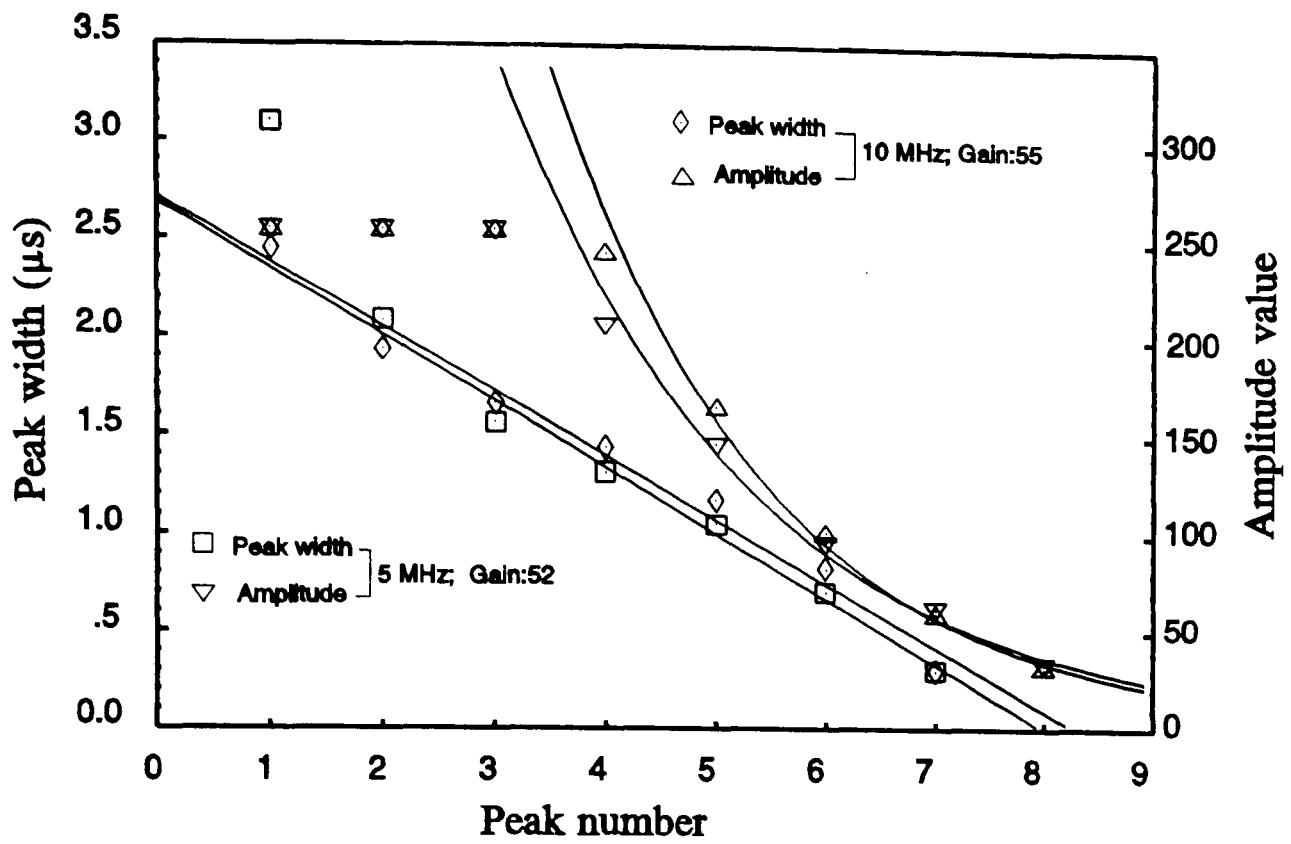


Figure 40 Amplitude and peak width from multiple reflections

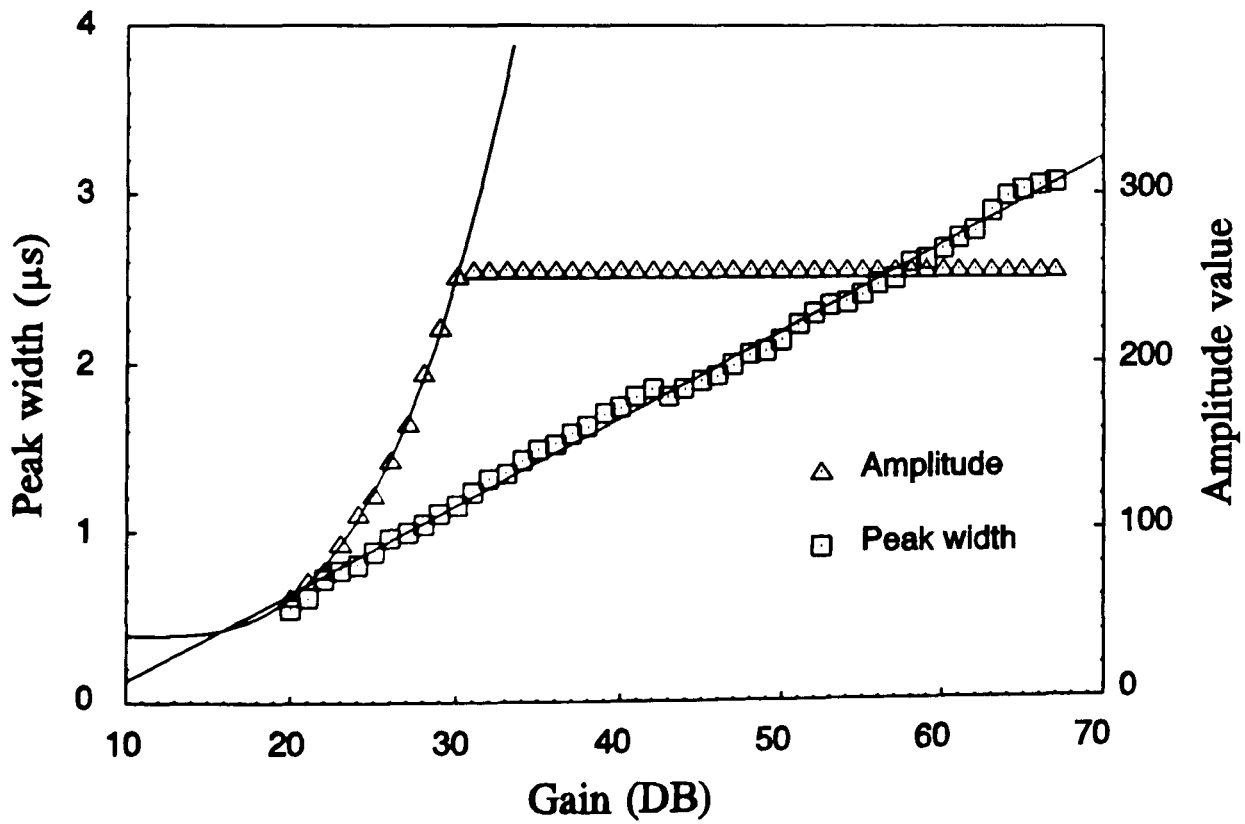


Figure 41 Amplitude and peak width with different gains

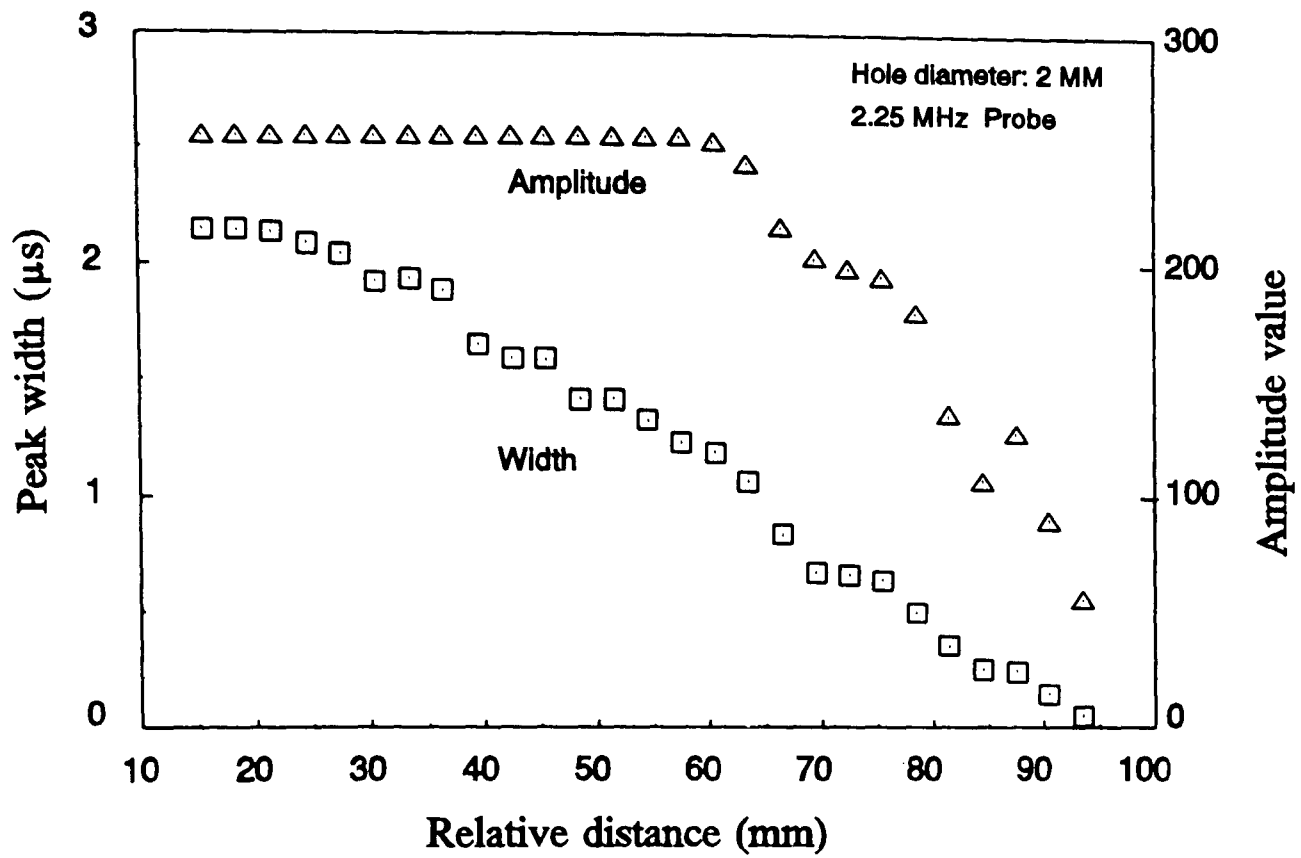


Figure 42 Defect distance test result

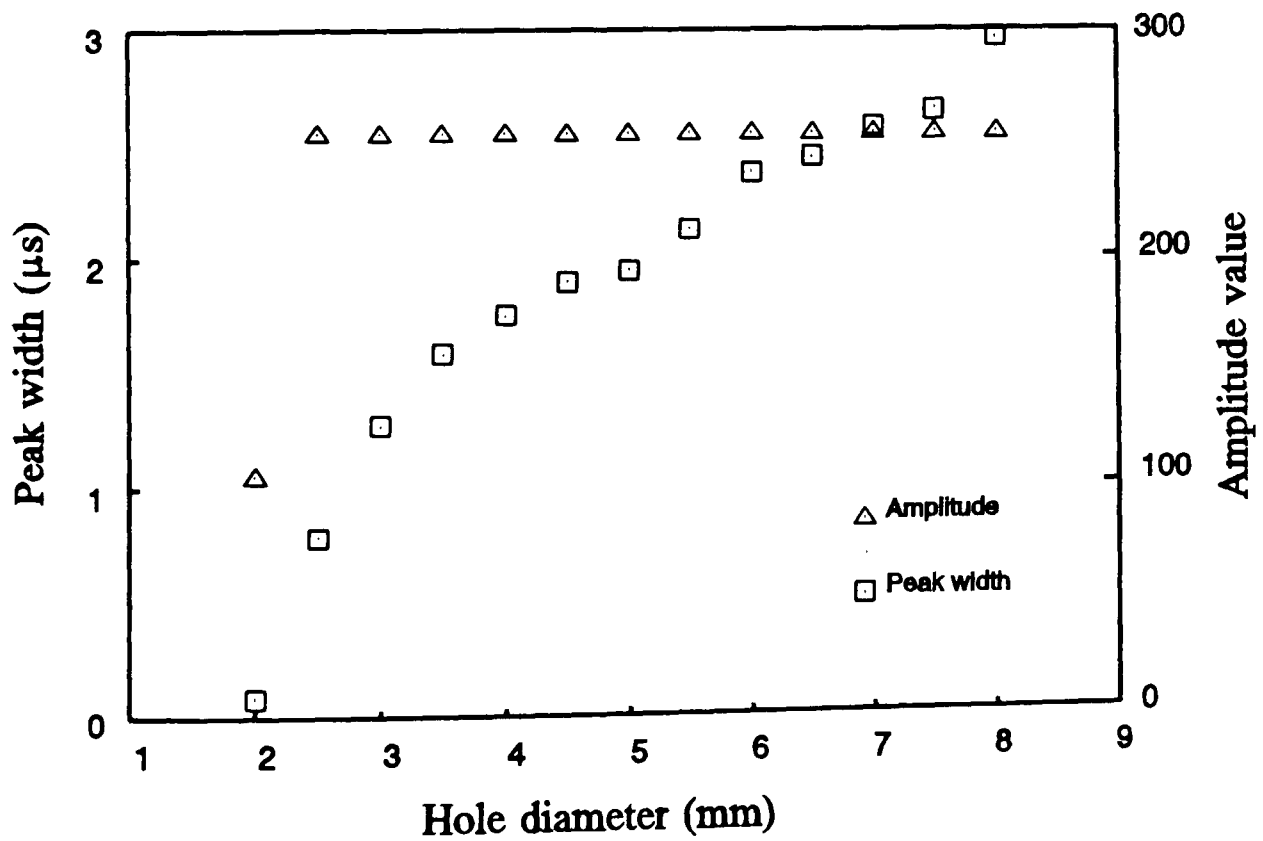


Figure 43 Defect size test result

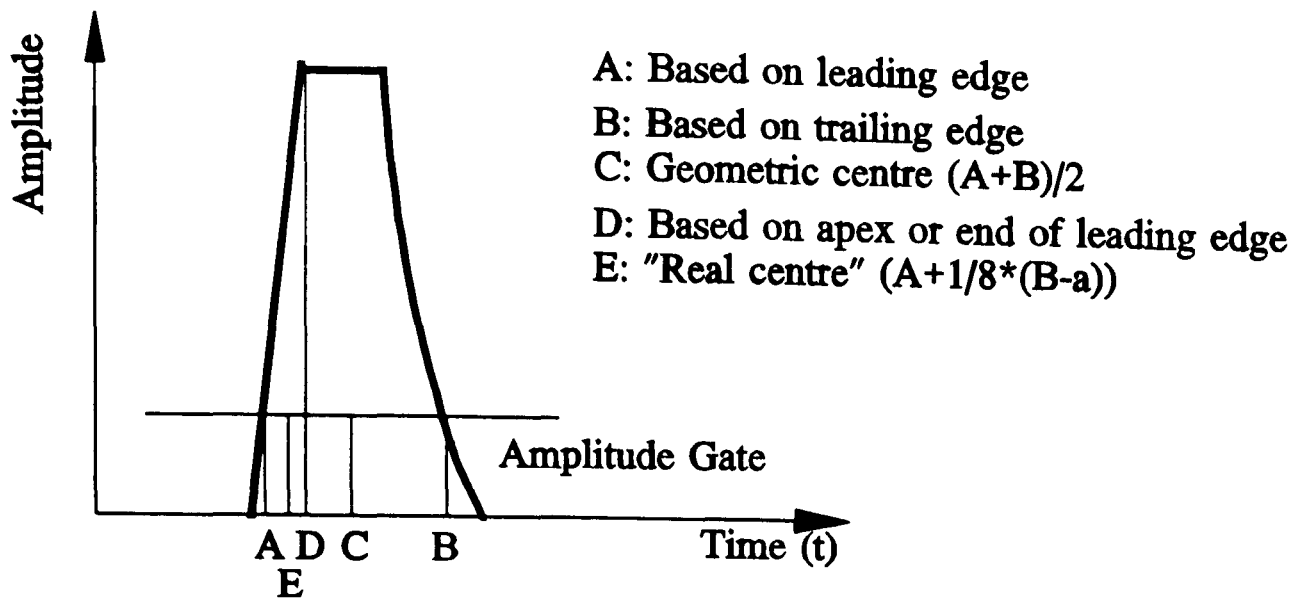


Figure 44 Schematic diagram of time measuring points

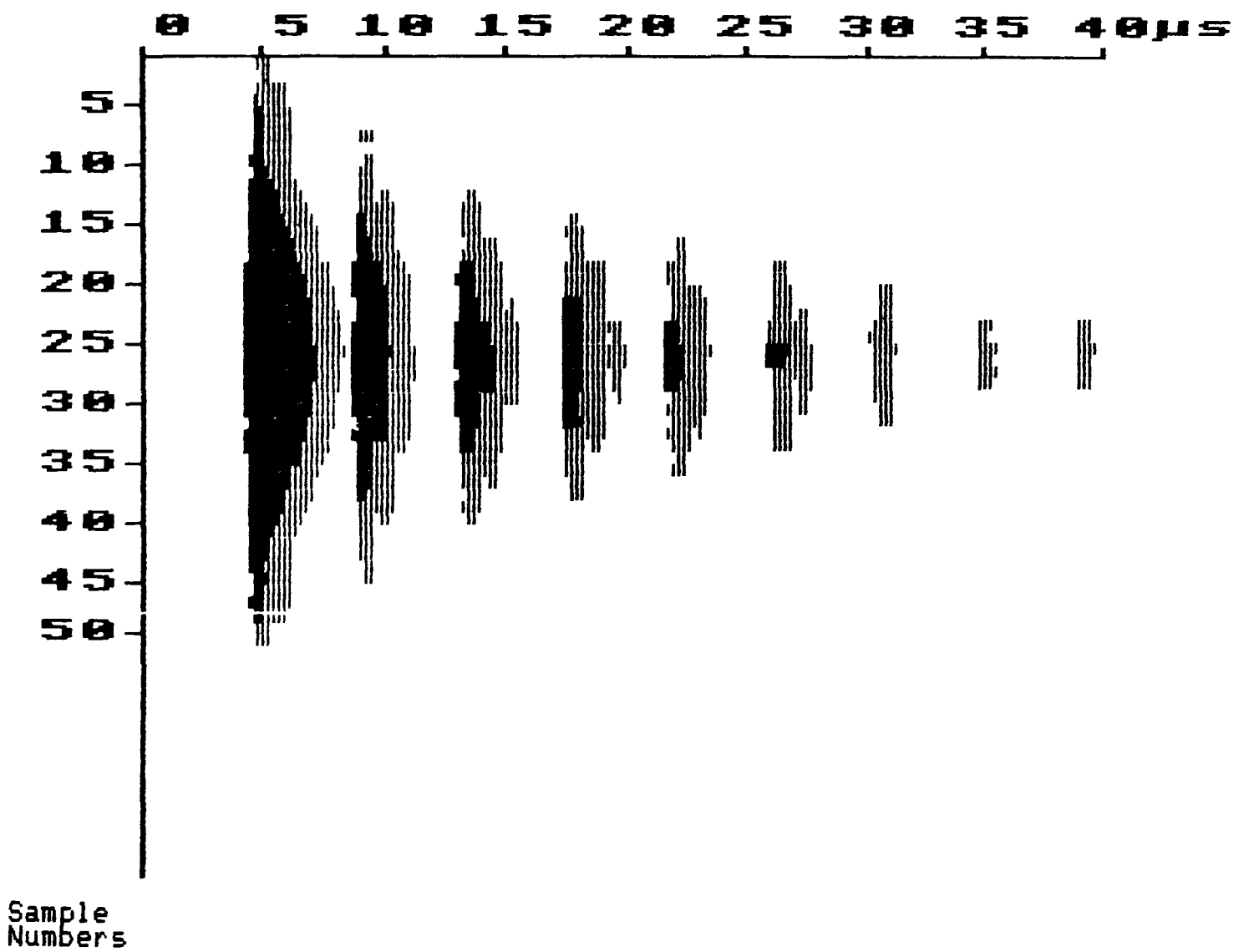


Figure 45 Multiple reflections with different gains

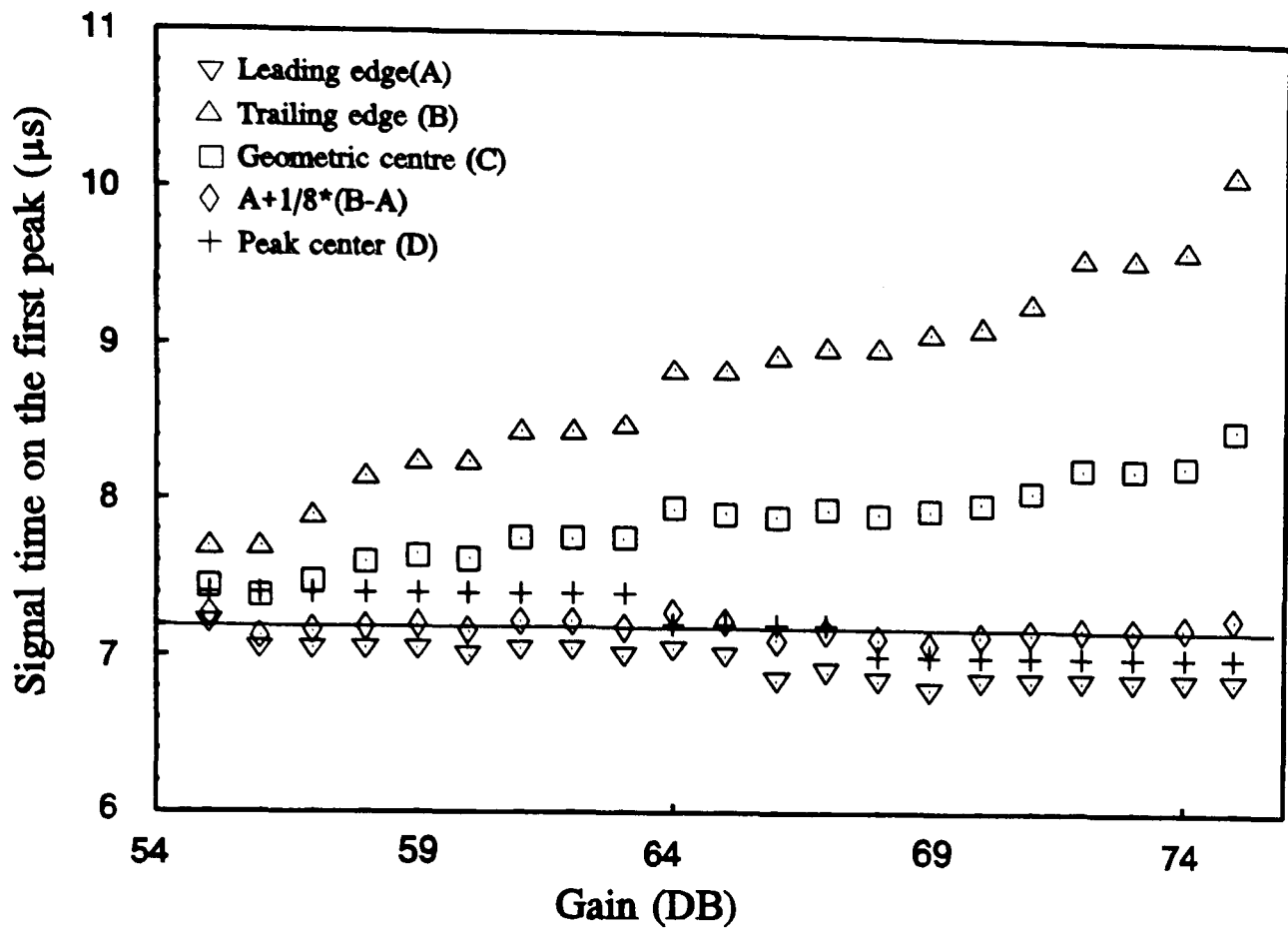


Figure 46 Peak time from different gains

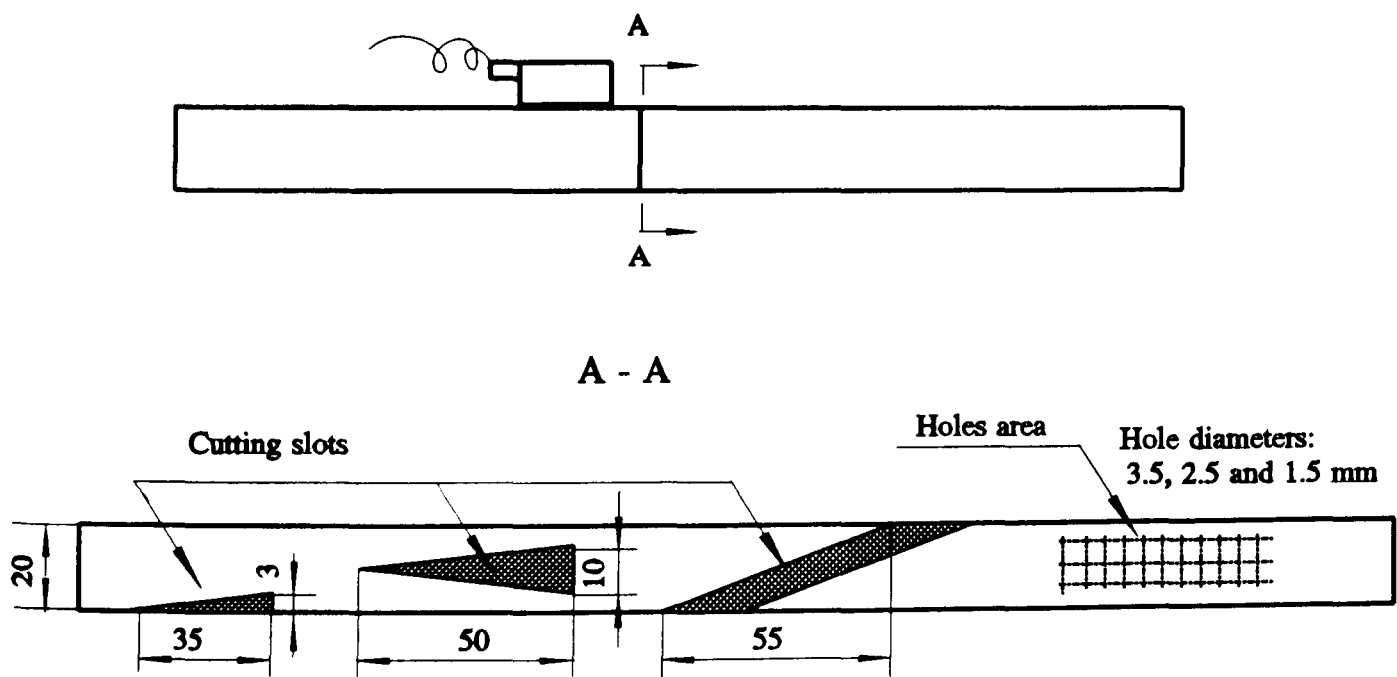
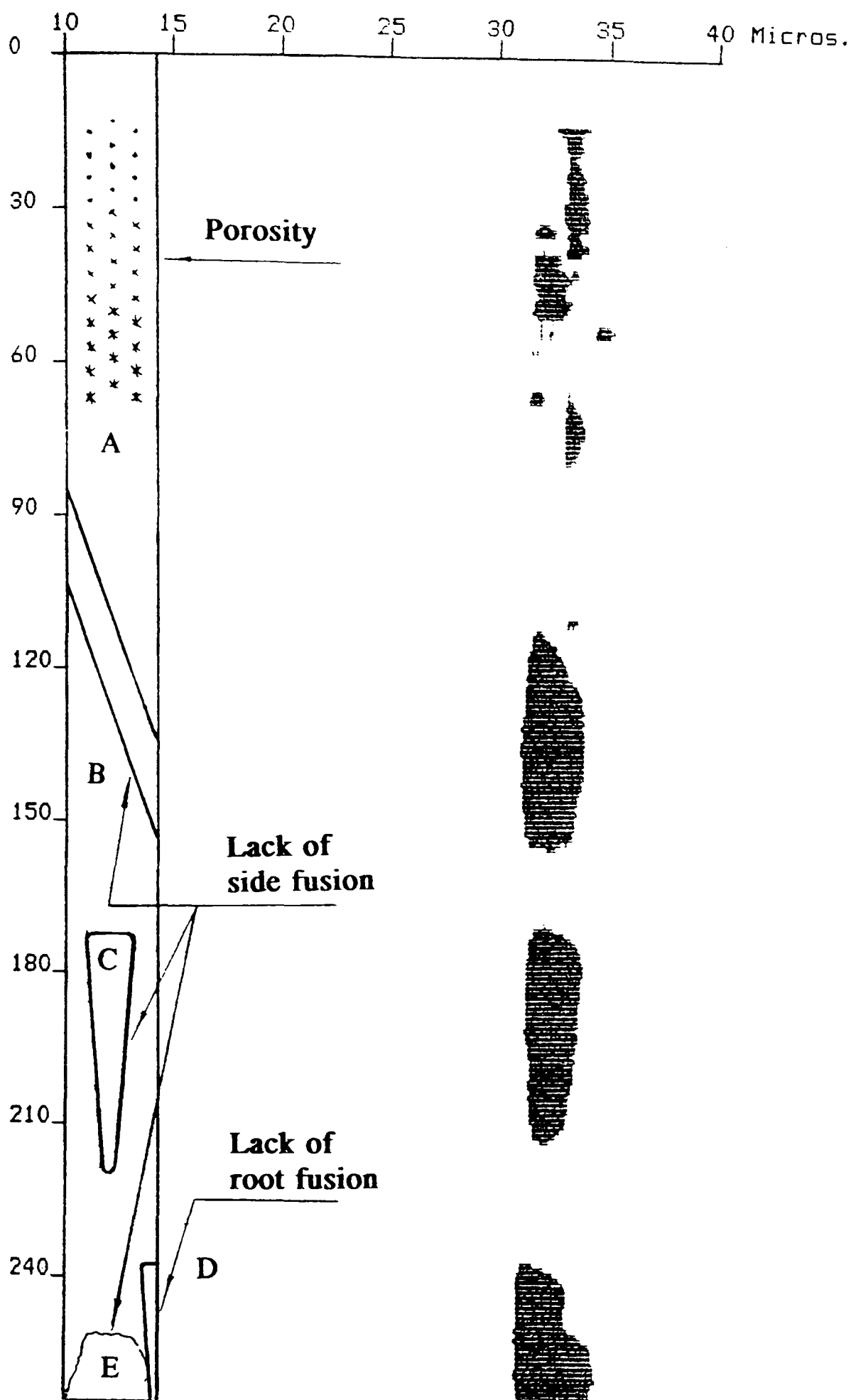


Figure 47 Schematic diagram of simulation block



a) Sample section

b) Ultrasonic responses

c) X-ray responses

Figure 48 Weld defects simulation sample diagram and results

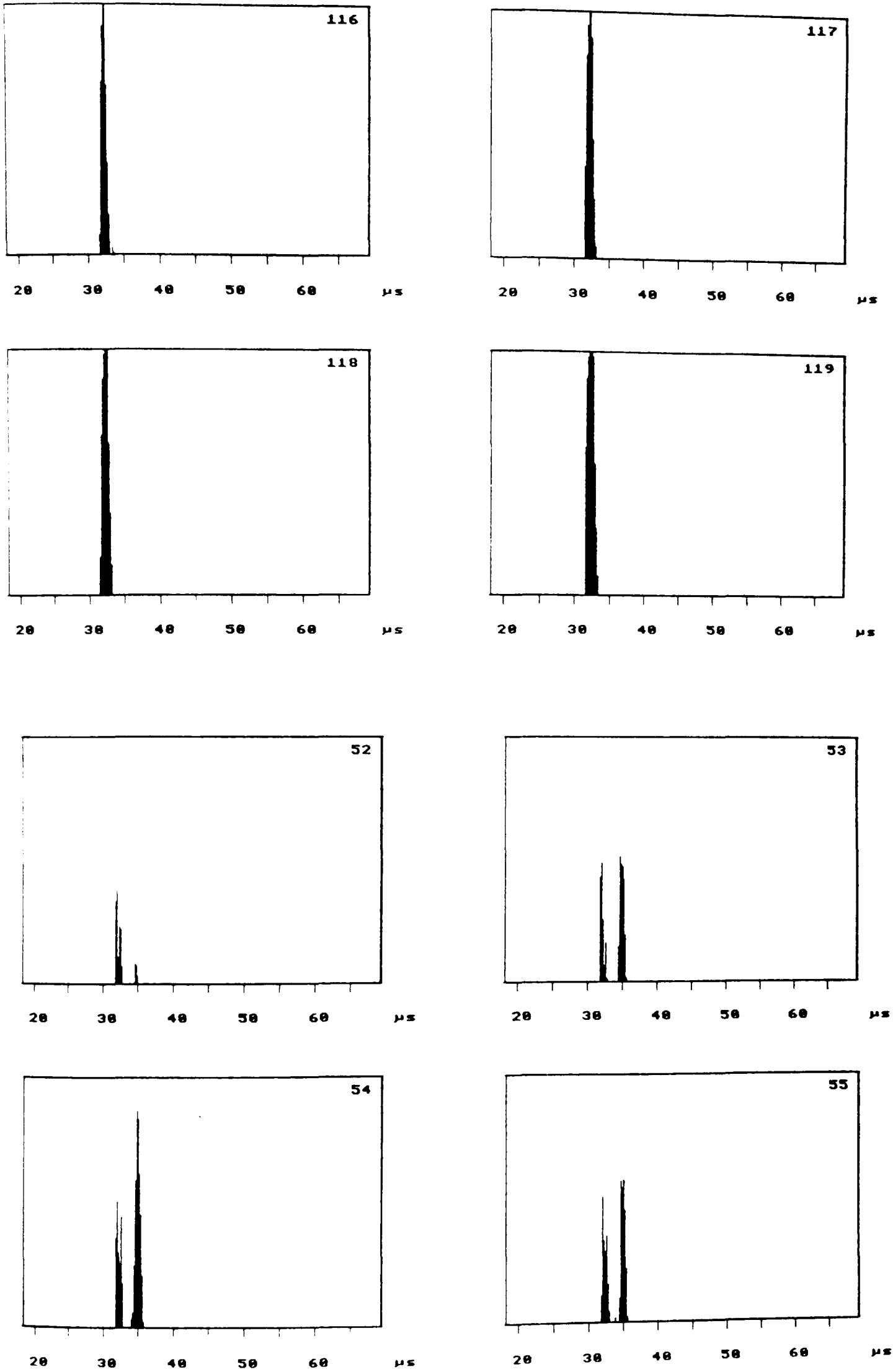
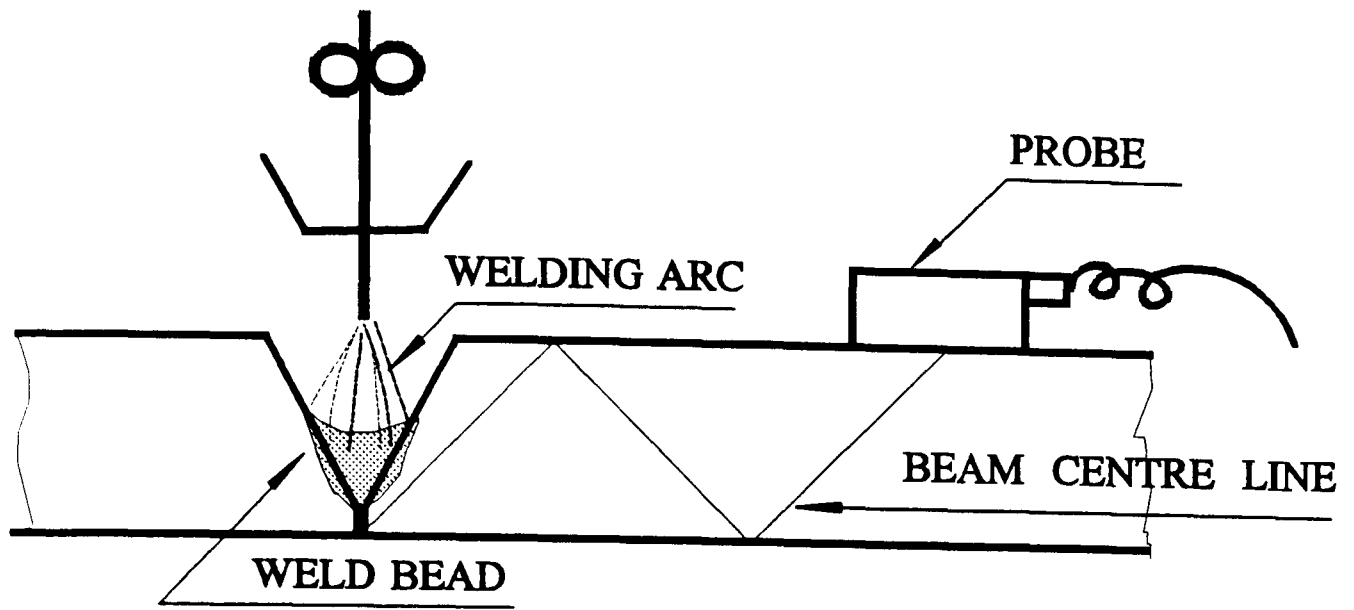
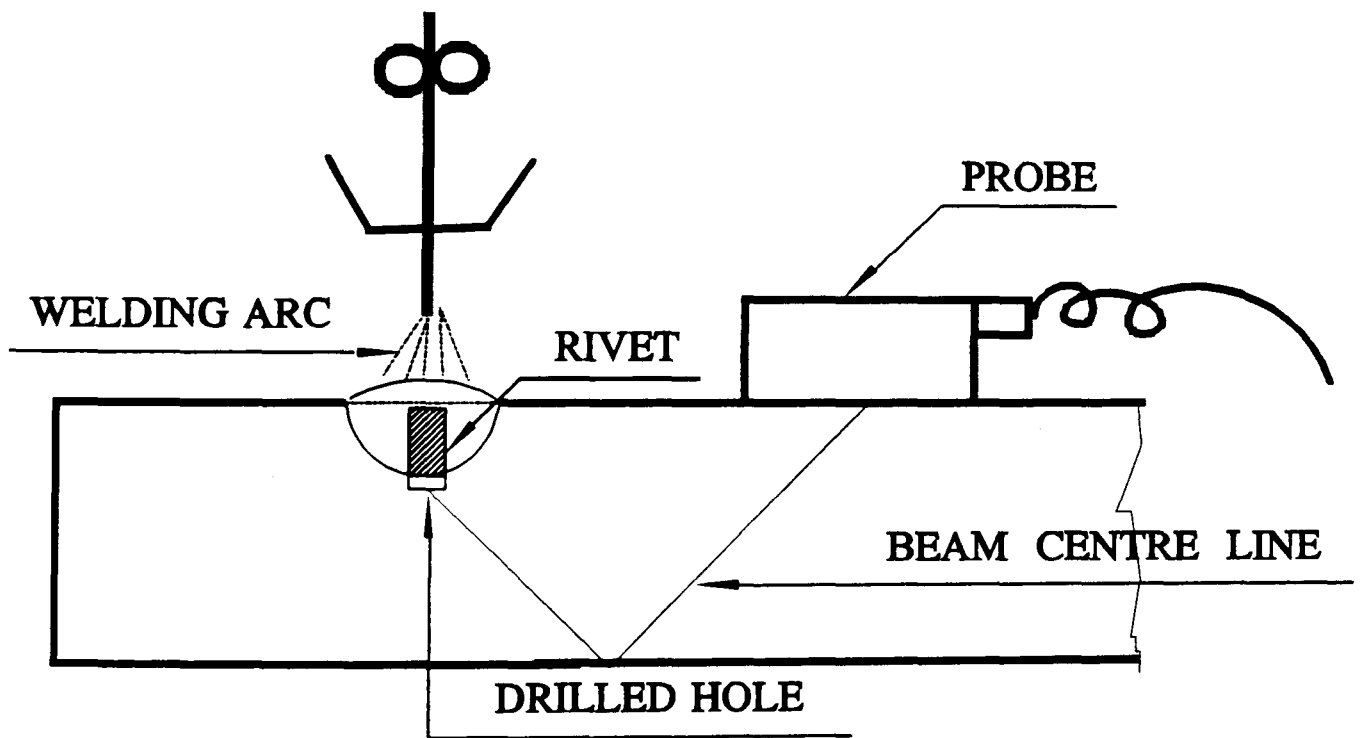


Figure 49 Some A-Scan graphs from defect simulation test (No.52-55: reflections from porosity; No.116-119: reflections from plane defects)

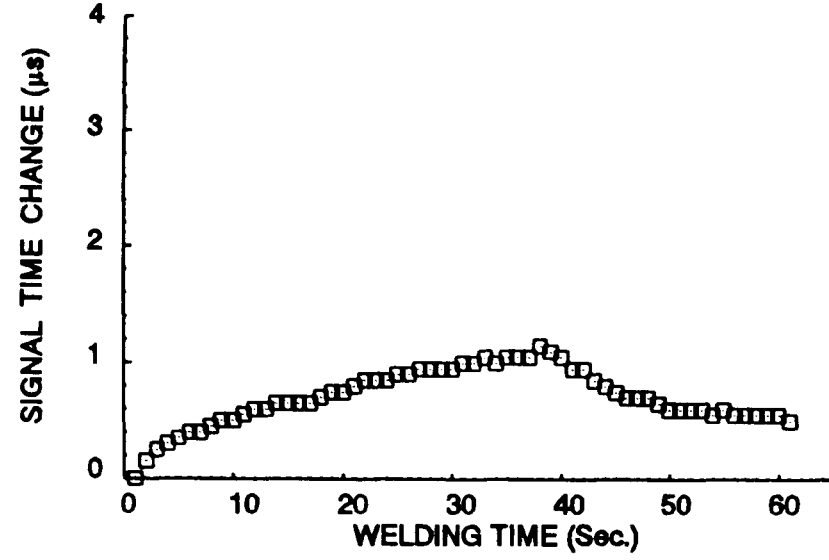


(b) Arrangement A

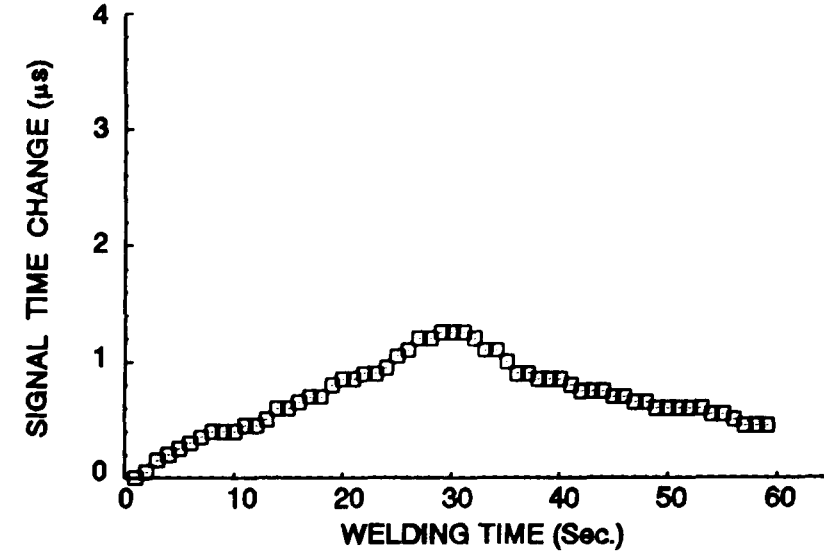


(a) Arrangement B

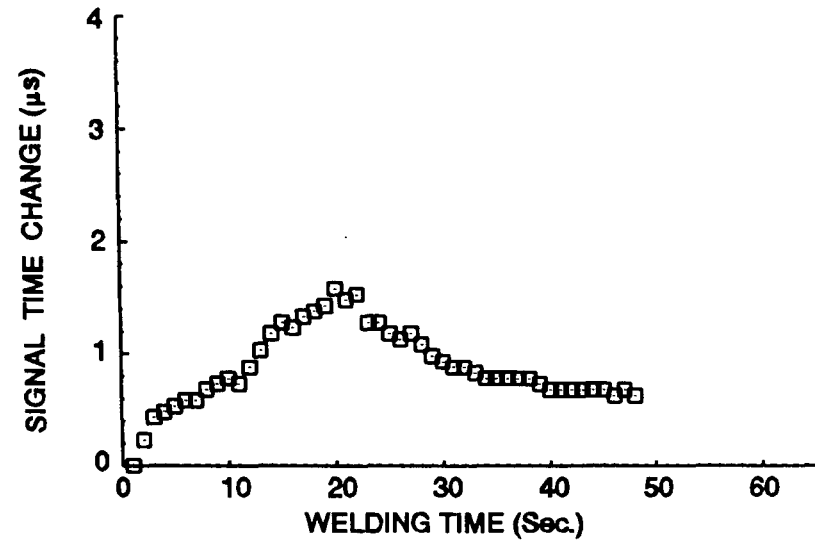
Figure 50 Schematic diagram of experimental arrangement



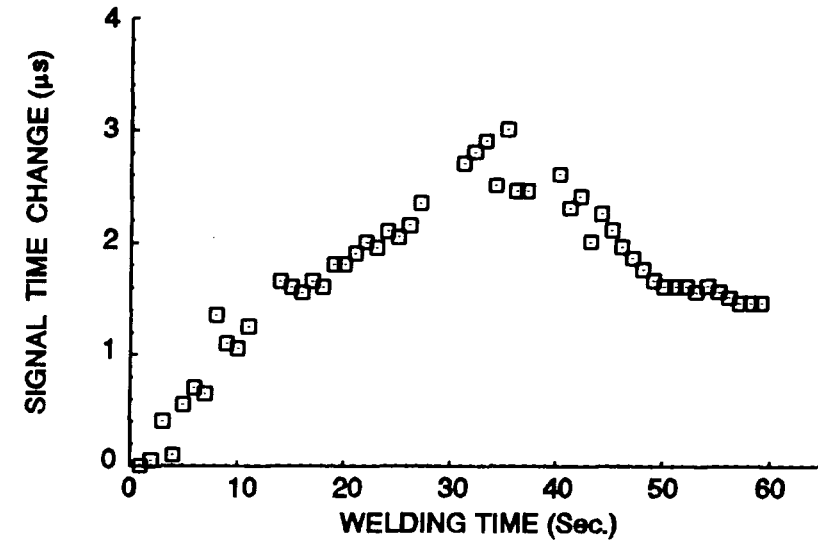
(a) Welding current: 111A



(b) Welding current: 133A



(c) Welding current: 210A



(d) Welding current: 273A

Figure 51 Temperature effect on signal time with different welding current

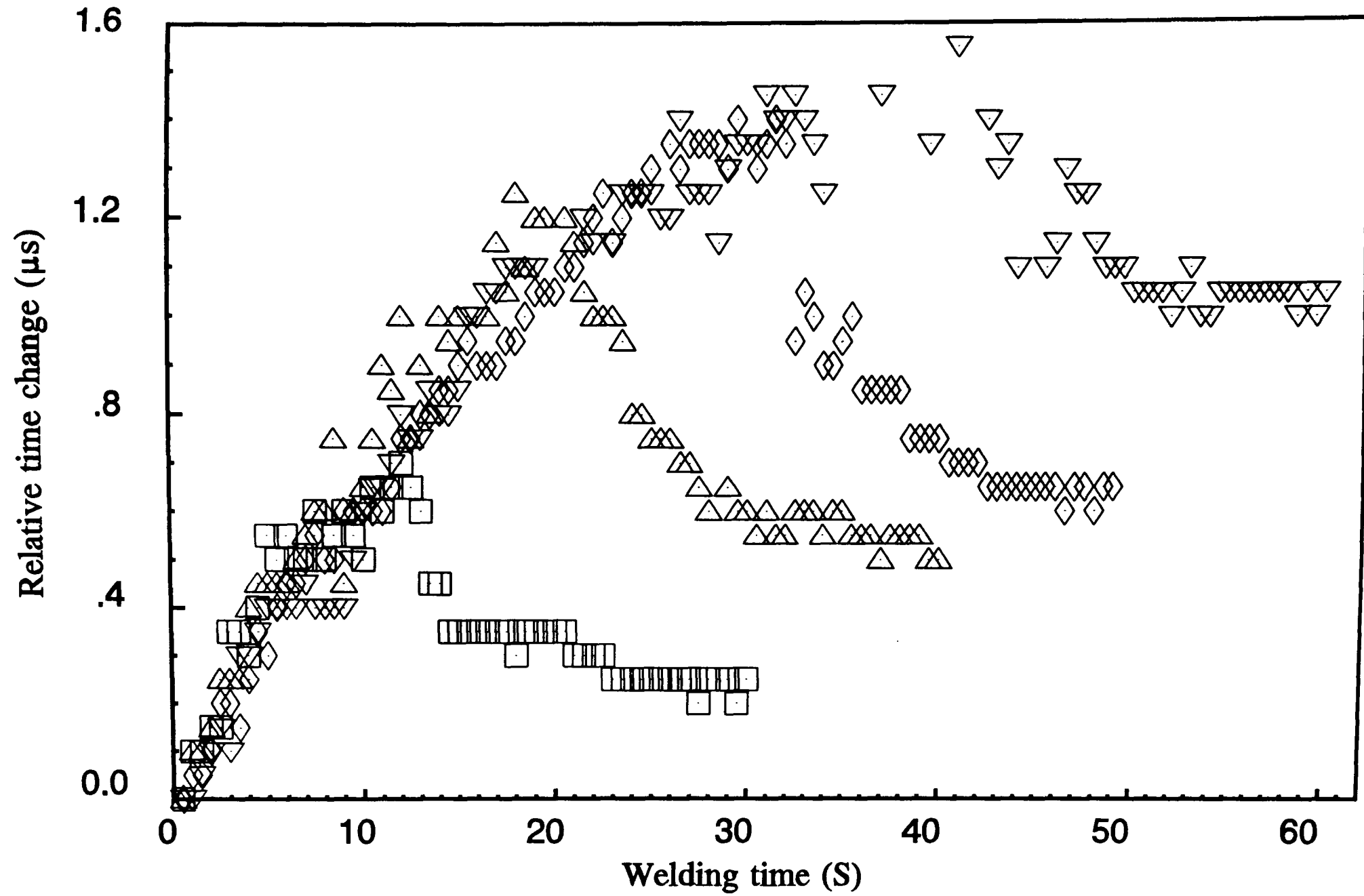
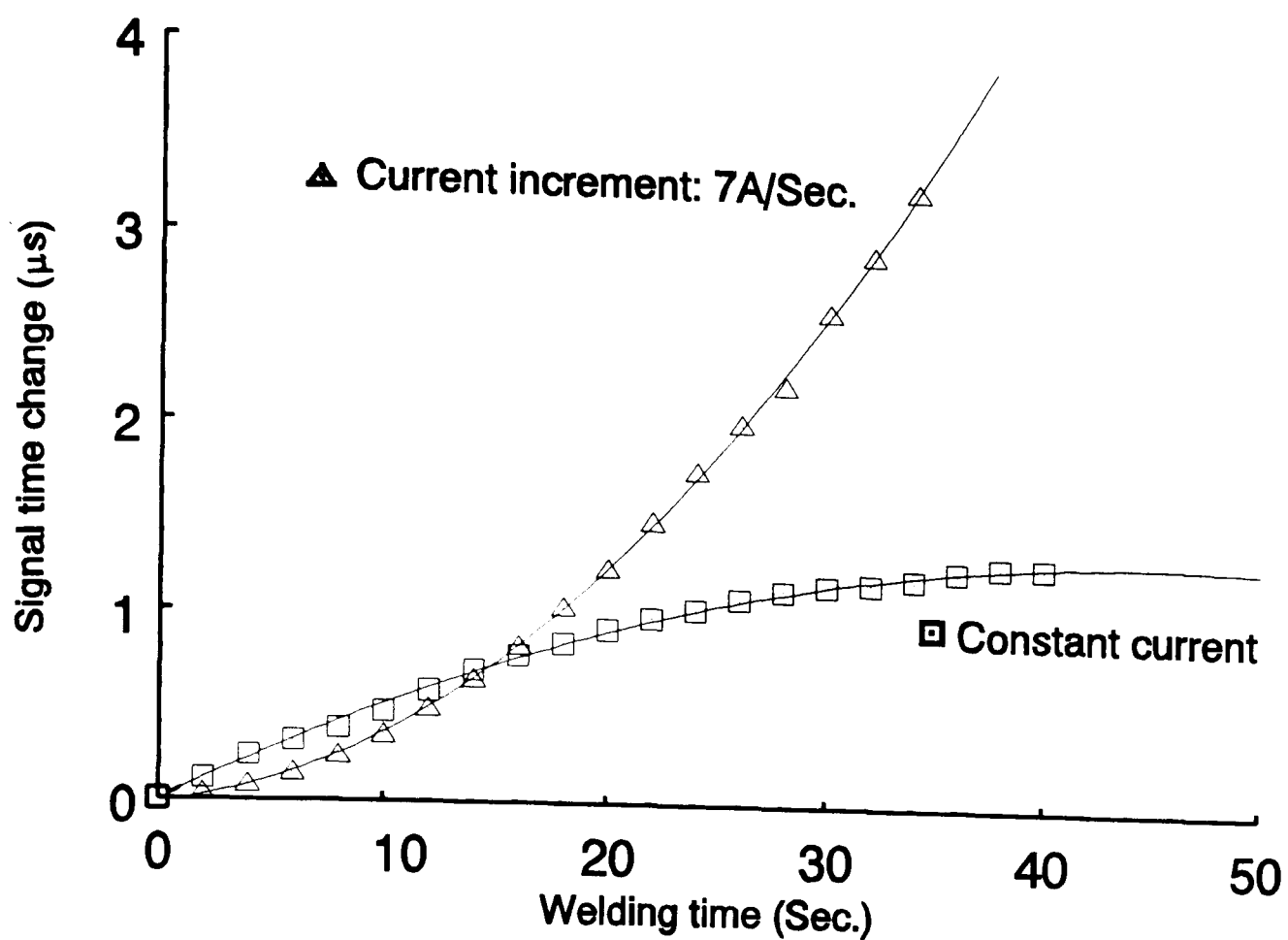
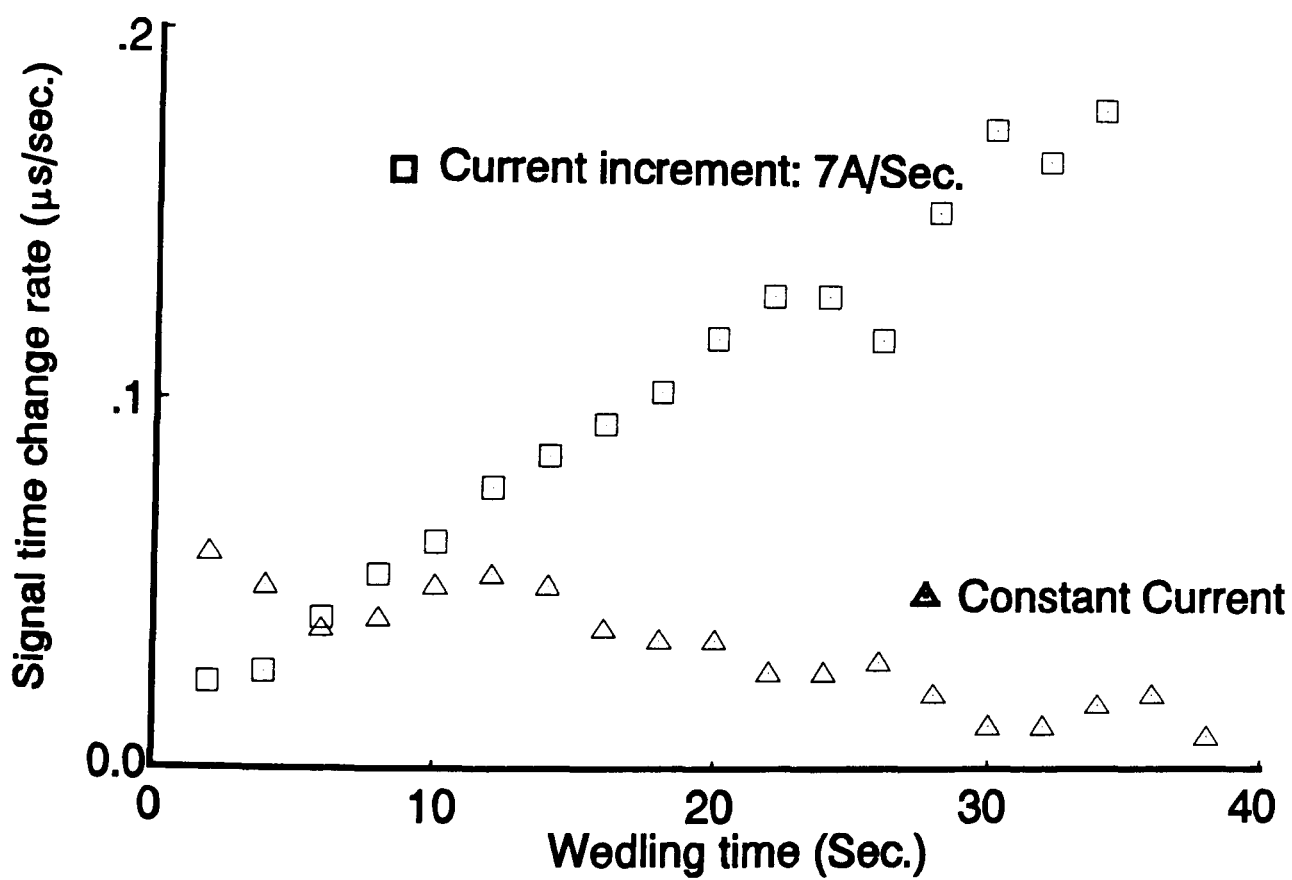


Figure 52 Signal time change varies with welding time



(a) Signal time change with welding time



(b) Signal time change rate

Figure 53 Comparison of results in constant current and in increasing current

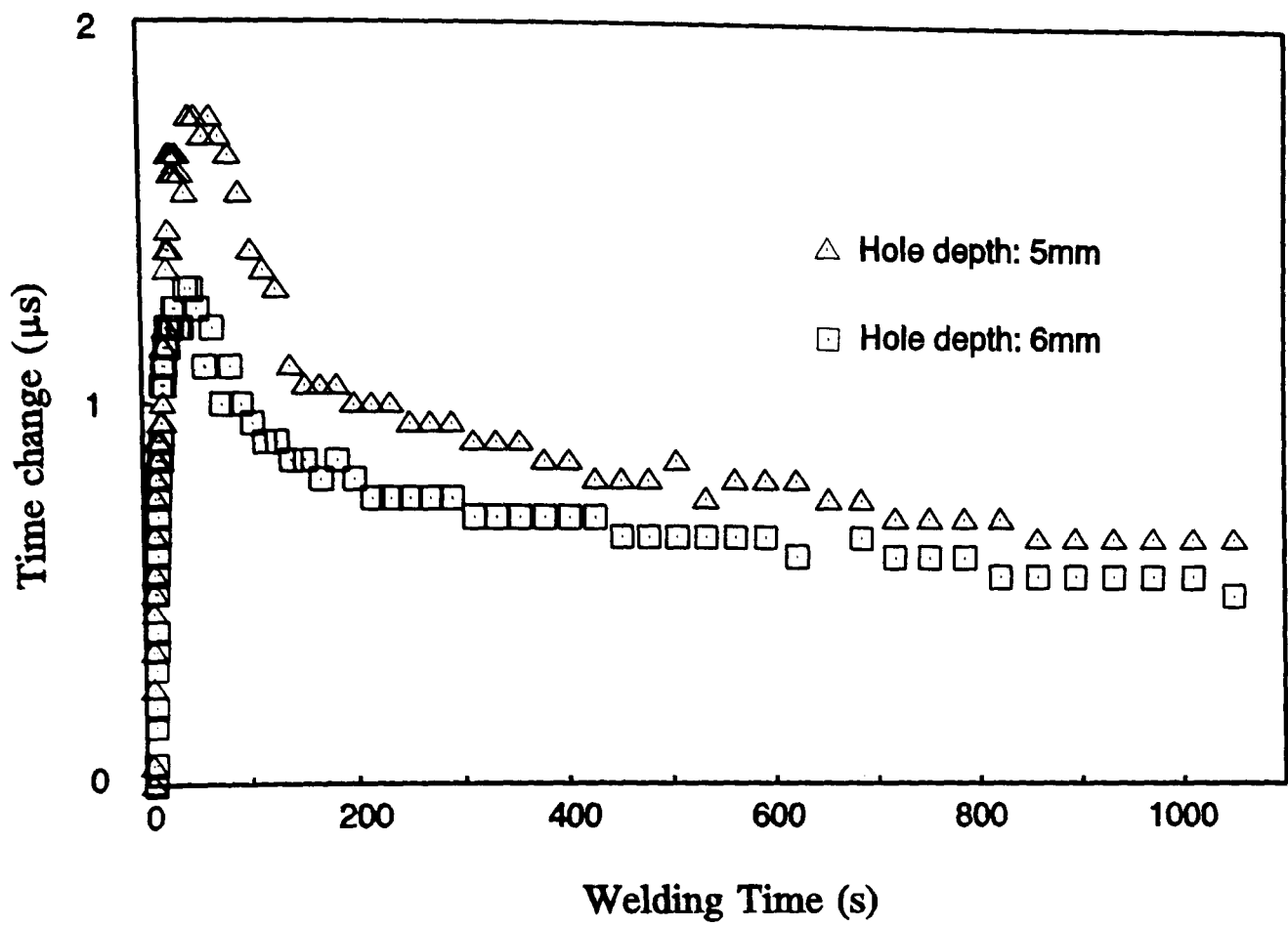


Figure 54 Signal time recovery process

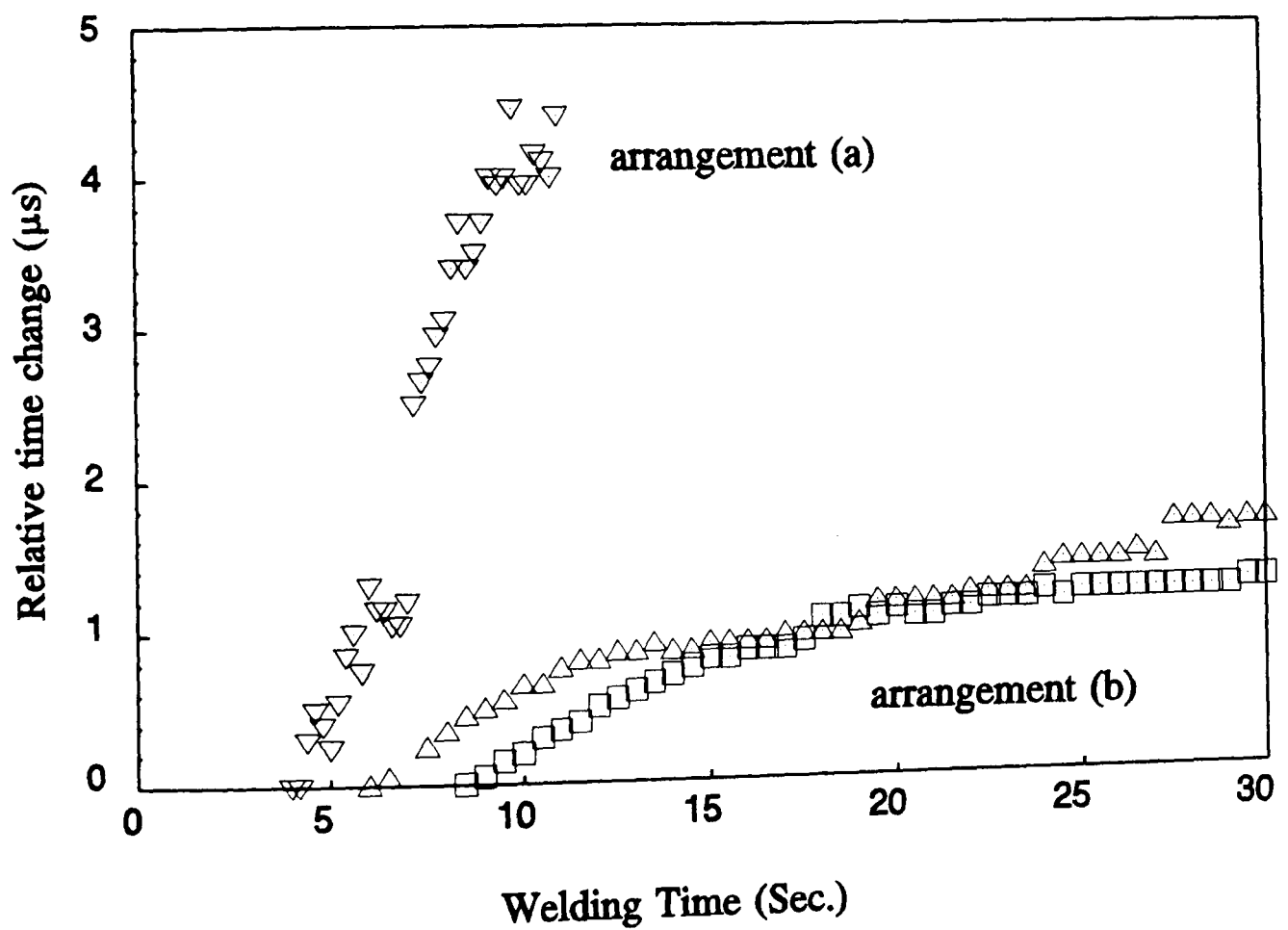


Figure 55 Heat effect on signal time in SAW process

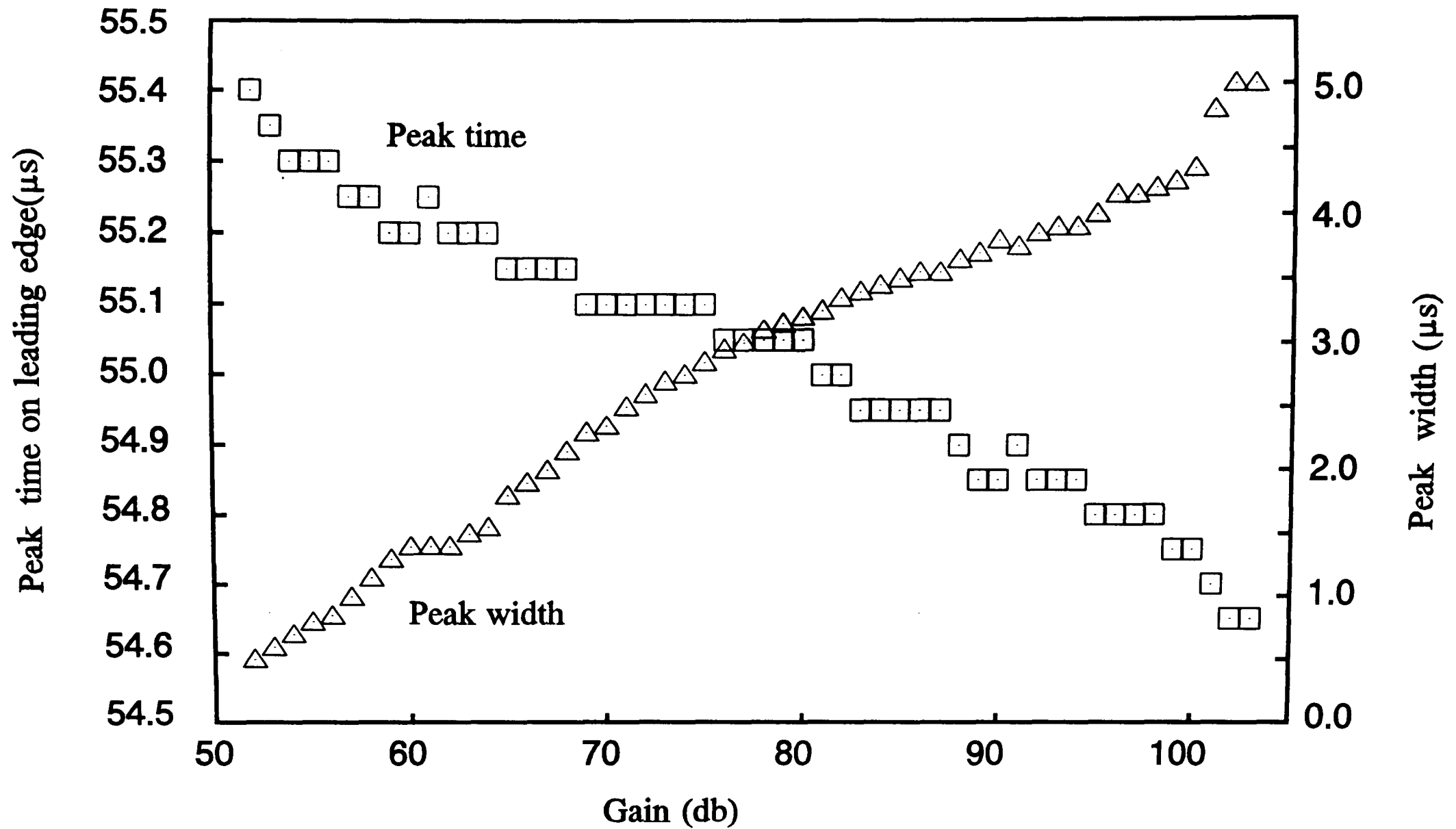
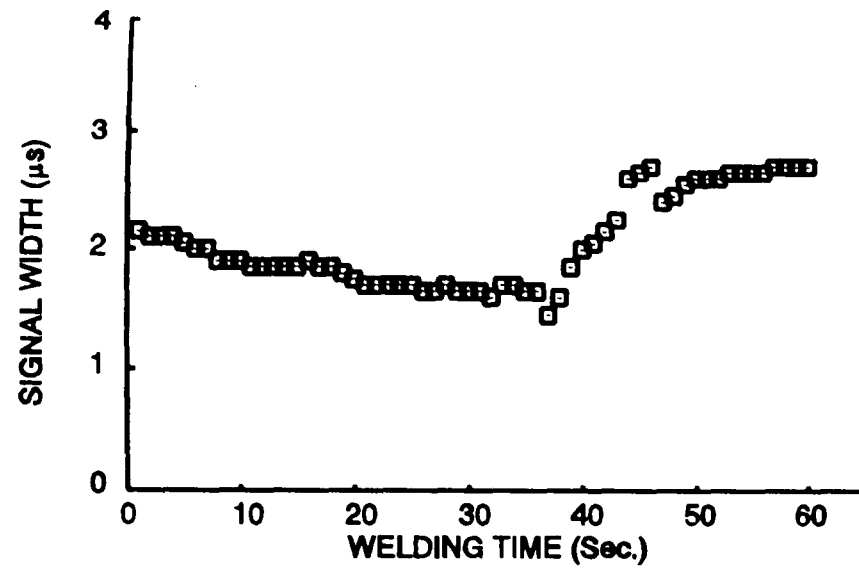
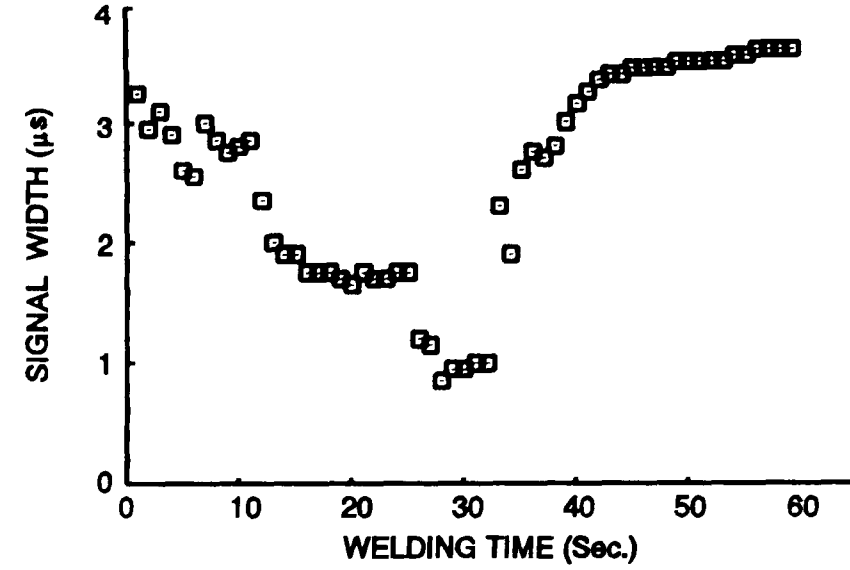


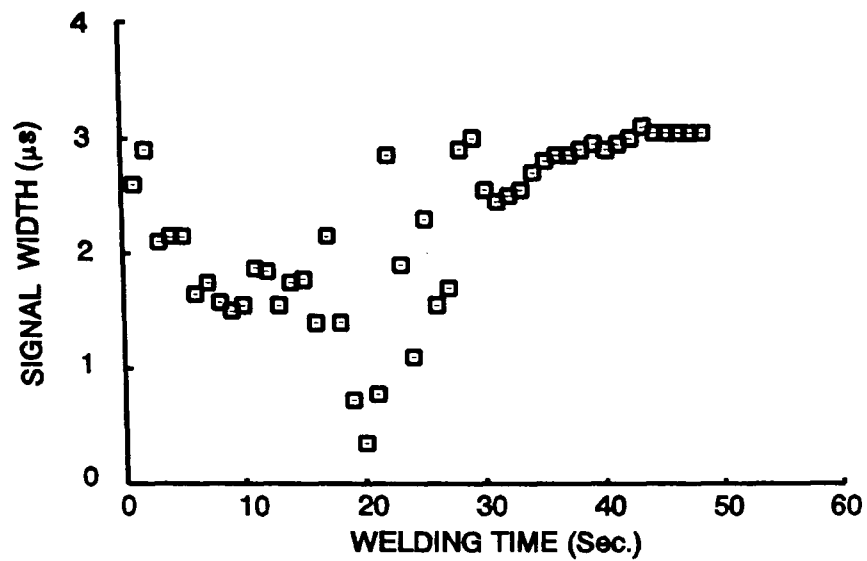
Figure 56 Gain versus peak time and peak width



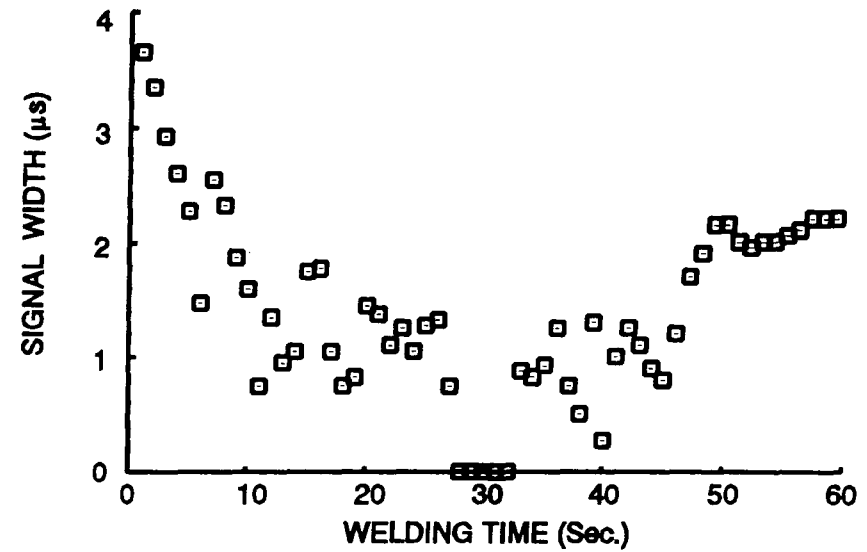
(a) Welding current: 111A



(b) Welding current: 133A

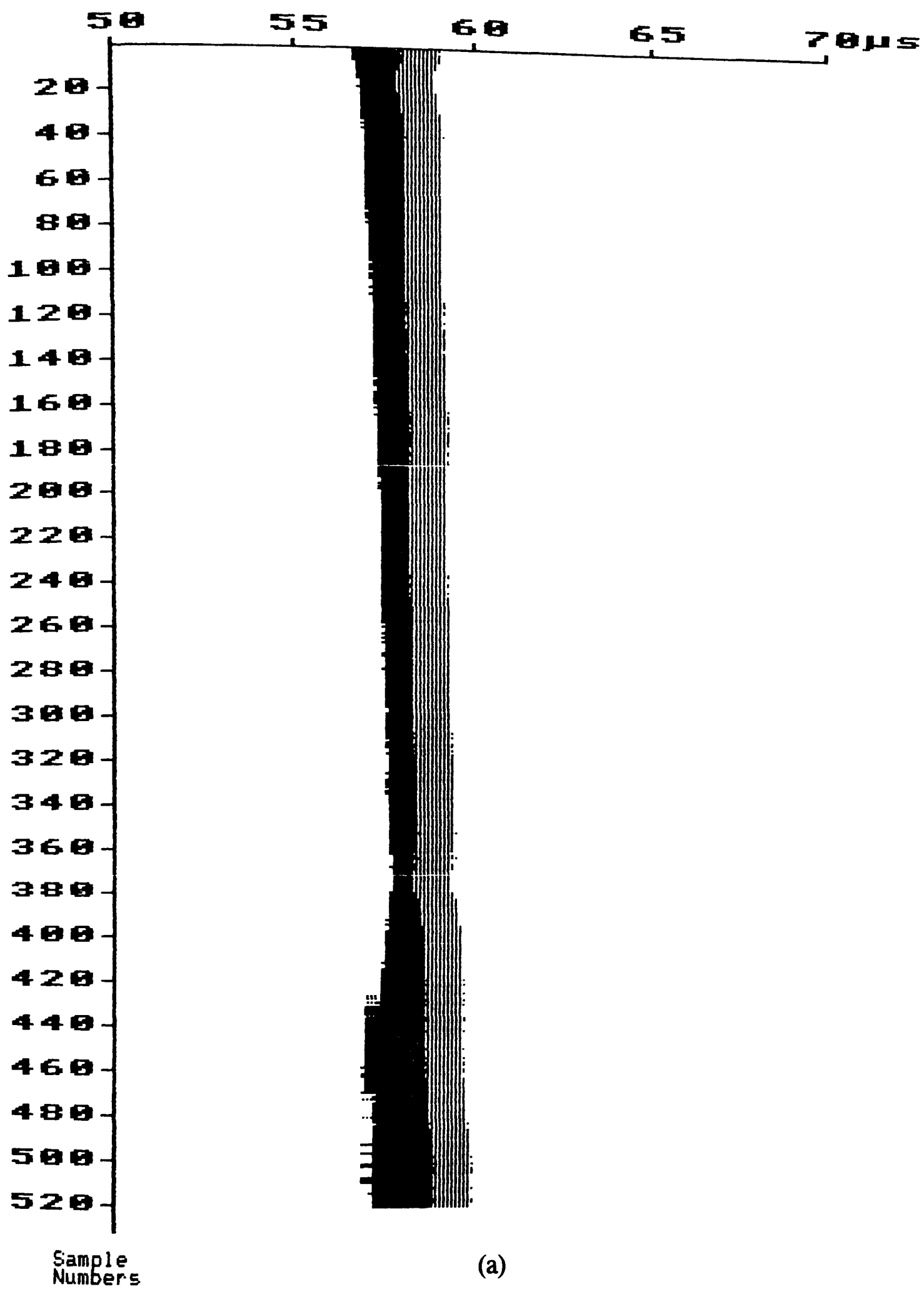


(c) Welding current: 210A



(d) Welding Current: 273A

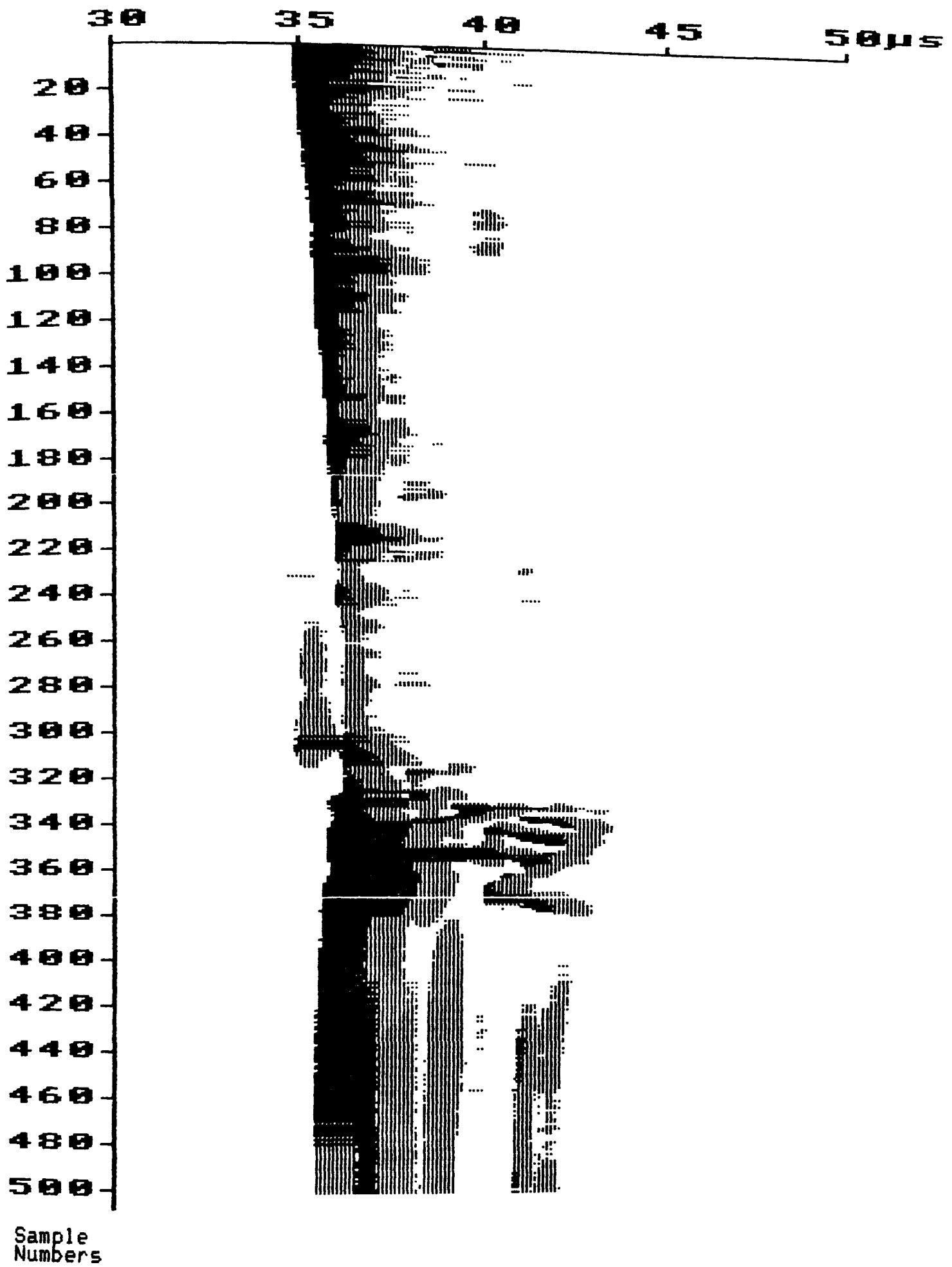
Figure 57 Temperature effect on peak width



Gain (db)	Freq. (MHz)	Reje.	I (A)	V (V)	Sample interval (Sec.)
75	2	2	111	14.6	0.1

(b)

Figure 58 (a) B-scan graph showing the temperature effects;
 (b) Experimental parameters

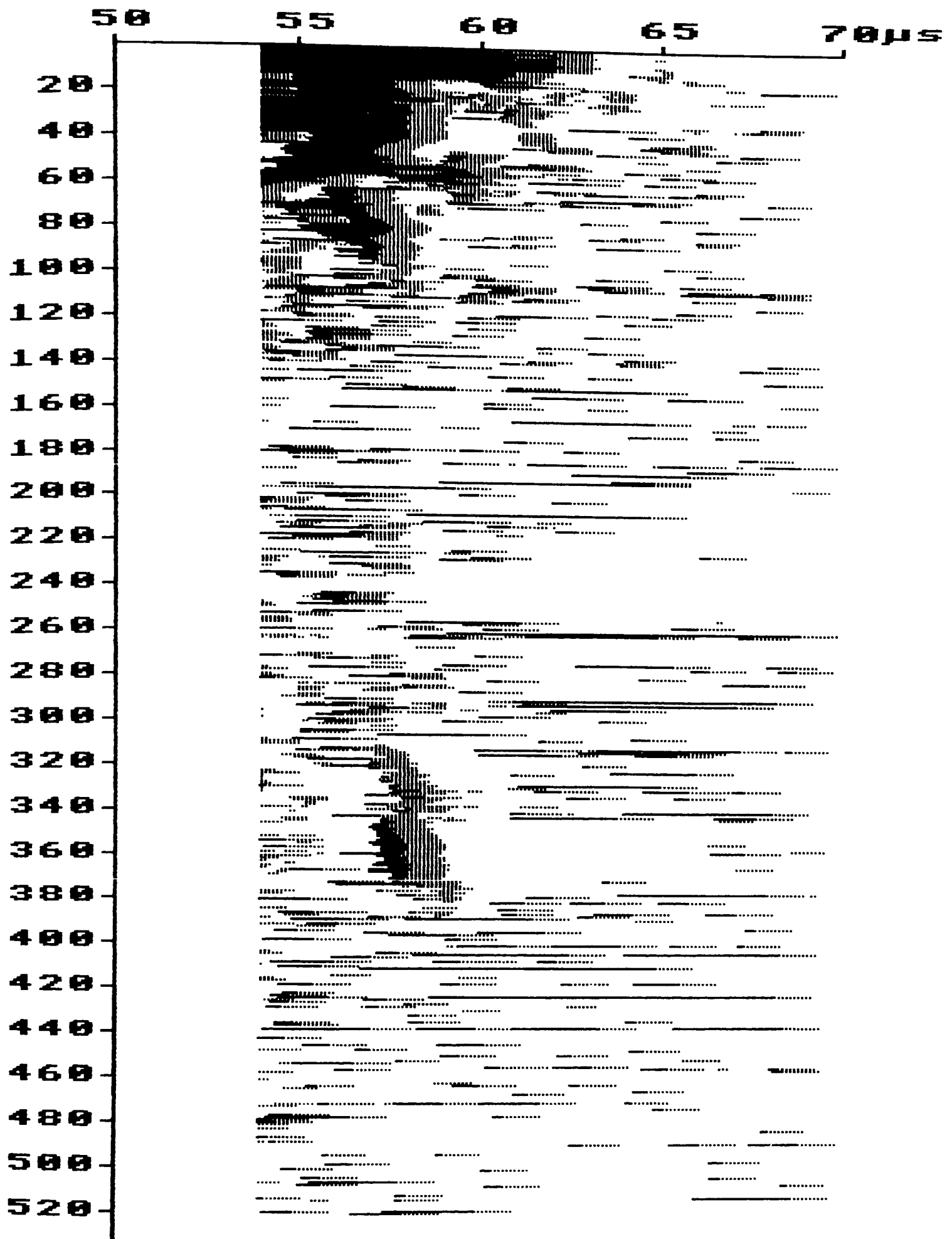


(a)

Gain (db)	Freq. (MHz)	Reje.	I (A)	V (V)	Sample interval (S)
85	2	2	150	15.3	0.1

(b)

Figure 59 (a) B-scan results showing temperature effects;
 (b) Experimental parameters



(a)

Sample
Numbers

Gain (db)	Freq. (MHz)	Reje.	I (A)	V (V)	Speed (mm/s)	sample interval (s)
102	broad	3	352	31.4	5.2	0.05

(b)

Figure 60 (a) B-scan results with much noise; (b) Experimental parameters

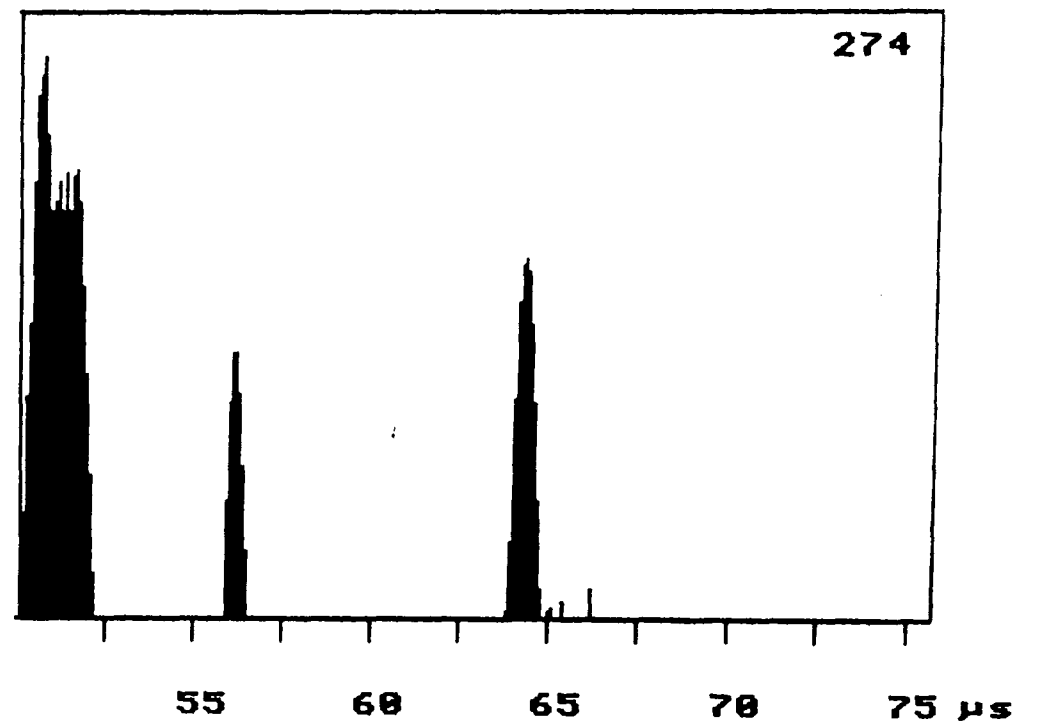
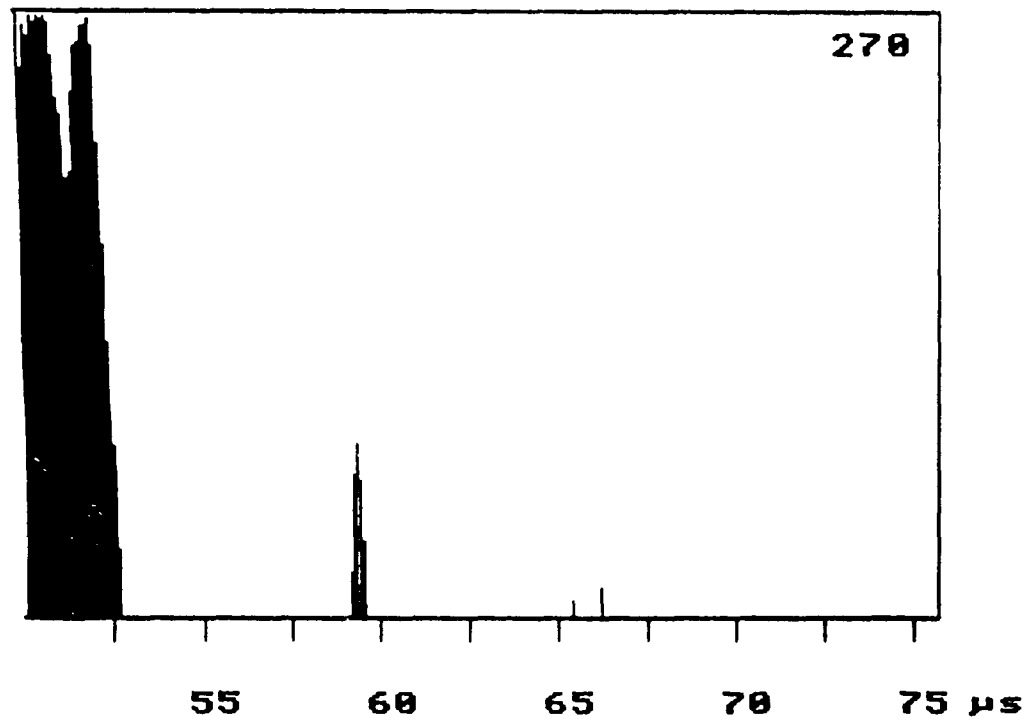
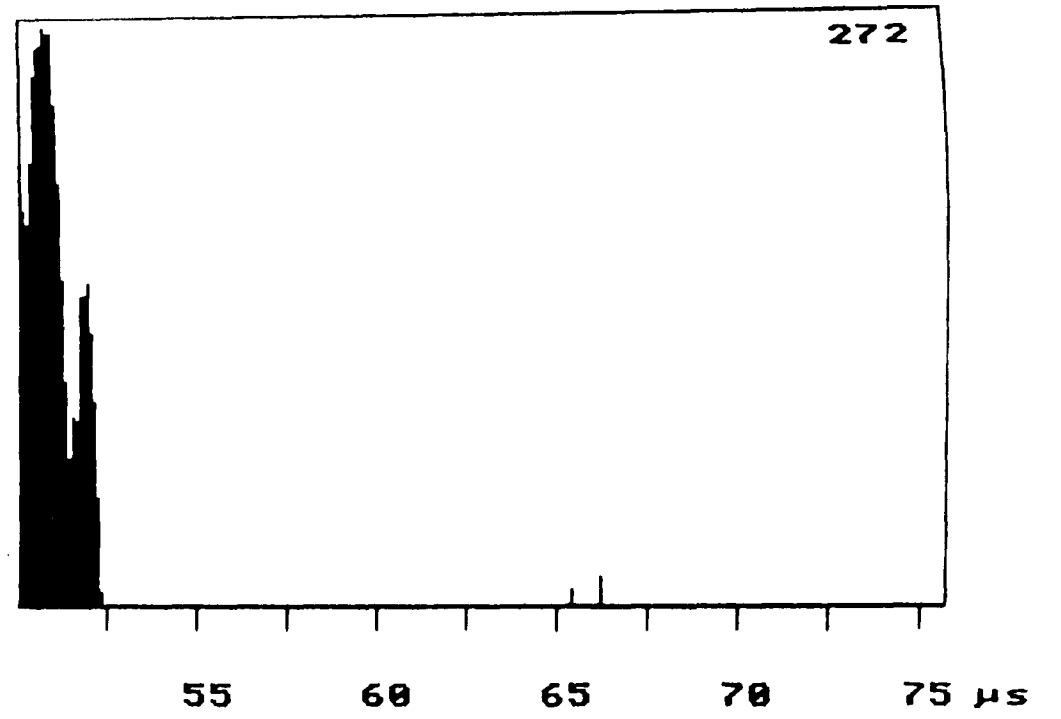
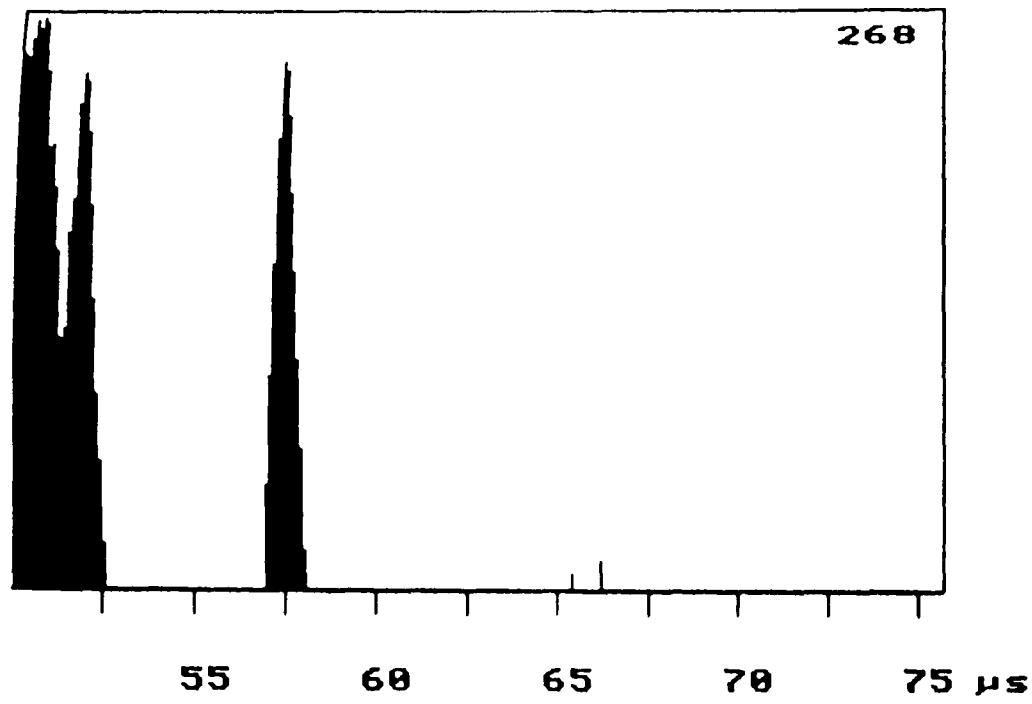
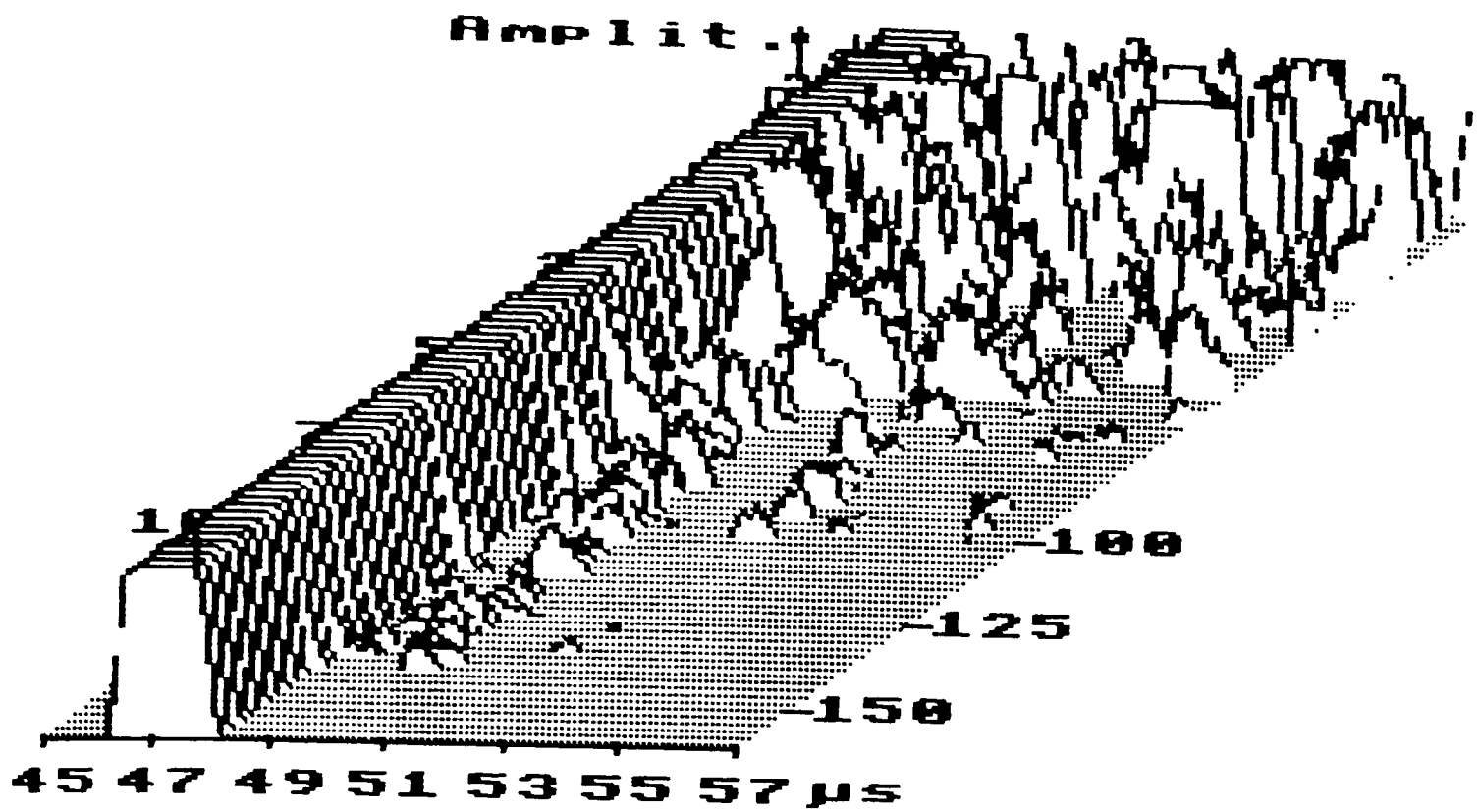
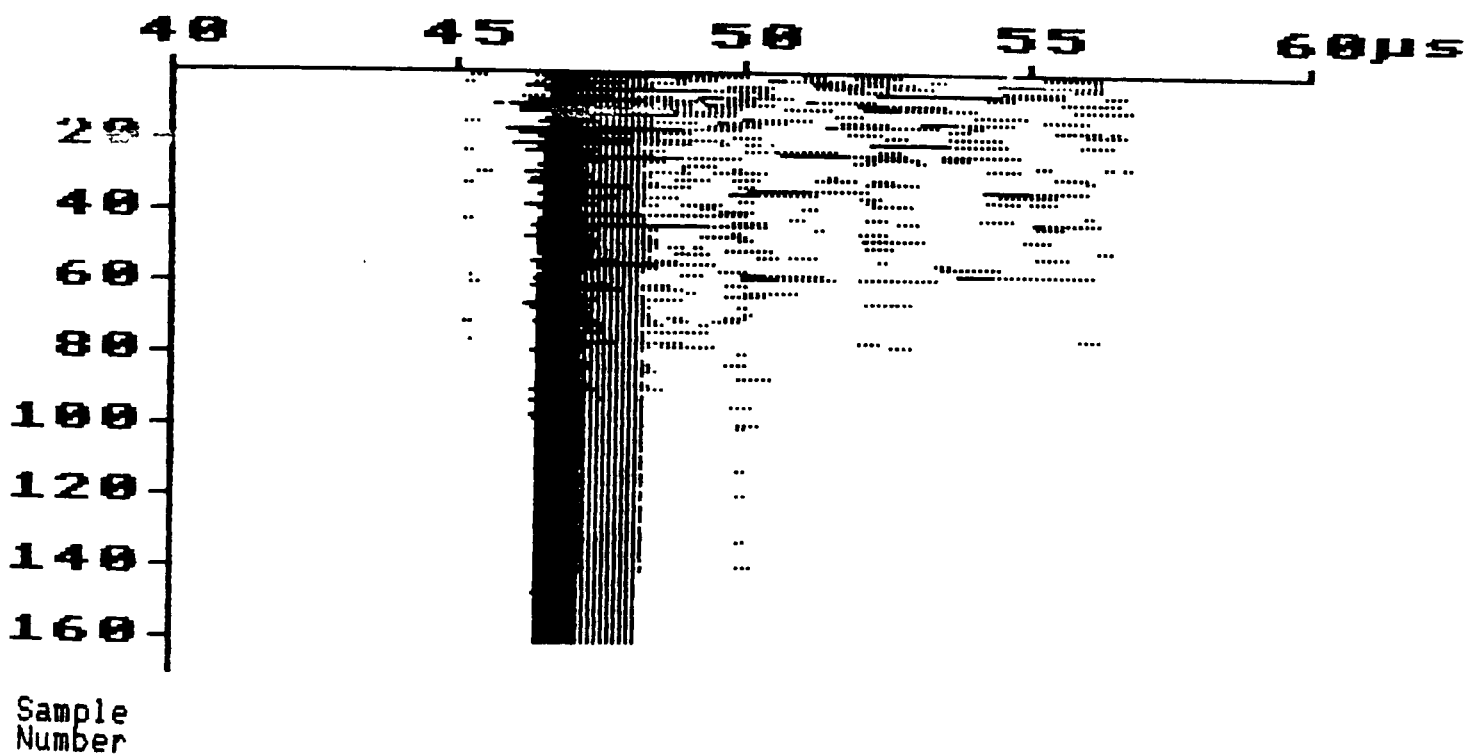


Figure 61 Examples of A-Scan signals with noise peaks



(a) 3 dimensional results



(b) B-scan results

Sample Number	1-20	21-40	41-60	61-80	81-100	101-120	121-140	141-160
Averaging times	1	2	4	8	16	32	64	128

(c) Table of sample numbers and averaging times

Figure 62 Effect of averaging times on signal to noise ratio.

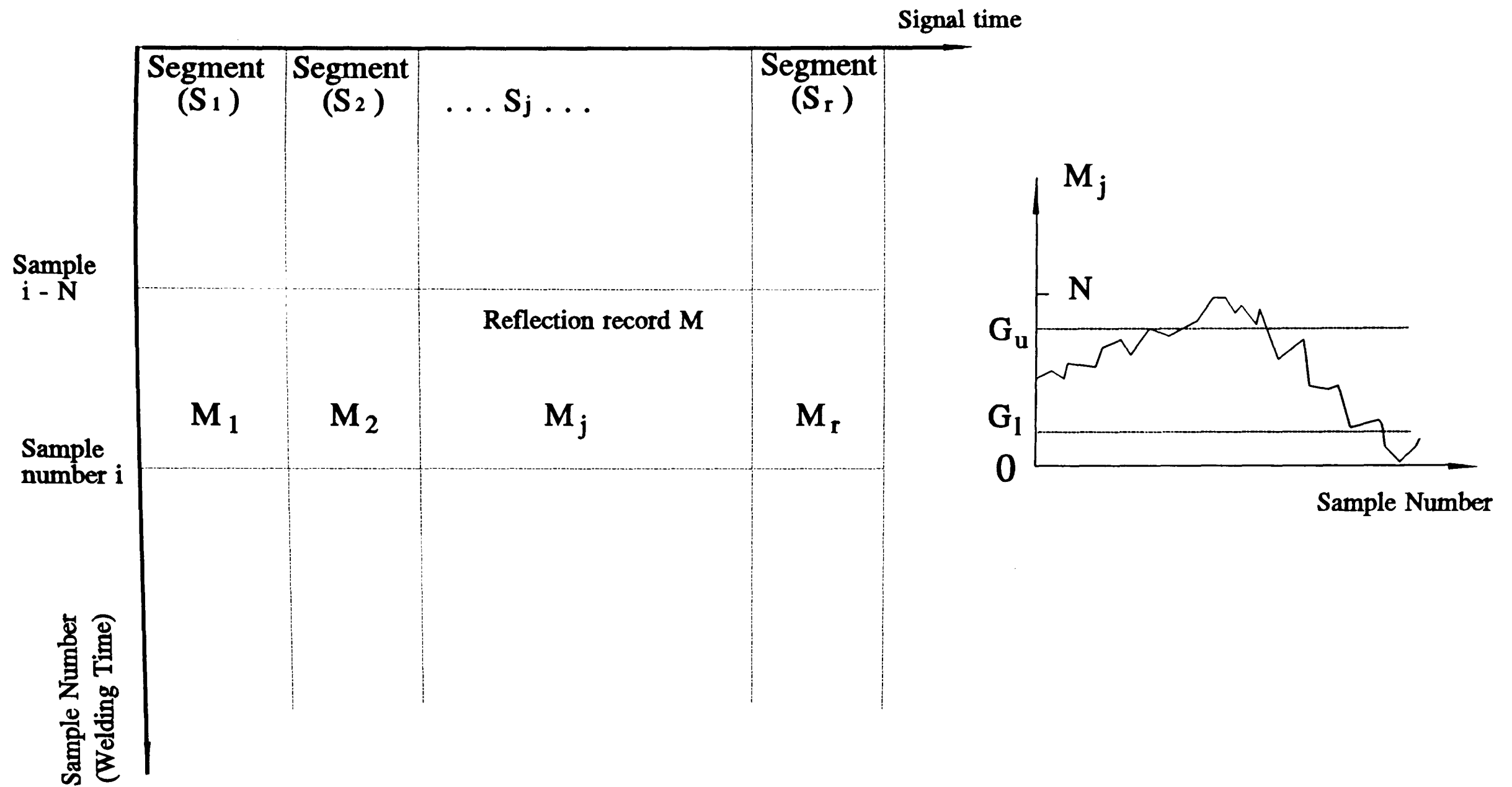


Figure 63 Schematic diagram of statistical data analysis

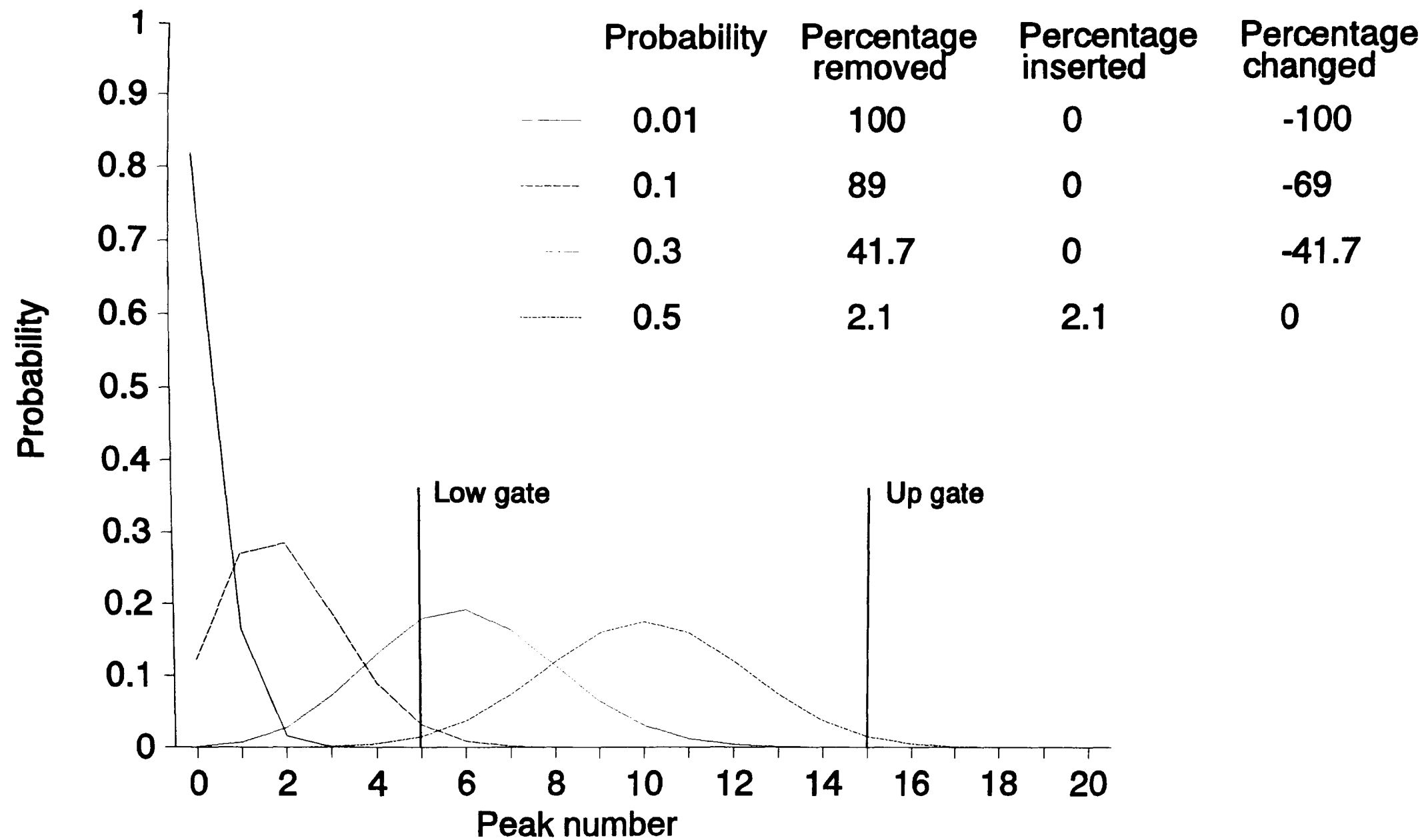
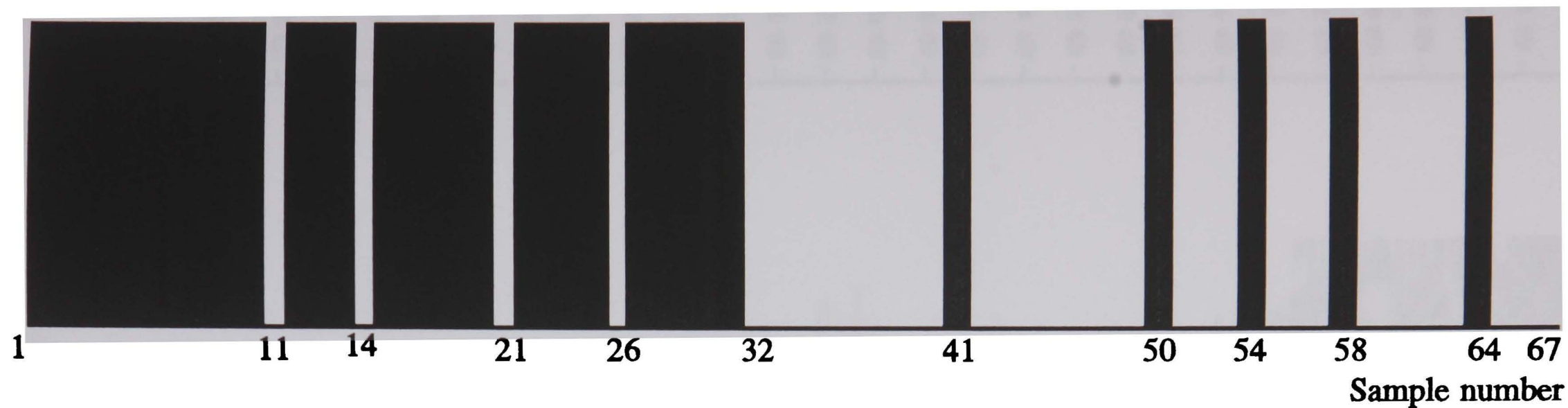
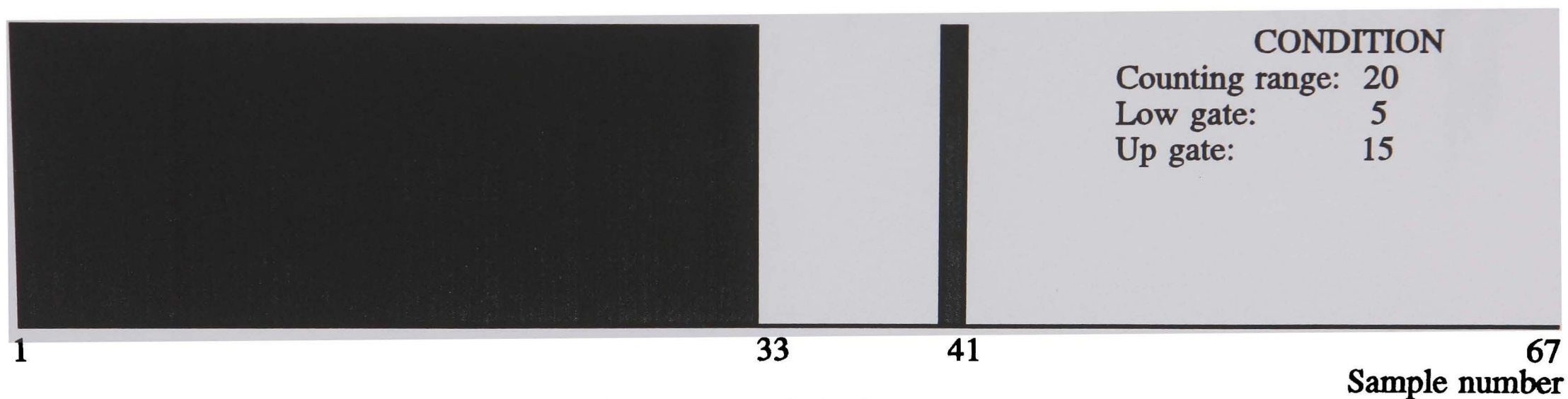


Figure 64 Effect of peaks probability on results of data analysis



(a) Original data



(b) Data after statistical analyzing

Figure 65 Simulation results from statistical data analysis

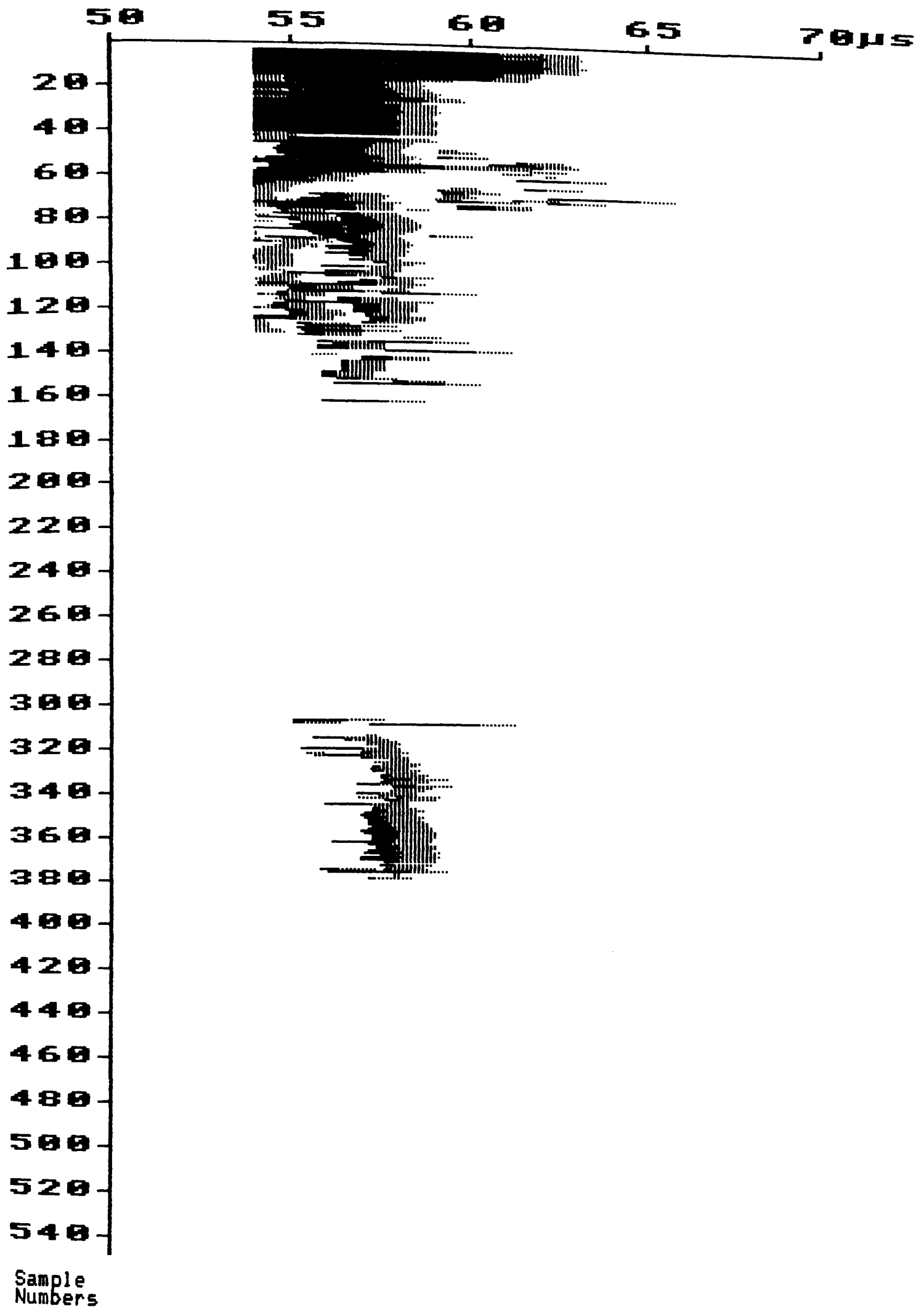


Figure 66 B-Scan results after data analysis showing the capability to remove noise.

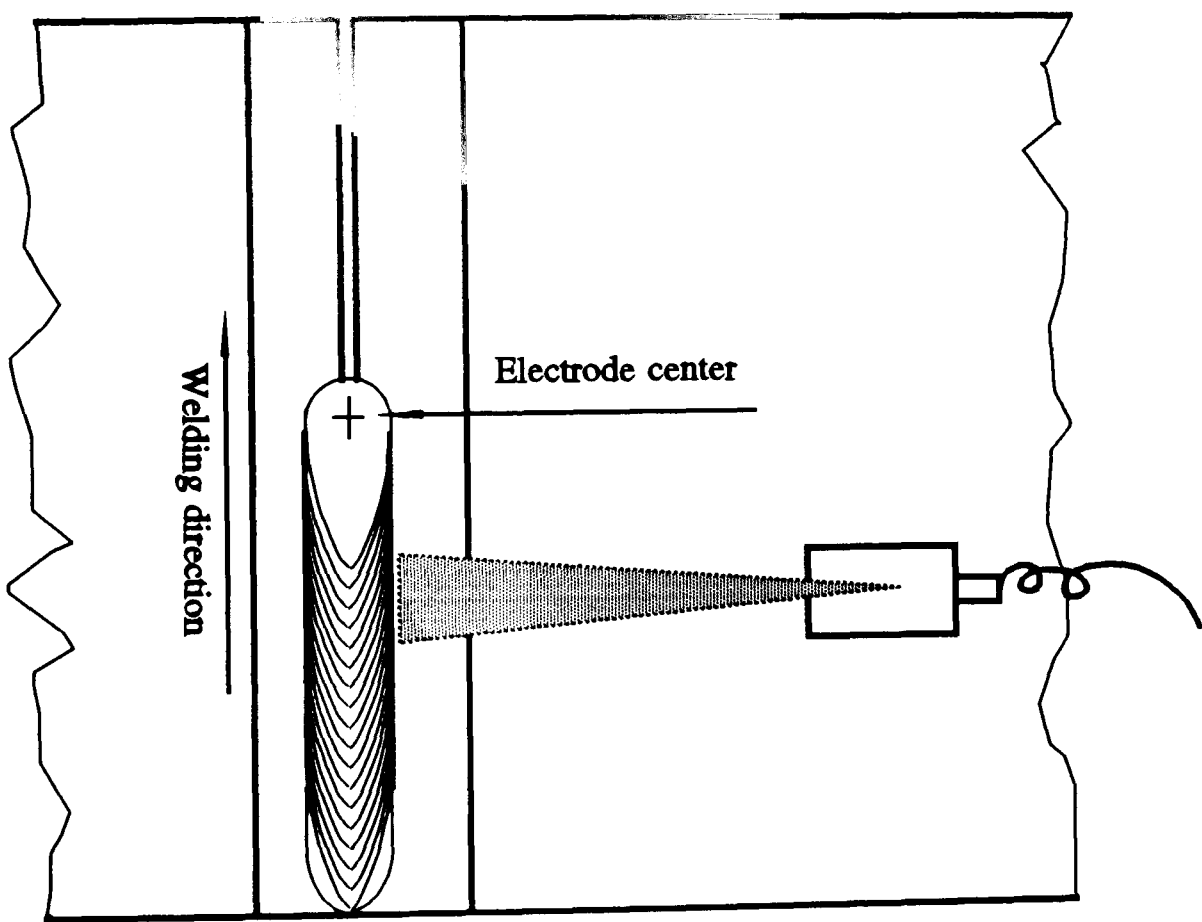
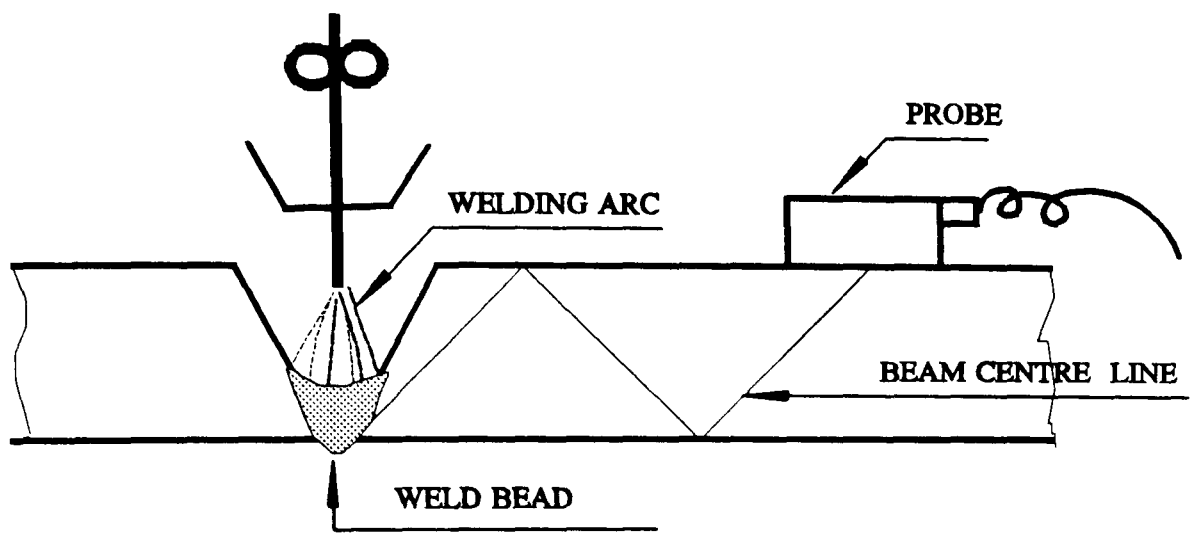
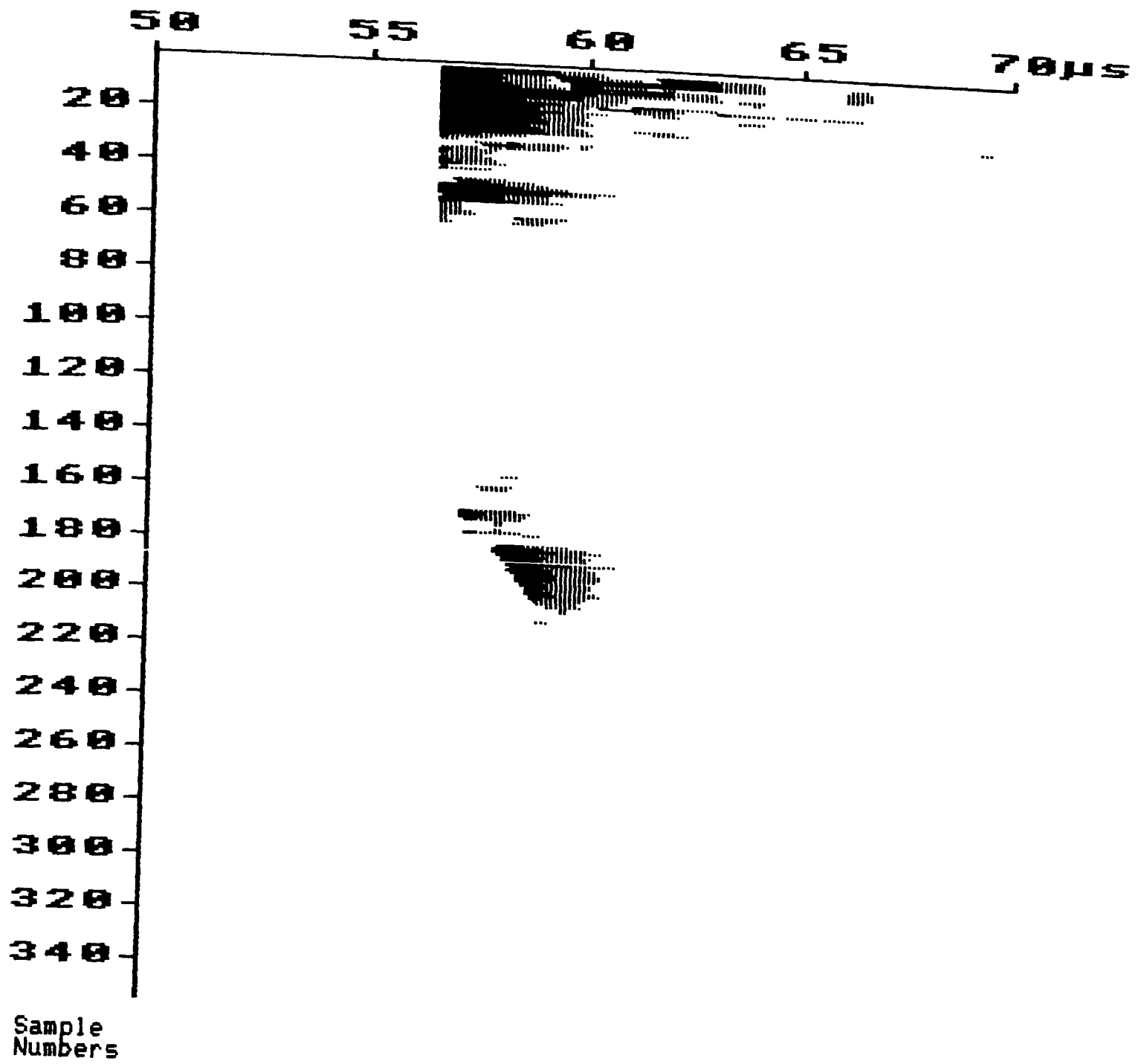


Figure 67 Schematic diagram of arrangement for detecting the lack of root fusion



(a) B-scan results

Gain (db)	Freq. (MHz)	Reje.	I (A)	V (V)	Speed (mm/s)	Sample interval (s)
102	broad	4	358	31.7	4.55	0.1

(b) Parameters

Figure 68 B-Scan graph from the lack of root fusion defect in SAW and the experimental parameters

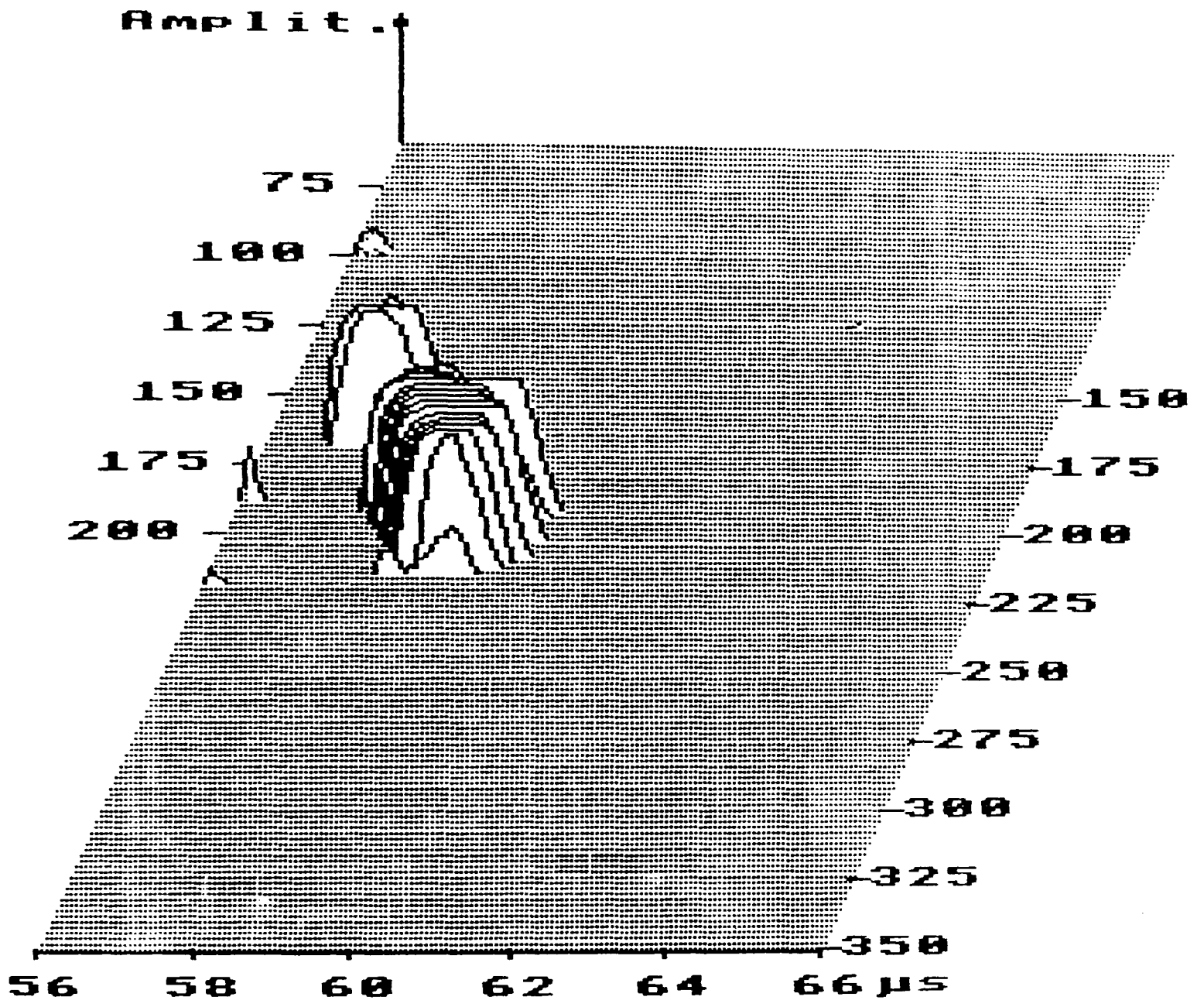


Figure 69 3-dimensional A-scan signals show the lack of root fusion defect in SAW process.

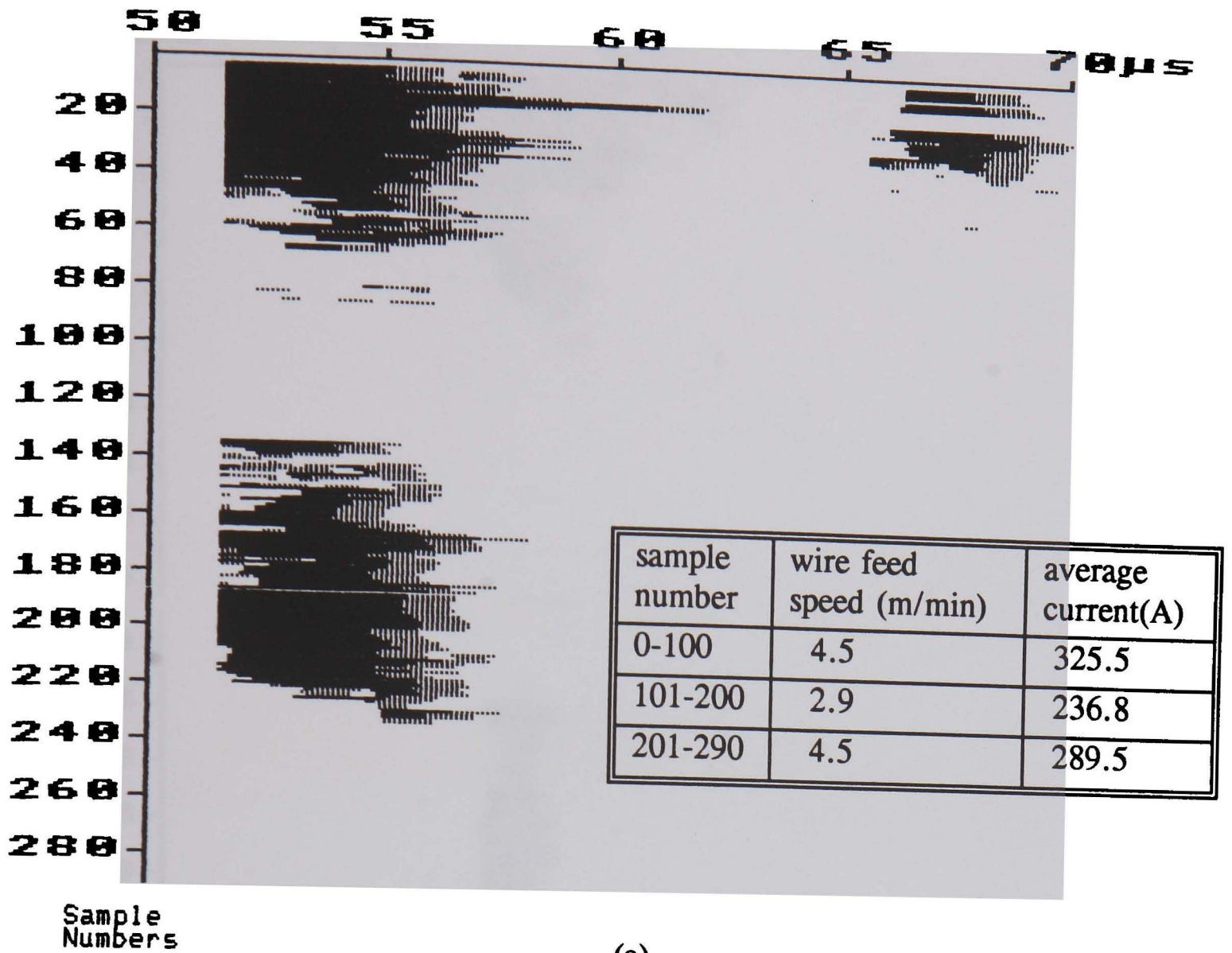


(a) Specimen photo



(b) X-ray Results

Figure 70 Specimen photo and X-ray results from the lack of root fusion defect in the SAW process (same as figures 68 & 69)



(a)



(b)

Gain (db)	Freq. (MHz)	Reje.	I (A)	V (V)	Speed (mm/s)	Sample interval (s)
102	broad	2		30.7	5.31	0.1

(c)

Figure 71 (a) B-scan results from lack of root fusion at low current range; (b) X-ray photo; (c) Experimental parameters

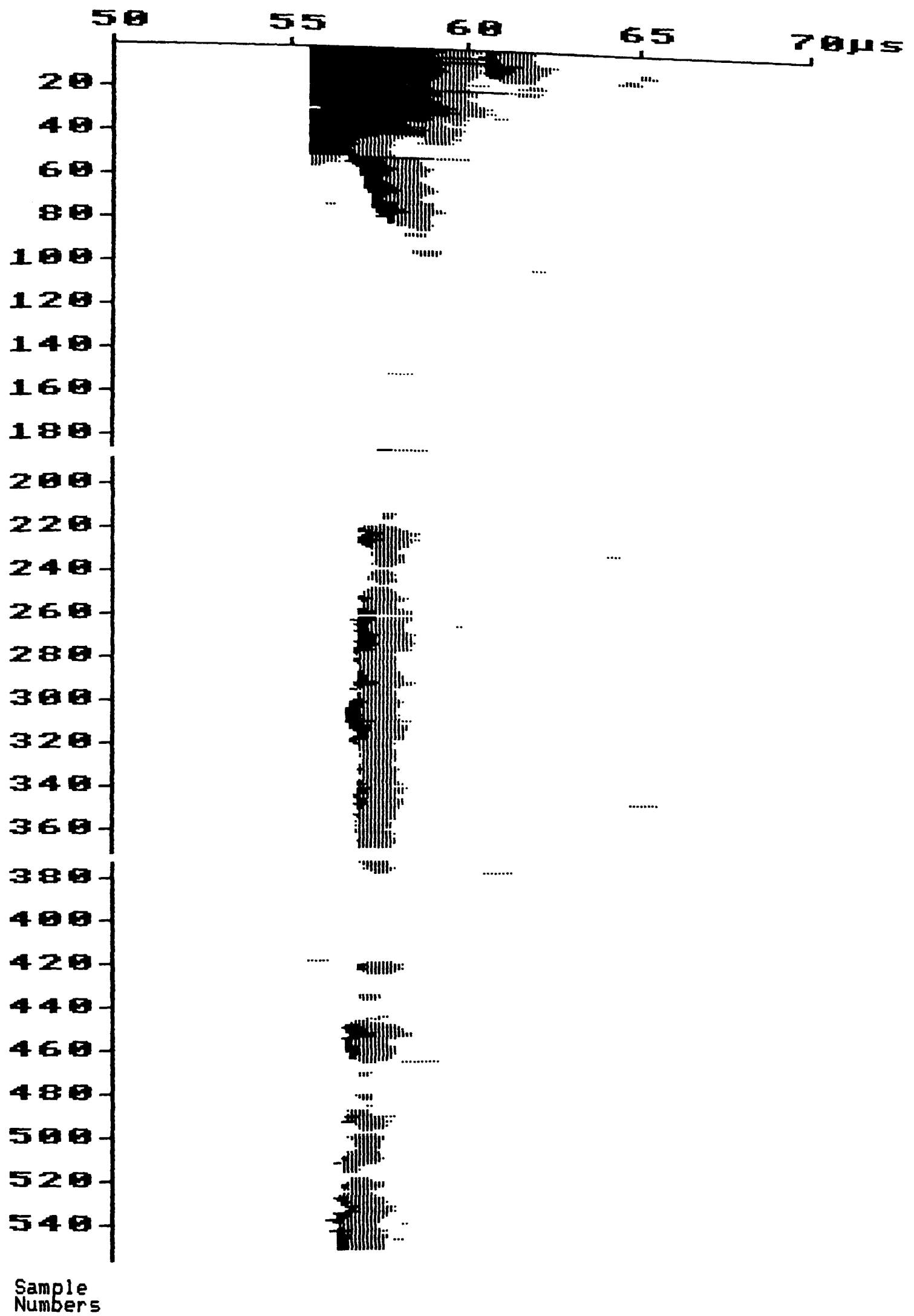
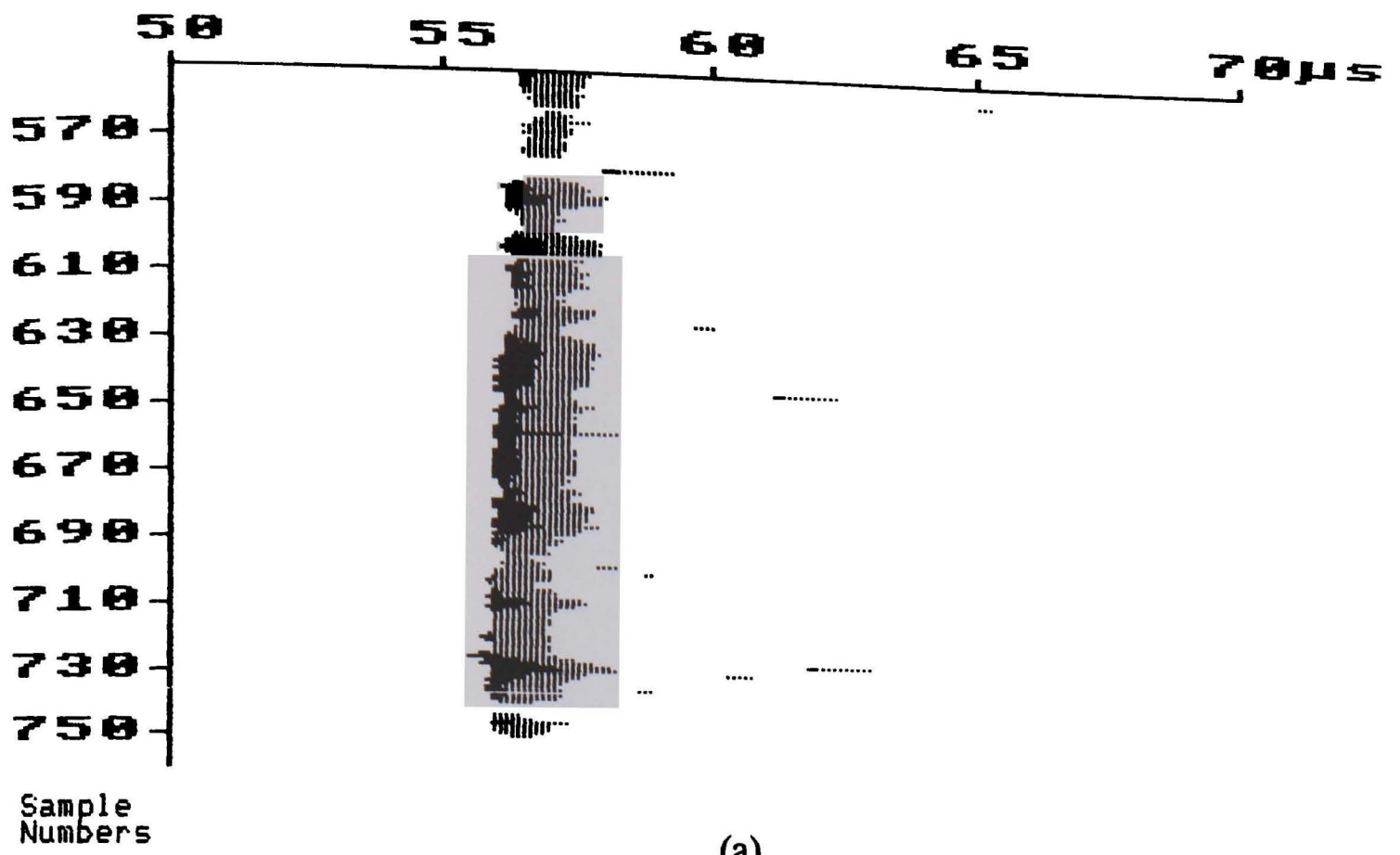


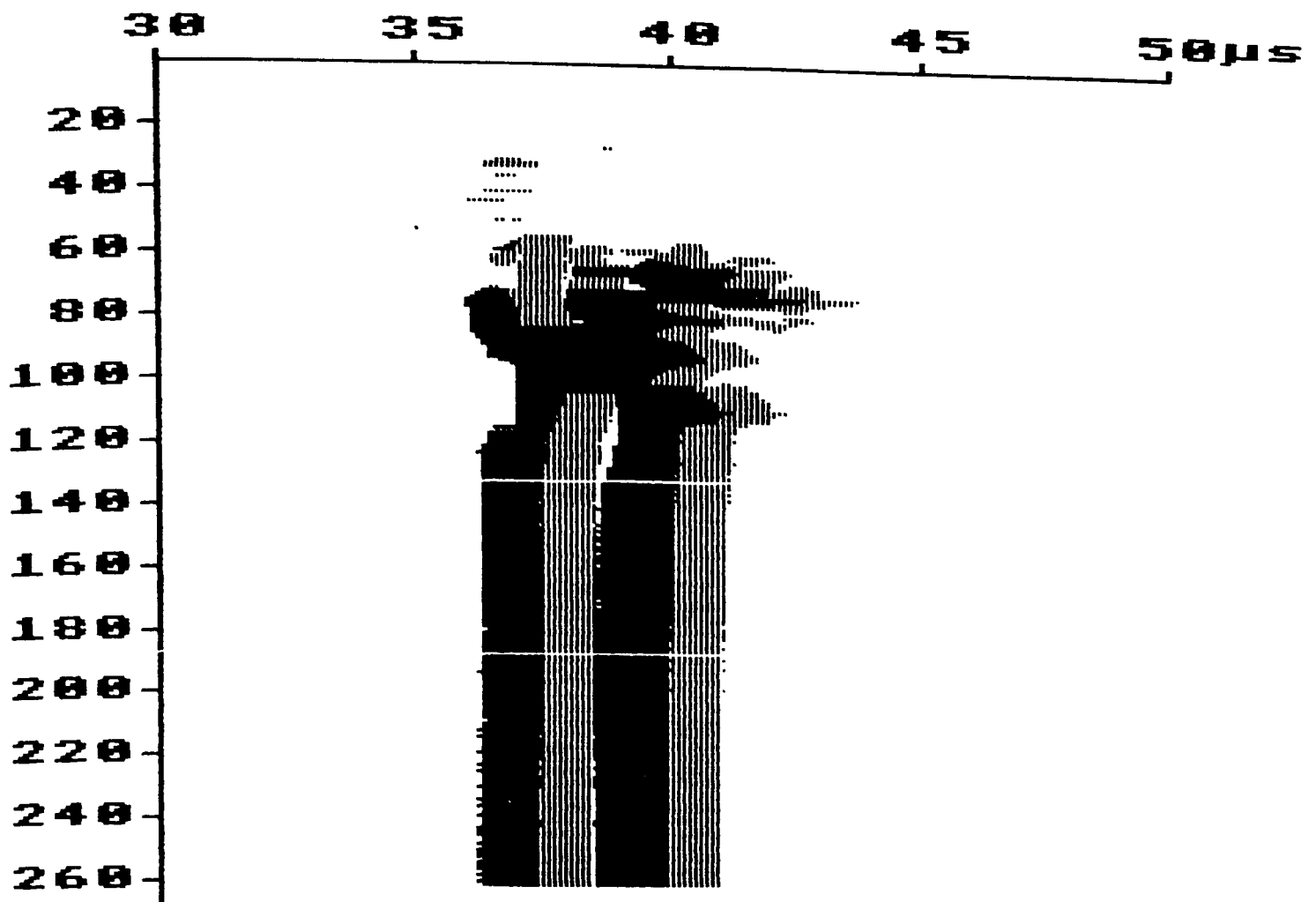
Figure 72(a) To be continued



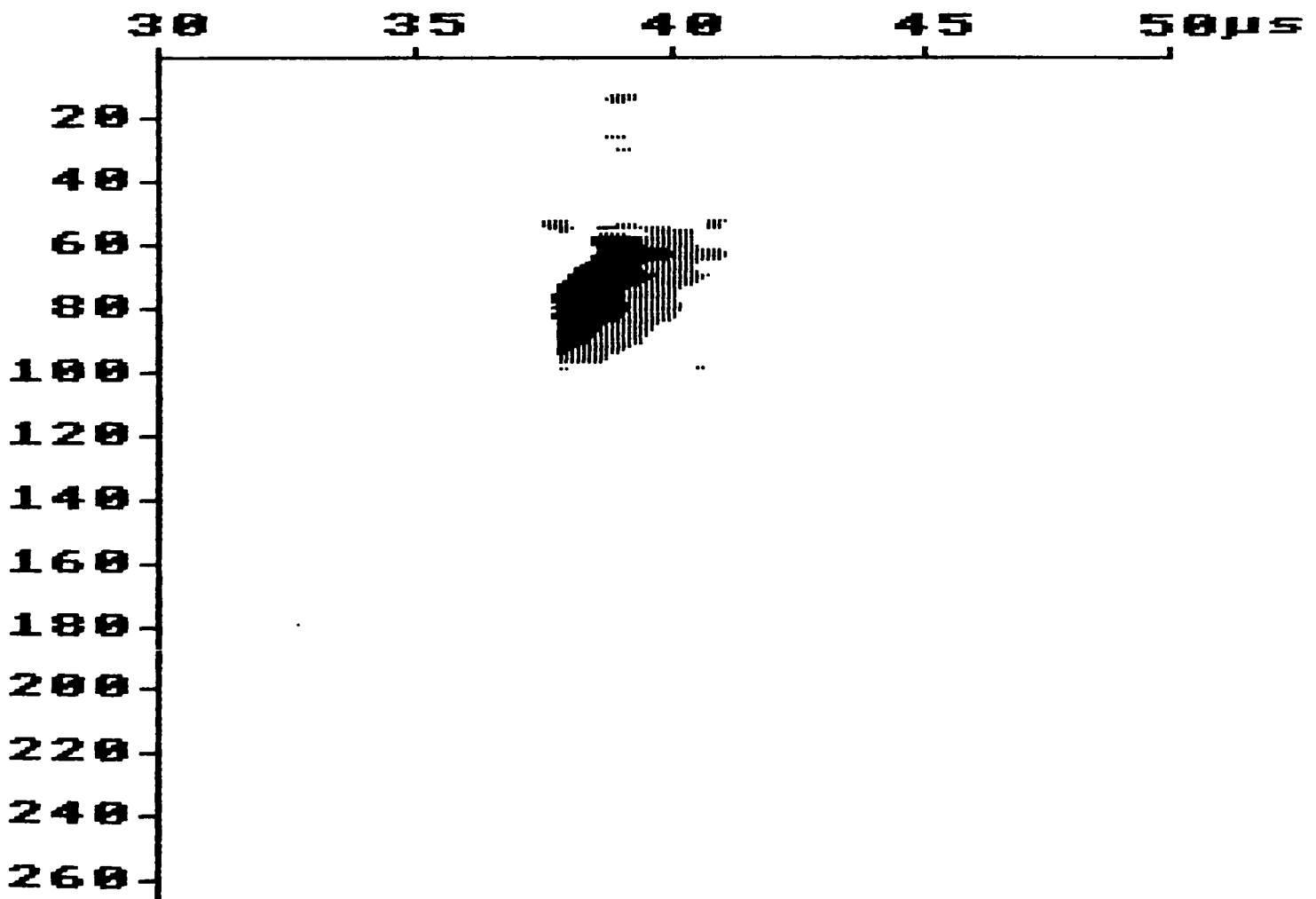
Gain (db)	Freq. (MHz)	Reje.	I (A)	V (V)	Speed (mm/s)	Sample interval (s)
104	broad	4	387	31.5	4.5	0.05

(c)

Figure 72 (a) B-scan results from lack of root fusion during general welding; (b) X-ray photo; (c) Experimental parameters

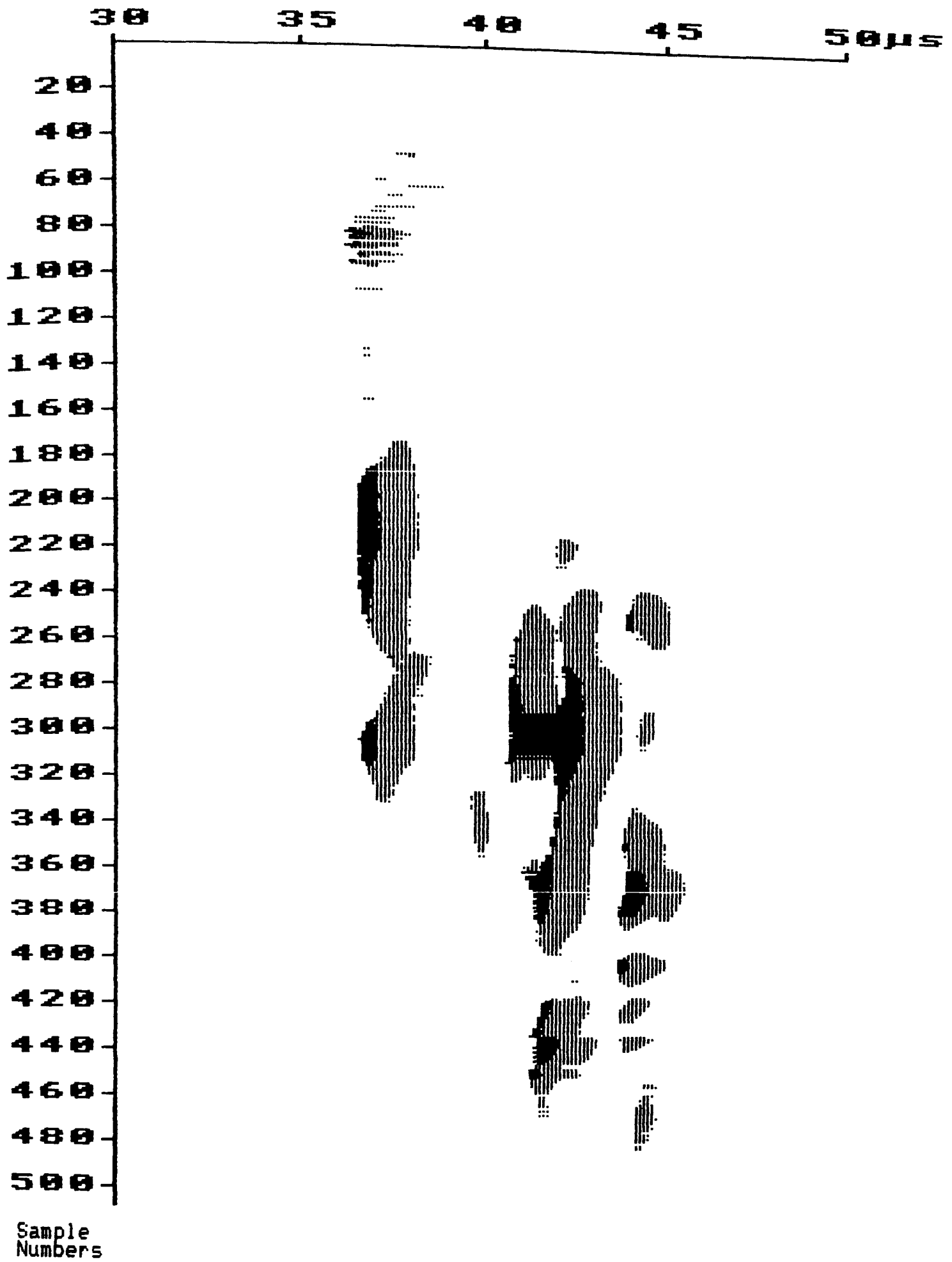


(a) B-scan results from the weld with porosity



(b) B-scan results from the weld without defects

Figure 73 Comparison of B-scan graphs with static probe experiment

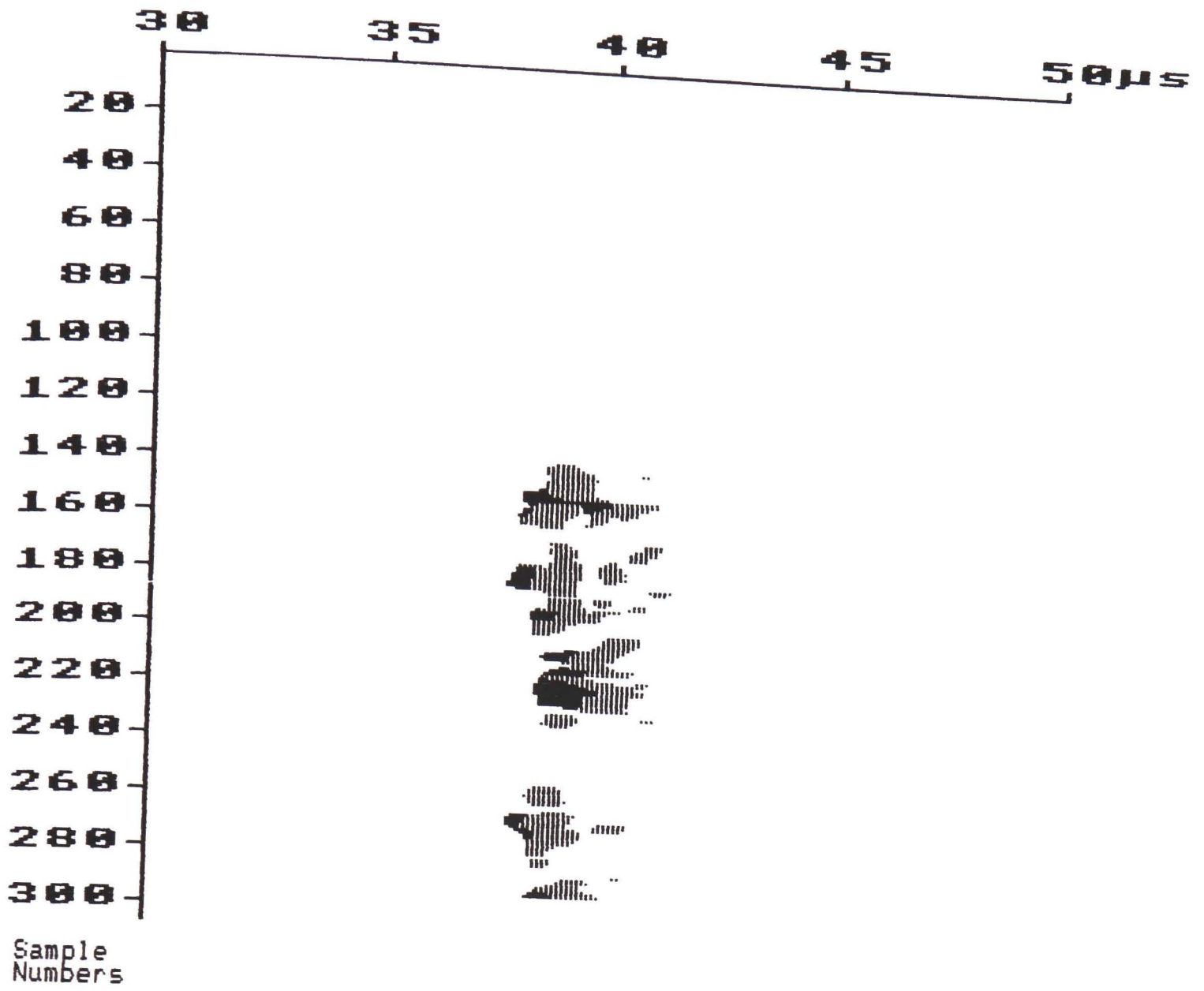


(a)

Gain (db)	Freq. (MHz)	Reje.	I (A)	V (V)	Speed (mm/s)	Sample interval (S)
84	2	2	310	30.8	4.45	0.05 & 0.1

(b)

Figure 74 (a) B-scan results from 'bead on plate' with a fixed probe;
 (b) Experiment parameters



(a) B-scan results

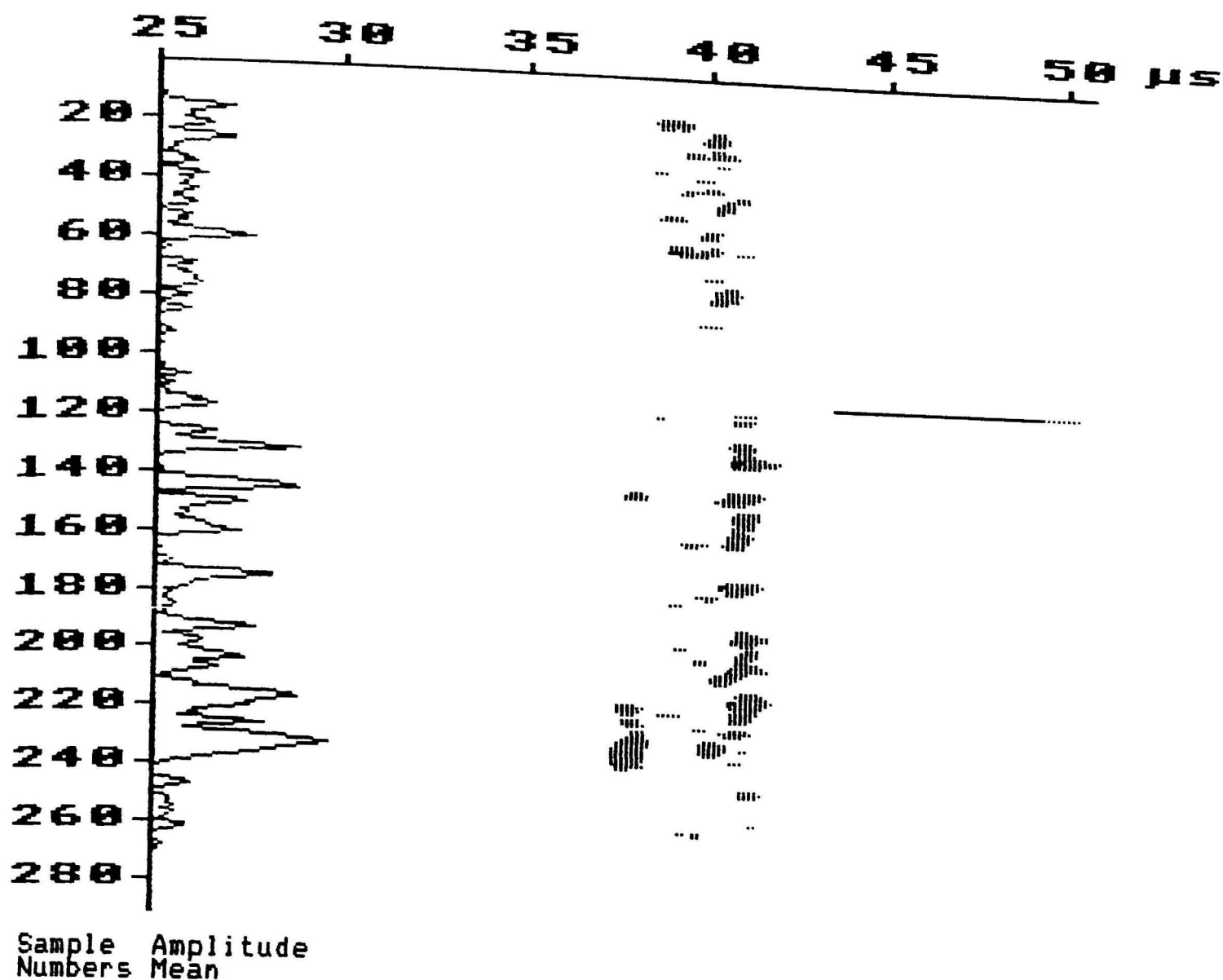


(b) Specimen photo

Gain (db)	Freq. (MHz)	Reje.	I (A)	V (V)	Speed (mm/s)	Sample interval (S)
76	2	2	159	15.4	3.9	0.1

(c) Experimental parameters

Figure 75 Experimental results showing weld porosity



(a) B-scan results

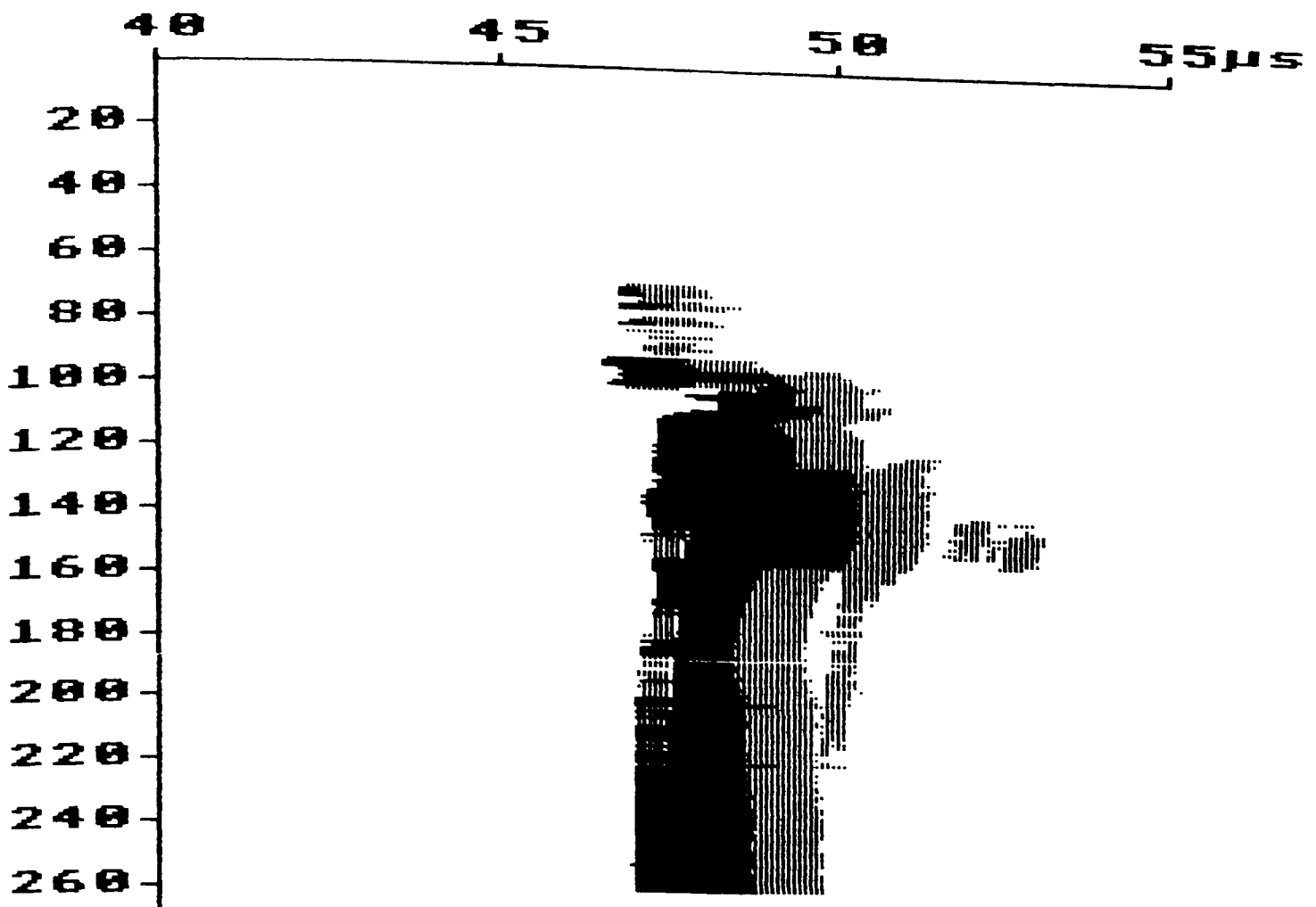


(b) Specimen photo

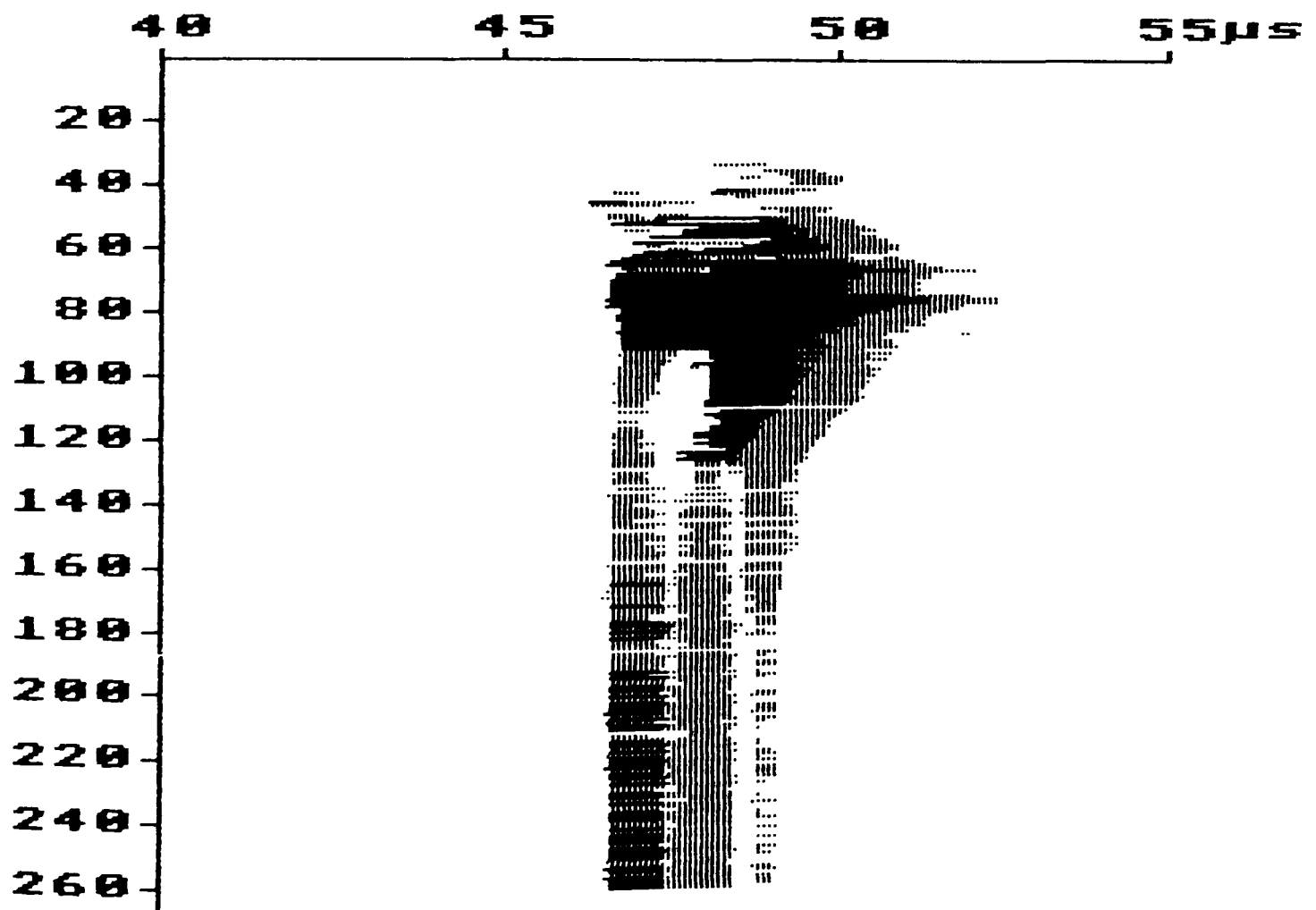
Gain (db)	Freq. (MHz)	Reje.	I (A)	V (V)	Speed (mm/s)	Sample interval (S)
78	2	2	170	15.5	3.7	0.1

(c) Experiment parameters

Figure 76 Experimental results show weld porosity (BCED=7.5mm)

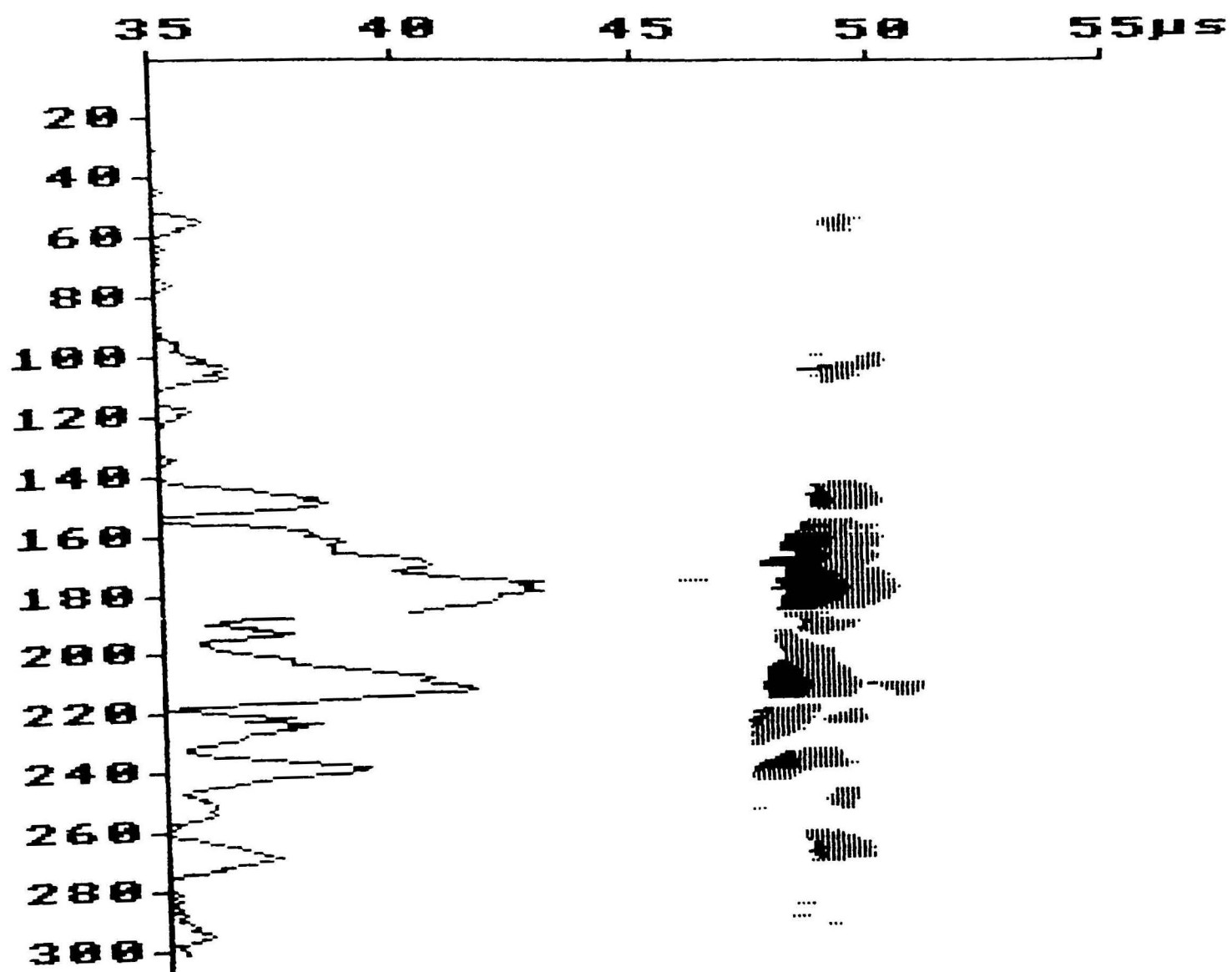


(a) Iron sulphide (FeS) initiated cracks



(b) Copper powder initiated cracks

Figure 77 B-scan graphs show the difference between FeS cracks and copper cracks.



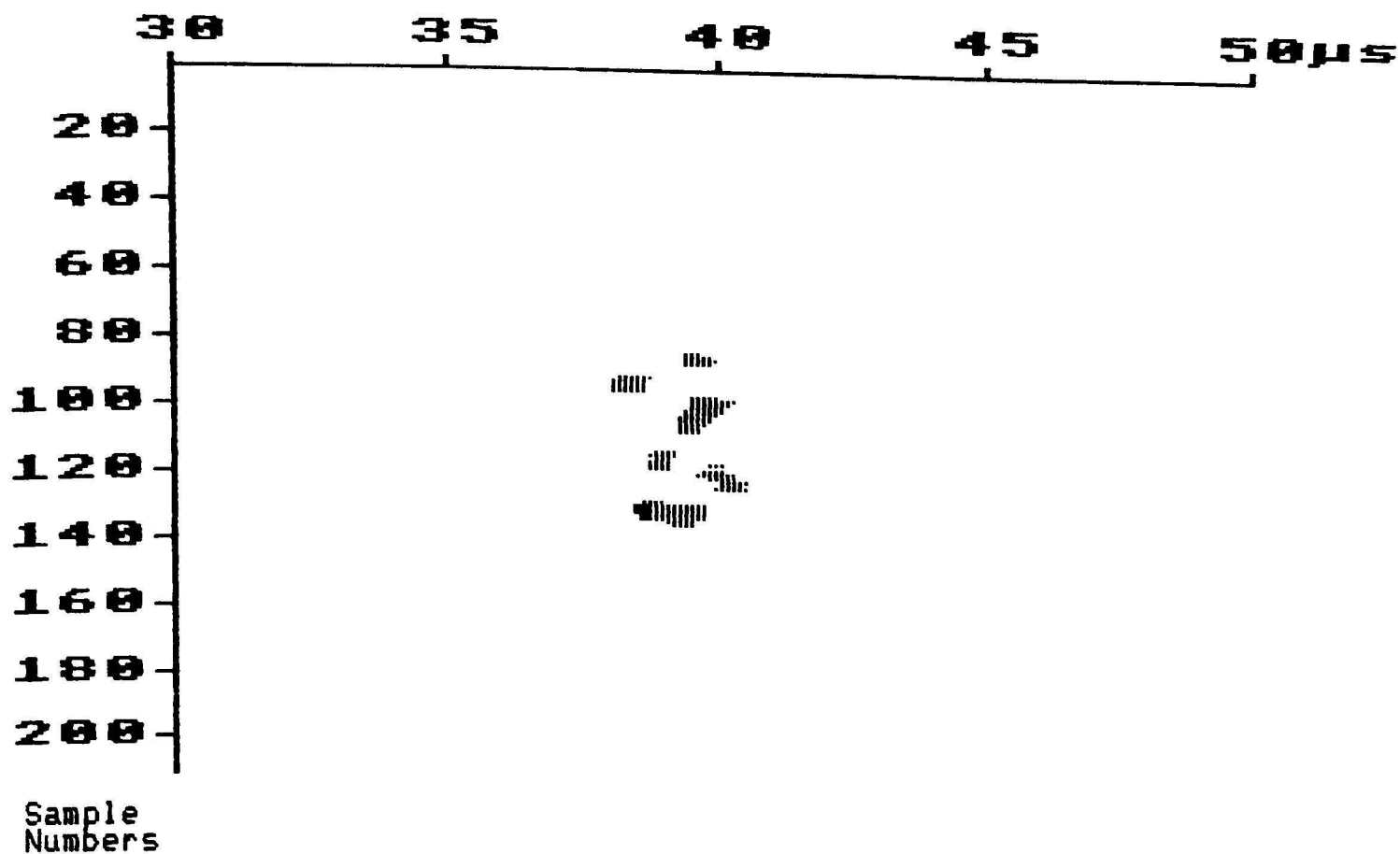
Sample Amplitude
Numbers Mean

(a) B-scan results



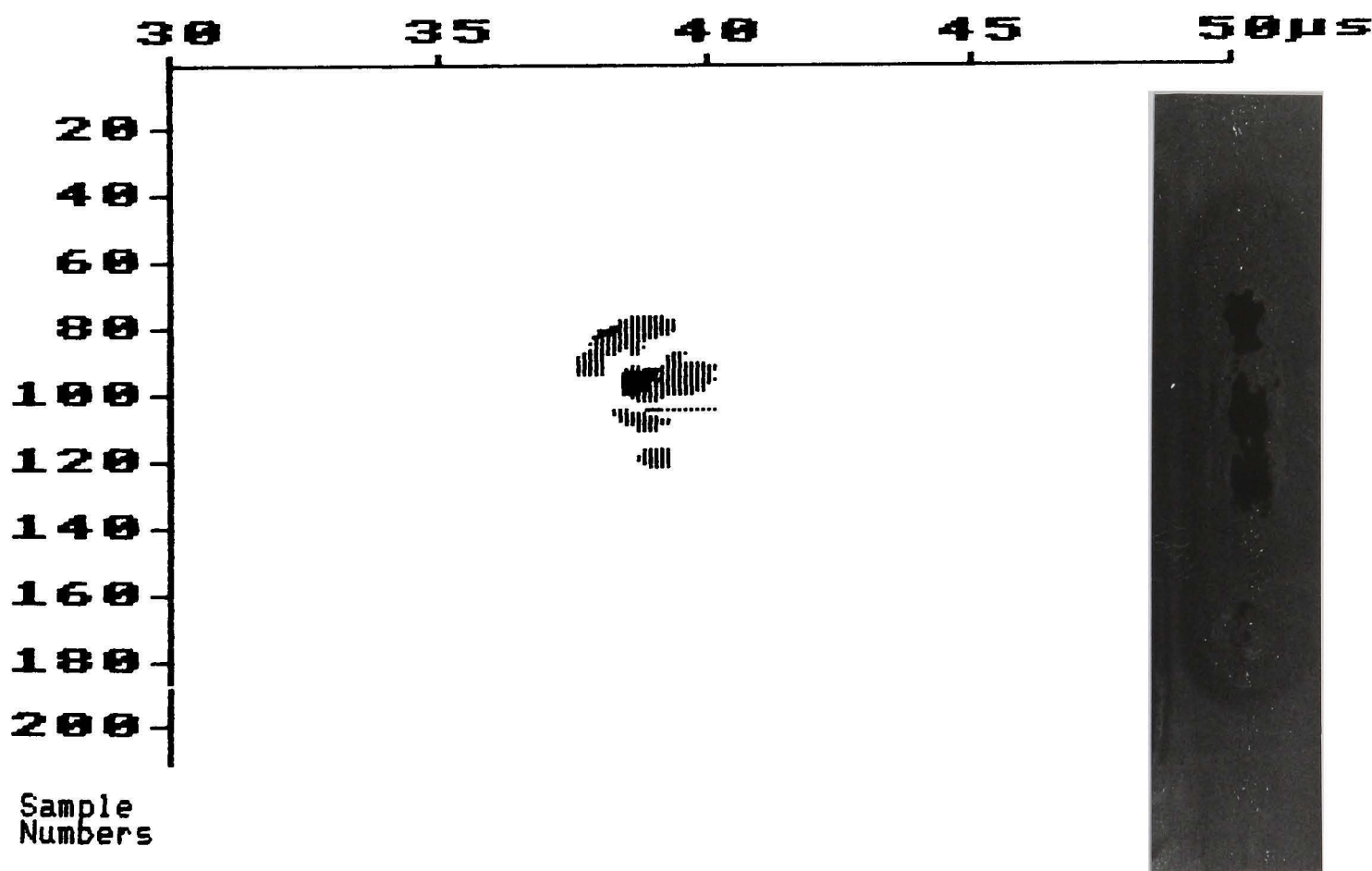
(b) Dye-penetrant result photo

Figure 78 On-line experimental results show cracks initiated by adding FeS.



Gain (db)	Freq. (MHz)	Reje.	I (A)	V (V)	Speed (mm/s)	Sample Interval(S)
72	2	2	193	15.6	3.97	0.1

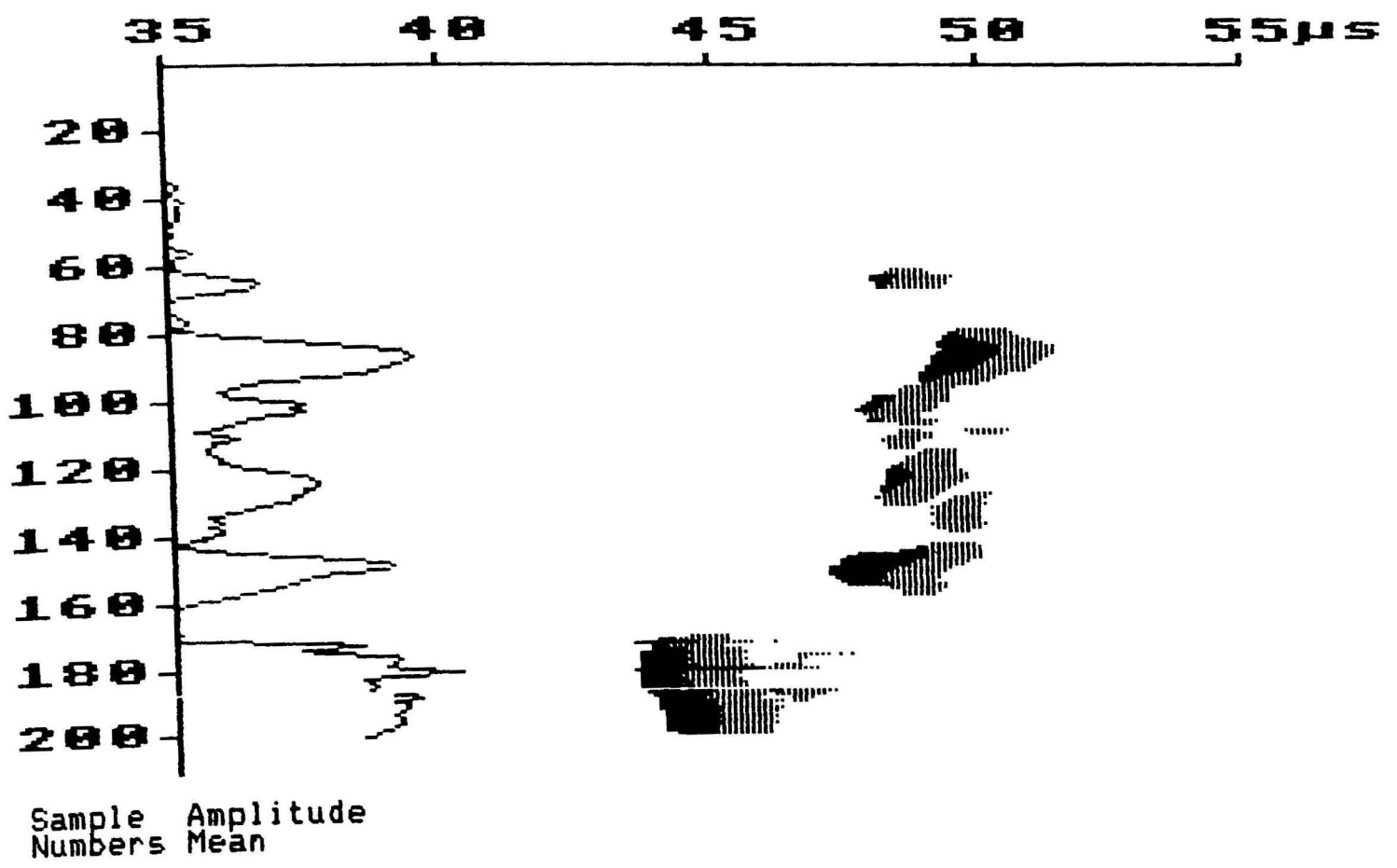
Figure 79 On-line experimental results and experimental parameters



(a) B-scan results

(b) Dye-penetrant results

Figure 80 B-scan results after welding and dye-penetrant results



(a) B-scan results



(b) Sample photo

Figure 81 On-line experimental results show undercuts and a blow hole.

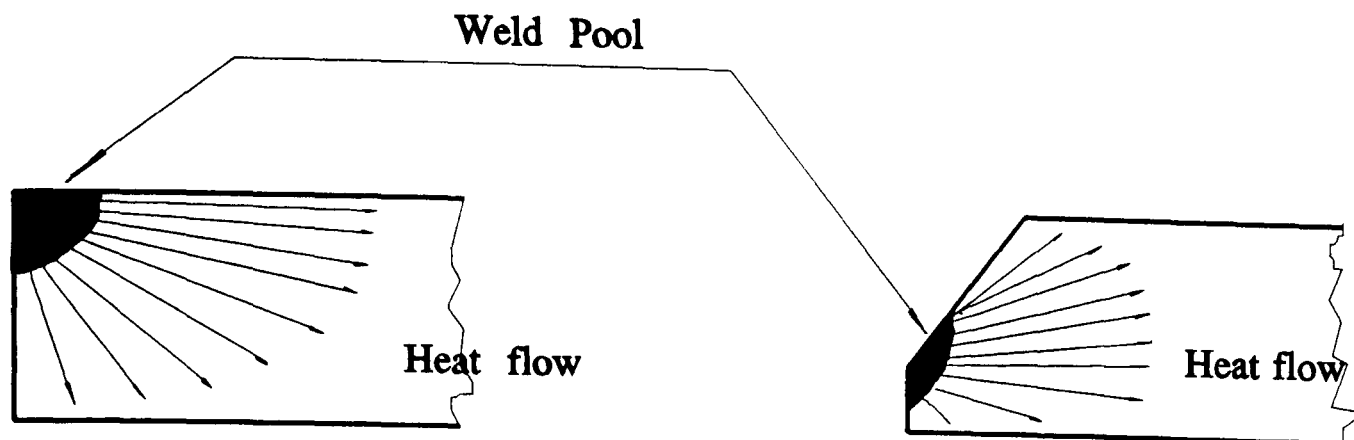


Figure 82 Schematic diagram of sample shape and heat stream

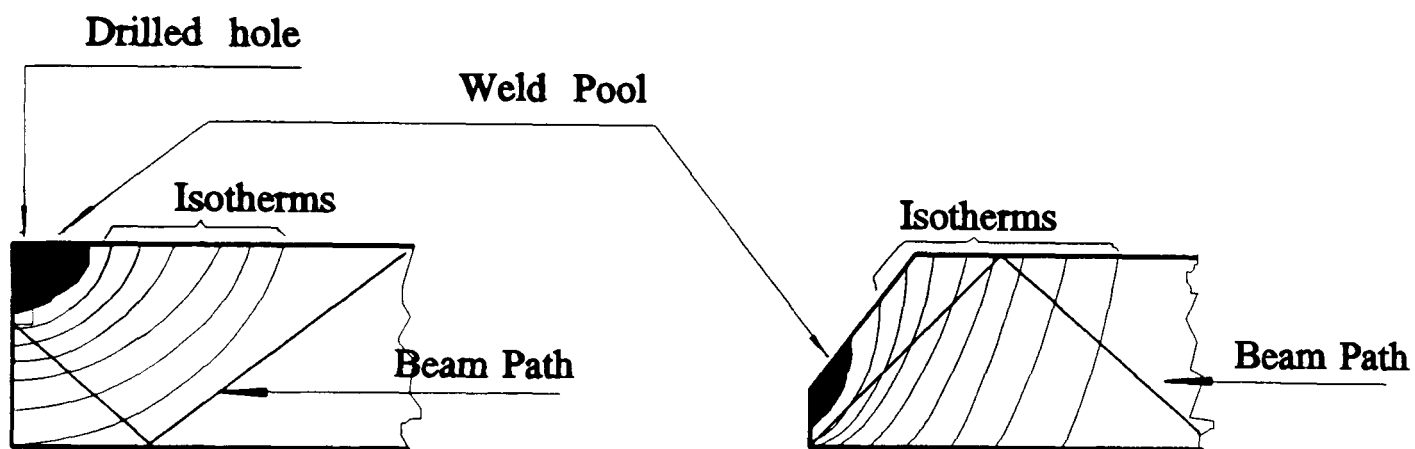


Figure 83 Schematic diagram of beam path direction and isotherm



Figure 84 Schematic diagram of ultrasound transfer process

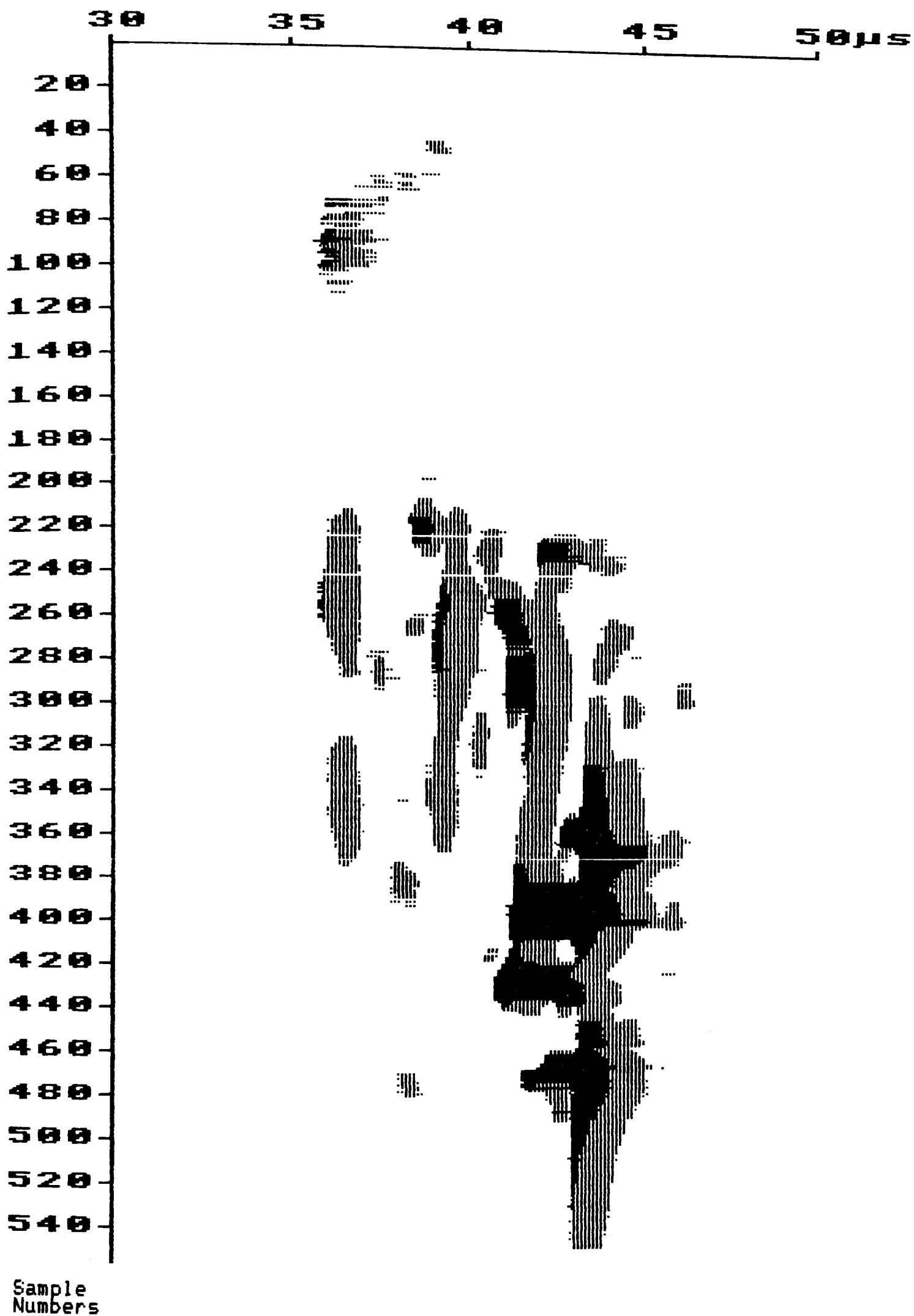


Figure 85 Noise reflections from austenitic grains in SAW process with 'bead on plate' (static probe).

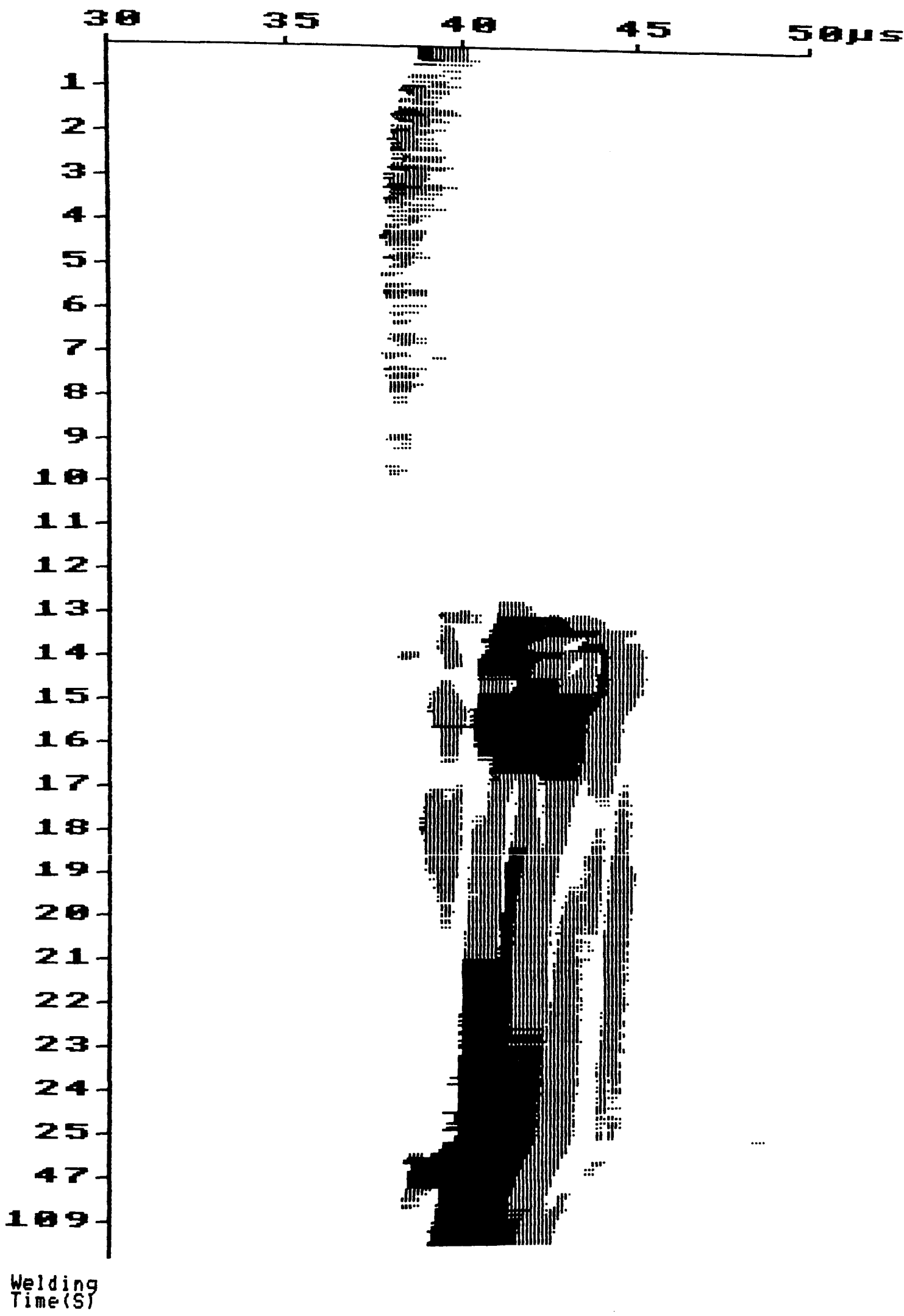
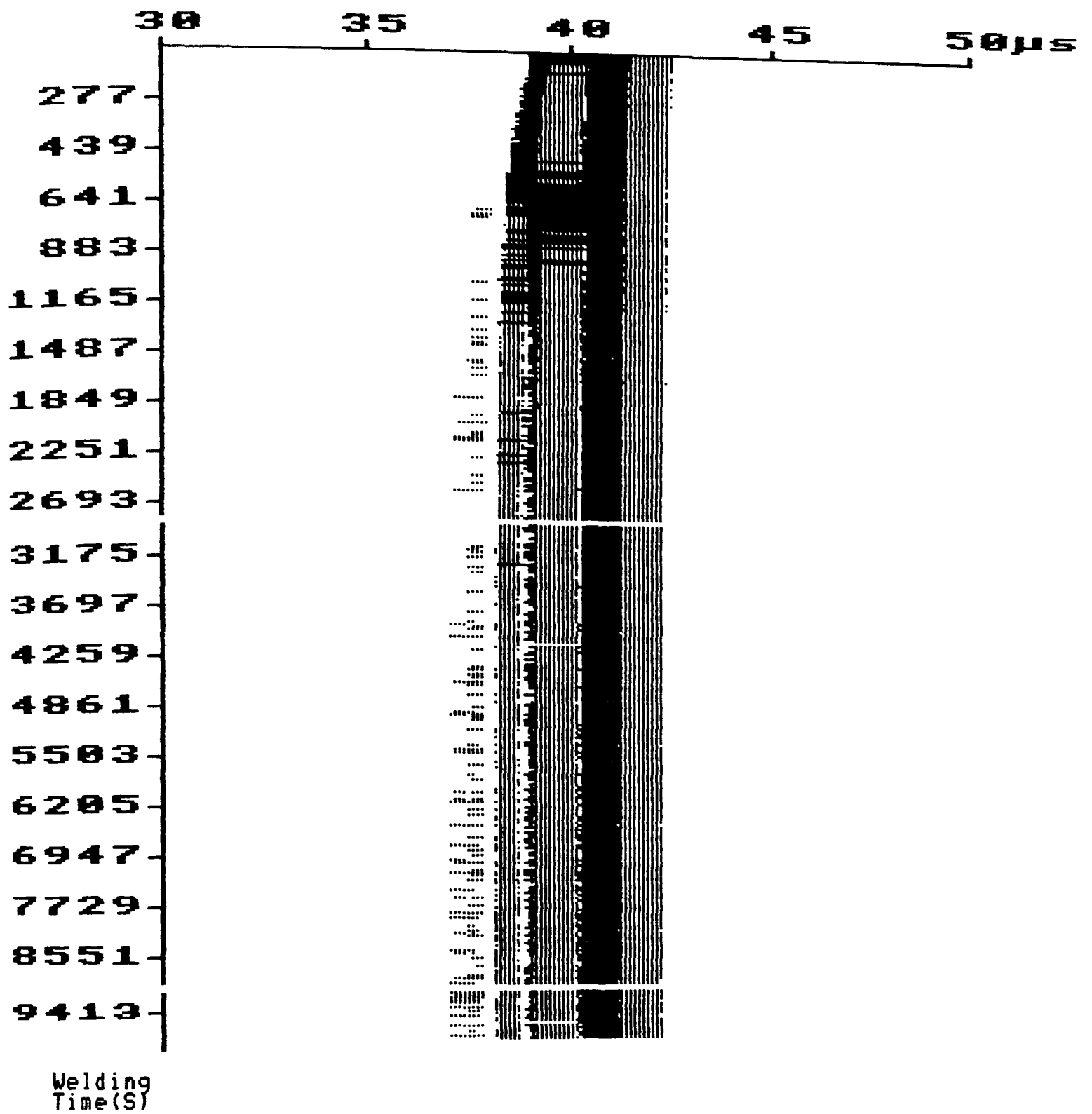


Figure 86(a) To be continued



(a)

Gain (db)	Freq. (MHz)	Reje.	I (A)	V (V)	Sample Interval (S)
68	2	2	200	15.6	0.05 &

(b)

Figure 86 (a) B-scan results from bead on austenite plate experiment with static probe; (b) Experimental parameters

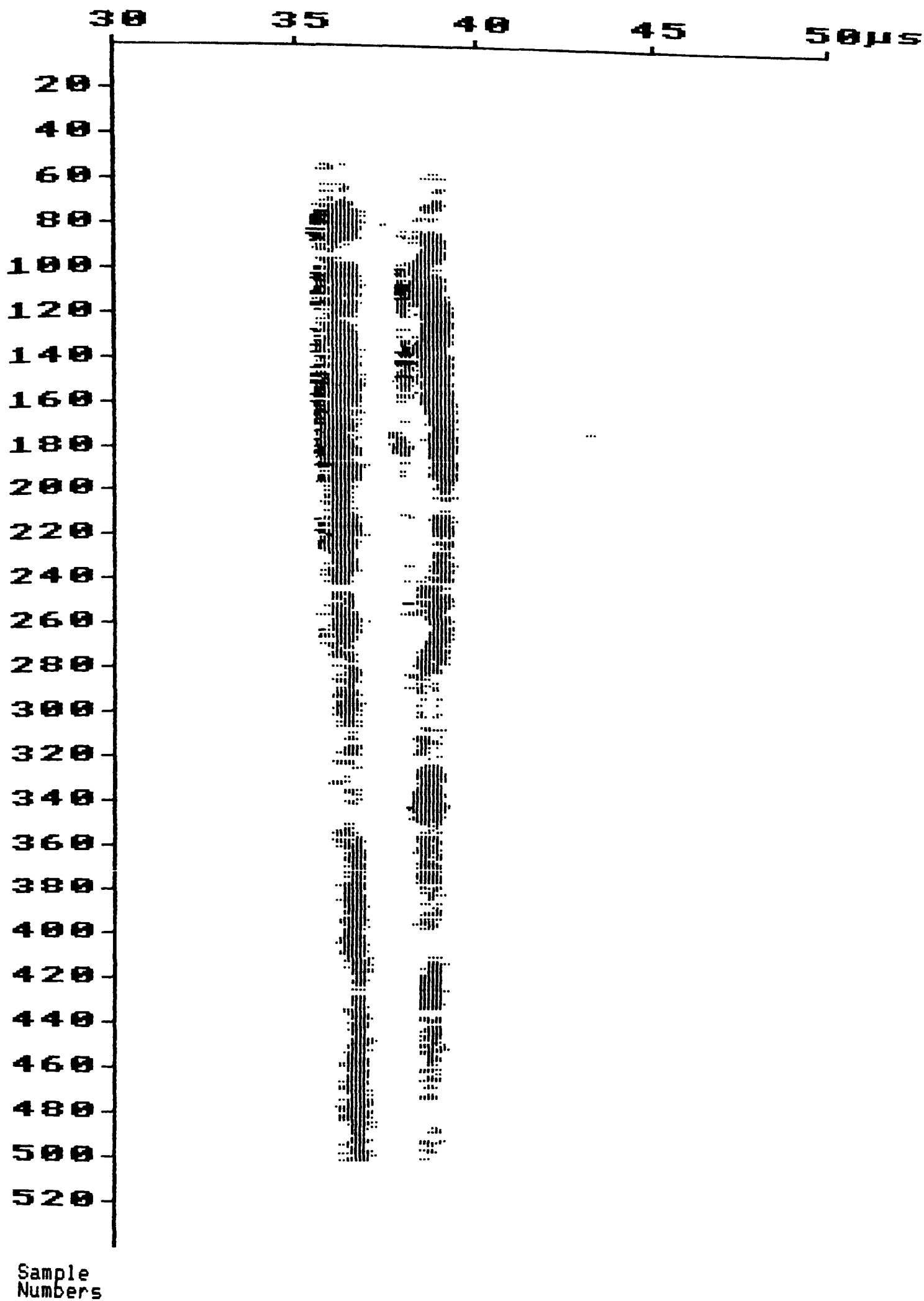
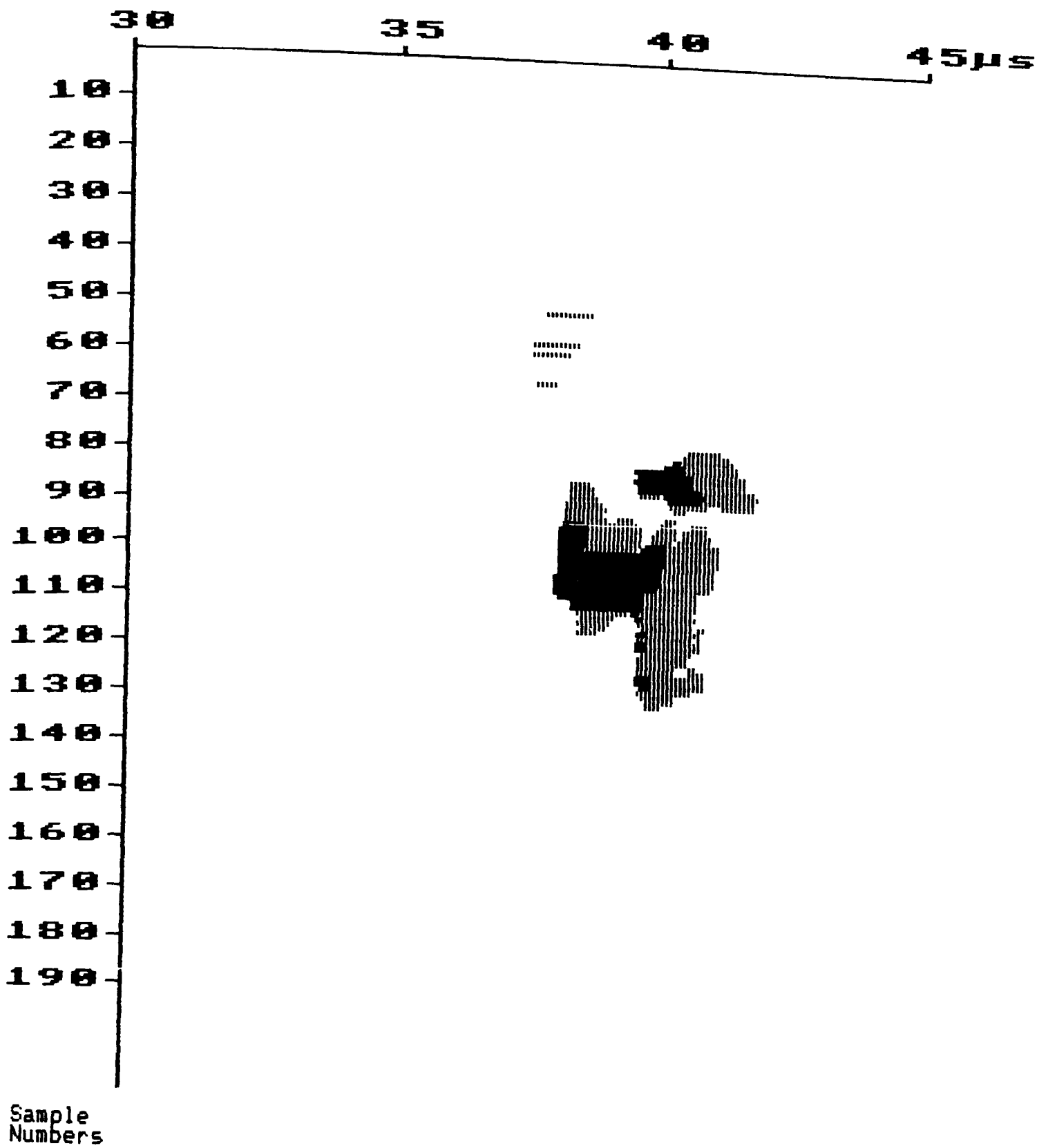


Figure 87 Reflections from large grains produced by heating on a plate surface with a oxygen/acetylene torch.

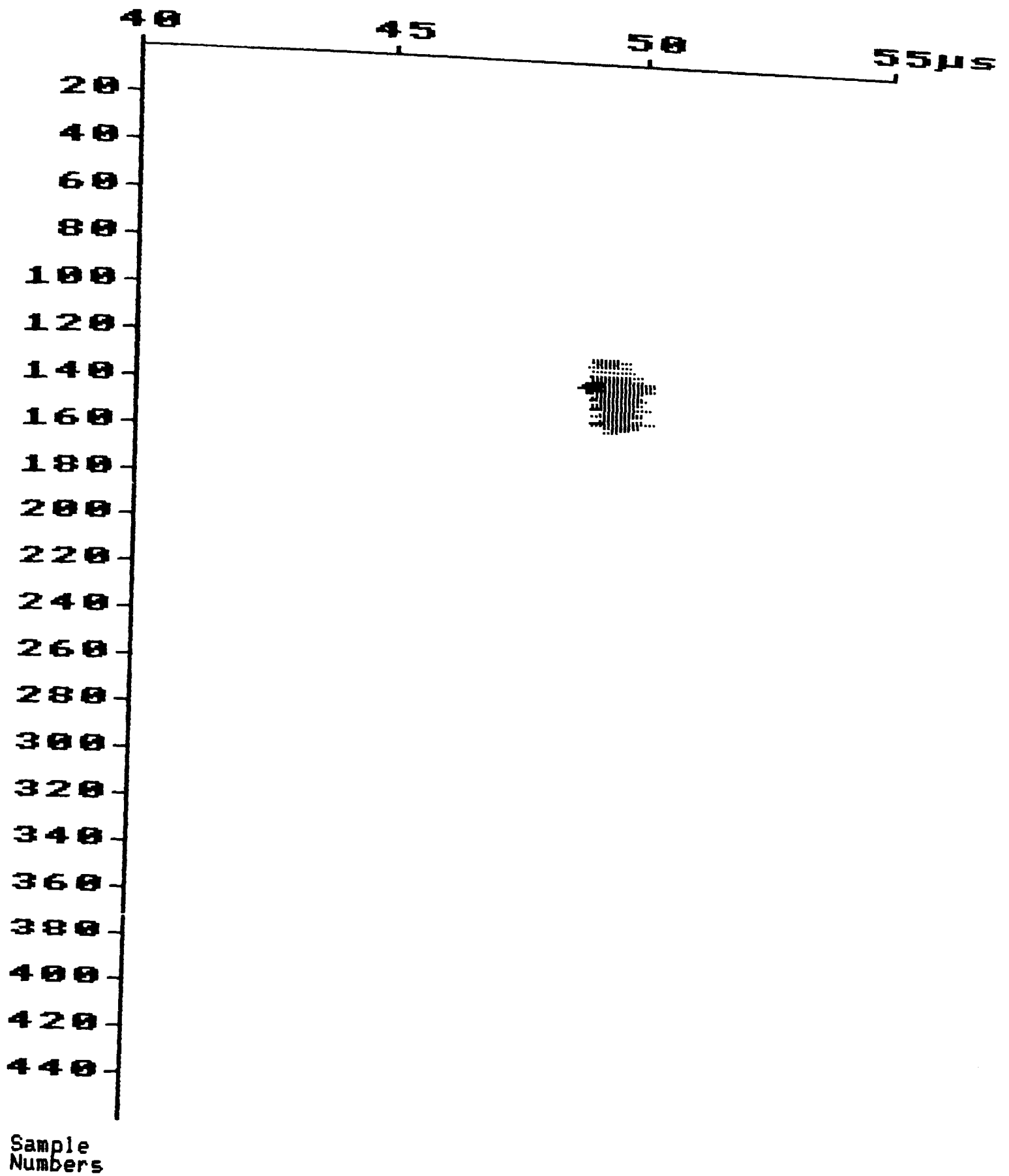


(a)

Gain (db)	Freq. (MHz)	Reje.	I (A)	V (V)	Sample Interval (S)
80	2	2	150	16	0.1

(b)

Figure 88 (a) Ultrasonic results from the TIG welding process show a small "quiet area" between the weld pool signal and the reflections from large grains; (b) Experimental parameters

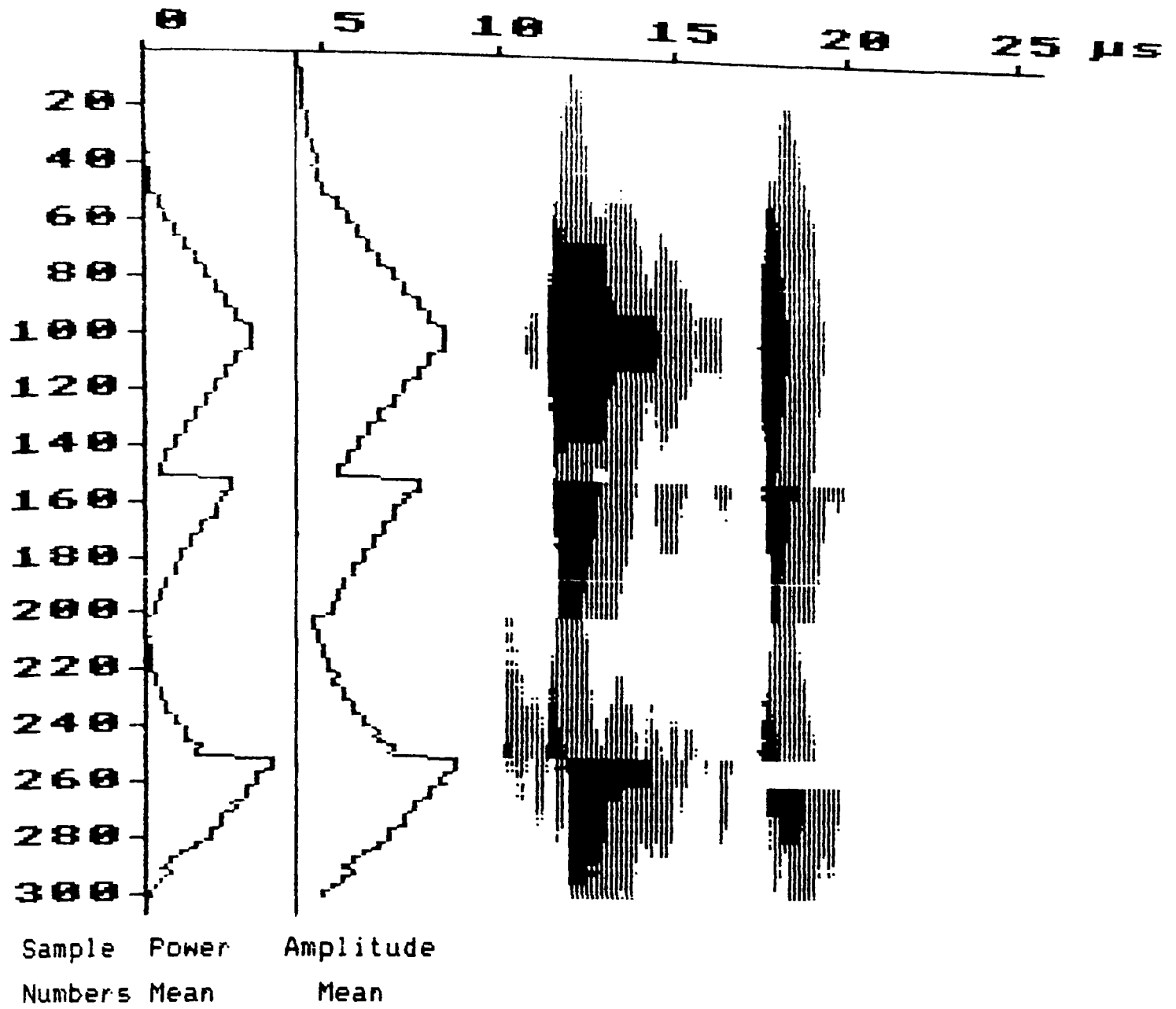


(a)

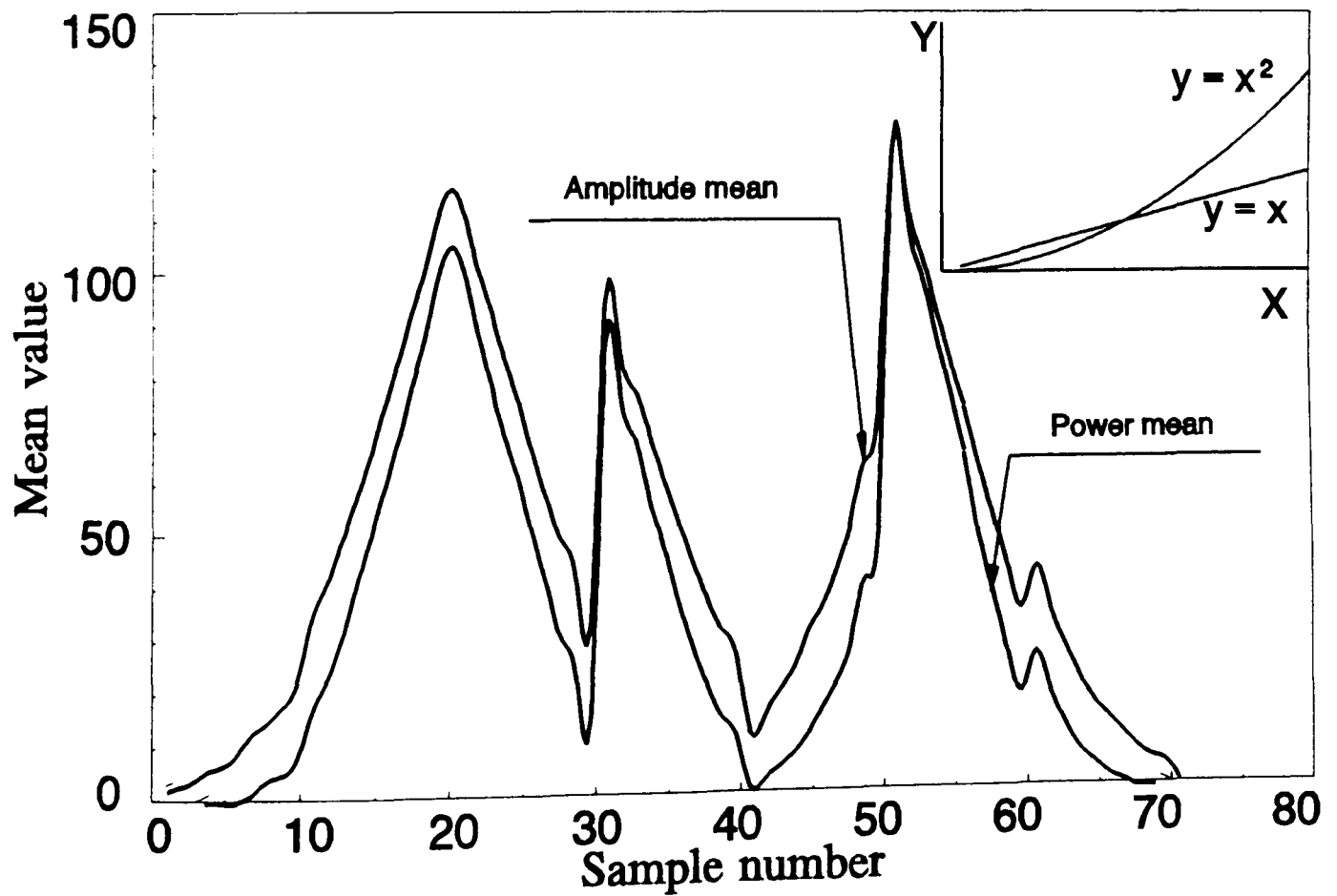
Gain (db)	Freq. (MHz)	Reje.	I (A)	V (V)	Sample Interval (S)
70	1	2	180	15.4	0.05

(b)

Figure 89 (a) Using 1MHz frequency ultrasound can effectively avoid grain noise; (b) Experimental parameters

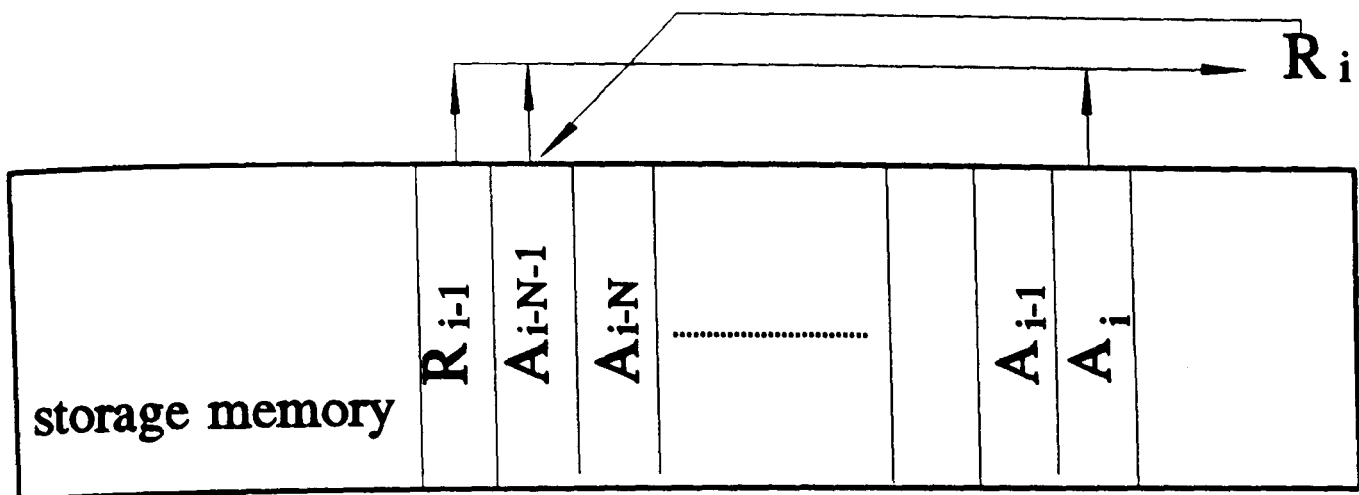


(a) B-scan results



(b) Comparison

Figure 90 Comparison of power mean and amplitude mean



$$R_{i-1} = \sum_{j=i-N-1}^{i-1} A_j \quad i \geq N-1$$

$$\begin{aligned}
 R_i &= \sum_{j=i-N}^i A_j \\
 &= \sum_{j=i-N-1}^i A_j - A_{i-N-1} \\
 &= \sum_{j=i-N-1}^{i-1} A_j + A_i - A_{i-N-1} \\
 &= R_{i-1} + A_i - A_{i-N-1}
 \end{aligned}$$

Figure 91 Schematic Diagram of averaging Methodology

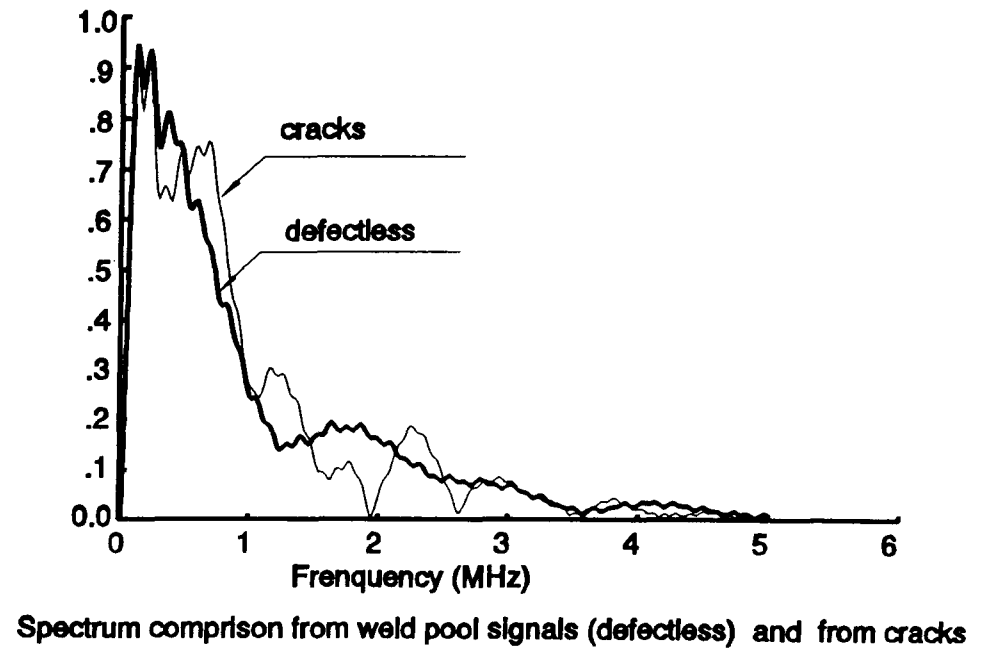
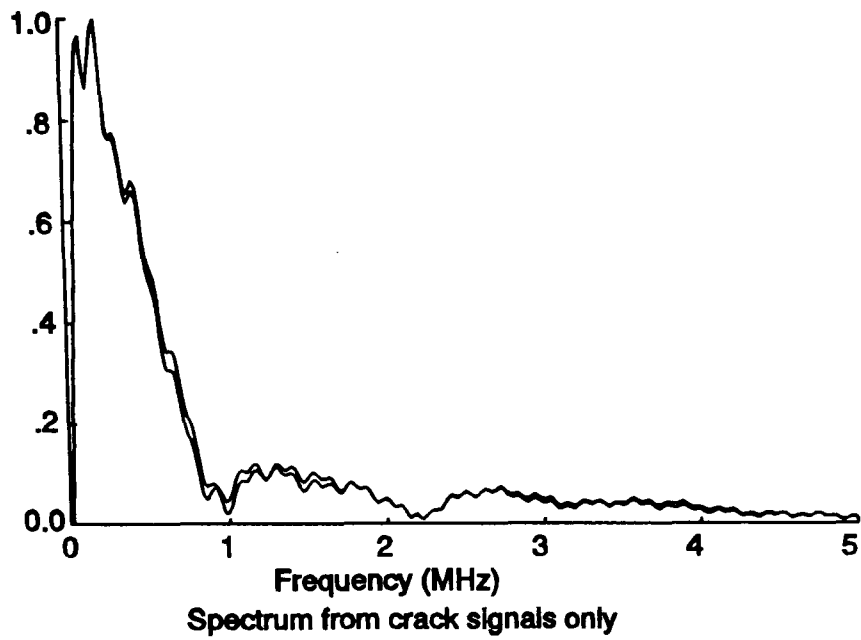
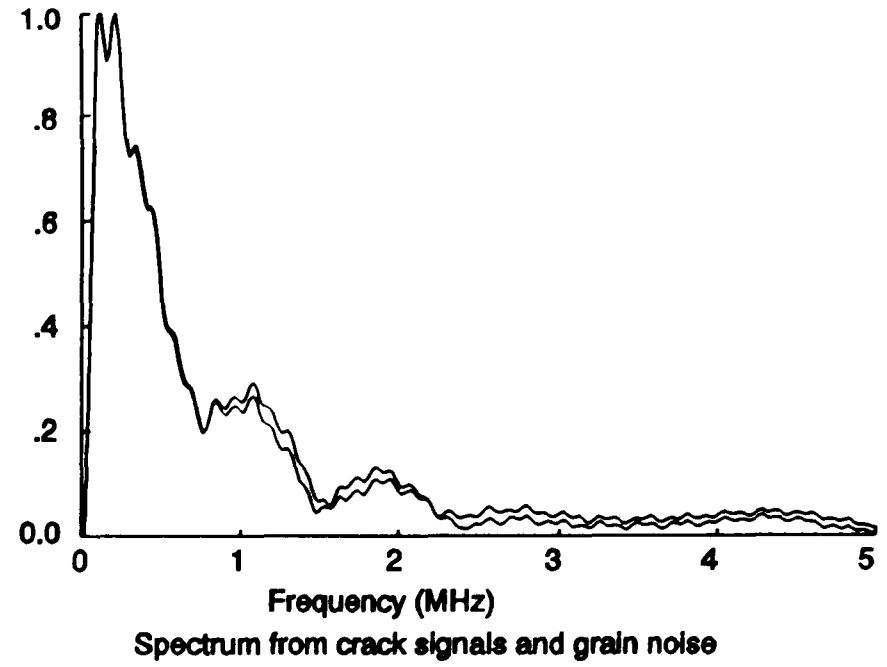
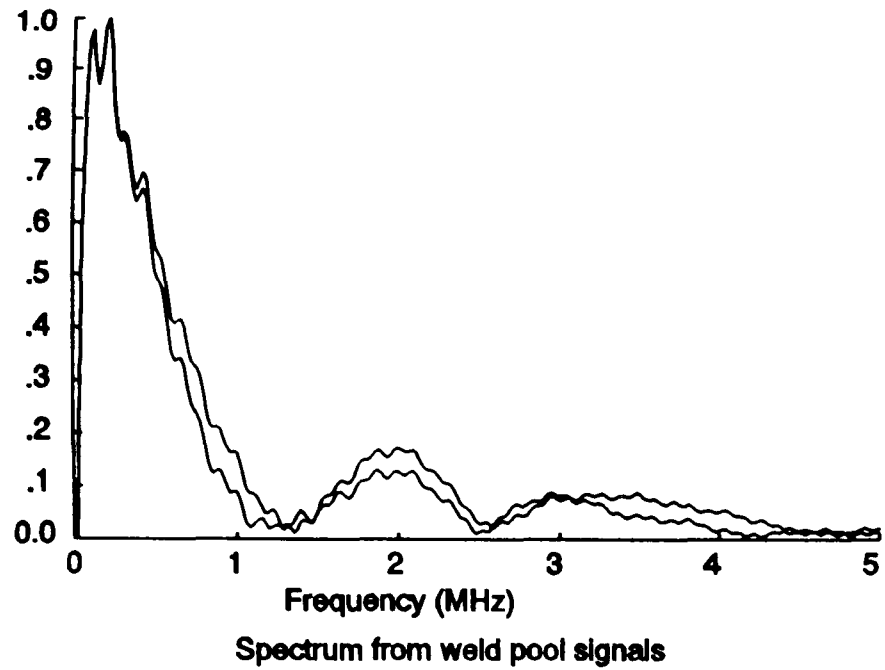


Figure 92 Spectrum comparison of different signals

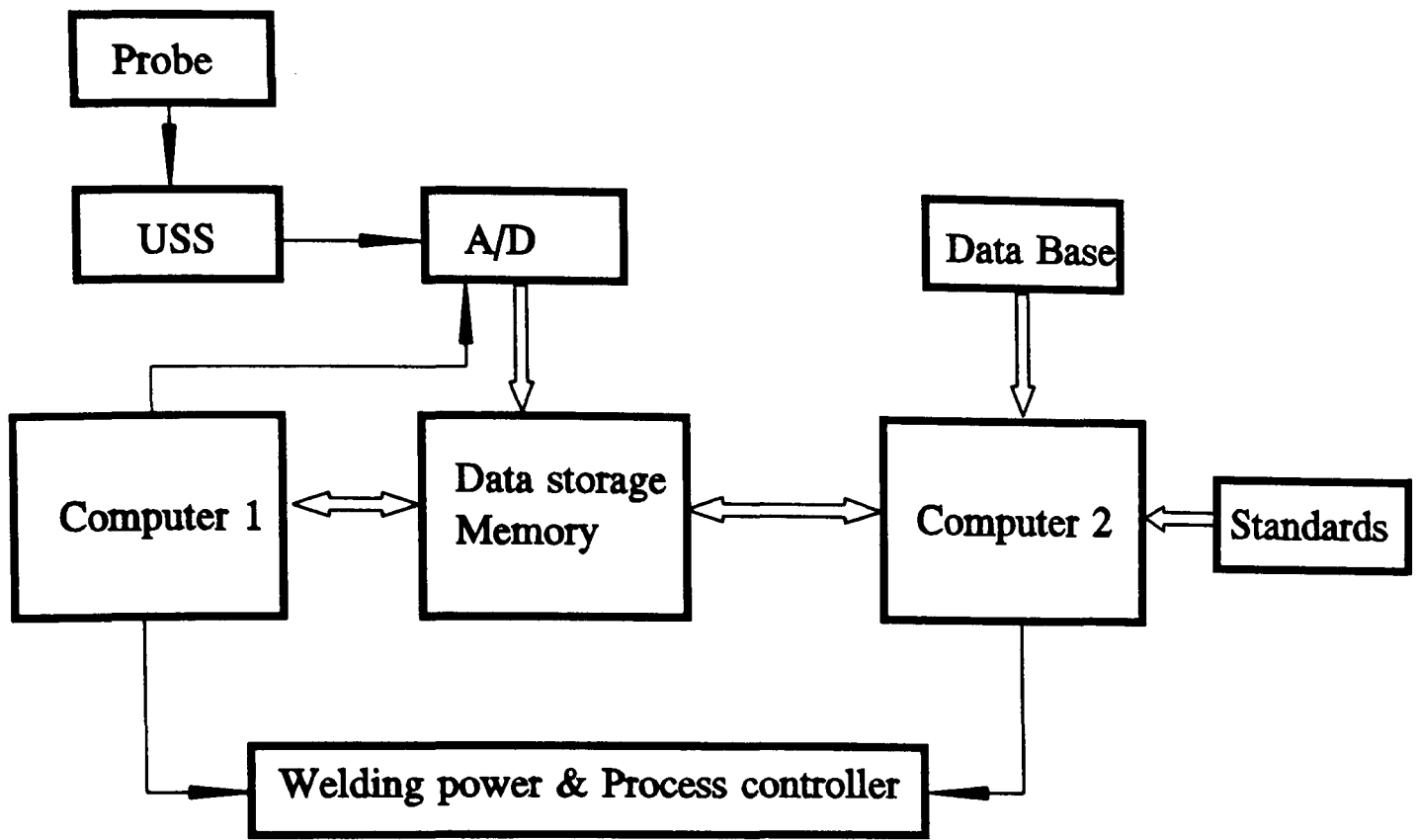


Figure 93 Schematic diagram of two computer system

APPENDIX A: EXPRESSION FOR THE ENERGY PASSED THROUGH THE INTERFACE IN SIMULATION BLOCK

Assumptions:

1. The material is inhomogeneous.
2. That all conditions are kept fixed during the experiment except for gains
3. At the interface, the percentage of energy passed through the interface is defined as factor (K).

Variables used are shown in figure a.1. According to the assumptions and the figure, we have:

$$E_{rb} = E_{ii}$$

$$E_{ra} = (1-K) * E_{ii}$$

Because the peak energy of ultrasonic

signals is proportional to the square of its amplitude, the above equation can be written as:

$$A_{rb} = A_{ii}$$

$$A_{ra} = \sqrt{(1-K)} A_{ii}$$

According to the definition of a decibel and the exponential attenuation expression:

$$G_1 = 20 \lg \frac{A_o}{A_{ob}}$$

$$G_2 = 20 \lg \frac{A_o}{A_{oa}}$$

$$\frac{A_{oa}}{A_{ob}} = 10^{\frac{(G_1 - G_2)}{20}} \tag{a.1}$$

$$A_{ob} = A_{rb} e^{\alpha L}$$

$$A_{oa} = A_{ra} e^{\alpha L} = \sqrt{(1-K)} A_{ii} e^{\alpha L} \tag{a.2}$$

Substitute equation (a.2) into equation (a.1) and obtain:

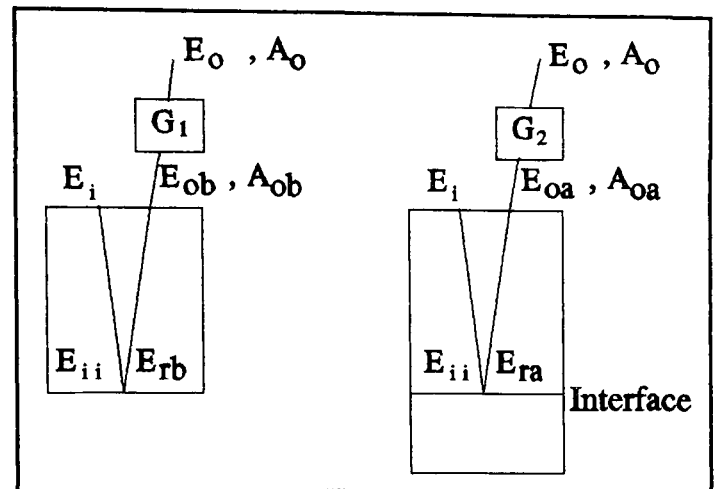


Figure a.1 Schematic diagram for proving expression of energy percentage passed through interface

$$\sqrt{(1-K)} = 10^{\frac{(G_1-G_2)}{20}}$$
$$K = 1 - 10^{\frac{(G_1-G_2)}{10}} \tag{a.3}$$

Substituting experimental readings G_1 and G_2 into the equation (a.3), we then obtain that the percentage passed through the interface at 92.06 and 96.02 respectively.

```

10MODE1:ONERRORGOTO1220
20HIMEM=&2FEF
30VDU28,0,8,39,0:VDU19,0,7,0,0,0:COLOUR3:PRINTTAB(15,1);"GRAPH"
40VDU19,3,1,0,0,0,:VDU19,1,6,0,0,0:PRINTTAB(0,2);$&A40;
50INPUTTAB(26,2)a$
60*DR.1
70b=0:c=?&74:d=?&75:e=?&76:f=?&77:g=?&79:S%=?&78:h%=0:i%=0:j=0:k%=1
000:l=4:m=0:n=0:o=0:N=0
80p%=300:q%=1020:r=0:s%=1:t=100:u=1:v=540:w=0:M%=0:x=0
90A$=GET$
100IFASC(A$)=2THENS%=2:VDU2:VDU1,27,1,68,1,8,1,12,1,65,1,0,1,27,1,33
,1,1,1,27,1,65,1,10,1,9:PRINTTAB(10,6);"Filename: ";a$;:VDU1,10,3:INPU
TTAB(10,6);"Step: 10 ";u;:IFu=0THENU=10
110IFA$="N"THENPROCy(11,0):b=z:N=aa:n=0
120IFA$="T"THENPROCy(30,1):ba=z:ca=aa:da=ca-ba
130IFA$="M"THENw=1:INPUTTAB(32,2),ea$;:PRINTTAB(32,2);" ";ea$;
140IFA$="S"THENS%=1:GOTO230
150IFA$="G"THEN230
160IFASC(A$)=20THENINPUTTAB(36,4)" ";TAB(36,4)r;
170IFA$="P"THENh%=1:GOTO230
180IFA$="R"ORA$=" "THEN200
190GOTO90
200*DR.0
210MODE7:IFA$=" "THENVDU14:END
220PAGE=&1900:CHAIN"MENU2"
230VDU4:fa%=180:PRINTTAB(10,6);"WAITING PLEASE";
240VDU24,0;0;1279;800;:CLG
250IFn=1ANDe=1THENF=OPENINA$:GOTO540
260ga$="":F=OPENINA$
270FORI%=1TO8:D%=&DFF+I%:ga$=ga$+CHR$(?D%):NEXT
280PRINTTAB(7,2);ga$;
290A%=BGET&F:?&A0A=A%:A%=BGET&F:?&A0B=A%:A%=BGET&F:?&A0C=A%:A%=BGET&
F:?&A0D=A%:ha%=BGET&F:ia%=BGET&F:ja%=BGET&F:IFja%=0THENja%=20
300A%=!&A0A:ka=(A%/100MOD3600)DIV60:la=A%DIV360000
310PRINTTAB(15,5);ha%;"-" ;ia%;"-91";TAB(30,5);la%;" ";ka;
320IFka<10THENPRINTTAB(30,5);la%;"0";ka;
330g=0:N%=1:ma=100:PTR&F=9:P%=9:IFb<0THENb=0
340IFE=0ANDf=0ANDb=0THEN500
350I%=BGET&F/16:PTR&F=PTR&F-1
360IFN%<bTHENPTR&F=PTR&F+3*I%+2:N%=N%+1:GOTO350
370IFN%=bTHENP%=PTR&F
380IFI%=0THEN470
390IFF=0THENPTR&F=PTR&F+2*I%:GOTO470

```

```

400na=0
410FORJ%=1TOI%:A%=BGET&F:T=BGET&F+(A%MOD16)*256:T=T/ja%
420IFT<naTHEN460
430IFT>gTHENg=T
440IFT<maTHENma=T
450na=T
460NEXT
470N%=N%+1:IFPTR&F>=(EXT&F-I%-2)THEN500
480PTR&F=PTR&F+I%+2:IFe=0ANDN%>NTHEN500
490GOTO350
500IFe=0THEN520
510N=N%:l=736/(N-b+1):PRINTTAB(15,4);N%-1;" ";
520IFf=0THEN540
530da=g-ma:ba=INT(ma-da/2):da=da*1.5:ca=g:oa%=INT((q%-p%)/da):PRINTT
AB(27,4);" ";INT(ma);",";INT(g+1);"us.";
540IFA$="P"THENPRINTTAB(6,6);"PRINT TIME(Y/N)";:A%=GET:IFA%=89THENT=
10
550IFr<baTHENr=ba
560pa=r:VDU28,0,6,39,6:CLS:PROCqa
570VDU4:ra=0:N%=b:PTR&F=P%:IFN%=0THENPTR&F=9:N%=1
580IFh%=1THENPROCsa:GOTO610
590PROcta:IFS%=2THENVDU2,1,10,1,9,1,9
600IFS%>0THENPRINT:PRINT"Totle peak number:";ua;" ";INT(va*1000/ua)
/1000;" ";INT(wa*1000/ua)/1000;:VDU3
610n=1:e=1:j=0:h%=0:VDU28,0,6,39,0
620IFS%>0ANDh%=0THEN*xa,0
630S%=0:GOTO90
640DEFPROcta
650ua=0:va=0:wa=0:IFw=1ANDM%=0THENM=OPENIN(ea$):M%=1
660ya=0:za=0:IFw=1ANDx=0THENPRINTTAB(0,2);"Print Max. Ampli.";:A%=GE
T:CLS:IFA%<>78THENx=1
670o=0:IFj=1THEN880
680IFPTR&F>(EXT&F-2)THEN990
690IFw=0THEN710
700PTR&M=2*N%+2:A%=BGET&M:GCOL0,3:MOVEya*2+p%,Y:DRAW2*A%+p%,Y-1:ya=A
%:A%=BGET&M:IFx=1THENMOVEza/2+p%+100,Y:DRAWA%/2+p%+100,Y-1:za=A%
710L%=BGET&FDIV16:PTR&F=PTR&F-1:IFL%=0THEN860
720I%=1
730PROCab:o=0:T=T/ja%:W=W/ja%
740IFS%=0ORN%MODu<>0THEN790
750IFS%=2THENVDU2
760IFT<rORT>caTHEN780
770PRINT" ";T;"(";W;")";:o=1:ua=ua+1:va=va+T:wa=wa+W
780IFI%MOD6=0ANDS%=2THENVDU1,10,1,9,1,9:VDU3ELSEVDU3

```

```

790T=T-ba:IFT>(ca-ba)THEN860
800IFT<0AND(T+W)>0THENW=W+T:T=0
810IFT<raTHEN850
820IFT<(pa-ba)THENT=pa-ba:W=W-(pa-ba)
830IFW<=0THEN850
840PROCbb:ra=T
850I%=I%+1:IFI%<=L%THEN730
860ra=0:IFPTR&F>=(EXT&F-L%-2)THENj=1:GOTO880
870PTR&F=PTR&F+L%+2
880N%=N%+1:Y=Y-1:IFN%>NTHEN990
890IF(N%-b)MODcb%>0THEN930
900IFT<>100THENVDU4:PRINT"Input welding time for ";N%:;INPUTA$ELSEA=
INT(N%*t)/10.0*0.1:A$=STR$(A)
910A%=LEN(A$):GCOL0,3:MOVEp%-12,Y:DRAWp%,Y:IFY>720THENMOVEp%-16-32*A
%,720ELSEMOVEp%-16-32*A%,Y+16
920VDU5:PRINTA$;:VDU4
930IFY<4ANDh%=1THENENDPROC
940IFS%=2ANDo=1THENVDU2,1,9:PRINT" |";INT(va*100/ua)/100;" ";INT(wa*
100/ua)/100;:VDU3
950IFS%=2ANDN%MOD(62*u)=0THENVDU2,1,12
960IFS%=2ANDN%MODu=0THENVDU2,1,10,1,9:PRINTTAB(0,0);N%;:VDU1,9,3
970IFS%=1THENA%=GET:CLS:PRINTTAB(0,0);N%;:IFA%=71THENS%=3
980GOTO670
990CLOSE&0:M%=0
1000MOVE1275,0
1010ENDPROC
1020DEFPROCqa
1030GCOL0,3:MOVEp%,740:DRAWq%,740:MOVEp%,740:DRAWp%,(740-N*1)
1040Y=740
1050cb%=5:IFoa%<=15THENcb%=10
1060IFoa%<=10THENcb%=20
1070FORI%=p%TOq%+4STEPoa%*cb%
1080MOVEI%,Y:DRAWI%,Y+12
1090VDU5:MOVEI%-280,796:COLOUR3:PRINT(I%-p%)/oa%+ba;
1100NEXT
1110MOVEq%+40,800:PRINT"us";:MOVEq%+32,796:PRINTCHR$(59);
1120Y=744:cb%=INT((N-b+1)/50)*5:IFcb%<5THENcb%=5
1130ENDPROC
1140DEFPROCbb
1150GCOL0,1:VDU19,1,6,0,0,0,:PROCdb(W)
1160IFW>cTHENGCOL0,3:PROCdb(W-1)
1170ENDPROC
1180DEFPROCdb(eb)
1190fb=T*oa%+p%:gb=T*oa%+eb*oa%+p%

```

```
1200MOVEfb,Y-2:DRAWfb,Y-1+2:PLOT85,gb,Y-2:PLOT85,gb,Y-1+2
1210ENDPROC
1220CLOSE£0:M%=0:VDU3:PRINTTAB(0,6);
1230IFERR=222ANDs%=1THEN1270
1240IFERR=222THEN1290
1250*DR.0
1260REPORT:PRINT" at line ";ERL;:END
1270s%=3:*DR.3
1280GOTO230
1290s%=1:*DR.1
1300PRINT"Cannot find, replace & HIT a key";:A=GET:GOTO230
1310DEFPROCsa
1320PROChb:PROCib
1330VDU2,1,12,3:ENDPROC
1340DEFPROChb
1350LOCALW%:VDU28,0,6,39,6,4
1360IFm=1THEN1400
1370PRINT:INPUT"TITLE";jb$
1380INPUT"CONDITION";C$;
1390IFjb$=""ANDC$=""THENVDU2:v=600:GOTO1510
1400VDU2,1,27,1,65,1,10,1,27,1,33,1,32:J%=(80-2*LEN(jb$))/4:FORkb%=1T
O2:VDU1,10,1,27,1,&6A,1,30,1,0
1410FORI%=1TOJ%:VDU1,32:NEXT
1420PRINTjb$;
1430NEXT
1440VDU2,1,27,1,33,1,1,1,10,1,10
1450VDU1,27,1,68,1,15,1,28,1,66,1,79,1,0
1460VDU1,9:PRINT"Disk:";CHR$(9);ga$;CHR$(9);"Filename:";CHR$(9);a$;:V
DU1,10,1,9
1470PRINT"Sample Date:";CHR$(9);ha%;"/";ia%;"/91";CHR$(9);"Sample Tim
e: ";la;":";ka;:VDU1,10,1,9
1480IFC$=""THEN1510
1490PRINT"Condition: ";:IFLEN(C$)<=60THENlb=LEN(C$)ELSElb=60
1500PRINTLEFT$(C$,lb);:VDU1,10,1,9,1,9:PRINTRIGHT$(C$,LEN(C$)-lb);
1510VDU1,10,1,10,1,27,1,65,1,8,3
1520m=1:ENDPROC
1530DEFPROCmb
1540LOCALN%,C%
1550VDU2,1,10,1,27,1,&6A,1,24
1560?&80=nb%MOD256:?&81=nb%DIV256:C%=nb%+639:?&8C=C%MOD256:?&8D=C%DIV
256:?&8E=0
1570CALL&B7E:ob%=?&80+256*?&81
1580IFob%>pb%ORi%>k%ORi%>(N+20)THEN1650
1590IF?&8E=1AND?&8F=0THEN1640
```

```

1600N%=?&8B*8:IFN%>0THENqb%=N%MOD256:rb%=N%DIV256:VDU1,27,1,&4B,1,qb%
,1,rb%:FORI%=1TON%:VDU1,0:NEXT
1610VDU1,27,1,&4B,1,?&8F,1,0:FORI%=0TO?&8F-1STEP8:FORJ%=3TO0STEP-1:sb
%=?(&C04+I%+J%):tb%=?(&C00+I%+J%):VDU1,sb%,1,tb%:NEXT:NEXT
1620IF?&8E=1THEN1640
1630GOTO1570
1640?&8E=0:i%=i%+8*4/1:VDU1,10:?&8B=0:C%=C%+640:?&8C=C%MOD256:?&8D=C%
DIV256:GOTO1570
1650VDU3:ENDPROC
1660DEFPROCib
1670nb%=&4180:pb%=&8000:IF(N-b)<300THENv=540
1680h%=1:l=INT(v/(N+1-b))*4:IFl<4THENl=4
1690k%=(N-b)*1/4+17
1700VDU24,0;0;1279;736;:CLG:VDU24,0;0;1279;780;:GCOL0,3:MOVEp%,736:DR
AWp%,0
1710Y=740:F=OPENINa$:VDU4:ra=0:N%=b:PTR&F=P%:IFN%=0THENPTR&F=9:N%=1
1720cb%=20
1730IFY<4THENPROCub
1740PROCta
1750ua%=N%:PROCmb:IFua%>NTHEN1770
1760GOTO1730
1770PROCvb:ENDPROC
1780DEFPROCub
1790VDU24,0;0;1279;736;:CLG
1800IFI%>=vTHENY=740:VDU24,0;0;1279;796;:nb%=&4180:GCOL0,3:MOVEp%,740
:DRAWp%,0:VDU2,1,12,3:PROChb:i%=i%-16:k%=k%-i%:i%=0:ENDPROC
1810Y=740:nb%=&4680:GCOL0,3:MOVEp%,740:DRAWp%,0
1820ENDPROC
1830DEFPROCab
1840A%=BGET&F:B%=BGET&F:T=((A%MOD16)*256+B%):PTR&F=PTR&F+2*L%-I%-1:W=
BGET&F:T=T-W:PTR&F=PTR&F-2*L%+I%
1850ENDPROC
1860DEFPROCy(X,wb)
1870PRINTTAB(X,4);"          ":INPUTTAB(X,4)z;aa;
1880IFwb=0THENE=0:l=736/(aa-z)
1890IFwb=1THENf=0:oa%=INT((q%-p%)/(aa-z))
1900ENDPROC
1910DEFPROCvb
1920VDU2:VDU1,27,1,68,1,15,1,0,1,27,1,33,1,1,1,10,1,9
1930IFt<>100THENPRINT"Welding";ELSEPRINT"Sample ";
1940IFw=1THENPRINT" Amplitude";:IFx=1THENPRINT" Maximum"
1950VDU1,10,1,9:IFt<>100THENPRINT"Time(S)";ELSEPRINT"Number ";
1960IFw=1THENPRINT" Mean          ";:IFx=1THENPRINT"Amplitude"
1970VDU3:ENDPROC

```



```

10ONERRORGOTO750
20MODE4
30LOMEM=&5310:HIMEM=&56FF
40DIMT(16),W(16)
50*DRIVE 0
60a%=40:b%=40:c%=1:d%=0:P%=0
70e%=0:f%=500: ?&FDD7=0
80CLS:g%=3:h=1:i%=0
90!&78=&50002E00: ?&7F=0:j=&2E00
100k=40:l=55*a%: ?&8A=1MOD256: ?&8B=1DIV256:m=k
110?&F8=1: ?&FDB2=23: ?&FDB0=7
120n=k*a%+12: ?&70=nMOD256: ?&71=nDIV256: ?&72=(1/a%-k)*b%/2: ?&73=40/b%
: ?&74=(h+1)*21.68+5-0.5*h
130CLS:N%=0:o%=0:p%=0:q%=0:r=0:s%=0
140PROct
150u=316:v=764: PROCw
160*DRIVE 1
170*FX21,0
180X=120:Y=764:x%=0
190y%=1:z%=1
200B%=INKEY(0)
210IFB%=83ANDy%=0THENy%=1:GOTO540
220IFy%=0THEN450
230IFB%=67THENy%=0
240IFB%=83THEN450
250IFB%=-1THEN200
260IFB%=73PROCaa: PROCba
270IFB%=66THENN%=e%:CLS:PRINTTAB(5,1);"RETURN TO THE VERY BIGINING!"
;: PROCba: ?&FDD7=0:N%=0: ?&78=jMOD256: ?&79=jDIV256
280IFB%=32ORB%=82THEN390
290CLS
300VDU28,0,7,39,0
310IFB%=65THENINPUTTAB(14,2);"          ";TAB(14,2)h: ?&74=(h+1)*21.68+5-0.
5*h
320IFB%=14THENINPUTTAB(31,3);"          ";TAB(31,3)e%,f%;
330IFB%=76ORB%=87THENPROCca
340IFB%=20THENINPUTTAB(37,2);"          ";TAB(37,2)m;: PROCba
350VDU28,0,7,39,4
360IFB%=84THENPROCba
370IFB%=16THENPROCda
380GOTO200
390VDU28,0,7,39,4: IFx%=0ANDN%>0THENCLS:PRINTTAB(0,0);"SAVE THE DATA
FROM CONVERSION(Y/N)?  N":A%=GET:ea%=410:IFA%=89THENPROCda

```

```

400fa%=?&78+256*?&79:IFx%=1THENfa%=fa%-j:!!&A51=&00000000:?&A51=jMOD2
56:?&A52=jDIV256:?&A55=fa%MOD256:?&A56=fa%DIV256:?&A57=0:?&A58=0:X%=&5
0:Y%=10:A%=1:CALL&FFD1
410CLOSE#0
420*DRIVE 0
430IFB%=82ORB%=71THENPAGE=&1600:MODE7:CHAIN"MENU2"
440END
450?&FDD6=0:?&FDD5=0:N%=N%+1
460IFN%<e%THEN?&FDD7=0:FORI%=1TOe%:?&FDD6=0:?&FDD5=0:NEXT:N%=e%
470CALL&50FA:CALL&5169
480fa%=?&78+256*?&79:IFfa%>&4FCDANDS%=0THENPROCda
490IFfa%>&4FCDAga%=1THENfa%=fa%-j:!!&A51=&00000000:?&A51=jMOD256:?&A5
2=jDIV256:?&A55=fa%MOD256:?&A56=?&AD%DIV256:?&A57=0:?&A58=0:X%=&50:Y%=
10:A%=1:CALL&FFD1:!!&78=&50000000:?&78=jMOD256:?&79=jDIV256
500Y=Y-4:IFY<u+4THENPROCha
510PROCia
520IFy%=0THEN570
530CLS:PROCja:PROCka
540VDU24,0;64;1279;320;
550GCOL0,0:VDU5:MOVE864,308:PRINTs%:GCOL0,1:MOVE864,308:PRINTN%:s%=N
%:VDU4
560VDU24,0;320;1279;764;
570IFN%>=f%THENCLS:PRINTTAB(10,1);"AT THE END!";:GOTO190
580GOTO200
590DEFPROCba
600VDU28,0,7,39,0
610IFI%=1THEN670
620IFB%=20THEN660
630IFB%<67THEN710
640INPUTTAB(31,2);"          ";TAB(31,2);k,1;:l=l*a%:k=k+0.2
650IFm>l/a%THENm=k
660n=m*a%+12:IFm<=kTHENn=k*a%:m=k
670?&70=nMOD256:?&71=nDIV256:W%=(1/a%-m)*b%/2:IFW%>255THENW%=255
680?&72=W%:?&5101=(m-k)*b%/2+1
690PRINTTAB(31,2);"          ";TAB(31,2);k;"-";1/a%;"",";m;
700IFB%=20THENENDPROC
710VDU24,0;0;1279;v;
720CLG:PROCw
730VDU28,0,7,39,4
740Y=764:ENDPROC
750p%=1
760IFERR=214ORERR=222THENPROCla:GOTOERL
775IFERR=198ORERR=190THENPROCla:GOTO1010
770REPORT:PRINT" at line ";ERL;" ";ERR

```

```
780CLOSE£0
790*DR.0
800?&78=jMOD256:?&79=jDIV256:!!&A51=&00000A04:!!&A55=&00000007:!!&A59=&
00000000
810END
820DEFPROCma(Y)
830*FX3,6
840*CAT
850*FX3,0
860D%=&E07:C%=A%:na%=0
870IFMID$(C$,2,1)="."THEND$=LEFT$(C$,1):na%=ASC(D%):C%=MID$(C$,3,LEN
(C$)-2)
880PRINTTAB(28,2);"                ";TAB(28,2);A$;
890FORI%=1TO31
900J%=1
910A%=D%?J%:IFA%>128ANDJ%=1THENA%=A%-128
920IFA%=32ANDJ%>LEN(C$)THEN990
930B$=CHR$(A%):IFB$<>MID$(C$,J%,1)THEN960
940J%=J%+1:IFJ%<8THEN910
950GOTO990
960D%=D%+8
970NEXT
980GOTO1060
990A%=D%?8MOD128
1000IFA%<>na%THEN960
1010IFD%?8>=128THENINPUTTAB(0,Y);"Exist & Locked,Input a new name";A$
:GOTO860
1020PRINTTAB(0,Y);"Exist, REPLACE?(Y/N)";STRING$(19," ");:A%=GET
1030PRINTTAB(0,Y);STRING$(40," ");
1040IFA%=89THEN1060
1050INPUTTAB(0,Y);"Input new NAME, Please                ";TAB(28,Y
);A$:GOTO860
1060PRINTTAB(0,Y);STRING$(40," "):ENDPROC
1070DEFPROCda
1080?&7F=0:CLS
1090INPUTTAB(0,2);"DATA FILE FOR PEAK DETECTOR ";A$
1100oa%=1:PROCma(3)
1110VDU28,0,4,39,0:$&A48=A$:PRINTTAB(30,0);A$;:VDU28,0,7,39,4
1120CALL&50ED
1130!!&A51=&00000A04:!!&A55=&00000007:!!&A59=&00000000
1140IFI%=0THEN?&A0A=a%:?&A42=N%MOD256:?&A43=N%DIV256:!!&A04=TIME
1150A%=1:X%=&50:Y%=10:CALL&FFD1
1160x%=1
1170IFp%=1THENGOTORA%
```

```
1070ENDPROC
1180DEFPROCia
1190GCOLOR,1
1200IF(N%-e%)MOD10=0THENMOVE112,Y:DRAW120,Y:VDU5:MOVE-220,Y+24:PRINTN
%:VDU4
1210pa=?&7D-1:IFpa<0THEN1270
1220FORI%=0TOpa
1230T(I%)=?(&B60+I%)+256*?(&B70+I%):W(I%)=?(&B80+I%):T(I%)=T(I%)-W(I%
)
1240X=120+(T(I%)/a%-k)*b%/2*qa
1250MOVEX,Y:DRAWX+W(I%)*b%/2/a%*qa,Y
1260NEXT
1270ENDPROC
1280DEFPROct
1290VDU28,0,7,39,0
1300PRINTTAB(7,0);"          CONVERSION";
1310PRINTTAB(0,2);"A--Ampl. GATE=";h;TAB(18,2);"T--Time GATE=";k;"-";
1/a%;",",m;
1320PRINTTAB(0,3);"S--Step C--cont. N--Conv. No. ";e%;"-";f%;
1330VDU28,0,7,39,4
1340ENDPROC
1350DEFPROCw
1360GCOLOR,1
1370VDU19,0,5,0,0,0
1380MOVE120,u:DRAW1144,u
1390MOVE120,60:DRAW1144,60
1400ra=k:C%=0
1410FORI%=120TO1144STEP102
1420C%=C%+1:MOVEI%,52:DRAWI%,60:MOVEI%,308:DRAWI%,312
1430VDU5:MOVEI%-280,52
1440IFC%MOD2<>0THENPRINTra:ra=ra+(1/a%-k)/5
1450NEXT
1460MOVE1176,52:PRINT"us"
1470qa=1024/(1/a%-k)*2/b%
1480VDU24,0;60;1279;v;
1490MOVE120,60:DRAW120,v
1500VDU4:ENDPROC
1510DEFPROCha
1520VDU28,0,21,39,8:PRINTTAB(0,13);""
1530VDU28,0,7,39,4:VDU24,0;320;1279;764;
1540Y=Y+32:MOVE120,u+4:DRAW120,420
1550ENDPROC
1560DEFPROcka
1570VDU24,124;64;1279;308;:CLG:MOVE120,60
```

```

1580FORI%=1TO?&72
1590A%=?(&FBFF+I%):DRAW(I%+2)*qa+128,A%+60:MOVE(I%+2)*qa+128,A%+60
1600NEXT
1610MOVE120,?&74+60:DRAW1144,?&74+60
1620ENDPROC
1630DEFPROCaa
1640CLS:sa%=0:ta=0:N%=0:?&FDD7=0
1650i%=1:INPUTTAB(0,1);"Input the filename to input";F$;
1660F=OPENINF$:d%=1
1670PRINTTAB(0,1);STRING$(40," ");:ua$=""
1680FORI%=1TO8:D%=&DFF+I%:ua$=ua$+CHR$(?D%):NEXT
1690IFLEFT$(ua$,4)<>"DATA"THENPRINTTAB(0,1);"It might be a wrong disk
, GO ON(Y/N)";:A%=GET:PRINTTAB(0,1);STRING$(40," ");:IFAZ<>89THEN1650
1700IFEXT&FMOD256=9THENva%=9
1710wa%=(EXT&F-11)/256
1720PRINTTAB(25,0);"Range          ";TAB(32,0);sa%+1;" ";wa%+sa%;
1730PTR&F=9:xa%=BGET&F+256*BGET&F:IFsa%>0THENxa%=xa%+sa%
1740PRINTTAB(0,0);"Tottle No.  ";xa%;
1750IF(EXT&FMOD256)<>11THENta=1:PTR&F=wa%*256+9:E%=BGET&F+256*BGET&F
1760IFta=1ANDwa%<>E%THEN1790
1770IFta=0ANDsa%+wa%<>xa%THEN1790
1780A%=&A5F:PTR&F=0:GOTO1800
1790PRINTTAB(0,10);"WRONG DISK,REPLACE & HIT A KEY";:A%=GET:PRINTTAB(
0,10);STRING$(40," ");:GOTO1650
1800FORI%=1TO9:B%=BGET&F:A%?I%=B%:NEXT
1810ya%=?&A66:b%=?&A67:a%=?&A68:k=ya%*8/a%:IF(1/a%-k)>25.5THENl=(k+25
.5)*a%
1820VDU28,0,4,39,0:PRINTTAB(31,2);k;"-";1/a%;" ";k;:m=k:VDU28,0,7,39,
4
1830A%=!&A60: !&A04=A%
1840?&A08=?&A64: ?&A09=?&A65
1850za%=255:PTR&F=266:A%=BGET&F:PTR&F=PTR&F+255:B%=BGET&F:IFAZ=B%THEN
za%=B%
1860CLOSE&F:VDU28,0,7,39,4
1870$&A48=F$: ?&50EE=&40:CALL&50ED: ?&50EE=&80
1880IFN%<e%THENN%=e%-1:P%=N%*256+11:?&FDD7=0:FORI%=1TOe%:?&FDD6=0:NEX
T:?&FDD5=0
1890IFN%>wa%+sa%THENPROCab:GOTO1660
1900!&A51=&0000FC00: !&A55=&00000100:P%=(N%-sa%)*256+11:?&A59=P%MOD256
:?&A5A=P%DIV256:?&A5B=P%DIV65536
1910A%=3:X%=&50:Y%=10:CALL&FFD1
1920N%=N%+1:?&FDD6=0:?&FDD5=0:PRINTTAB(37,2);N%-1;
1930IFN%>xa%THENCLOSE&0:GOTO1960
1940IFN%>f%THENCLOSE&0:GOTO1960

```

```
1950B%=INKEY(0):IFB%<>83THEN1890
1960N%=0:?&FDD7=0:?&FDD5=0:PRINTTAB(37,2);N%;" ";:ENDPROC
1970DEFPROCla
1980IFERR=222THENCLOSE£0
1990IFc%=1THEN2050
2000IFoa%=1THENPRINTTAB(0,2);"Disk full, replace & HIT a key";
2010VDU7:VDU7:PRINTTAB(0,2);:IFd%=1THENPRINT"Change for next disk!";E
LSEPRINT"Cannot find, replace & HIT a key";
2020A=GET:PRINTTAB(0,2);STRING$(40," ");:d%=0
2030c%=1:*DR.1
2040ENDPROC
2050c%=3:*DR.3
2060ENDPROC
2070DEFPROCab
2080CLOSE£0
2090PROCla:sa%=sa%+wa%
2100F=OPENINF$:wa%=(EXT£F-11)DIV256:ta=0:CLOSE£F
2110IFwa%=0THENPROCla:GOTO2100
2120ENDPROC
2130DEFPROCja
2140oa%=?&7D-1:IFoa%<0THENENDPROC
2150J%=0:FORI%=0TOoa%:D%=&B70+I%:T%=256*(?D%MOD16)+?(&B60+I%):W%=?(&B
80+I%):IFW%>1THENPRINTTAB(20*J%);(T%-W%)/b%;TAB(20*J%+8);"(";W%/b%;")"
;:J%=J%+1
2160NEXT
2170ENDPROC
>
```

```

10ONERRORGOTO1250
20MODE4
30LOMEM=&54C8:a%=&3200
40IFTOP>a%THENPRINTTAB(0,4);"No room for the program":END
50*DR.0
60b%=40:c%=40:d%=1000:e%=900:f=0
70e=?&AFF:g=?&AFE/2:?&FDD7=0
80CLS:h%=3:i=10:j%=1:k=0:M%=0
90l=1:m=320:n=450:o=150:W%=2
100?&FDB1=(m+5)/4.39+40
110p=30:q=50*b%:?&8A=qMOD256:?&8B=qDIV256
120?&F8=1:?&FDB2=23:?&FDB0=7:?&78=a%MOD256:?&79=a%DIV256:?&7A=&CD:?&
7B=&4F
130p%=p*b%/8:?&FDD4=p%-1:?&87=(q-p%*8)/b%*c%/2+1
140CLS:VDU28,0,13,39,0
150N%=0:r%=0:s%=0:t%=0:u=0
160PRINTTAB(7,0);"TABLE OFF    AUTO";TAB(35,0);"DIRE.";TAB(0,2);"A--
Ampl. GATE=";l;TAB(18,2);"T--Time GATE=";INT((p%+1)*8/b%*10)/10;"-";IN
T(q/b%*10)/10;TAB(38,2);"us"
170PRINTTAB(0,1);"N--NS ";e;" "; "P--PN ";g;" "; "B--Data BASE FO:";i
;" ";?&B00;
180PRINTTAB(0,3);"L--I&V LEVEL=";m;TAB(18,3);"W--WIRE FEED=";n/100
;TAB(35,3);"M/Min";
190PRINTTAB(0,4);"S--Step C--cont. Space--Stop D--Displ.";
200PRINTTAB(0,5);CHR$(94);"W-Welding ";CHR$(94);"S-Save ";CHR$(94);
"N-No.";e%;"-";d%;" ";f;
210PROCv
220VDU4:?&7F=1:?&7C=0:w%=1
230*DRIVE 1
240x%=?&FDBOAND8:IFx%=0THENPRINTTAB(0,1);"Check remote control";:GOT
O240ELSEPRINTTAB(0,1);STRING$(40," ")
250VDU5:MOVE750,536:PRINTN%:VDU4
260COLOUR1:y%=1:z%=1
270*FX15,0
280B%=INKEY(0)
290x%=?&FDBOAND8:IFx%=0THENz%=0
300IFz%=1THEN360
310IFr%>0THEN340
320IFz%=0ANDx%=8THEN?&FDB0=3:r%=TIME
330IFW%=2ANDz%=0THEN650
340REPEAT:IFTIME>=A%+i+1THENVDU7
350UNTILTIME>=A%+i:A%=TIME:GOTO810
360IFW%=0ANDB%=32THENPROCaa:y%=1:GOTO870

```

```

370IFB%<>-1ANDy%=0THENy%=1:GOTO870
380IFy%=0ANDw%=0THEN330
390IFB%=83THEN810
400IFy%=0THEN?&FDD1=0:GOTO860
410IFB%=3THEN?&FDD7=0:N%=0:GOTO860
420IFB%=-1THENa%=TIME:GOTO280
430IFB%=32ORB%=82THEN680
440IFB%=77THENPROCba:GOTO210
450IFB%=67THENy%=0:A%=TIME:GOTO280
460VDU28,0,6,39,0
470IFB%=20THENca%=(ca%+1)MOD2:?&FDB0=ca%*16+7:PRINTTAB(7,0);"TABLE ON";:IFca%=0THENPRINTTAB(7,0);"TABLE OFF";
480IFB%=4THEN?&F8=(?&F8+1)MOD2:PRINTTAB(35,0);"STAT.";:IF?&F8=1THENPRINTTAB(35,0);"DIRE.";
490IFB%=70THENINPUTTAB(34,1);" ";TAB(35,1)i
500IFB%=65THENINPUTTAB(14,2);" ";TAB(14,2)l
510IFB%=14THENINPUTTAB(26,5);" ";TAB(26,5)e%,d%;
520IFB%=13THENINPUTTAB(36,5);" ";TAB(36,5)f;:?&FDD7=0:FORI%=1TOf:
?&FDD6=0:NEXT:?&FDD5=0
530IFB%=78THENINPUTTAB(5,1);" ";TAB(6,1)e;:?&AFF=e
540IFB%=76ORB%=87THENPROCda
550IFB%=2THENINPUTTAB(37,1);" ";TAB(37,1)A%;:?&B00=A%
560IFB%=80THENINPUTTAB(14,1);" ";TAB(15,1)g;:?&AFE=g
570VDU28,0,13,39,6
580IFB%=66THENF$="SEGSET":PROCa:PROcfa:?ga%=13:ga%?1=255
590IFB%=6THENc%=c%/2:GOTO210
600IFB%=68ORB%=19THENPROCha
610IFB%=84THENPROCia
620IFB%=23THEN660
630IFB%=16THENw%=0:GOTO650
640GOTO280
650?&7F=0:?&5301=&60:?&A42=N%MOD256:?&A43=N%DIV256:IFB%=16THEN280
660W%=0:?&FDB0=5:F%=INT(357000/o):?&FDB4=F%MOD256:?&FDB5=F%DIV256:FORI%=0TO20000:NEXT:PROCja
670?&FDB0=23:A%=TIME:ka%=TIME:VDU28,0,5,39,0:PRINTTAB(0,0);"WELDING TABLE ON";:VDU28,0,13,39,6:GOTO280
680IFW%=0THENPROCaa
690IFk=0ANDw%=0THENPROCla:GOTO720
700IFk=0AND?&7F=0THENPRINTTAB(0,2);"Save peak data(Y/N) Y";:A=GET:IFA=89ORA=13THENw%=0:PROCla:GOTO720
710GOTO740
720!&A55=&00000000:ma=?&78+?&79*256-a%:?&A55=maMOD256:?&A56=maDIV256
730IF?&7F=0THENa%=1:X%=&50:Y%=10:CALL&FFD1:CLOSE£0
740!&A51=&00000A04: !&A55=&00000007: !&A59=&00000000

```



```
750IFN%>0THEN?&A40=N%MOD256:?&A41=N%DIV256
760*DRIVE 0
770IFS%=2THENEND
780MODE7
790IFB%=82THENCHAIN"MENU2"
800VDU14:END
810CALL&545E:N%=N%+1
820CALL&50FA:CALL&5293
830IF(z%=0ORy%=0)ANDi<15THEN880
840IFy%=0AND(?&B00>16OR?&87>150)THEN880
850PRINT:PRINT:PROCna
860CALL&5000
870IFy%=1ANDz%=1THENVDU5:GCOL0,0:MOVE750,536:PRINTM%;:GCOL0,1:MOVE75
0,536:PRINTN%:VDU4,h%:M%=N%
880IF?&7C=1THENk=1:?&7F=1:?&7C=0
890IFN%>=d%THENPROCaa:GOTO240
900IFN%>e%THENi=i+20
910IFI>3000THENi=3000
920GOTO280
930DEFPROCv
940VDU28,0,13,39,6:VDU24,0;0;1279;580;:CLG
950GCOL0,1:IFc%<0.5THENC%=20
960VDU3,19,0,5,0,0,0
970MOVE80,60:DRAW1100,60
980J%=0
990I%=(J%*c%-8*p%*c%/b%)*2+80
1000IFI%<80THEN1070
1010IFI%>1100THEN1080
1020MOVEI%,50:DRAWI%,70
1030MOVEI%-280,50
1040VDU5
1050GCOL0,1
1060PRINTJ%
1070J%=J%+50/c%:GOTO990
1080GCOL0,1:MOVE80,60:DRAW80,570:DRAW1110,570:DRAW1110,60
1090MOVE1132,58:PRINT"us":MOVE1124,52:PRINTCHR$(59);
1100VDU5
1110FORI%=25TO250STEP25:MOVE60,I%*2+60:DRAW80,I%*2+60:MOVE-260,I%*2+7
6:IFI%>240THEN1130
1120PRINTI%/25*10
1130NEXT
1140A%=(q-p%*8)/b%*c%/2+1:IFA%>255THENA%=255
1150?&87=A%:VDU24,84;64;1100;566;
1160VDU4:CLS:ENDPROC
```

```

1170DEFPROCia
1180VDU28,0,5,39,0
1190INPUTTAB(31,2);"          ";TAB(31,2);p,q;
1200p%=p*b%/8;q=q*b%;A%=0:IFp%>255THENp%=255
1210IFp%<0THENp%=0
1220?&FDD4=p%-1:?&8A=qMOD256:?&8B=qDIV256:PRINTTAB(31,2);"          ";TA
B(31,2);INT((p%+1)*8/b%*10)/10;"-";INT(q/b%*10)/10;
1230PROCv
1240ENDPROC
1250s%=1:IFw%=2THEN3250
1260IFERR=199ORERR=191THEN1320
1270IF(ERR=198ORERR=190)ANDw%=1THEN1980
1280IFERR=198ORERR=190THEN1330
1290REPORT:PRINT" at line ";ERL;" ";ERR
1300?&FDB0=3:FORI%=0TO150:NEXT:?&FDB0=7
1310CLOSE£0:s%=2:GOTO740
1320IFw%=3THEN1960
1330CLOSE£0:IFj%<>1THEN1360
1340j%=3:*DR.3
1350GOTO1380
1360PRINTTAB(0,2);"Disk full,change & HIT a key";:A=GET
1370j%=1:*DR.1
1380!&A51=&00000A04:!!&A55=&00000007:!!&A59=&00000000:GOTO2070
1390DEFPROCcoa(Y)
1400*FX3,6
1410*CAT
1420*FX3,0
1430D%=&E07:C$=A$:pa%=0
1440PRINTTAB(0,Y);STRING$(40," ");
1450IFMID$(C$,2,1)=". "THEND$=LEFT$(C$,1):pa%=ASC(D$):C$=MID$(C$,3,LEN
(C$)-2)
1460FORI%=1TO31
1470J%=1
1480A%=D%?J%:IFAZ>128ANDJ%=1THENAZ=A%-128
1490IFAZ=32ANDJ%>LEN(C$)THEN1560
1500B$=CHR$(AZ):IFB$<>MID$(C$,J%,1)THEN1530
1510J%=J%+1:IFJ%<8THEN1480
1520GOTO1560
1530D%=D%+8
1540NEXT
1550GOTO1620
1560AZ=D%?8MOD128
1570IFAZ<>pa%THEN1530
1580IFD%?8>=128THENINPUTTAB(0,Y);"File Locked,Input a new name";A$:GO

```

```

TO1430
  1590PRINTTAB(0,Y);"Exist, REPLACE?(Y/N)";:A%=GET
  1600IFA%=89THEN1620
  1610INPUTTAB(0,Y);"Input new NAME";TAB(28,Y);A$:GOTO1430
  1620PRINTTAB(0,Y);STRING$(40," "):ENDPROC
  1630DEFPROCha
  1640r%=1:CLS:IFB%=68THENINPUTTAB(0,4);"Start number to display";TAB(3
5,4);r%;
  1650?&FDD7=0:?&FDD6=0:?&FDD5=0:CLS
  1660IFB%=68THENU=1:PRINTTAB(0,4);"DISPLAYING":?&FDD7=0:FORI%=1TOR%:?&
FDD6=0:NEXT:r%=r%-1:?&FDD5=0:GOTO1850
  1670IFN%>1THENr%=0:GOTO1690
  1680N%=?&A40+?&A41*256:r%=?&A42+256*?&A43
  1690w%=3:PRINTTAB(0,4);"TOTTLE NUMBER(Y/N) Y";r%;",",N%";:A%=GET
  1700IFA%=78THENINPUTTAB(0,4);"INPUT TOTTLE NUMBER(NO%,N%): ";TAB(27,
4);r%;N%;
  1710INPUTTAB(0,2);"FILENAME FOR CONVERTER";TAB(28,2);qa$
  1720PRINTTAB(0,4);"SAMPLE NUMBER TO BE SAVED:";r%;",",N%";"
";
  1730A%=qa$:ra%=0
  1740PROCcoa(5)
  1750PRINT"      WAITING, PLEASE!";
  1760IFr%>0THEN?&FDD7=0:FORI%=0TOR%:?&FDD6=0:NEXT:?&FDD5=0
  1770$&A40=A%:?&A0A=p*b%/8:?&A0B=c%:?&A0C=b%:?&A0D=(N%-r%)MOD256:?&A0E
=(N%-r%)DIV256
  1780CALL&50E0
  1790A%=!&A04:A%=TIME+(TIME-A%)/1200:!&A04=A%:!&A31=&00000A04:!&A35=&0
000000B:!&A39=&00000000:A%=1:X%=&30:Y%=10:CALL&FFD1:sa%=11
  1800IFr%=(N%-1)THEN!&A31=&0000FC00:!&A35=&00000100:GOTO1830
  1810A%=?&87:?&A35=A%
  1820!&A31=&0000FC00:?&A39=sa%MOD256:?&A3A=(sa%MOD65536)DIV256:?&A3B=s
a%DIV65536
  1830A%=1:X%=&30:Y%=10:CALL&FFD1
  1840IFu<>1THENSa%CHR$sa%SQR256:F%=?&A30:A%=?&87:PTR&F%=sa%-1:BPUT&F%,
A%
  1850CALL&5000:r%=r%+1:PRINTTAB(35,4);r%;
  1860?&FDD6=0:?&FDD5=0
  1870IFu=1THEN1920
  1880IFr%<N%THEN1810
  1890CLOSE£0:CLS
  1900IFs%=1THEN760
  1910ENDPROC
  1920A%=GET:IFA%=83THEN1850
  1930PRINTTAB(0,4);STRING$(40," "):?&FDD7=0:IFN%>0THENFORI%=1TON%:?&F
DD6=0:NEXT:CLG:CALL&5000ELSECLG

```

```

1940u=0:VDU5:MOVE750,536:PRINTN%:VDU4:ENDPROC
1950?&FDD6=0:?&FDD7=0:u=0:ENDPROC
1960F%=?&A30:A%=(r%-t%):PTR&F%=256*(r%-t%)+9:BPUT&F%,A%MOD256:BPUT&F%
,A%DIV256:A%=?&87:BPUT&F%,A%
1970CLOSE&0:CLS:t%=r%
1980IFj%=1THEN2010
1990j%=1:*DR.1
2000PRINTTAB(0,1);"Disk full,Replace a new one & HIT a key":A%=GET:PR
INTTAB(0,1);STRING$(40," ");:GOTO1720
2010j%=3:*DR.3
2020GOTO1720
2030ENDPROC
2040DEFPROCla
2050CLS
2060INPUTTAB(0,2);"Input filename:";A$
2070PROCcoa(3):$&A48=A$
2080CALL&50ED
2090VDU28,0,6,39,0:PRINTTAB(30,0);A$;:VDU28,0,13,39,6
2100?&A0A=b%:!&A04=TIME
2110A%=1:X%=&50:Y%=10:CALL&FFD1
2120!&A51=&00003100:?&A51=a%MOD256:?&A52=a%DIV256
2130IFs%=1THEN720
2140ENDPROC
2150DEFPROCda
2160IFB%=87THENTa=m:m=n
2170REPEAT
2180REPEAT:A%=INKEY(1):UNTILA%<>-1
2190IF A%=85 THEN m=m+5:IF m>500 AND B%=76 THEN VDU7:IF m>=960 THEN m=960
2200IF A%=68 THEN m=m-5:IF m<=10 THEN m=10
2210IF B%=76 THEN ?&FDB1=(m+5)/4.39+40:PRINTTAB(14,3);"    ";TAB(14,3);m
2220IF B%=87 THEN n=m:F%=INT(357000/n):PRINTTAB(31,3);"    ";TAB(31,3);n
/100;:IF W%=0 THEN ?&FDB4=F%MOD256:?&FDB5=F%DIV256
2230UNTILA%=13
2240IF B%=87 THEN m=ta
2250ENDPROC
2260DEFPROCaa
2270ua%=TIME:?&FDB0=3:VDU28,0,6,39,0:W%=1:PRINTTAB(0,0);"    TABLE
OFF";:VDU28,0,13,39,6:IF r%<ka% THEN r%=ka%
2280PRINTTAB(0,3);"Welding & Total time:";(r%-ka%)/100;" , ";(ua%-ka%
)/100;" Sec.":FOR I%=0 TO 100:NEXT:?&FDB0=7:ENDPROC
2290DEFPROCja
2300F%=INT(357000/n):?&FDB4=F%MOD256:?&FDB5=F%DIV256:ENDPROC
2310DEFPROCea
2320ga%=TOP-2:*DR.0

```

```
2330F=OPENIN(F$):va%=EXT&F
2340FORI%=0TOva%:A%=BGET&F:?(ga%+I%)=A%:NEXT
2350CLOSE&F
2360ENDPROC
2370DEFPROCba
2380IFN%>0THENPRINT"Save peak DATA first!":ENDPROC
2390F$="MEAN":PROCa
2400PROCwa
2410?ga%=13:?(ga%+1)=255:ENDPROC
2420DEFPROCna
2430ra%=?&7D-1:IFra%<0THENENDPROC
2440J%=0:FORI%=0TOra%:D%=&B70+I%:T%=256*(?D%MOD16)+?(&B60+I%):W%=(?&B
80+I%):IFW%>1THENPRINTTAB(20*J%);(T%-W%)/c%;TAB(20*J%+8);"(";W%/c%;")"
;:J%=J%+1
2450NEXT
2460ENDPROC
>
```

```

3000DEFPROCwa
3002CLS:INPUTTAB(0,2);"Input start & End point(1-255)";f,xa
3003ya%=?&87:IFf<1ORf>ya%THENf=1
3004IFxa<fORxa>ya%THENxa=ya%
3005?&82=xa:?&83=f:ya%=xa-f:INPUTTAB(0,2);"Start and End sample number:
";TAB(30,2);f,xa
3010a%=&4000:?&FDD7=0:IFf<2THENf=1:?&FDD6=0:GOTO3025
3020FORI%=1TOf:?&FDD6=0:NEXT
3025?&FDD5=0:za=xa-f
3030FORI%=0TOza:CALL&5437:?(a%+2*I%)=(?&81+?&80*256)/ya%:?(a%+2*I%+1)
=?&84:?&FDD6=0:?&FDD5=0:NEXT
3032VDU28,0,13,39,6:VDU24,0;0;1279;590;
3035xa=zaDIV300+1:IFzaMOD300=0THENxa=zaDIV300
3040FORI%=1TOxa
3050CLG:GCOL0,1:MOVE40,70:DRAW1239,70:FORJ%=40TO250STEP40:MOVE40,70+2
*J%:DRAW1239,70+2*J%:VDU5:MOVE-232,102+2*J%:PRINTJ%:NEXT:MOVE40,70
3060IFI%>zaDIV300THENf=zaMOD300ELSEf=300
3062ab=0:bb=0
3065FORJ%=0TOf:A%=? (a%+2*J%+(I%-1)*300):MOVEJ%*4+44,2*ab+70:DRAWJ%*4+
44,2*A%+70:ab=A%:A%=? (a%+2*J%+1+(I%-1)*300):MOVEJ%*4+44,2*bb+70:DRAWJ%
*4+44,2*A%+70:bb=A%
3066IFJ%MOD40=0THENVDU5:MOVE4*J%-224,30:PRINTJ%+(I%-1)*300;:MOVE4*J%+
44,70:DRAW4*J%+44,62:MOVEJ%*4+44,2*A%+70
3068NEXT
3070VDU4:IFf=300ANDI%<xaTHENPRINTTAB(0,2);"Press any key to see next
group of data";:A=GET
3080NEXT
3120VDU4:PRINTTAB(0,2);"Save MEAN data?(Y/N) Y";:A=G
ET:IFA=78THEN3200
3130INPUTTAB(0,2)"Input filename for mean data: ";A$;
3135*DR.1
3140w%=2:j%=1
3142PROCcoa(2):F=OPENOUT(A$)
3145BPUT&F,?&83:BPUT&F,?&82:BPUT&F,zaMOD256:BPUT&F,zaDIV256
3150FORI%=0TO2*za+1:A%=? (a%+I%):BPUT&F,A%:NEXT
3160CLOSE&0
3200*DR.0
3220PRINTTAB(0,2);STRING$(40," ");
3225IFs%=1THENGOTO210
3230ENDPROC
3250CLOSE&0:IFj%=1THEN3280
3260IFj%=3THENPRINTTAB(0,2);"Disk full, change disk & hit a key ";:A%
=GET

```

```
3265j%=1:*DR.1
3270GOTO3140
3280j%=3:*DR.3
3290GOTO3142
>
3000DEFPROCga
3010*FX4,1
3020VDU28,0,13,39,6:CLS
3030PRINTTAB(0,0);"NS";TAB(6,0);"T1";TAB(12,0);"T2";TAB(18,0);"n";TAB
(24,0);"NCmin";TAB(30,0);"NCmax";TAB(0,1);"1";
3040C=?&B00*16/20:PRINTTAB(6,1);C;;A=GET:IFA=13THEN3070
3050J%=6:PRINTTAB(6,1);"      ";:I%=0:PROCxa
3060?&B00=C*20/16
3070FORI%=0TOe-1
3080PRINTTAB(0,I%+1);I%+1;
3090PRINTTAB(6,I%+1);?(&B00+I%)*16/20;
3100C=?(&B10+I%)*16/20:PRINTTAB(12,I%+1);C;
3110A=GET:IFA=13THEN3140
3120IFA=136ANDI%>0THENI%=I%-1:GOTO3080
3130J%=12:PRINTTAB(12,I%+1);"      ";:PROCxa
3140?(&B10+I%)=C*20/16:?(&B00+I%+1)=?(&B10+I%)+1
3150C=?(&B20+I%):PRINTTAB(18,I%+1);C;
3160A=GET:IFA=13THEN3190
3170IFA=136THEN3100
3180J%=18:PRINTTAB(18,I%+1);"      ";:PROCxa
3190?(&B20+I%)=C
3200C=?(&B30+I%):PRINTTAB(24,I%+1);C;
3210A=GET:IFA=13THEN3240
3220J%=24:IFA=136THEN3150
3230PRINTTAB(24,I%+1);"      ";:PROCxa
3240?(&B30+I%)=C:C=?(&B40+I%):PRINTTAB(30,I%+1);C;
3250A=GET:IFA=13THEN3280
3260J%=30:IFA=136THEN3200
3270PRINTTAB(30,I%+1);"      ";:PROCxa
3280?(&B40+I%)=C:NEXT
3290*DR. 2
3300*S. BINIA AFD B50
3310*DR. 1
3320*FX4,0
3330ENDPROC
3340DEFPROCxa
3350S%=0:A=A-48:IFA<0ORA>9THENA=0
3360PRINTTAB(J%,I%+1);A;
3370B=GET:IFB=13THEN3430
```

```
3380IFB=127THENA=0:GOTO3360
3390IFB=46THENS%=1:GOTO3360
3400ya=B-48:IFya<0ORya>9THEN3370
3410IFS%=1THENA=A+ya/10:GOTO3430
3420A=A*10+ya:GOTO3360
3430C=A:PRINTTAB(J%,I%+1);C;
3440IFJ%<17THENPRINTTAB(J%,I%+1);INT(C*20/16)*16/20;
3450ENDPROC
```

>


```
100NERRORGOTO2020
20MODE4
30DIMP$(7),D$(16)
40CLS:a%=1:b%=0:c=0:d=0
50e=?&70+256*?&71:f=1:f%=f*23+25
60CLS:VDU28,0,12,39,0
70g$="PLOT":h=0:i=0:j%=0
80FORI%=1TOLEN(g$):PROCK(MID$(g$,I%,1)):PRINTTAB(14+2*I%,0);CHR$(23
0);CHR$(232);TAB(14+2*I%,1);CHR$(231);CHR$(233);:NEXT
90N%=?&72:l%=?&72:m$="":n=?&72:o%=?&72:p%=?&73:D$=$&A50
100PRINTTAB(0,3);"Data file: ";TAB(0,2);"Disk Title";
110PRINTTAB(0,4);"Sample Date: ";TAB(0,5);"Sample Time: ";
120VDU24,0;0;1279;580;
130VDU23,230,0,0,&66,&66,&66,&7E,&60,&C0
140*DRIVE1:CLG
150INPUTTAB(15,3);"          ";TAB(15,3);F$
160PRINTTAB(15,3);"          ";TAB(15,3);F$;TAB(15,9);STRING$(19," ");
170F=OPENIN(F$)
180IFEXT&F=0THENPROC r:IFA%=1THEN150
190IFEXT&F=0ANDa%=3THEN170
200b%=1
210s$=""
220FORI%=1TO8:D%=&DFF+I%:s$=s$+CHR$(?D%):NEXT
230PRINTTAB(15,2);s$;
240PRINTTAB(25,2);"Time Gate";TAB(25,3);"Ampl. Gate";TAB(25,4);"Peak
Freq.";TAB(25,5);"Conv. Freq.";
250IFLEFT$(s$,4)<>D$THENPRINTTAB(0,9);"It might be a wrong disk, GO
ON(Y/N)";:A%=GET:PRINTTAB(0,9);STRING$(40," ");:IFA%<>89THEN150
260IFEXT&F MOD 256=9THENp%=?&76
270t%=(EXT&F-11)/256:IFh=1THENO%=o%-t%:h=0
280PRINTTAB(25,7);"Range   ";o%+1;" ";t%+o%;
290PTR&F=9:u%=BGET&F+256*BGET&F:IFo%>0THENU%=u%+o%
300PRINTTAB(25,6);"Tottle No. ";u%;
310IF(EXT&F MOD 256)<>11THENN=1:PTR&F=t%*256+9:E%=BGET&F+256*BGET&F
320IFn=1ANDt%<>E%THEN350
330IFn=0ANDo%+t%<>u%THEN350
340A%=?&74+256*?&75:PTR&F=0:GOTO360
350PRINTTAB(0,10);"WRONG DISK,REPLACE & HIT A KEY";:A%=GET:PRINTTAB(
0,10);STRING$(40," ");:GOTO150
360FORI%=1TO9:B%=BGET&F:A%?I%=B%:NEXT
370v%=?&A66:w%=?&A67:x%=?&A68
380PRINTTAB(36,2);(v%+1)*8/x%;TAB(36,3);f%;
390A%=!&A60
```

```

400y%=(A%/6000)MOD60:z%=(A%/360000)MOD24:A$=":"
410aa$=STR$(z%)+A$+STR$(y%)
420PRINTTAB(15,5);"      ";TAB(15,5);aa$
430ba$=STR$(?&A64)+"/"+STR$(?&A65)+"/"+"91":PRINTTAB(15,4);"
";TAB(15,4);ba$;TAB(36,4);x%;TAB(36,5);w%;
440ca%=255:IFt%=1THEN460
450PTR&F=266:A%=BGET&F:PTR&F=PTR&F+255:B%=BGET&F:IFA%=B%THENca%=B%
460IFc=1THENC=0:GOTO690
470PROCda
480VDU24,84;64;1096;566;
490PRINTTAB(0,6);"E---END of program"
500PRINTTAB(0,7);"N---Sequen. No."
510PRINTTAB(0,8);"P---Plot: Width 60 mm:Left margin 18 mm";
520REPEAT:A%=INKEY(10):UNTILAZ<>-1
530IFA%=65THENINPUTTAB(36,3);"      ";TAB(36,3);f%;PRINTTAB(36,3);"
";TAB(36,3);f%;
540IFA%=78THENINPUTTAB(15,7);"      ";TAB(15,7);N%;GOTO690
550IFA%=69THENCLOSE&F:GOTO650
560IFA%=68THENPROCea
570IFA%=4THENPROCfa
580IFA%=80THEN850
590IFA%=72THENPROCga
600IFA%=32THENN%=N%+1:GOTO690
610IFA%=82THEN670
620IFA%=77THENPROCha
630IFA%=1THENCLOSE&F:GOTO90
640GOTO520
650*DR. 0
660MODE7:VDU14:END
670*DRIVE 0
680CHAIN"MENU2"
690IFN%>u%THENPRINTTAB(0,10);STRING$(40," ");TAB(10,10);"At END":N%=
N%-1:GOTO520
700PRINTTAB(15,7);"      ";TAB(15,7);N%
710IFN%>t%+o%THENPROCia:c=1:GOTO170
720IFN%<o%ANDi=0THENN%=o+1
730IFN%<o%ANDi=1THENh=1:i=0:CLOSE&F:PRINTTAB(0,10);"Change back for
previous disk!";:A=GET:c=1:GOTO170
740ja%=(N%-o%-1)*256+p%
750PTR&F=ja%:ka%=&4EFF
760GCOLOR,1:CLG
770MOVE80,f%*2+64:DRAW1110,f%*2+64:MOVE80,60
780la%=0:J%=0
790VDU28,0,12,39,9:CLS

```

```

800FORI%=0TOca%:D%=BGET&F:ka%?I%=D%:DRAW84+I%*4,60+D%*2:MOVE84+I%*4,
60+D%*2
810IFD%>f%ANDla%=0THENPRINTTAB(J%MOD39,2*INT(J%/40));(v%+1)*8/x%+I%*
2/w%;:la%=1
820IFD%<f%ANDla%=1THENPRINTTAB(J%MOD39,1+2*INT(J%/40));(v%+1)*8/x%+I
%*2/w%;:la%=0:J%=J%+6
830NEXT
840VDU28,0,12,39,0:GOTO520
850P$(1)="Sample Time:"+aa$:P$(2)="Sample Date:"+ba$:P$(4)="Sequenti
al No.:"+STR$(N%):P$(5)="Data File:"+F$:P$(6)="Disk Title:"+s$
860VDU28,0,12,39,9:CLS:VDU28,0,12,39,0
870IFN%=P%THENPRINTTAB(0,9);"They have been PLOTTED, GO ON(Y/N)":A%=G
ET:PRINTTAB(0,9);STRING$(40," ");:IFA%<>89THEN520
880P%=N%
890PRINTTAB(0,9);"TITLE";STRING$(35," ");:INPUTTAB(7,9);m$
900PROCma
910GOTO500
920DEFPROCda
930CLG:GCOL0,1
940VDU19,0,5,0,0,0
950MOVE80,60:DRAW1100,60
960J%=0
970I%=(J%*w%-8*(v%+1)*w%/x%)*2+80
980IFI%<80THEN1050
990IFI%>1100THEN1060
1000MOVEI%,50:DRAWI%,70
1010MOVEI%-280,50
1020VDU5
1030GCOL0,1
1040PRINTJ%
1050J%=J%+50/w%:GOTO970
1060GCOL0,1:MOVE80,60:DRAW80,570:DRAW1110,570:DRAW1110,60
1070MOVE1132,50:PRINTCHR$(230);"s";
1080VDU5
1090FORI%=35TO250STEP35:MOVE60,I%*2+60:DRAW80,I%*2+60:MOVE-260,I%*2+7
6:PRINTI%/35*10:NEXT
1100VDU4
1110ENDPROC
1120DEFPROCma
1130na%=N%";TAB(10,9)
1140INPUTTAB(0,9);"Condition
;n$;
1150oa=1:IFn$=""ANDm$=""THENoa=0
1160IFoa=1THENPRINTTAB(0,9);"Print information(Y/N) Y? ";:A=GET:I

```

```

FA=76THENOa=0
1170INPUTTAB(0,9);"Select width(40,60,80mm)          60      ";TAB(35,9);
W%
1180IFW%=0THENW%=60
1190PRINTTAB(16,8);W%;:INPUTTAB(0,9);"Select length(short:0 long:1)
0      ";TAB(35,9);L%:IFL%>1THENL%=1
1200INPUTTAB(0,9);"Select LEFT margin(8 To 150mm) 10      ";TAB(35,9)
;V%
1210V%=V%/2.7+3:IFV%<6THENV%=6
1220IFV%*2.7+W%>200THENV%=(200-W%)/2.7
1230PRINTTAB(0,9);STRING$(40," ");TAB(34,8);INT((V%-3)*2.7);" ";
1240W=INT(W%/20)/2/(2-L%):IFW<0.5THENW=0.5
1250IFW>2THENW=2
1260VDU1,27,1,65,1,1+L%,1,27,1,108,1,0
1270VDU1,27,1,68,1,V%,1,V%+3,1,V%+6,1,V%+9,1,V%+12,1,V%+15,1,V%+18,1,
V%+21,1,0
1280VDU1,27,1,85,1,1
1290VDU1,9
1300l%=(5-((v%+1)*8/x%MOD5))*w%/2-1:pa%(((v%+1)*8/x%DIV5)+1)*5
1310l%=l%MOD25:VDU1,10
1320ka%=&4EFE
1330FORN%=1TO257
1340H%=ka%?N%*W:IFN%=1ORN%=257THENH%=255*W
1350VDU1,10
1360IFH%=0THEN1440
1370VDU1,9
1380IFH%<8THEN1410
1390FORI%=1TOH%DIV8:VDU1,&A0+L%:NEXT
1400IFH%MOD8=0THEN1440
1410VDU1,27,1,&4B,1,8,1,0
1420FORI%=1TO(H%MOD8):VDU1,1+2*L%:NEXT
1430FORI%=(H%MOD8)TO7:VDU1,0:NEXT
1440IFN%=l%+1THENl%=l%+25:GOTO1470
1450NEXT
1460GOTO1490
1470VDU1,10,1,27,1,&6A,1,3*(1+L%),1,9,1,8,1,&A0+L%
1480GOTO1450
1490VDU1,8
1500IFW>1THENFORI%=0TO125+2*L%:VDU1,&E8,1,27,1,&6A,1,6*(1+L%),1,8:NEX
T:VDU1,&E9,1,27,1,&6A,1,6*(1+L%),1,8:NEXT
1510IFm$=""THEN1570
1520FORI%=1TO(32*(L%+1)-LEN(m$))/2:VDU1,27,1,&4A,1,24:NEXT
1530VDU1,32,1,32,1,32
1540H$="D"

```

```

1550FORI%=1TOLEN(m$):PROCqa(MID$(m$,I%,1),H$):VDU1,27,1,&4A,1,24,1,8,
1,8:NEXT
1560FORI%=1TO(INT((32*(1+L%)-LEN(m$))/2)+LEN(m$)):VDU1,27,1,&6A,1,24:
NEXT
1570I%=(5-((v%+1)*8/x%MOD5))*w%/2:I%=I%/2
1580VDU1,10,1,9,1,8,1,27,1,&6A,1,3*(1+L%)
1590FORI%=0TO125+2*L%:VDU1,27,1,&4A,1,6*(1+L%),1,&R7,1,8:IFI%<>I%THEN
1660
1600A$=STR$(pa%):pa%=pa%+10*10/w%:VDU1,27,1,&6A,1,15:IFLEN(A$)=1THENV
DU1,27,1,&4A,1,12
1610VDU1,8,1,8,1,8:I%=I%+25
1620H$="S"
1630FORJ%=1TOLEN(A$):PROCqa(MID$(A$,J%,1),H$):VDU1,27,1,&4A,1,24,1,8:
NEXT
1640FORJ%=1TOLEN(A$):VDU1,27,1,&6A,1,24:NEXT
1650VDU1,10,1,27,1,&4A,1,15-3*(1+L%),1,9,1,8:IFLEN(A$)=1THENVDU1,27,1
,&6A,1,12
1660NEXT
1670A$="microsecond":IFoa=0THENA$=CHR$(230)+"s"
1680VDU1,8,1,8,1,8,1,27,1,&4A,1,48
1690FORI%=1TOLEN(A$):PROCqa(MID$(A$,I%,1),H$):VDU1,27,1,&4A,1,24,1,8:
NEXT
1700IFoa<>0THEN1750
1710VDU1,27,1,&6A,1,96:FORI%=1TO26:VDU1,32:NEXT
1720A$=STR$(na%):VDU1,27,1,&6A,1,24*LEN(A$)
1730FORI%=1TOLEN(A$):PROCqa(MID$(A$,I%,1),H$):VDU1,27,1,&4A,1,24,1,8:
NEXT
1740GOTO1880
1750VDU1,9,1,9:A$=STR$((v%+1)*8/x%):B$=A$
1760IFLEN(B$)<=4THEN1800
1770FORI%=1TOLEN(A$)
1780IF(MID$(A$,I%,1))="."THENB$=LEFT$(A$,I%+1):GOTO1800
1790NEXT
1800P$(3)="Time Gate(us):"+B$:P$(7)=n$
1810VDU1,27,1,&6A,1,192
1820FORJ%=1TO7
1830IFJ%=7ANDn$=""THEN1870
1840FORI%=1TOLEN(P$(J%)):PROCqa(MID$(P$(J%),I%,1),H$):VDU1,27,1,&4A,1
,24,1,8:NEXT
1850FORI%=1TOLEN(P$(J%)):VDU1,27,1,&6A,1,24:NEXT
1860VDU1,9
1870NEXT
1880IFV%>6ORoa=0THENFORI%=1TO32:VDU1,27,1,&6A,1,24*(1+L%):NEXT:VDU1,2
7,1,&6A,1,9:GOTO1900

```

```
1890VDU1,12
1900VDU3:N%=P%:ENDPROC
1910DEFPROCqa(A$,H$)
1920?e=ASC(A$)
1930X%=eMOD256:Y%=eDIV256:A%=10:CALL&FFF1
1940VDU1,27,1,82,1,10
1950IFH$="D"THEN1990
1960VDU1,27,1,&4B,1,8,1,0
1970VDU1,e?8,1,e?7,1,e?6,1,e?5,1,e?4,1,e?3,1,e?2,1,e?1
1980GOTO2010
1990VDU1,27,1,&4B,1,16,1,0
2000VDU1,e?8,1,e?8,1,e?7,1,e?7,1,e?6,1,e?6,1,e?5,1,e?5,1,e?4,1,e?4,1,
e?3,1,e?3,1,e?2,1,e?2,1,e?1,1,e?1
2010ENDPROC
2020IFERR=222ORERR=214THENPROCr:GOTOERL
1525IF$&A50<>"DATA"THEN200
2030CLOSE£0:VDU3:REPORT:PRINTERR;" at line ";ERL;
2040*DR.0
2050END
2060DEFPROCra(A$)
2070?e=ASC(A$)
2080X%=eMOD256:Y%=eDIV256:A%=10:CALL&FFF1
2090VDU23,230,e?1,e?1,e?2,e?2,e?3,e?3,e?4,e?4
2100VDU23,231,e?5,e?5,e?6,e?6,e?7,e?7,e?8,e?8
2110ENDPROC
2120DEFPROCk(A$)
2130LOCALI%
2140?e=ASC(A$)
2150X%=eMOD256:Y%=eDIV256:A%=10:CALL&FFF1
2160FORI%=1TO8
2170B%=e?I%:B%=B%DIV16
2180PROCsa
2190e?(I%+8)=ta%
2200B%=e?I%:B%=B%MOD16
2210PROCsa
2220e?(I%+16)=ta%
2230NEXT
2240VDU23,230,e?9,e?9,e?10,e?10,e?11,e?11,e?12,e?12
2250VDU23,231,e?13,e?13,e?14,e?14,e?15,e?15,e?16,e?16
2260VDU23,232,e?17,e?17,e?18,e?18,e?19,e?19,e?20,e?20
2270VDU23,233,e?21,e?21,e?22,e?22,e?23,e?23,e?24,e?24
2280ENDPROC
2290DEFPROCsa
2300ua%=&C0:J%=8:ta%=0
```

```
2310IFINT(B%/J%)>0THENTa%=ta%+ua%
2320IFJ%=1THEN2350
2330B%=B%MODJ%:J%=J%/2:ua%=ua%/4
2340GOTO2310
2350ENDPROC
2360DEFPROCcha
2370CLOSE&F:F=OPENUPF$
2380PRINTTAB(0,9);STRING$(80," ");
2390INPUTTAB(0,9);"N1,N2";va,wa:IFva<>0THENwa=wa+11
2400IFva<=0THENva=1
2410PTR&F=(va-1)*256+wa
2420B%=BGET&F:PRINTTAB(0,9);" ";TAB(0,9);PTR&F;":":B%;:
INPUTTAB(10,9);A$:IFA$=""THEN2420
2430IFA$="."THENPRINTTAB(0,9);STRING$(40," "):ENDPROC
2440B%=EVAL(A$)
2450PTR&F=PTR&F-1:BPUT&F,B%:GOTO2420
2460DEFPROCcr
2470IFERR=222THENCLOSE&0
2480IFa%=1THEN2530
2490PRINTTAB(0,10);:IFb%=1THENPRINT"Replace disk & Hit a key when ready";ELSEPRINT"Cannot find,Replace & Hit a key";
2500A=GET:PRINTTAB(0,10);STRING$(40," "):b%=0
2510a%=1:*DR.1
2520ENDPROC
2530a%=3:*DR.3
2540ENDPROC
2550DEFPROCia
2560CLOSE&0
2570PROCcr:o%=o%+t%
2580F=OPENINF$:t%=(EXT&F-11)DIV256:n=0:i=1
2590IFt%=0THENPROCcr:GOTO2580
2600ENDPROC
2610DEFPROCfa
2620PRINTTAB(0,10);STRING$(40," ");
2630INPUTTAB(0,10);"Start No. & End No.";xa,ya
2640CLOSE&F:F=OPENUP(F$)
2650PTR&F=(xa-1)*256+10
2660FORI%=1TO256*(ya-xa+1)
2670BPUT&F,0
2680NEXT
2690PRINTTAB(0,10);STRING$(40," ");
2700CLOSE&F:F=OPENIN(F$):ENDPROC
2710DEFPROCga
2720VDU28,0,12,39,9:CLS
```

```
2730B%=0:za%=0:ab=(v%+1)*8/x%:bb%=0
2740IFN%=0ORN%=j%THENPRINT"DISPLAY SIGNAL FIRST,PLEASE!";:GOTO2830
2750FORI%=0TO254
2760A%=? (ka%+I%):IFA%=0ORza%=0THEN2790
2770IFA%<=B%ANDza%=1THENI=I%-1:PRINTTAB(10*bb%);B%;"(" ;INT(I/w%*200)/
100+ab;")";:bb%=bb%+1
2780IFA%<=B%THENza%=0
2790IFA%>B%THENza%=1
2800B%=A%
2810NEXT
2820A%=0:VDU28,0,12,39,0:j%=N%
2830ENDPROC
2840DEFPROCea
2850VDU28,0,12,39,9:d=d+1
2860cb%=(N%-o%-1)*256+11
2870FORI%=0TO9:D$(I%)=STR$(I%):NEXT:D$(10)="A":D$(11)="B":D$(12)="C":
D$(13)="D":D$(14)="E":D$(15)="F"
2880VDU2,1,27,1,65,1,9,1,0,1,27,1,68,1,10,1,20,1,0,1,27,1,33,1,1,1,9,
1,9
2890PRINT"Sequential NUMBER is:";N%;"      Filename: ";F$:VDU10,1,10,1
,9
2900FORI%=0TO31
2910PRINT~8*I%;" ";
2920FORJ%=0TO7
2930PTR&F=cb%+8*I%+J%:db%=BGET&F:A%=db%DIV16:B%=db%MOD16:PRINTD$(A%);
D$(B%);" ";
2940NEXT
2950PRINT" ";
2960FORJ%=0TO7
2970PTR&F=cb%+8*I%+J%:db%=BGET&F:eb$=STR$(db%):PRINTeb$;" ";:IFLEN(eb
$)=1THENPRINT" ";
2980IFLEN(eb$)=2THENPRINT" ";
2990NEXT
3000VDU1,10,1,9
3010NEXT
3020VDU1,10,1,10
3030IFdMOD2=0THENVDU1,12
3040VDU3,28,0,12,39,0:ENDPROC
```

>


```

10MODE1:ONERRORGOTO300
20HIMEM=&2EFF
30DIMD$(16)
40VDU28,0,7,39,0:VDU24,0;0;1279;800;:VDU19,0,7,0,0,0:a=?&72:COLOUR3
:PRINTTAB(15,1);"3-D GRAPH"
50VDU19,3,1,0,0,0,:VDU19,1,6,0,0,0:PRINTTAB(0,2);"Disk:";TAB(20,2);
"Filename";
60INPUTTAB(30,2);b$;:PRINTTAB(30,2);b$;" ";TAB(0,3);"G--Graph on
screen P--Plot on paper";
70*DRIVE 1
80S%=?&78:L%=0:VDU28,0,6,39,0,4:c%=0:d%=0:e=0:f%=1000:g=4:c=0:h%=40
0
90i%=1:j%=0
100A$=GET$
110IFA$="G"THEN180
120IFA$="P"THENC=1:GOTO180
130IFA$="R"ORA$=" "THEN150
140GOTO100
150*DRIVE 0
160MODE7:IFA$=" "THENVDU14:END
170PAGE=&1900:CHAIN"MENU2"
180VDU4:k%=180:PRINTTAB(10,6);"WAITING PLEASE! ";
190CLG:l$=""
200s%=200:F=OPENINb$:j%=1
210FORI%=1TO8:D%=&DFF+I%:l$=l$+CHR$(?D%):NEXT
220PRINTTAB(7,2);l$;
230A%=BGET&F:?&AOA=A%:A%=BGET&F:?&AOB=A%:A%=BGET&F:?&AOC=A%:A%=BGET&
F:?&AOD=A%:m%=BGET&F:n%=BGET&F:o%=BGET&F:IFo%=0THENo%=20
240A%=!&AOA:p=(A%/100MOD3600)DIV60:q=A%DIV360000
250PRINTTAB(0,5);"Date(dd-mm-yy) ";m%;"-";n%;"-91";TAB(25,5);"Time "
;q;":";p;
260IFp<10THENPRINTTAB(30,5);q;":0";p;
270PRINT:IFA$="D"THENPROCr:GOTO100
280GOSUB620
290GOTO100
300CLOSE&0:VDU3
310IFERR=222THENPROCr:GOTOs%
320*DR.0
330END
340DEFPROCv
350LOCALW%:VDU28,0,6,39,6,4
360PRINT:INPUT"TITLE";w$
370INPUT"CONDITION";C$;

```

```

380VDU2,1,27,1,65,1,8,1,0,3:ENDPROC
390DEFPROCx
400IFC$=""ANDw$=""THEN480
410VDU2,1,27,1,33,1,1,1,27,1,65,1,12,1,10,1,10
420VDU4:PRINT"          Disk:          ";l$:VDU1,27,1,&6A,1,30:FORI%=1TO
51:VDU1,32:NEXT:PRINT"Filename:      ";b$;:VDU1,10
430PRINT"          Time and Date: ";q:"";p;"  "m%"/";n%"/91";
440VDU1,10,1,27,1,&6A,1,30:FORI%=1TO51:VDU1,32:NEXT:PRINT"Amplitude
Gate: ";G
450IFC$<>""THENPRINT"          Condition: ";C$;
460VDU1,10,1,10,1,27,1,33,1,33,1,10:J%=(78-LEN(w$))/4
470FORI%=1TOJ%:VDU1,32:NEXT:PRINTw$;:VDU1,12,3
480ENDPROC
490DEFPROCy
500LOCALN%,C%
510VDU2,1,10,1,27,1,&6A,1,24:C%=0
520?&80=z%MOD256:?&81=z%DIV256:C%=z%+639:?&8C=C%MOD256:?&8D=C%DIV256
:?&8E=0
530CALL&B7E:aa%=?&80+256*?&81
540IFaa%>s%ORD%>f%THEN610
550IF?&8E=1AND?&8F=0THEN600
560N%=?&8B*8:IFN%>0THENba%=N%MOD256:ca%=N%DIV256:VDU1,27,1,&4B,1,ba%
,1,ca%:FORI%=1TON%:VDU1,0:NEXT
570VDU1,27,1,&4B,1,?&8F,1,0:FORI%=0TO?&8F-1STEP8:FORJ%=3TO0STEP-1:da
%=(?&C04+I%+J%):ea%=(?&C00+I%+J%):VDU1,da%,1,ea%:NEXT:NEXT
580IF?&8E=1THEN600
590GOTO530
600?&8E=0:d%=d%+8*4/g:VDU1,10:?&8B=0:C%=C%+640:?&8C=C%MOD256:?&8D=C%
DIV256:GOTO530
610VDU3:ENDPROC
620VDU28,0,6,39,5:CLS:INPUT"N1,N2,T1,T2,AG";ga%;ha%;ia%;ja%;G;
630CLG:IFG>10THENG=10
640IFc=1THENPROCv:GOTO660
650PRINT"PRINT ON THE PAPER?(Y/N)  N";:A=GET:IFA=89ORA=121THENC=1:PR
OCv
660F$b$:ka%=(G+1)*23
670F=OPENINF$
680PTR&F=6:G%=BGET&F*2/5:la%=BGET&F/2:S%=1:N=ha%-ga%:ma=0:IFN>h%THEN
S%=(N/h%)+1:N=INT((N+1)/S%)
690na%=(EXT&F-11)DIV256
700oa=4:pa=2:IFN<60THENOa=8:pa=1
710u%=(ia%-G%)*la%:qa=192/(255-ka%):ra%=500/N:IFra%<1THENra%=1
720IFra%>4THENra%=4
730ja%=(ja%-G%)*la%:IFja%>255THENja%=255

```

```

740CLS:PRINT"(N1,NE,T1,T2,AG)=";ga%;",";ha%;",";ia%;",";ja%/la%+G%";
",";G;" ";F$;:VDU28,0,6,39,6
750sa%=0:IFu%<0THENSa%=ABS(u%):u%=0
760ta%=ja%-u%:wa%=N*ra%+240:XW%=1160-wa%:ua=XW%/(ta%+sa%):va%=0:xa%=
604:N%=ga%:IFN%<S%THENN%=S%
770?&7A=u%:?&7B=ja%:?&7C=ka%:CLOSEF:$&A78=F$:CALL&B60
780GCOL0,3:MOVEwa%,792:DRAWwa%,604:MOVEwa%,792:DRAWwa%-4,776:MOVEwa%
-4,776:DRAWwa%+4,776:PLOT85,wa%,792
790MOVEwa%-224,792:VDU5:PRINT"Amplit.":VDU4
800IFN%>(ma+na%)THENPROCya
810P%=(N%-ma-1)*256+11:PROCza:MOVEwa%,xa%:?&7A=u%
820IFN%MOD(pa*S%)<>0THEN930
830ab=0:L%=0:?&7A=u%:IFsa%>0ANDN%MOD2=0THENGCOL0,1:DRAWwa%+ua*sa%,xa
%:MOVEwa%+ua*sa%,xa%
840FORI%=u%TOja%
850IFL%=0THENCALL&B6D:I%=?&7A:J%=I%+sa%-u%
860IFL%=0AND(N%MOD(2*S%)=0ORoa=8)THENGCOL0,1:DRAWwa%+ua*J%,xa%:MOVEw
a%+ua*J%,xa%
870IFL%=0AND(N%MOD(2*S%)=1ORoa=8)THENMOVEwa%+ua*J%,xa%
880IFI%>=?&7BTHEN920
890Y=(?(&2F00+I%)-ka%)*qa
900IFY>=0THENGCOL0,0:MOVEwa%+ua*(I%+sa%-u%),xa%:DRAWwa%+ua*(I%+sa%-u
%),xa%+Y-8:MOVEwa%+ua*(I%+sa%-u%)+4,xa%:DRAWwa%+ua*(I%+sa%-u%)+4,xa%+Y
-8:GCOL0,3:MOVEwa%+ua*(I%+sa%-u%-1),xa%+ab:DRAWwa%+ua*(I%+sa%-u%),xa%+
Y:L%=1:ab=Y
910IFY<0ANDL%=1THENL%=0:?&7A=I%:DRAWwa%+ua*(I%+sa%-u%),xa%:MOVEwa%+u
a*(I%+sa%-u%),xa%
920NEXT
930IFN%MOD(25*S%)=0ANDwa%>384THENMOVEwa%-16,xa%:GCOL0,3:DRAWwa%,xa%:
MOVEwa%-352,xa%+16:VDU5:PRINTN%:VDU4
940IFN%MOD(25*S%)=0ANDwa%<448THENMOVEwa%+XW%,xa%:GCOL0,3:DRAWwa%+16+
XW%,xa%:MOVEwa%+XW%-208,xa%+16:VDU5:PRINTN%:VDU4
950wa%=wa%-ra%:xa%=xa%-oa:N%=N%+S%
960MOVEwa%,xa%:IFxa%<32ANDN>142ANDc=1THEN1160
970IF(N%-ga%)/S%>h%ANDc=1THEN1000
980IFxa%<32THEN1090
990IFN%<(ha%+1)THEN800
1000GCOL0,3:MOVEwa%,xa%:DRAWwa%+(ta%+sa%)*ua,xa%:S%=INT((ta%+sa%)/50)
*10
1010VDU5:FORI%=0TO(ta%+sa%)STEPS%:MOVEwa%+I%*ua,xa%-5:DRAWwa%+I%*ua,x
a%+5:MOVEwa%-280+I%*ua,xa%-36
1020IF(wa%+I%*ua)>24THENPRINTia%+I%/la%;
1030NEXT
1040CLOSEF0

```

```
1050I%=I%-S%:IF(wa%+I%*ua)<1152THENMOVEwa%+I%*ua+48,xa%-32:PRINT"us";
:MOVEwa%+I%*ua+40,xa%-36:PRINTCHR$(59);
1060MOVE0,28:PRINT"B-BACK; F-FORE; G-AGAIN; R-RETURN"
1070IFc=1THEN1160
1080IFc=1ANDN%>ha%THENPROCx
1090A$=GET$:IFA$="G"THENVDU4:GOTO620
1100IFA$="B"THENS%=2:GOTO1170
1110IFA$="P"THENC=1:GOTO1160
1120IFA$="F"THENS%=3:GOTO1170
1130IFA$="N":xa%=604:CLG:GOTO800
1140IFA$<>"R"THEN1090
1150VDU24,0;0;1279;800;:VDU28,0,6,39,0:CLG:A$="":RETURN
1160z%=&4180:s%=&7D80:VDU2,1,27,1,65,1,8,3:PROCy:IFN%<ha%THENVDU2,1,2
7,1,&6A,1,144,3:xa%=604:CLG:GOTO990ELSEPROCx:GOTO1090
1170A%=GET:IFA%<48ORA%>57THEN1090
1180VDU19,S%,A%-48,0,0,0:GOTO1170
1190DEFPROCza
1200!&A51=&00002F00:!!&A55=&000000FF:??&A59=P%MOD256:??&A5A=P%DIV256:??&A
5B=P%DIV65536:??&A5C=0
1210A%=3:X%=&50:Y%=10:CALL&FFD1
1220ENDPROC
1230DEFPROct
1240CLOSE&0:IFi%=1THEN1290
1250IFj%=1THENPRINTTAB(0,6);"Change for next disk!";ELSEPRINTTAB(0,6)
;"Cannot find, replace & HIT a key";
1260A=GET:PRINT:j%=0
1270i%=1:*DR.1
1280ENDPROC
1290i%=3:*DR.3
1300ENDPROC
1310DEFPROCya
1320CLOSE&0
1330PROct:ma=ma+na%
1340F=OPENINF$:na%=(EXT&F-11)DIV256:??&7A=u%:??&7B=ja%:??&7C=ka%:CLOSE&F
1350IFna%=0THENPROct:GOTO1340
1360$&A78=F$:CALL&B60
1370ENDPROC
```

>

```
10VDU15
20a=&1600:b=&1900
30DIMc$(100)
40PRINT"Input the file name to compact":INPUTF$
50F=OPENIN(F$):P%=EXT&F:IFb+P%>=PAGE THENPRINT"File is too long, change address first!":PRINT"PAGE IS: ";~PAGE:END
60?&A50=F: !&A51=&00001900: ?&A55=P%MOD256: ?&A56=P%DIV256: ?&A58=0: ?&A57=0: !&A59=&00000000
70A%=3: X%=&50: Y%=10: CALL&FFD1
80CLOSE&F: d=-1
90PROCe
100REPEAT
110PROCf
120UNTIL?b=255
130PROCe
140PRINTTAB(0);"Original length: "; ~(b-&1900): PRINTTAB(0);"NEW length: "; ~(a-&1600)
150PRINT"Save compacted file(Y/N) Y": A=GET: IFA<>89ANDA<>13 THEN200
160INPUT"Input the file name "; F$
170F=OPENOUT(F$): P%=a-&1600
180?&A50=F: !&A51=&00001600: ?&A55=P%MOD256: ?&A56=P%DIV256: ?&A58=0: ?&A57=0: !&A59=&00000000
190A%=3: X%=&50: Y%=10: CALL&FFD1
195CLOSE&F
200PAGE=&1600: END
210DEFPROCf
220LOCALg, h
230g=0
240PROCe
250PROCe
260h=a
270PROCe
280PROCi
290IF?b=42OR?b=&DCTHENPROCj
300IF?b<>13 THENREPEAT: PROCk: UNTIL?b=13
310PROCe
320IFg=4 THENa=a-4
330?h=a-h+2
340ENDPROC
350DEFPROCe
360IFa>b THENPRINT"Cannot compact any more!": END
370?a=?b: a=a+1
380b=b+1: g=g+1
```

```
390ENDPROC
400DEFPROCK
410IF?b=32THENb=b+1:l=l+1:ENDPROC
420IF?b=34THENPROCm:ENDPROC
430IF?b=&F4THENPROCn:ENDPROC
440IF(?b>64AND?b<91)OR(?b>96AND?b<123)OR?b=95THENPROCo:ENDPROC
450IF?b>47AND?b<58THENPROCp:ENDPROC
460IF?b=38THENPROCq:ENDPROC
470IF?b=&EDTHENPROCr:ENDPROC
480IF?b=&E4OR?b=&E5THEN540
490IF?b=58THENPROCe:ENDPROC
500IF?(a-1)=58AND?b=42THENPROCj:ENDPROC
510IF?(a-1)=&8CAND?b=&8DTHENPROCe:PROCe:PROCe:PROCe:ENDPROC
520PROCe
530ENDPROC
550FORI%=1TO5
560PROCi
570PROCe
580NEXT
590ENDPROC
600DEFPROCm
610REPEAT
620PROCe
630UNTIL?b=34
640PROCe
650ENDPROC
660DEFPROCn
670REPEAT
680b=b+1
690UNTIL?b=13
700?a=&F4:a=a+1:g=g+1
710ENDPROC
720DEFPROCo
730LOCALs$,t
740s$=""
750REPEAT
760IFFNuTHENSs$=s$+CHR$(?b):b=b+1
770UNTILNOTFNU
780IFS$="OPT"THENPROCv(s$):ENDPROC
790E$="":w$=s$
800IF?b=36OR?b=37THENE$=CHR$(?b):s$=s$+E$:b=b+1
810IFLEN(w$)=1ANDASC(w$)>64ANDASC(w$)<91THENPROCv(s$):ENDPROC
820t=FNx
830y$=FNz(t)
```

```
840IFE$<>""THENy$=y$+E$
850PROCv(y$)
860PRINTs$;TAB(20);y$
870ENDPROC
880DEFPROCv(N$)
890LOCALI
900FORI=1TOLEN(N$)
910?a=ASC(MID$(N$,I,1))
920a=a+1:g=g+1
930NEXT
940PROCi
950ENDPROC
960DEFFNx
970LOCALI
980I=t-1:J=I+1:aa=FALSE:ba=FALSE
990REPEAT
1000I=I+1:IFI>dTHEN1020
1010aa=(c$(I)=w$)
1020J=J-1:IFJ<0THEN1040
1030ba=(c$(J)=w$)
1040UNTILaaORbaOR(J<0ANDI>d)
1050IFaaTHEN=I
1060IFbaTHEN=J
1070d=d+1
1080IFd>100THENPRINT"Increase the limit of the array VAR$(100) AND re
compact "
1090c$(d)=w$
1100=d
1110DEFFNz(ca)
1120da$=CHR$(caMOD26+97)
1130IFca<26THEN=da$
1140=da$+CHR$(caDIV26+96)
1150DEFPROCq
1160LOCALea,fa
1170PROCe
1180REPEAT
1190fa=?b
1200ea=(fa>47ANDfa<58)OR(fa>64ANDfa<71)
1210IFeaTHENPROCe
1220UNTILNOTea
1230ENDPROC
1240DEFPROCr
1250PROCe
1260REPEAT
```

```
1270IF?b<>58AND?b<>13THENb=b+1
1280UNTIL?b=13OR?b=58
1290ENDPROC
1300DEFFNu
1310LOCALfa
1320fa=?b
1330=(fa>64ANDfa<91)OR(fa>96ANDfa<123)OR(fa>47ANDfa<58)ORfa=95
1340DEFPROCi
1350REPEAT
1360IF?b=32THENb=b+1:l=l+1
1370UNTIL?b<>32
1380ENDPROC
1390DEFPROCj
1400REPEAT
1410PROCe
1420UNTIL?b=13OR?b=58
1430ENDPROC
1440DEFPROCp
1450PROCga
1460PROCi
1470IFFNuTHEN?a=32:a=a+1:g=g+1
1480ENDPROC
1490DEFPROCga
1500REPEAT
1510PROCe
1520UNTIL?b<48OR?b>57
1530ENDPROC
>
```



```
100ONERRORGOTO340
20HIMEM=&78C0:LOMEM=&7300
30VDU15
40DIMa(13),b%(100),c(9)
50*FX229,0
60*FX200,0
70d=0:T$="":e=0:ga%=0:LE%=0
80CLS:DR%=2
90PRINTTAB(0,8);"A__ASSEMBLER"
100PRINTTAB(0,10);"M__MODIFY ASSEMBLY BLOCK"
110PRINTTAB(0,9);"D__DISPLAY"
120PRINTTAB(0,11);"L__LIST"
130PRINTTAB(0,12);"R__RUN"
140PRINTTAB(0,13);"T__TRANSFER"
150PRINTTAB(0,14);"S__STOP"
160PRINTTAB(0,15);"*__LOAD OR SAVE FILE"
170REPEAT:A%=INKEY(100):UNTILA%<>-1:A%=CHR$(A%)
180IF?&7B80<>&52THEN170
190IFA%=2THENga%=1
200IFA%=3THENga%=0
210IFA$="A"GOSUB3620
220IFA$="T"THENPROCf
230IFA$="R"THENPROCg
240IFA$="D"THENPROCh:GOTO80
250IFA$="S"THEN300
260IFA$="L"THENPROCi
270IFA$="*"THENPROCj:*DR.0
280IFA$="M"THENPROck
290GOTO80
300*FX229,0
310*FX220,27
320*FX4,0
330END
340IF?&7B80<>&52THEN170
350IFERR=28THENA%=ERL:REPORT:PRINT:GOTOA%
360IFERR=13THEN190
370IFERR=214ANDDR%=2THEN390
380REPORT:PRINT" at line ";ERL:END
390DR%=0:*DR.0
400GOTO ERL
410DEFPROCh
420LOCALA$,B$,l%,I%,J%,m%,n%,o%,p%,q%,r%,s%
430*FX15,1
```

```
440*FX4,1
450CLS
460PRINTTAB(0,20);"START ADDRESS FOR DISPLAY";:INPUTA$:1%=EVAL("&" + A
$)
470CLS
480PRINTTAB(0,0);"PRESS M TO MODIFY & S TO SEARCH"
490PRINT"PRESS N FOR NEXT SCREEN                PRESS P FOR PREVIOUS
S SCREEN"
500PRINT"PRESS RETURN FOR RETURN"
510r%=4
520s%=r%:t%=2
530J%=1%MOD8:IFJ%=0THEN550
540l%=1%-J%
550b%=1%-2
560FORI%=r%TO19
570IFl%>=&10000THENl%=1%-&10000
580IFl%<&10THENPRINTTAB(1,I%);"          ";TAB(1,I%);"000";~l%::GOTO620
590IFl%<&100THENPRINTTAB(1,I%);"          ";TAB(1,I%);"00";~l%::GOTO620
600IFl%<&1000THENPRINTTAB(1,I%);"          ";TAB(1,I%);"0";~l%::GOTO620
610PRINTTAB(1,I%);"          ";TAB(1,I%);~l%;
620l%=1%-2
630FORJ%=2TO9
640PRINTTAB(3*J%,I%);:A%=1%?J%:IFA%<16THENPRINT"0";~A%;TAB(28+J%,I%)
;".":;GOTO680
650PRINTTAB(3*J%,I%);~A%;
660IFA%>31AND A%<126THENPRINTTAB(28+J%,I%);CHR$(A%);:GOTO680
670PRINTTAB(28+J%,I%);".":;
680NEXT
690l%=l%+10
700NEXT
710PRINTTAB(6,s%);"";
720REPEAT
730A=INKEY(100)
740UNTILA<>-1
750IFA=13GOTO810
760IFA=80THENl%=b%-126:r%=4:GOTO480
770IFA=77THENl=1810
780IFA=78THENr%=4:GOTO480
790IFA=83THENr%=4:GOTO830
800GOTO720
810PRINT:*FX4,0
820ENDPROC
830A$="":A$=A$+GET$:A$=A$+GET$
840u=EVAL("&" + A$):l%=b%+10
```

```

850CLS:PRINT"SEARCHING FOR ";~u
860REPEAT:v=(?1%=u):1%=1%+1:UNTILvOR?1%=&FFOR1%>=&FFFF
870IFvTHEN1%=1%-1:GOTO480
880PRINT"CANNOT FIND IN WHOLE PROGRAM":A%=GET:1%=b%+2:GOTO480
890DEFPROCf
900CLS
910PRINTTAB(1,10);
920INPUT"START ADDRESS FOR TRANSFER";B$:INPUT"END ADDRESS";E$:INPUT"
NEW ADDRESS";N$
930B%=EVAL("&" + B$):E%=EVAL("&" + E$):N%=EVAL("&" + N$)
940IFN%>B%ANDN%<E%THENPRINT"THE NEW ADDRESS IS IN THE OLD BLOCK(Y/N)
":GOTO1010
950IFB%>E%PRINT"WRONG ADDRESS":ENDPROC
960IFB%>N%AND(B%-N%)<(E%-B%)THENPRINT"SOME OLD BLOCK WILL BE FLUSHED
(Y/N)":REPEAT:A=INKEY(100):UNTILA<>-1:IFA=89GOTO220:ENDPROC
970I%=?B%:?N%=I%
980B%=B%+1:N%=N%+1
990IFB%<=E%GOTO970
1000ENDPROC
1010REPEAT:A=INKEY(100):UNTILA<>-1
1020IFA=89GOTO1040
1030ENDPROC
1040w%=N%+E%-B%
1050I%=?E%:?w%=I%:E%=E%-1:w%=w%-1
1060IFE%>=B%GOTO1040
1070ENDPROC
1080DEFPROCg
1090FORI%=1TO6:a(I%)=2:NEXT:a(4)=3:a(7)=3:a(8)=3
1100CLS:?&76=&80:x=0
1110FORy%=0TO18STEP2
1120D%=&A60+y%:A%=?D%+256*D%?1:I%=y%/2:c(I%)=A%
1130NEXT
1140z%=0:aa%=0:T$=""
1150INPUT"START ADDRESS OF RUNNING";A$
1160I%=EVAL("&" + A$)
1170PRINT"S___STEP: T___TOTTLE: E___EXIT           D---DISP.: B___BRK:
K___ERASE BRK"
1180V%=3:T$=""
1190*FX15,1
1200REPEAT:A%=INKEY(100):UNTILA%<>-1:A%=CHR$(A%)
1210IFA$="S"THEN1450
1220IFA$="A"THENGOSUB1330:?&70=EVAL("&" + A$):GOTO1680
1230IFA$="X"THENGOSUB1330:?&72=EVAL("&" + A$):GOTO1680
1240IFA$="Y"THENGOSUB1330:?&71=EVAL("&" + A$):GOTO1680

```

```

1250IFA$="P"THENGOSUB1330:?&73=EVAL("&" +A$):GOTO1680
1260IFA$="C"THENA$="":FORI%=0TO3:A$=A$+INKEY$(200):NEXT:1%=EVAL("&" +A
$):GOTO1680
1270IFA$="B"THEN1350
1280IFA$="T"THENVDU15:T$="RUN":GOTO1450
1290IFA$="K"THENFORy%=0TO9:c(y%)=0:NEXT:GOTO1190
1300IFA$="E"THENENDPROC
1310IFA$="D"THENPROCh:CLS:GOTO1170
1320GOTO1190
1330A$=""
1340FORI%=0TO1:A$=A$+INKEY$(200):NEXT:RETURN
1350FORy%=0TO9
1360PRINT"B";y%;" ";~c(y%);:INPUT"      "A$
1370IFA$=""THEN1400
1380IFA$="."THEN1410
1390c(y%)=EVAL("&" +A$)
1400NEXT
1410FORy%=0TO18STEP2
1420D%=&A60+y%:I%=y%/2:?D%=c(I%)MOD256:D%?1=c(I%)DIV256
1430NEXT
1440GOTO1190
1450IFaa%=1THEN1480
1460w%=?1%:q%=&7A00+w%:I%=?q%:IFI%=255THENPRINT"BAD PROG":ENDPROC
1470s%=&7B00:GOSUB2630:aa%=1:ba$=LEFT$(ca$,1)
1480IF(da%=&75ORda%=&76)ANDBa$="S"THENPRINT"Address &75,&76 is FORBID
EN!":GOTO1170
1490IFda%>&6FANDda%<&77AND(ba$="L"ORba$="S")THENPRINT"Using addresses
&70-&76 causes MISTAKE!      Go on?(y/n)":REPEAT:A=INKEY(10
0):UNTILA<>-1:IFA<>89THEN1170
1500IF?1%=&BATHEN?&72=?&76:1%=1%+1:GOTO1680
1510IF?1%=&9ATHEN?&76=?&72:1%=1%+1:GOTO1680
1520IF?1%=&40THENea=?&76+256:1%=256*ea?2+ea?3:?&73=ea?1:?&75=?&75+3:G
OTO1680
1530IF?1%=0THEN1%=1%+1:x=1:T$="":GOTO1680
1540?&78D0=&EA:?&78D1=&EA:?&78D2=&EA
1550?&78D0=?1%:IFB%>1THEN?&78D1=1%?1
1560IFB%>2THEN?&78D2=1%?2
1570fa%=1%
1580IFT%=11ANDda%<80THEN1%=1%+da%+2:?&78D1=&16:GOTO1650
1590IFT%=11THEN1%=1%+da%-254:?&78D1=&16:GOTO1650
1600IF?1%=&20THENea=?&76+256:?ea=1%MOD256:ea=ea-1:?ea=1%DIV256:1%=da%
:?&76=?&76-2:d=d+1:GOTO1680
1610IF?1%=&60ANDd>0THEND=d-1:ea=?&76+256:1%=ea?1*256+ea?2:?&76=?&76+2
:1%=1%+3:GOTO1680

```

```

1620IF?1%=&60THENPRINT"AT THE END":T$="":GOTO1170
1630IFba$="J"ANDT%=12THEN1%=?da%+256*(da%?1):GOTO1680
1640IFba$="J"THEN1%=da%:GOTO1680
1650CALL&78C0
1660IF?&74=0ANDT%=11THEN1%=fa%+2
1670IFT%<>11THEN1%=1%+B%
1680IFT$="RUN"ANDe<>1THEN1700
1690PRINT"A=";~?&70;" X=";~?&72;" Y=";~?&71;" S=";~?&75;" NS=";~?&76;
" P=";~?&73;" PC=";~1%
1700w%=?1%:q%=&7A00+w%:I%=?q%:IFI%=255ANDe<>1THENPRINTTAB(0);~1%;TAB(
5);~?1%,"BAD PROG"
1710IFI%=255ANDe=1THENRETURN
1720s%=&7B00:GOSUB2630
1730IFe=1THENRETURN
1740ba$=LEFT$(ca$,1)
1750IFx=1THENx=0:GOTO1170
1760IFT$<>"RUN"THEN1190
1770FORy%=0TO9:IF1%=c(y%)THENT$="":GOTO1170
1780NEXT
1790GOTO1450
1800REM
1810PRINTTAB(0,0);"                               ";TAB(0,1);"PRESS RETU
RN TO DISPLY                               ";TAB(0,2);"USE ARROW KEY TO MODIFY
"
1820PRINTTAB(0,0);"PRESS I TO INSERT A BLANK AND K TO KILL"
1830PRINTTAB(0,3);"                               ";
1840PRINTTAB(3*J%,I%);"";
1850J%=2:I%=4:l%=b%
1860PRINTTAB(3*J%,I%);"";
1870REPEAT:A=INKEY(100):UNTILA<>-1
1880IFA=73THEN2130
1890IFA=75THEN2180
1900IFA=136GOTO1960
1910IFA=137GOTO1980
1920IFA=138GOTO2000
1930IFA=139GOTO2020
1940IFA=13THEN480
1950GOTO2060
1960J%=J%-1:IFJ%<2THEN1%=1%-8:I%=I%-1:J%=9
1970GOTO2030
1980J%=J%+1:IFJ%>9THEN1%=1%+8:I%=I%+1:J%=2
1990GOTO2030
2000I%=I%+1:l%=1%+8:IFI%>19 I%=19:l%=1%-8
2010GOTO2030

```

```
2020I%=I%-1:l%=l%-8:IFI%<s%THENI%=5:l%=l%+8
2030B$="0":PRINTTAB(3*J%,I%);"";
2040*FX15,1
2050REPEAT:A=INKEY(10):UNTILNOTA
2060A%=INT(A)
2070IFA>47ANDA<71THENA$=CHR$(A%):B$=B$+A$:B%=RIGHT$(B$,2):PRINTTAB(3*
J%,I%);B$;:l%?J%=EVAL("&" +B$)
2080IFA=13THENl%=b%+2:GOTO480
2090IFA>135ANDA<140THEN1900
2100IFA=73GOTO2130
2110IFA=75GOTO2180
2120GOTO2050
2130n%=b%+128:m%=l%+J%
2140FORp%=0TOn%-m%
2150o%=n%-p%:q%=?o%:o%?1=q%
2160NEXT
2170?m%=0:GOTO480
2180n%=b%+128:m%=l%+J%
2190FORp%=m%TOn%+1
2200q%=p%?1:?p%=q%
2210NEXT
2220n%?1=0:A=13:GOTO480
2230DEFPROC i
2240ha=0:ia%=1
2250INPUT"START ADDRESS FOR LIST";A$:l%=EVAL("&" +A$)
2260FORI%=1TO6:a(I%)=2:NEXT:a(4)=3:a(7)=3:a(8)=3
2270CLS
2280b%(1)=l%:S%=1
2290r%=&7A00:s%=&7B00
2300V%=2
2310w%=?l%:A=0
2320N%=r%+w%:I%=?N%:IFI%<>255THEN2340
2330l%=l%+1:GOTO2310
2340PRINTTAB(0,0);"P___PREVIOUS PAGE ";S%;" N___NEXT PAGE"
2350PRINT
2360GOSUB2530
2370IFha=1THEN2500
2380V%=V%+1:C%=D%+40:IFV%>22THEN2400
2390l%=l%+B%::GOTO2360
2400REPEAT:A=INKEY(100):UNTILA<>-1:IFA=13THEN2500
2410*FX15,0
2420IFA<>78ANDA<>80THEN2500
2430IFA=78THENA%=INKEY(100):A=A%-48
2440IFA=80THEN2460
```

```

2450IFA%<>-1ANDA<=ia%-S%THENS%=S%+A:GOTO2480ELSESE%=S%+1:ia%=S%:b%(S%)
=1%:V%=2:CLS:GOTO2340
2460A%=INKEY(100):A=A%-48
2470IFA%<>-1ANDA<S%THENS%=S%-AELSESE%=S%-1
2480V%=2:1%=b%(S%):CLS:GOTO2340
24901%=b%(1):CLS:GOTO2340
2500IFA=68PROCh:CLS:GOTO2480
2510IFga%=1THENVDU2:VDU1,12:VDU3
2520ENDPROC
2530REM
2540w%=?1%:A=0
2550N%=r%+w%:I%=?N%:IF I%<>255THEN 2620
2560IFga%=1THENVDU2
2570PRINTTAB(0,V%);~1%;" ";:IFw%<16THENPRINTTAB(5,V%);"0";~?1%;:GOTO2
590
2580 PRINT TAB(5,V%);~?1%;
2590 PRINT "          *****          ";
2600ba$="":IFw%>31ANDw%<128THENba$=CHR$(w%)
2610PRINTba$:B%=1:RETURN
2620IFga%=1THENVDU2
2630IFe<>1ANDT$<>"RUN"THENPRINTTAB(0);~1%;
2640ja%=I%+s%
2650IFI%<&73THEN2720
2660IFI%>&E7THENT%=12:B%=3:GOTO2770
2670IFI%>&E1THENT%=13:B%=2:GOTO2770
2680IFI%>&C9THENT%=11:B%=2:GOTO2770
2690IFI%>&7ETHENT%=10:B%=1:GOTO2770
2700IFI%>&72THENT%=9:B%=1
2710GOTO2770
2720C$=$ja%:ba$=LEFT$(C$,3):ka$=RIGHT$(C$,1):C%=ASC(ka$)
2730T%=(w%-C%)/4+1:B%=a(T%)
2740ba%=C%MOD16
2750IFw%=C%AND(ba%=0ORba%=2)THENT%=3
2760GOTO2780
2770ba$="":FORJ%=0TO2:1a%=2-J%:ma%=ja%?1a%:ba$=CHR$(ma%)+ba$:NEXT
2780IFe=1THENRETURNELSEda%=0
2790IFB%>1THENDa%=1%?1
2800IFB%>2THENDa%=256*1%?2+da%
2810IFT$="RUN"THENca$=ba$:RETURN
2820N$=STR$(w%)
2830IFda%=0ANDB%=1THENPRINTTAB(5);~w%;:GOTO2900
2840IFw%<16PRINTTAB(5);"0";w%;:GOTO2860
2850PRINTTAB(5);~w%;" ";
2860IFB%>2AND1%?1<16THENPRINTTAB(8);"0";~1%?1;~1%?2;:GOTO2900

```

```

2870IFB%>2AND1%?2<16THENPRINTTAB(8);~1%?1;"0";~1%?2;:GOTO2900
2880IFB%>2THENPRINTTAB(8);~1%?1;~1%?2;:GOTO2900
2890IFB%>1THENPRINTTAB(8);~1%?1;
2900IFT%=1THENPRINTTAB(14);ba$;" (&;~da%;" ,X)";:GOTO3020
2910IFT%=2THENPRINTTAB(14);ba$;" &;~da%;:GOTO3020
2920IFT%=3THENPRINTTAB(14);ba$;" £&;~da%;:GOTO3020
2930IFT%=4THENPRINTTAB(14);ba$;" &;~da%;:GOTO3020
2940IFT%=5THENPRINTTAB(14);ba$;" (&;~da%;" ),Y";:GOTO3020
2950IFT%=6THENPRINTTAB(14);ba$;" &;~da%;" ,X";:GOTO3020
2960IFT%=7THENPRINTTAB(14);ba$;" &;~da%;" ,Y";:GOTO3020
2970IFT%=8THENPRINTTAB(14);ba$;" &;~da%;" ,X";:GOTO3020
2980IFT%=9ORT%=10THENPRINTTAB(14);ba$;:GOTO3020
2990IFT%=11THENPRINTTAB(14);ba$;" &;:IF da%<128 THEN PRINTTAB(19);~(
1%+2+da%);:GOTO3020 ELSE PRINT TAB(19);~(1%+da%-254);:GOTO3020
3000IFT%=13THENPRINTTAB(14);ba$;" &;~da%;" ,Y";:GOTO3020
3010PRINTTAB(14);ba$;" (&;~da%;" )";
3020ca$=ba$:ka$="":ba$="":FORna%=0TOB%-1:A%=1%?na%:ba$=CHR$(A%):IFA%<
320RA%>127THENba$="."
3030ka$=ka$+ba$:NEXT
3040PRINTTAB(35);ka$
3050VDU3:RETURN
3060DEFPROCj
3070CLS:b%=TOP-2:??&920=&15:??&921=&9
3080GOSUB3190:b%=A%:REPEAT:A%=A%+1:UNTIL?A%=13AND A%?1>&80 :oa=A%-b%+
2
3090*DR.2
3100PRINTTAB(0,23);"L___*LOAD          S___*SAVE":REPEAT:A=INKEY(100):
UNTILA<>-1:A$=CHR$(A)
3110IFA$="L"THEN3400
3120IFA$="S"THEN3140
3130GOTO3100
3140A%=&3DA0:PRINTCHR$(136);"WAITING!"
3150REPEAT:A%=A%+1:UNTIL(?A%=79AND A%?1=80AND A%?2=84)OR?A%=&FF
3160IF?A%=&FFTHENPRINT"CANNOT FIND THE START ADDRESS!"
3170REPEAT:A%=A%+1:UNTIL?A%=13
3180b%=A%:GOTO3270
3190PRINTTAB(0,23);"          WAITING PLEASE!";:A%=&3C00
3200REPEAT:A%=A%+1:UNTIL?A%=93OR?A%=255
3210IF?A%=255THENPRINT"CANNOT FIND THE END ADDRESS!"
3220A%=A%-1
3230FORI%=1TO5:A%=A%-1:IF?A%=13THEN3260
3240NEXT
3250GOTO3200
3260RETURN

```



```

3270GOSUB3190:n%=A%+2
3280IFn%=b%+2THENPRINTTAB(0,23);"NO ASSEMBLY PROGRAM TO SAVE!":A%=GET
:ENDPROC
3290A%=?&910:IFA%=1THENA$=$&915:PRINTTAB(0,23);"SAVE ";A$;" ";~b%;" "
;~n%;"?":REPEAT:A=INKEY(100):UNTILA<>-1
3300IFA%<>1THEN3320
3310IFA=13THEN3330
3320PRINTTAB(0,23);"                               ";TAB(0,23);
"FILENAME";:INPUTA$:$&915=A$
3330?&92A=b%MOD256:?&92B=b%DIV256:?&92E=n%MOD256:?&92F=n%DIV256:A%=0
3340M=b%:N=n%-2:?&940=?N:?&941=N?1:?N=13:N?1=255
3350A%=0:X%=&20:Y%=9:CALL&FFDD
3360PRINTTAB(0,23);"DELETE THE FILE IN THE MEMORY?":?N=?&940:N?1=?&94
1:REPEAT:A=INKEY(100):UNTILA<>-1:IFA<>89THENENDPROC
3370FORK%=0TO30:b%?K%=N?K%:IFN?K%=&FFTHEN3390
3380NEXT
3390ENDPROC
3400PRINTTAB(0,23);"FILENAME                               ";TAB(8,23);:I
NPUTA$:?&910=1:$&915=A$
3410GOSUB3190:b%=A%
3420?&70=b%MOD256:?&71=b%DIV256:?&72=oa:?&73=?&70:?&74=?&71
3430!&911=b%
3440$&900=A$
3450CALL&7900
3460LE%=?&73+256*(?&74):ENDPROC
3470DEFPROck
3480CLS:INPUT"Start EXECUTION address",pa$:INPUT"Start Assembly addre
ss",P$:INPUT"End Assembly address",qa$
3490pa%=EVAL("&"+pa$):P%=EVAL("&"+P$):qa%=EVAL("&"+qa$)
3500IFpa%=P%THENPRINT"NEEDNOT MODIFYING!":A%=GET:ENDPROC
3510IFpa%>P%ANDpa%<=qa%THENPRINT"Addresses are not suitable for modif
ying":A%=GET:ENDPROC
3520ra%=P%-pa%:CLS:PRINTTAB(10,12);CHR$(141);CHR$(136);"MODIFYING";TA
B(10,13);CHR$(141);CHR$(136);"MODIFYING";
3530FORI%=0TO6:a(I%)=2:NEXT:a(4)=3:a(7)=3:a(8)=3
3540I%=P%:e=1
3550IFI%>=qa%THEN3610
3560IF?I%<>32AND?I%<>&4CTHEN3600
3570sa%=I%?1+256*I%?2:IFsa%>qa%ORsa%<P%THEN FORI%=0TO2:A%=?(I%+I%):?(
pa%+I%)=A%:NEXTI%:GOTO3590
3580A%=?I%:?pa%=A%:ta%=sa%-ra%:pa%?1=ta%MOD256:pa%?2=ta%DIV256
3590I%=I%+3:pa%=pa%+3:GOTO3550
3600GOSUB1700:FORI%=0TO(B%-1):A%=?(I%+I%):?(pa%+I%)=A%:NEXTI%:I%=I%+B
%:pa%=pa%+B%:GOTO3550

```

```
3610e=0:ENDPROC
3620REM
3630FORI%=0TO3STEP3
3640P%=&5000
3650IFP%<TOP AND P%>&1600THENPRINT"Increase the start address, Please
!" :A=GET:RETURN
3660[
3670OPTI%
3680]
3690NEXT
3700RETURN
>
```

```

10 VDU3
15 *KEY 2 PROCforw!M
20 LP=55:LL=74:LM=15:SN=12:N%=1:U%=0:PP=295
30 CLS
40 PRINT TAB(10,3);"PRINT FORMAT"
50 PRINT
60 PRINT "P__page form   C__character form       E__execute       U
__underline"
70 A$=INKEY$(50)
80 IF A$="P" THEN PROCpset:GOTO30
90 IF A$="C" THEN PROCcset:GOTO30
100 IF A$="U" THEN U%=1
110 IF A$<>"E" THEN 70
120 TP=INT(PP*6/25.4)
130 B%=INT(6*(TP/6-LP*SN/72))
140 VDU2
150 VDU1,27,1,64
160 VDU1,27,1,45,1,0
170 IF U%=1 THEN VDU1,27,1,45,1,1
180 VDU1,27,1,67,1,TP
190 VDU1,27,1,78,1,B%
200 VDU1,27,1,81,1,LL
210 VDU1,27,1,108,1,LM
220 VDU1,27,1,65,1,SN
230 VDU1,27,1,33,1,N%
240 VDU1,9
250 VDU3:PRINT"SET the paper please; Press any key when ready"
260 END
270 DEFPROCpset
280 CLS
290 PRINT TAB(5,5);"P__length of page   ";LP
300 PRINT TAB(5,7);"L__length of line   ";LL
310 PRINT TAB(5,9);"M__left margin     ";LM
320 PRINT TAB(5,11);"S__line space       ";SN
330 PRINT TAB(2,20);"press R to return"
340 A$=GET$
350 IF A$="P" THEN PRINT TAB(25,5);"      ";TAB(25,5);:INPUT LP:IF LP
>70 THEN LP=70
360 IF A$="L" THEN PRINT TAB(25,7);"      ";TAB(25,7);:INPUT LL:IF LL
>80 OR LL<=LM THEN LL=75

```

```
370 IF A$="M" THEN PRINT TAB(25,9);"          ";TAB(25,9);:INPUT LM:IF LM
<0 OR LM>=LL THEN LM=5
380 IF A$="S" THEN PRINT TAB(25,11);"        ";TAB(25,11);:INPUT SN:IF
SN>127 THEN SN=12
390 IF A$<>"R" THEN 280
400 ENDPROC
410 DEFPROCcset
420 CLS
430 PRINT TAB(0,5);"NUMBER                CHARACTER"
440 PRINT TAB(5,6);"0  PICA mode"
450 PRINT TAB(5,7);"1  ELITE mode"
460 PRINT TAB(5,8);"4  condensed mode"
470 PRINT TAB(5,9);"8  emphasized mode"
480 PRINT TAB(4,10);"16  double strike mode"
490 PRINT TAB(4,11);"17  ELITE/double strike mode"
500 PRINT TAB(4,12);"20  condensed/double strike mode"
510 PRINT TAB(4,13);"24  emphasized/double strike mode"
520 PRINT TAB(4,14);"32  enlarged mode"
530 PRINT TAB(4,15);"33  ELITE/enlarged mode"
540 PRINT TAB(4,16);"36  condensed/enlarged mode"
550 PRINT TAB(4,17);"40  emphasized/enlarged mode"
560 PRINT TAB(4,18);"48  double strike/enlarged mode"
570 PRINT TAB(4,19);"49  ELITE/double strike/enlarged mode"
580 PRINT TAB(4,20);"52  cond./double strike/enlarged mode"
590 PRINT TAB(4,21);"56  empha./double strike/enlarged mode"
600 PRINT TAB(0,23);"empha.>cond.>normal>super.>double"
610 PRINT TAB(2,2);"WHICH MODE";:INPUT N%
620 IF N%<0 OR N%>56 THEN PRINT"WRONG CHOICE":GOTO420
630 ENDPROC
650 DEFPROCforw
660 VDU1,12
670 VDU3
680 ENDPROC
```

>

A REAL TIME MULTIFUNCTIONAL WELDING SENSOR

By R. Fenn, Y. Lu & J. Bradbury

Some years ago, an ultrasonic sensor capable of monitoring and controlling weld penetration in weldments over 10 mm thickness was patented. This sensor employed crude computer control, although control was almost as a "null" meter, and has been further developed by increasing the control role of the computer system. Initially, simultaneous seam tracking was added by utilising the leading edge of ultrasonic beam spread. Seam following accuracy of ± 0.3 mm was found, whilst the device still controlled weld penetration in real time at welding speeds in excess of 10 mms⁻¹.

By changing the ultrasonic probe type, penetration control in thin plate, using G.T.A.W., was possible. Although the simple, slow computer used originally was still employed excellent accuracy in both seam following and penetration were maintained. Electro-magnetic arc deflection, to compensate for distortion during welding, was simultaneously controlled by this computer.

A real time defect detection system, operating by the trailing edge of the ultrasound signal and examining the solidifying weld, is almost completed and will be incorporated into the system. To do this large and faster RAM capacity is required, but will also allow a limited expert system to be included and extended.

Introduction

Since the late 1970's/early 1980's there has been much work undertaken to develop real time sensors and control systems for automated welding, especially for robotic usage^[1-10]. From very simple mechanical devices, more sophisticated electronic devices were evolved, the majority of which were based on some type of non-destructive testing^[1-3,7]. All these devices, whether proposed or produced, offered a number of very distinct advantages; they had to work at real welding speeds and preferably in real time, to enhance achievable accuracy level equal to, or better than, that of robot reproducibility. Most of the early devices (and some of the later ones) were simply seam-following devices using very simple logical systems frequently limited by the ability of computers at that time.

Early in the development of weld sensors attempts were made to provide these devices with greater abilities than simple seam tracking. Various parameters were monitored and related to various weld dimensions, although little commonality existed in the desired objectives^[1-4,8,10-12]. Fairly soon, the requirement to guarantee the depth of weld penetration and keep this dimension constant was evolved^[3,4,9,10,13]. In the U.K., it was the demands of the nuclear industry, with its need to maximise quality and durability, that prompted research into weld penetration control; it was probably the same pressure that initiated similar work in the U.S.A.^[13-18]. A number of approaches were utilised by the various groups, but only two techniques (real time radiograph and ultrasonic monitoring) were capable of direct measurements.^[19,20]

At Brunel University, the work commenced by using low frequency transverse

ultrasound techniques to monitor the achievement of root penetration during shielded metal arc welding (S.M.A.W.).^[13] These early trials proved the veracity of the approach, showing that real time monitoring of welding could detect and measure the accuracies of lack of root penetration during welding.^[13] The results were of this work were so positive that the work was extended into automatic welding and over a much longer time scale to ensure that some fundamental knowledge of the process could be gained.^[12,14-19]

During the course of this work, both transverse and longitudinal ultrasound waves were studied, as were their interactions with the weld bead and heat affected zone^[19]. What this work demonstrated was that: 1) shear wave ultrasound had two important advantages over compression waves (a) their reflection from the liquid/solid interface and (b) the possibility of monitoring penetration from the top face only. 2) Other ultrasounds signals - due to beam spread - were present and could give further information about the welding operation^[12,15]. 3) The sensor system made possible by these U.S. Waves would be mechanically very simple, with the probes rigidly attached to the welding head. There was thus no requirement for underside monitoring or other complex parts which had to be integrated with the welding torch forward motion. All this work was performed on steel with thicknesses between 10 and 22 mm, although during the course of this project a further short program was undertaken which validated the abilities on this technique when applied to 10 mm plus thickness aluminium.^[10] By the completion of this first research program, it was possible to patent the system and to plan for further extensions of this sensor system capability by utilising the information on the other ultrasonic signals and by modification to account for thinner plate sections.

Deconvolution Of information carried by the other ultrasound signals

Figure 1a is the reproduction of an early schematic diagram of the process; note that in this representation only the 100% (center line) ultrasonic beam was drawn and is the signal used for penetration monitoring and control, whilst figure 1b demonstrates the more realistic situation accounting for ultrasonic beam spread.^[15] From the second diagram it would appear that the leading edge signal was essentially reflected back from the weld seam millimetrically in advance of the front edge of the weld pool; whilst the trailing edge signal interrogated the solidifying/recently solidified weld bead. Thus, the potential for both seam following and some defect detection as well as penetration control, was indicated. For many reasons, not the least of which was a philosophical limitation (more later), the decision to exploit the seam following capability was taken. To undertake this work, a basic requirement to locate and identify the appropriate signals from all of the possible received signals, had to be fulfilled. Figure 2 demonstrates how the signals appeared on an ultrasonoscope, not only had this signals to be identified, but they had to be measured and compared with the desired values.^[21-27] After much work, the decision really reduced to how wide to have the monitoring windows and which part of the ultrasonic signal within a window was used as the trigger of the responding system (figure 3 illustrates a schematic diagram of the ultrasonoscope display and the control windows employed). In the case of seam

following system, the triggered signals drove a stepper motor which drove a slide (and hence the welding torch) orthogonally to the welding direction (see figure 4). As mechanical motion was required the effects of momentum and inertia had to be considered and the motion rate was maximised at 25 mms^{-1} , which using the usual welding preparation meant about 0.1 seconds from weld center line to either extreme edge (of the preparation). Overall movement possible was 125 mm either side of the welding bead center line. Using an ultrasound signal did not produce unnecessary delays in system response. Ultimate accuracy of this system was related to the wave length of the ultrasound employed (and hence, an inverse of the frequency). As 2.5 to 5 MHz was employed for all this sensing work, the best achievable dimensional accuracy was 0.3mm (about twice the accuracy of motion reproducibility of an industrial robot.^[21,24,28] Certainly, if only the ultimate in seam tracking accuracy had been required then a much higher frequency ultrasound would have been employed, but at the cost of much greater losses (of return signal) for the penetration control device. Obvious modifications, such as "ganging" together ultrasound probes and using individual probes to undertake individual sensing functions was considered, and will be dealt with later.

By this stage of the work there existed a computer controlled sensing system, capable of operating in real time, at welding speeds of 10 mms^{-1} , which controlled weld penetration and seam following to $\pm 0.3 \text{ mm}$ in plate thickness of 10 mm or greater. Unfortunately, most industrial high level automation system are employed to weld together plates $< 10 \text{ mm}$ and probably $< 1 \text{ mm}$, thus some system for these cases had to be devised.

Sensing Of thin plate weld penetration

Once a critical ratio of plate thickness to ultrasonic crystal diameter had been violated, by reducing plate thickness, the use of shear wave in operation (and hence monitoring) becomes impossible. Other physical limitations were also apparent, for example as the welding plates become thinner, the U.S. probes moved closer to the welding joint. Such situation presented no thermal problems, but mechanical ones (as shown in figure 5). It is more usual practice to examine "thin" plates by bulk U.S. Waves, in this case Lamb or Rayleigh waves, which, in the case of plates $< 2 \text{ mm}$ thick, performed essentially identically.^[25]

Work was performed on thin plates (generally) 0.5 to 0.6 mm thick, which meant it was still possible to differentiate the upper and lower surface sound path. Such differences caused differential transit length, with the top surface wave travelling over the ridge of the weld bead, whilst the bottom face wave followed up (and down) any lack of penetration (or around the periphery of the under bead). Thus, by timing the difference in time of flight between the upper and lower waves, it became possible to note the changes in beam path length and hence infer the shape of the weld pool and achievement of full penetration (see figures 6 and 7). As can be seen in figure 7, there exists an area of uncertainty, where lack of penetration and excessive penetration presented the same Δt value (i.e. both present Δt positive of similar magnitude) and

this situation presents the ultimate penetration control system limit, which was shown to be $\pm 5\%$ of the plate thickness (plates 0.5 to 1.6 mm thickness). Where Δt was 0 or negative, no action was taken; indeed these signals were not sent to the control computer, which allowed much simpler computing equipment to be employed for overall system control.^[24-28]

Seam following, when welding thin plate, presented more challenges than did thick plate, as the thinner material is much more likely to respond to contractional stresses by lateral movement than thicker plates are. It was found, during the course of the work, that the stepper motor driven seam tracking signal could not respond adequately to such distortion; it was frequently too slow. When this occurred, the welding head went into a mode of apparently random oscillation (termed "nervous breakdown") by reacting and then over reacting to small correction movements until the system was obviously out of control. What was required was some form of lower inertia arc deflection other than by mechanical means.

In all the thin plate welding work gas tungsten arc welding was used and from this the ability to employ magnetic arc deflection became realisable.^[25] Commercial magnetic arc deflection system proved not to be useful. Such systems require pre-programming of the deflection sequence, had the requirements for arc-deflection be known in advance (this infers, of course, that the distortion be known in advance), then the deflection system would not have been required in this control device! What was required was a controlled arc deflection system that used some seam sensing technique and used deviations norm the desired to activate magnetic deflection (see figure 8). Ultrasonic sensing gave exactly the correct type of signals for this purpose and when combined with a simple control statement (in the computer software) produced a two stage orthogonal control function. Minor seam gap irregularities (due to distortion) were compensated for by magnetic arc deflection whilst larger gaps were covered by the Y axis stepper motion (as was normal in thick plate seam control)^[25-29]. In service, this system proved to be sufficiently sophisticated that it was possible to rotate the arc and essentially draw "figures of eight" in the weld pool. Figure 9 shows the GTAW torch and final E.M. deflection arrangement used for welding 0.5 mm sheet, which could bridge gaps of over 3 mm wide and yet still produce full penetration.

Much of this ability of the thin plate sensor was due to the logic in-built in the software; figure 8 shows schematically the arrangement employed with the transducers fixed at a constant distance from the welding torch center. Using known distance produced a desired beam path length and hence variations from those norminated distances caused first stage motion (EM deflection) and then, if sufficiently large, stage 2 motion. This device proved to be only possible using Rayleigh waves and monitored the frequency modulation (due to thickness) of edge reflected signals, which were heterodyned to determine distance (& thus gap size).^[25] Figure 10 shows the block diagram of this system. Overall, the accuracy of seam following using this Rayleigh wave based system was better than ± 0.3 mm and operated in real time and at real welding speeds; indeed, the principal limitation on the whole system was nothing mechanical, but simply computer speed.

Analysis Of trailing U.S. Signal data

Ultrasound beam spread (as shown in figure 1b) indicated that the trailing edge signal should carry some information about the (recently) solid or solidifying weld bead. Information carried by the leading edge signal had been proved to carry sufficient information to make seam tracking possible; it thus followed that the trailing edge signal (in U.S. therms, the direct corollary of the leading edge signal) should also carry significant data. Previous signal examination had shown that there were signal perturbations on that beam, but little sense could be made of these signals. Two items of information were needed to be able to deconvolute and make sense of defect signals and these were: 1) standard defects from which to produce standard return signals and 2) long duration recordings of defect signals to allow time based signal variations to be printed and examined.

A standard test block was constructed from perspex and this contained drilled holes, lack of fusion and horizontally aligned cracks. Using the usual shear wave probes (2.5 or 5 MHz) this block was used to produce reference signals. Even digitising these (known) defect signals and storing them on computer did not fulfil the requirement of recording time based variations. To undertake this task a small digital device to store and process signals in the B-scan mode, similar to a "Zipscan" was built and had a 200 seconds recording memory.^[30,31] Typical output from this device is shown in figure 11; using this recording device produced V.D.U., paper and digital output such that long term study became possible. By identifying a standard series of signals it became viable to instruct the computer to recognise defects from the trailing signal. Attempts to verify the defect signals, by producing real defects to order within the weld, were fraught with difficulty; some defects were produced as and when they were required, others just had to be formed haphazardly.^[31] Eventually, a sufficient library of real defect signals was collected and the data cross-correlated with direct measurement patterns to be determined. This work is currently on-going, but it is possible to determine gas porosity at < 1 mm diameter and cracks (and planar defects) at about the 0.25mm size level (finer detection level by radiography)^[31]

At the time of welding, all three functions of the sensors are proven and understood (certainly for thick plate welds); two of the three functions are combined (in the control) software and the defect detection programs very soon will be. In the case of the thin plate sensor, the two functions (penetration and seam following) exist as a unity, but the defect detection work has only just begun and will cover thickness up to 4 mm (by Rayleigh wave sensing).

Discussion

It is the contention of this paper that a simple ultrasonic sensor has been developed to a stage where it is capable of performing three tasks simultaneously. These are: 1) seam following, 2) penetration control and 3) defect detect and that all three functions are monitored in real time and at real welding speeds. This claim refers to the functions of the sensors only, there is no claim to have produced a tri-control sensing

device. Two of the functions (penetration and seam following), may indeed, be controlled; the third (defects) is not available for control and this is the root of the philosophical problems referred to earlier. It is possible to identify a number of defects, but what control function is available to correct/counteract the problem so as to prevent further occurrence? Weld penetration may be corrected by variations in the welding current, seam following problems are corrected by simple left/right orthogonal movement, but we have reached no solution as to how defects may be prevented by the parameters within our power to control. Simply to employ the sensor to mark defective areas, a ring warning alarm, (besides controlling the other two functions) seems to be a waste of technology. When all three functions are fully integrated into the controller, the only way forward, surely, will be to control the whole unit by some kind of artificial intelligence shell. A start was made on this route in 1986 using a very simple expert system which actually produced a "head-up-display" (HUD) on a VDU with the opportunity of operator interrupt/override functions.^[21,24] This approach was not followed through and was abandoned after 1 successful demonstration due to time pressure. (All this time only two functions were under control, but both were displayed by schematic models and both were manually variable by the operator). Current thinking favours a simple expert system shell which will allow access to welding quality standards, such that if a defect is located the system will "pull down" the appropriate standard (porosity, cracks etc) and act accordingly. If the defect is within acceptable dimensions then no action will be initiated but if the defect is unacceptably large, then some action will be initiated (be it a total close down of the process or a recording of defect type and location) to draw attention to this problem.

There are two further areas for development with this sensor arrangement, 1) high speed (e.g. laser) welding process and 2) post solidification defect detection. Prior work has demonstrated, very clearly, that this sensing technique is based on fundamental effects and that if a weld pool is present, then this sensor can be expected to work.^[13,16] A practical limitation is the rate of which it could react (already $< 1 \mu\text{s}$) but this could be further reduced by faster computers and these devices are becoming both faster and cheaper day by day. Laser welding using this sensor system is currently under serious development to be employed in ship building, even it though only two functions will be controlled.

It is the desire to detect defects occurring some time after solidification (e.g. some hot cracking types) that will test the limits of the sensor as currently envisaged. Any desire to extend the ability of this sensor in the defect detection mode would inevitably diminish its abilities in the other two functions. (this really could only be achieved by rotating the ultrasound probes rearwards, a move which could possibly reduce its abilities in the other two functions). Figure 12a shows this rotation and the limitations that it would impose, although the usage of a second U.S. Probe (figure 12b) could serve a very useful purpose for past weld defect detection. Work will commenced in the near future to "gang" together two probes (on each side of the weld), the second probe to view the solid weld bead some distance behind the weld pool.^[32]

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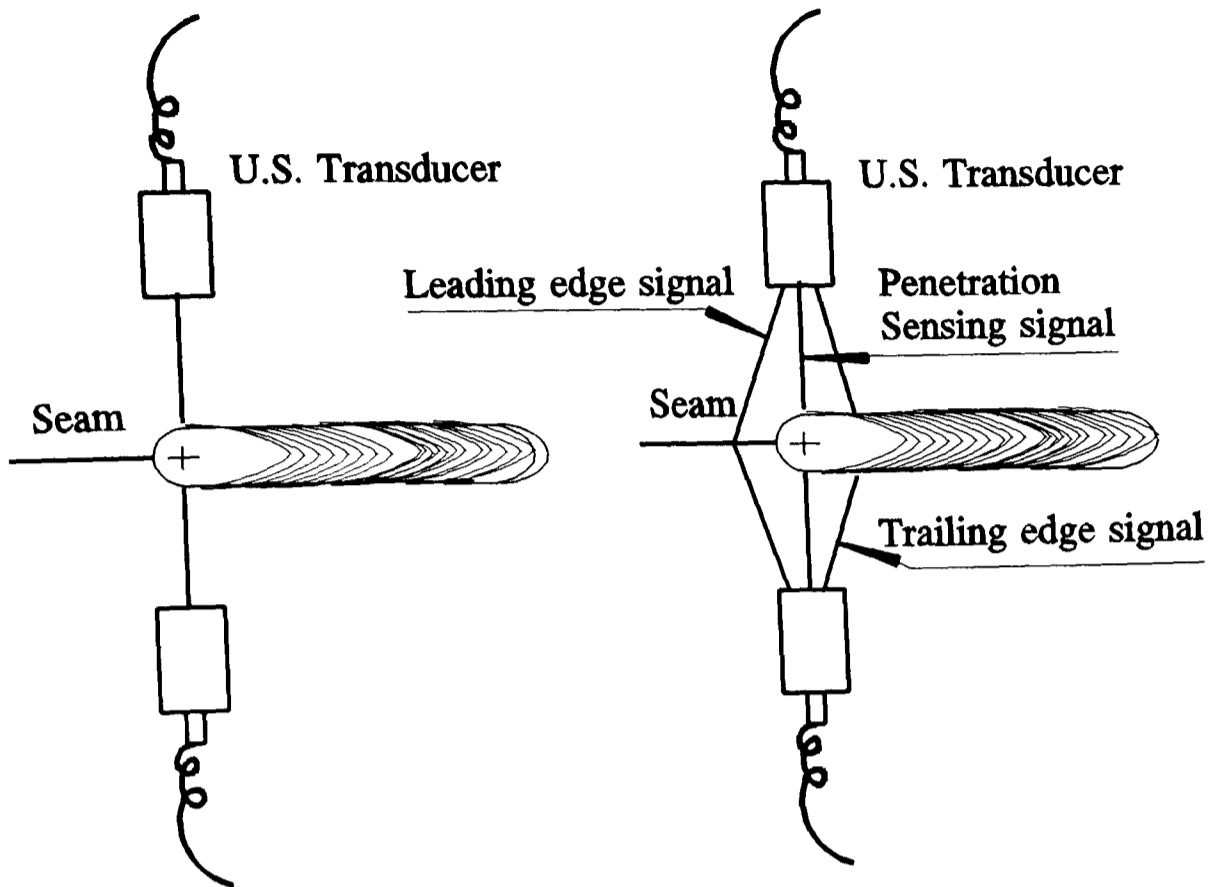


Figure 1 Schematic diagram of U.S. beam path: a) single line b) beam spread

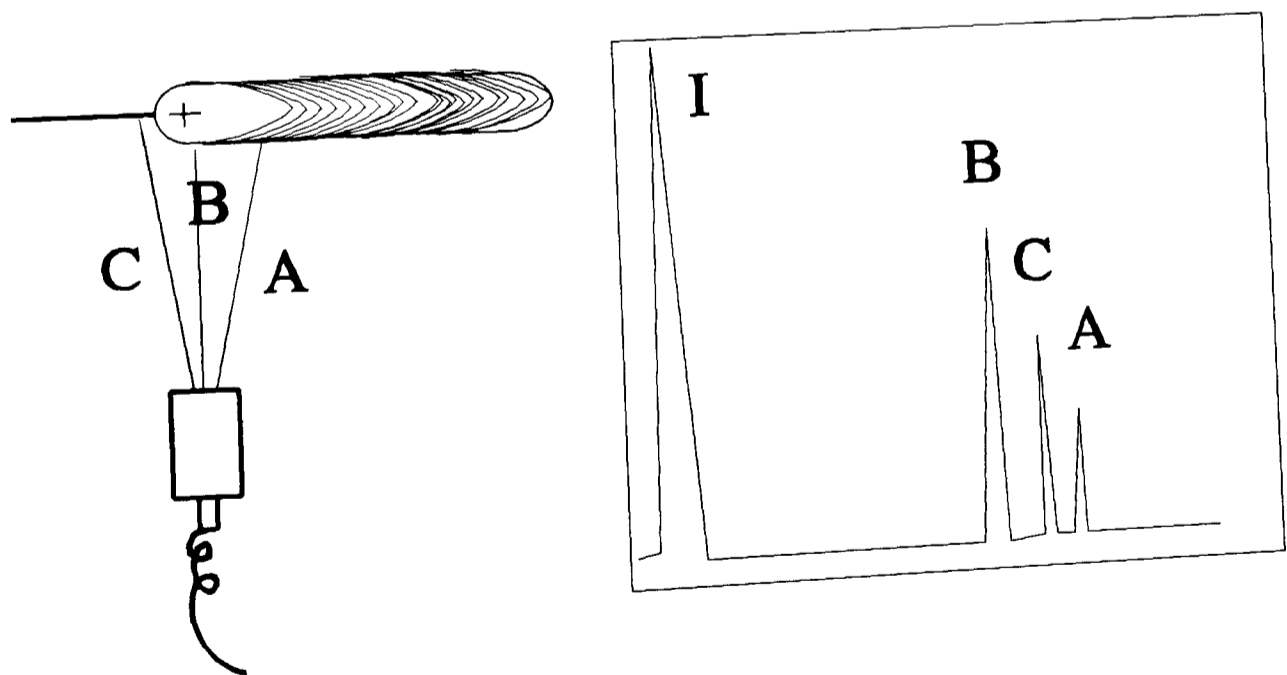


Figure 2 Schematic diagram of 3 signals showing on U.S. scope

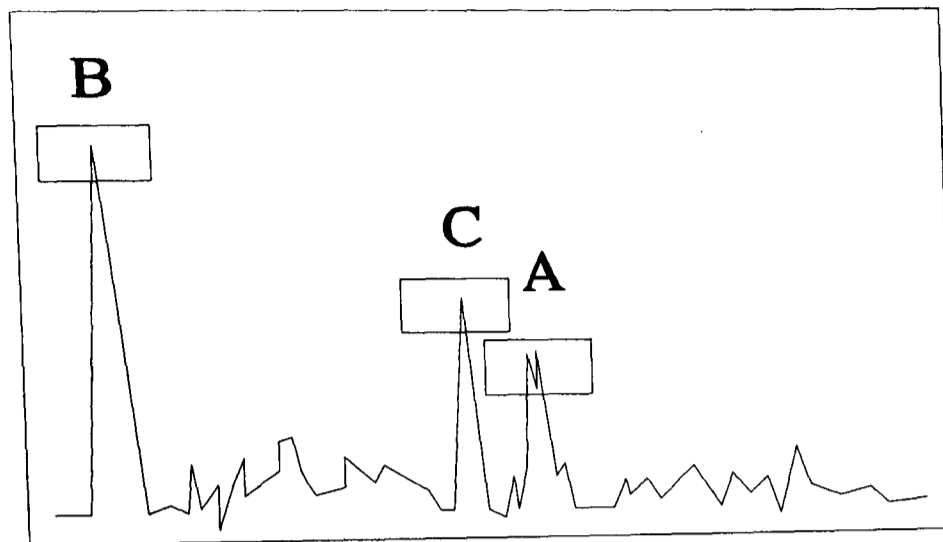


Figure 3 Time Window and U.S. signals

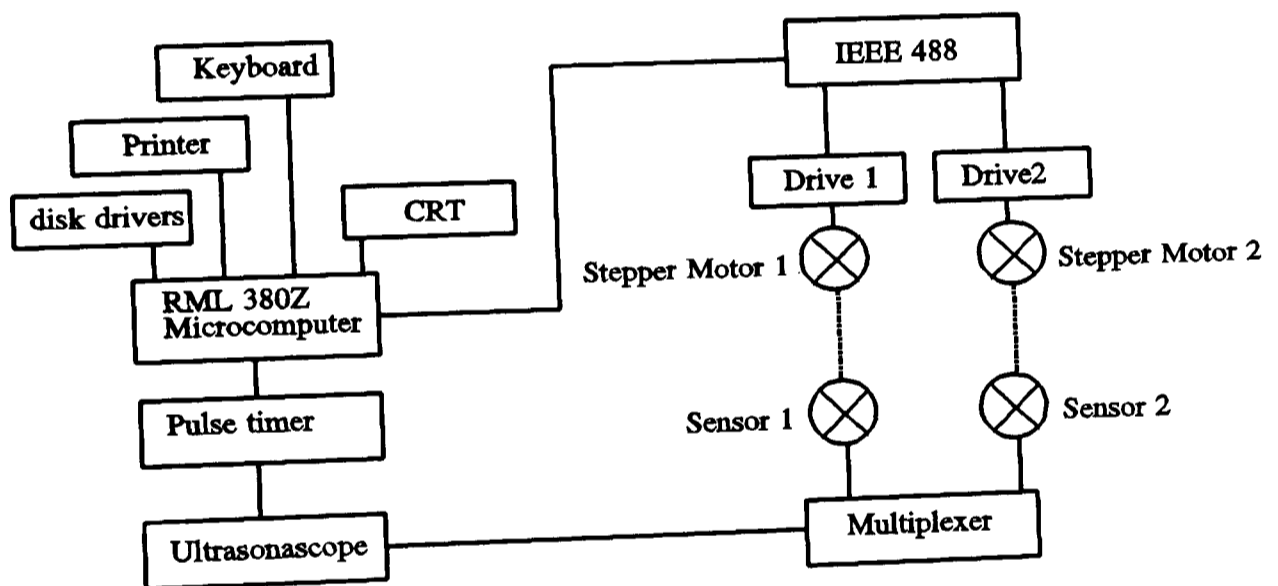


Figure4 Block diagram of computer control system

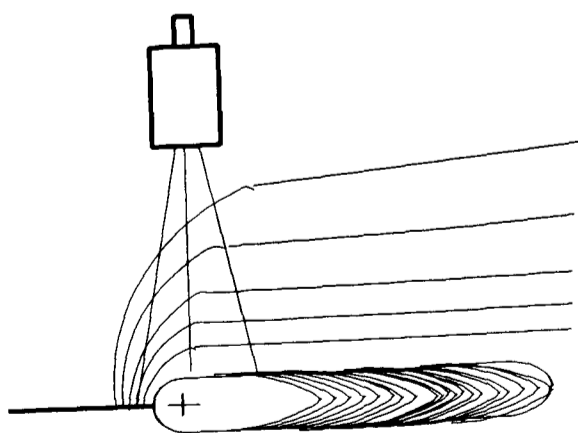


Figure 5 Diagram of probe and thermal flux around weld pool

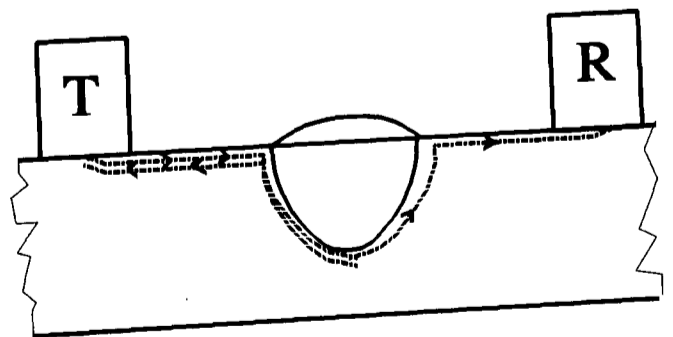


Figure 6 Behaviour of ultrasonic Rayleigh wav

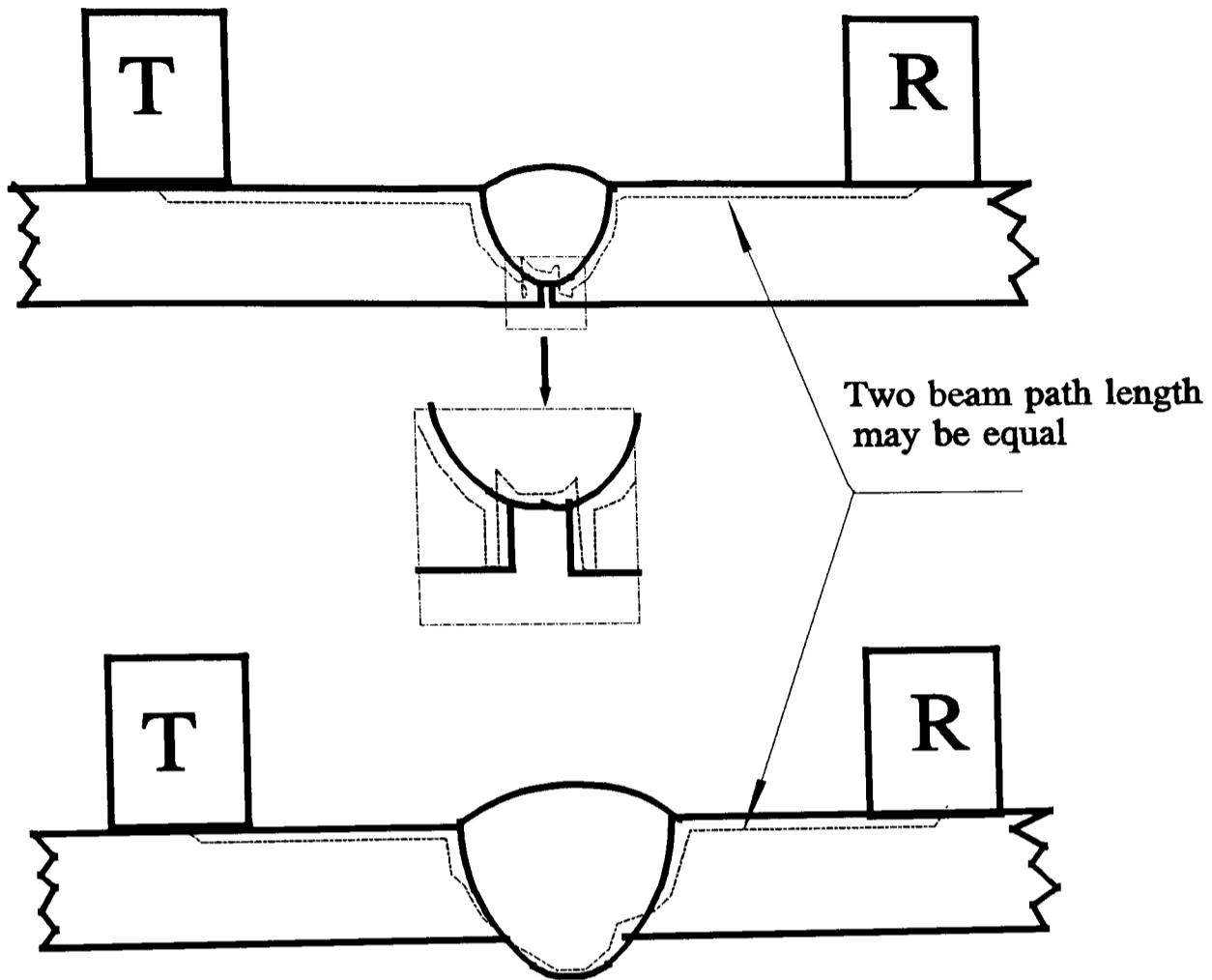


Figure 7 Area of uncertainty of lack of penetration/and over penetration

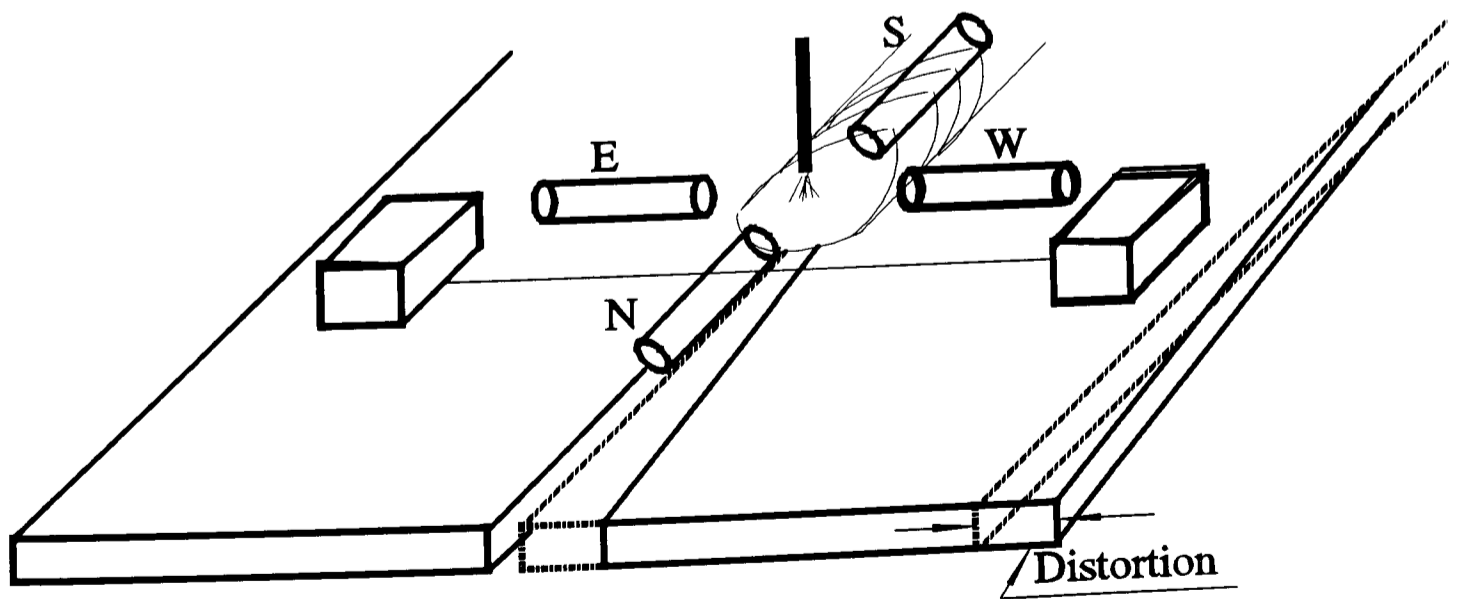


Figure 8 Schematic diagram of thin plate sensor

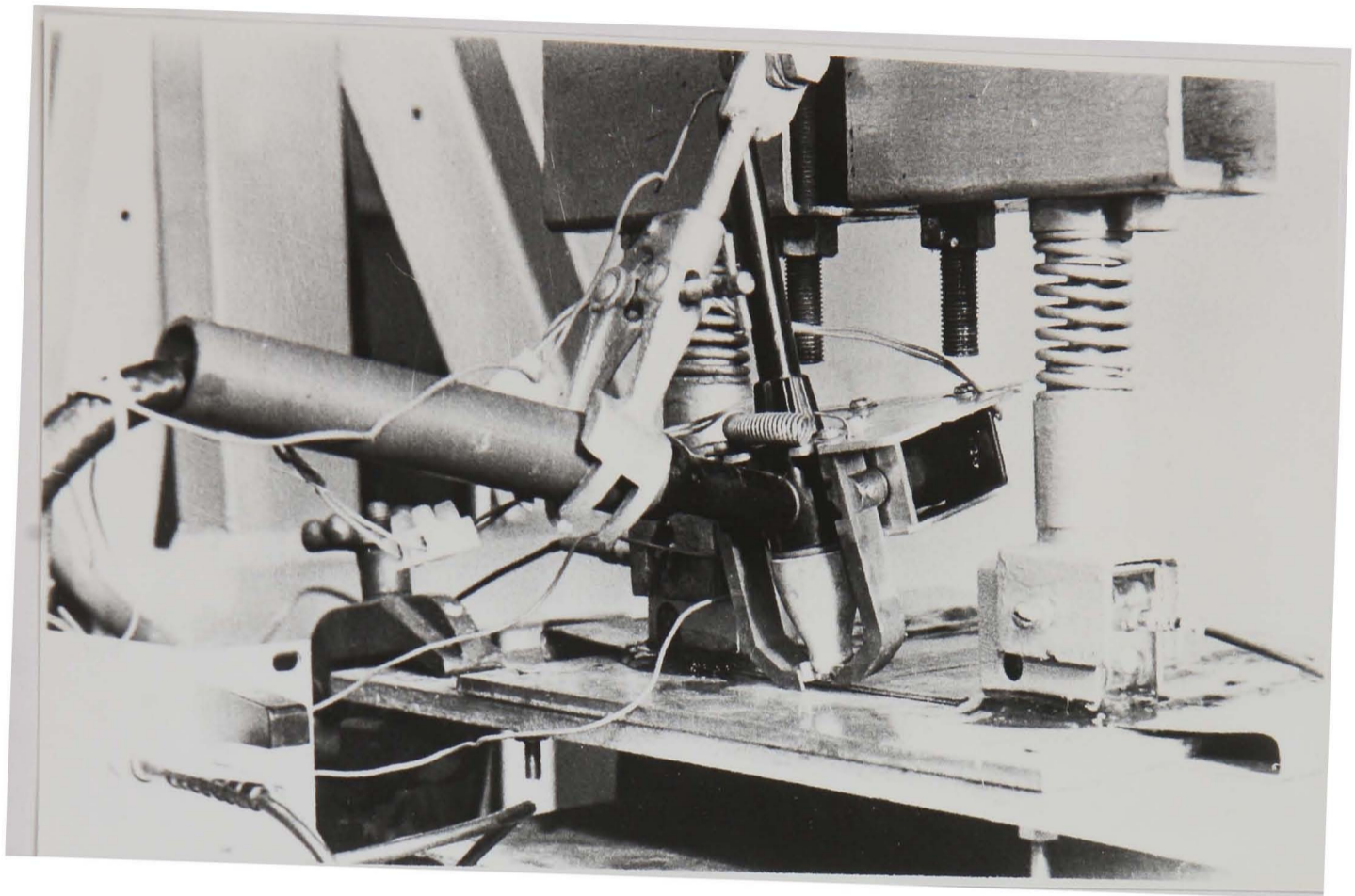


Figure 9 Magnetic deflection probes around G.T.A.W. torch
(For 1 mm plate, from reference 25)

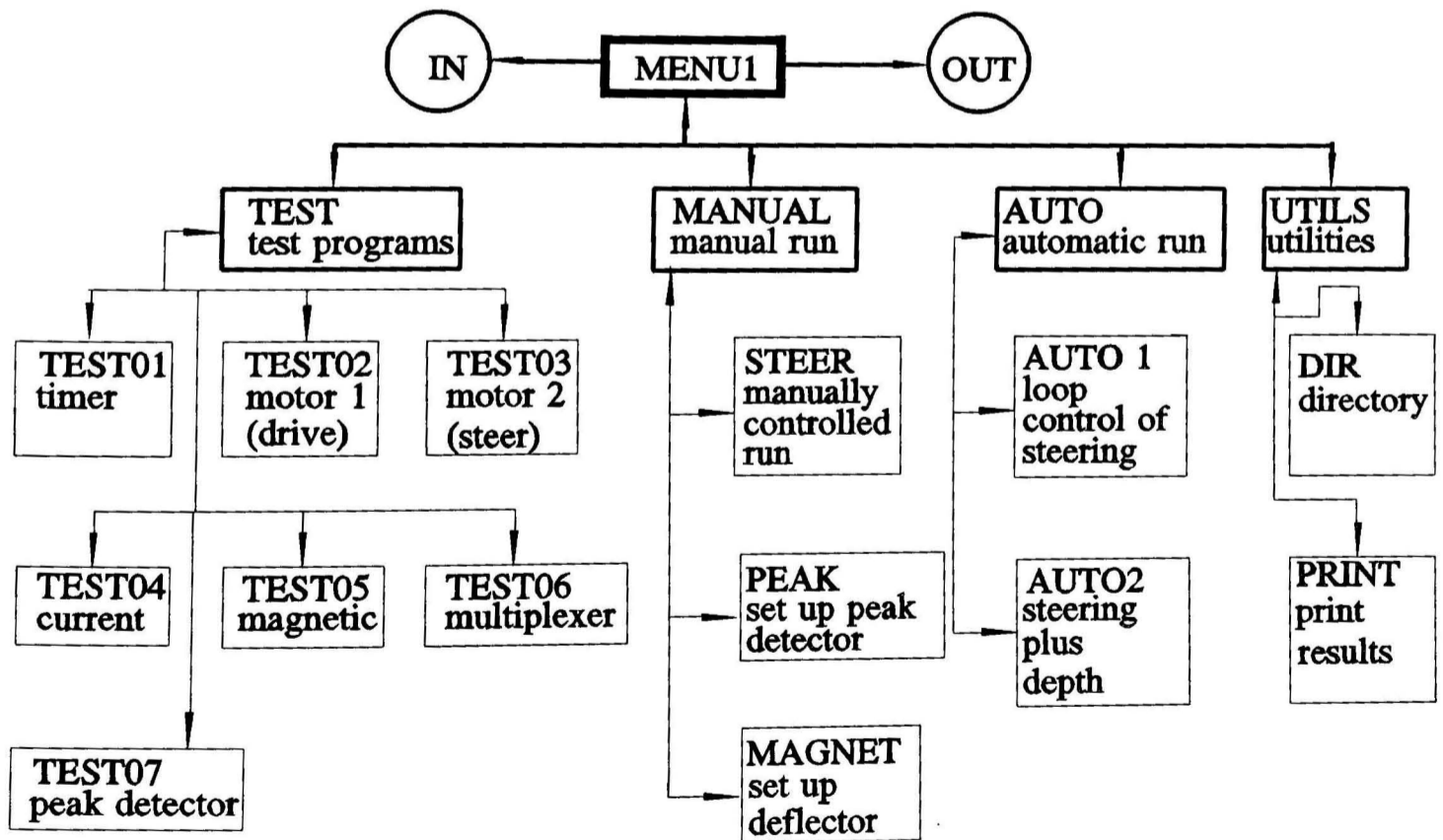


Figure 10 Block diagram of Rayleigh wave sensor

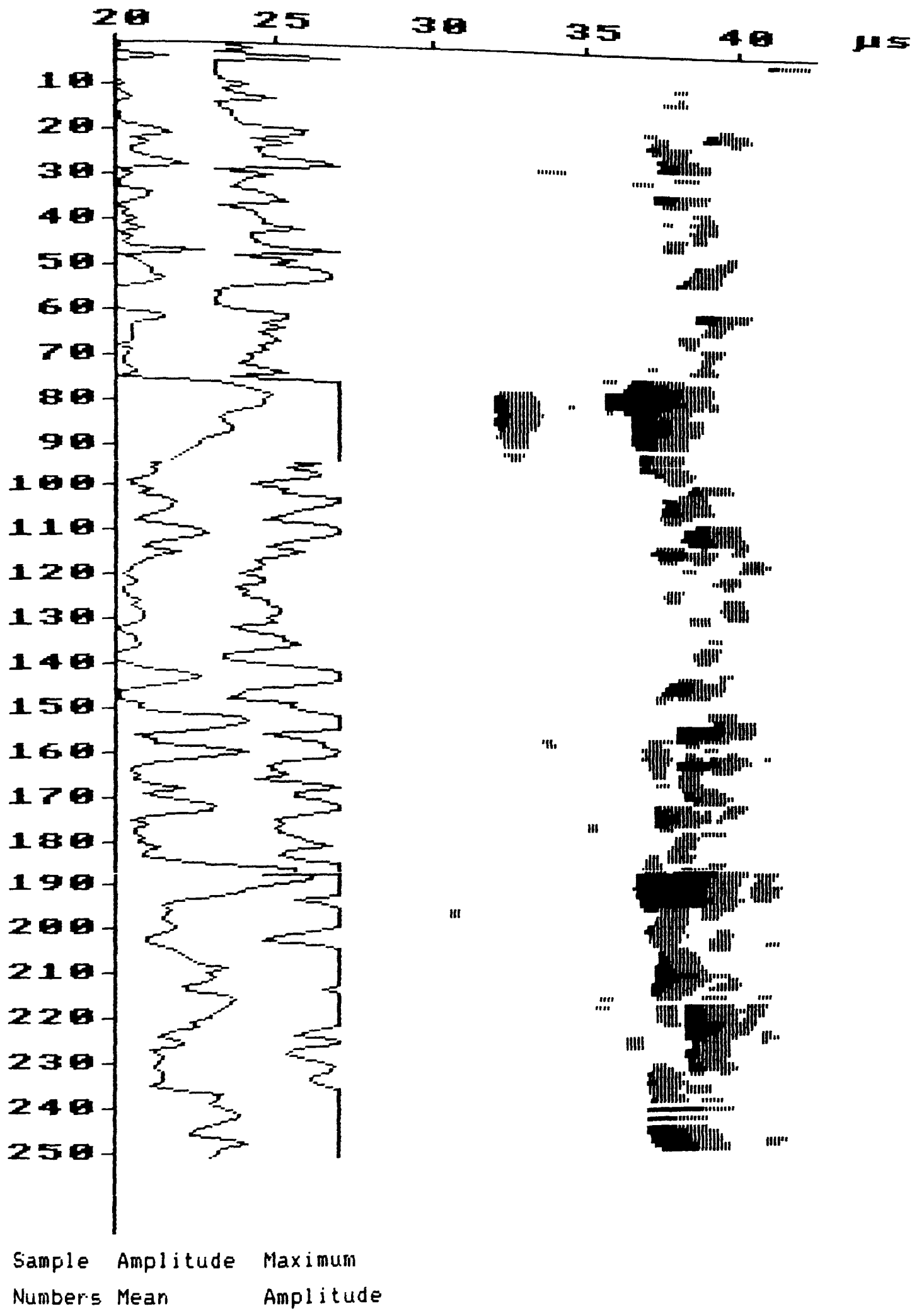


Figure 11 B-scan for random porosity (average pore size bout 0.75 mm)