Design of an instrumented Smart Cutting Tool and its Implementation and Application Perspectives

Chao Wang, Kai Cheng, Xun Chen, Timothy Minton, and Richard Rakowski

Advanced Manufacturing and Enterprise Engineering (AMEE) Department, School of Engineering and Design, Brunel University, Uxbridge UB8 3PH, UK

Corresponding authors: chao.wang@brunel.ac.uk and kai.cheng@brunel.ac.uk

Abstract

This paper presents an innovative design of a smart cutting tool, using two surface acoustic wave (SAW) strain sensors mounted onto the top and side surface of the tool shank respectively, and its implementation and application perspectives. This surface acoustic wave - based smart cutting tool is capable of measuring the cutting force and the feed force in a real machining environment, after a calibration process under known cutting conditions. A hybrid dissimilar workpiece is then machined using the SAW - based smart cutting tool. The hybrid dissimilar material is made of two different materials, NiCu alloy (Monel) and steel, welded together to form a single bar; this can be used to simulate an abrupt change in material properties. The property transition zone is successfully detected by the tool; the sensor feedback can then be used to initiate a change in the machining parameters to compensate for the altered material properties.

Keywords

Force measurement, Smart cutting tool, smart machining, surface acoustic wave (SAW) strain sensor, instrumented cutting tool.

I. INTRODUCTION

In modern advanced manufacturing, high precision machining is essential, together with a trend for machining high value added components with an ever higher dimensional accuracy and finer surface roughness. With high quality surface roughness requirements, some indirect condition monitoring methods have been proposed to monitor cutting forces and acoustic emissions (AE) with high precision. A change in the cutting force and increase in the number of events in the AE signal is directly related to the cutting/tooling conditions and thus will have a direct effect on the machining outcome [1-3]. Wear and breakage of cutting tools can also increase the cutting forces and add vibrations to the tool holder, resulting in a loss of dimensional accuracy, poor surface roughness and even chatter marks on the machined workpiece [4]. In order to avoid such damage, some devices have been specially designed and applied to measure the cutting forces. Various types of dynamometer have been developed by companies to measure these cutting forces with high accuracy and with a high frequency response. Additionally, these dynamometers also measure cutting forces as part of condition monitoring systems widely used in laboratory environments. However, there are some limitations in their use, such as the decrease in the reliability of the sensors in such a harsh operating environment. Moreover, due to the size and weight of these products, they are not applicable for all layout-constrained machines and could also interfere with cutting performance because of the stiffness reduction on the tooling system [5]. The current state of the art for smart cutting tools include those with integrated thin film sensors, designed to detect the wear of the cutting tools [6], with also the addition of internally cooled tools to reduce temperature of the cutting tool tip with tooling developed with micro-channels [7]. As smart features in cutting tools are becoming more important in modern manufacturing, the advanced modern sensor technologies have been adopted as an essential trend in design of innovative smart cutting tools. Over the last decade or so, sensors based on surface acoustic waves (SAW) form an important part of the sensor family, these have seen diverse applications ranging from gas and vapour detection to strain, pressure and temperature measurement [8-11]. This paper presents the development of a smart cutting tool with two surface acoustic wave (SAW) strain sensors mounted onto a tool shank to measure cutting force and feed force in real time during the machining process. To evaluate the performance of the proposed smart cutting tool in a real machining environment; calibration (section II, F), sensitivity, cross talk and hysteresis (section II, G) have been investigated and compared with a Kistler dynamometer. The sensing of cutting tool failure is crucial for any unmanned manufacturing system, since such a tool failure is directly related to damage of the work material and it is most likely to cause additional troubles for the machine tool and other unforeseen issues in subsequent manufacturing processes. The development of a SAW-based smart cutting tool is therefore proposed to measure the cutting force in smart machining.

The use of computer numerical control (CNC) machine tools has rapidly expanded since 1990s. The advantage of CNC technology is that it reduces the skill requirements for machine operators. Moreover, cutting parameters of the CNC systems, such as spindle speed and feedrate, have been prescribed by a part-programmer based on his experience or from a fixed machine database, in order to protect the tool [12, 13]. It is well-known that tool breakage could increase not only total machining costs but also the total machining time. On the other hand, ‘tool overprotection’ has caused CNC machines to operate under inefficient operating conditions. Due to these limitations of the conventional CNC system and machining algorithms, adaptive machining through adaptive control by constraint (ACC) has been developed to maintain the main cutting force constant, in order to avoid tool breakage and maintain high productivity [14].

This paper presents the innovative design concept (section II, A), application principle (section II, B), operation (section II, C) and implementation process (section II, D) for the SAW-based smart cutting tools, for use particularly in precision turning operations. The implementation and application perspectives for those smart cutting tools are explored and discussed, against smart machining requirements from a number of industrial applications [15, 16]. Smart cutting is of great potential and industrial significance particularly for high value added machining purposes, such as machining of difficult-to-cut materials (Titanium, Inconel and Si-based infrared devices) and hybrid dissimilar materials.

II. Design of the Surface acoustic wave - based smart cutting tool and its implementation

A. Design conception

Sensor-based smart cutting tools are built with autonomous and self-learning capabilities, which will lead to an increased metal removal rate (MRR), improved part quality and surface roughness, reduced costs, and lead to working in optimal cutting conditions. They are featured in plug-and-produce, self-condition monitoring, self-positioning adjustment, self-learning, autonomous and highly automated CNC machining environments. This paper is to investigate a smart cutting tool with two surface acoustic wave (SAW) strain sensors as the sensing unit mounted onto a conventional tool shank in order to measure both cutting force and feed force in real machining environments for industry-driven applications of smart machining.

B. Surface acoustic wave (SAW) sensors for smart tooling

In acoustic emission (AE), the sound waves produced when a material undergoes stress as a result of an external force, are the plane wave propagating in an infinite homogeneous medium. Surface acoustic waves are ultrasonic waves propagating along the surface of solids; the transmission and reception principle is based on piezoelectric transducers. SAW sensors often consist of hundreds of electrodes, namely inter-digital transducers (IDTs) as shown in Fig. 1, fabricated like comb-shapes on the top surface of piezoelectric substrate materials like quartz and lithium-niobate. The function of an IDT is to convert electrical energy into mechanical energy, and vice versa, for generating and detecting the SAW [17-19]. When the IDTs are directly connected to an antenna, the SAW can be excited remotely by electromagnetic waves. It is therefore possible to construct passive, wireless, remotely operable SAW devices.

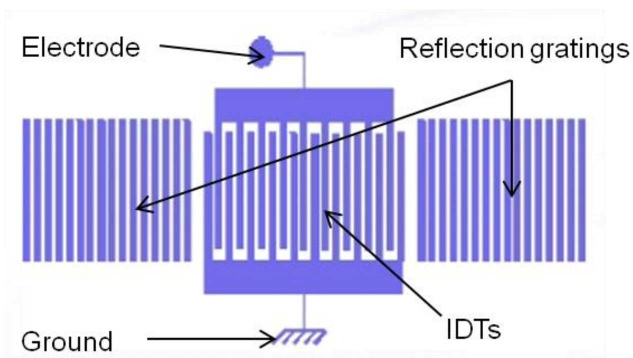


Fig. 1. Surface acoustic wave strain sensor structure schematic.

The SAW strain sensor substrate is made of quartz with a Y-rotated, X-propagating quartz (ST-X quartz) and the electrodes are made of aluminium (Al). Rayleigh waves can be generated using quartz with velocity of 3158 m/s, moreover, the energy of the Rayleigh wave is confined close to the surface and dies out within two or three wavelengths in depth from the surface. The resonant frequency of the SAW is chosen to be 433 MHz [20]. Based on the resonant frequency (fr) and the velocity (V), the elastic wavelength (λ) can be determined using equation (1).

$$\lambda = \frac{V}{fr} = \frac{3158\, m/s}{433\, MHz} = 7.29\ \mu m \quad (1)$$

The distance between successive IDT electrodes P is 3.645 µm, which is half of the elastic wavelength. The geometries of the SAW structure used in the simulation are listed in Table 1. The SAW strain sensors used in this application, provided by SENSEOR, as shown in Fig. 2 with dimensions of 7 mm × 5 mm.

TABLE I

GEOMETRIES OF SAW SUBSTRATE AND IDT

Substrate thickness	350 µm
Periodicity of electrode	3.645 µm
Width of electrode	1.00 µm
Al electrode thickness	0.10 µm

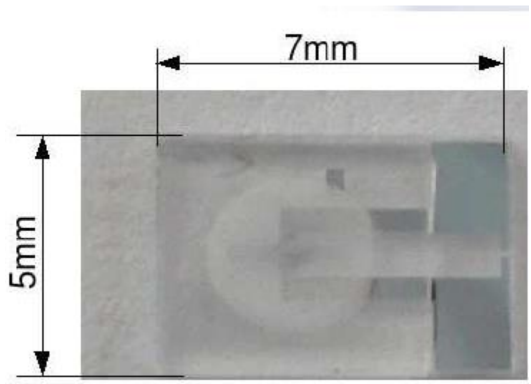


Fig. 2. SAW strain sensor with dimensions

C. Wireless passive operation and LabVIEW user-interface

Wireless SAW strain sensor interrogation is carried out using a wireless interrogator WR D005 purchased from SENSeOR Company as shown in Fig.16. The interrogator is composed of an emission part and a reception part and is functional as a transceiver and receiver. The interrogation unit sends an interrogation signal (a pulse) to the SAW strain sensors where a surface acoustic wave is generated and then propagates from the IDT. Then the interrogation unit is switched into ‘’listening mode’’ to receive the signal sent back from the SAW sensors which contain the information of the measured physical phenomenon [21, 22].

The customized user-interface has been developed in LabVIEW [23]. In order to read the signal output of the SAW sensor through RS232 connection in LabVIEW, several communication protocols, such as input/output connection channel (COM5), baud rate (57600), data bits (8) and buffer size (4096), need to be defined as shown in Fig. 3. The output string includes frequency, received power, emitted power and measurement variance to indicate the working condition of the SAW strain sensor. The two output frequencies of the SAW strain sensors are displayed in Fig. 3.

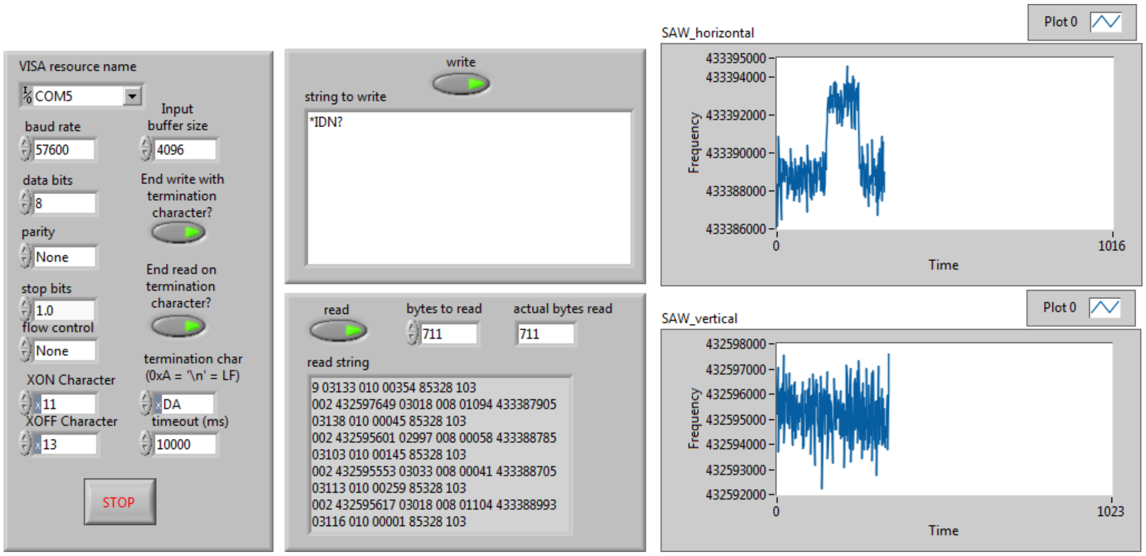


Fig. 3. Custom user interface developed in LabVIEW for reading the output frequency of the SAW sensors.

D. *Surface acoustic wave instrumented tool holder setup*

Two SAW strain sensors have been installed by using Vishay Mbond 200 glue onto the modified tool shank for both the cutting and the feed force measurements as shown in Fig. 4. Both sensors are located 45 mm away from the cutting tip and just in front of the clamp fixture. The current arrangement can keep the sensors at a safe distance away from swarf and running chips whilst making sure that the sensors are mounted at a point where the maximum strain occurs. An antenna is fixed at the end of the tool shank in order to, as far as possible, avoid chip strikes during machining, which could generate distinct peaks that could affect the force measurement [24]. Plastic covers will be fixed onto the tool shank in which the sensors are located to prevent damaging the SAW sensors by the swarf generated during machining.

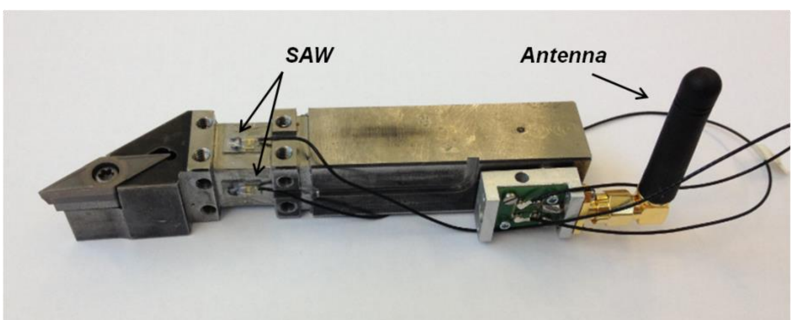


Fig. 4. Cutting tool shank instrumented by surface acoustic wave strain sensors.

In order to increase sensitivity of the smart cutting tool in force measurement, the tool shank has been modified, as shown in Fig. 4. The tool shank cross section, where the SAW sensors are attached, is machined down by 3 mm X 3mm in both depth and width. Meanwhile, in order to ensure that the dynamic response of the modified tool shank is still in an acceptable range to measure the cutting force and feed force, dynamic response testing was carried out. The proposed experimental setup, as shown in Fig. 5, includes the impact hammer, accelerometer, sensor power supply and NI data acquisition card (DAQ). Fig. 6 shows the dynamic response of the modified tool shank is 1595 Hz and 1411 Hz in the cutting force direction and the feed force direction, respectively. The results of the dynamic response indicate that the spindle rotation speed cannot be operated adjacent to 1595 Hz and 1411 Hz in order to prevent resonating of the modified tool shank that could lead to damage the surface acoustic wave (SAW) strain sensors due to excessive strain and as well as chattering during machining process.

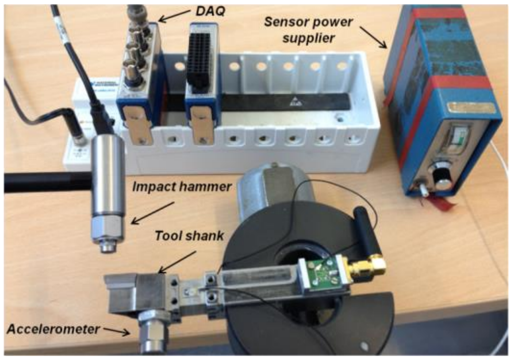
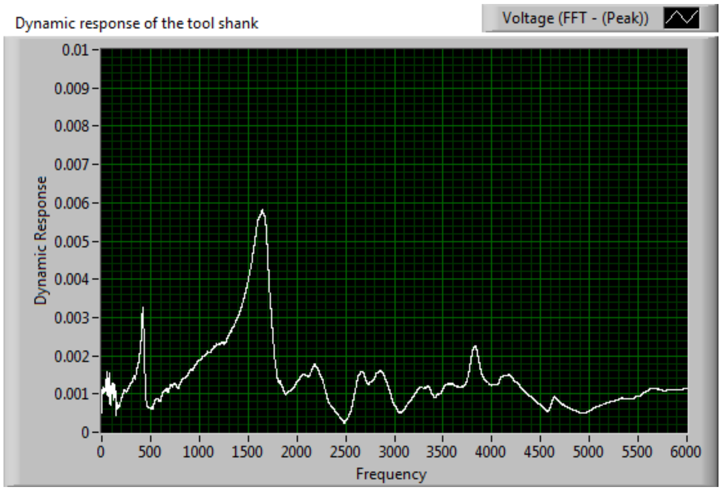
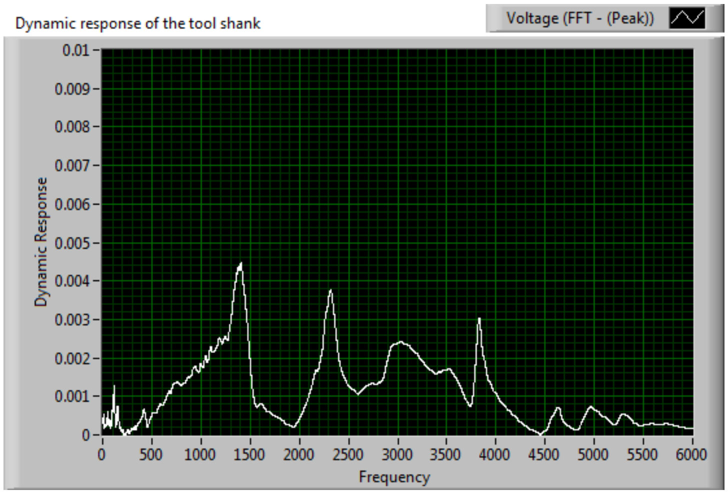


Fig. 5. Experimental setup of using impact hammer and accelerometer to measure dynamic response of the modified tool shank.



(a)



(b)

Fig. 6. Dynamic response of 1595 Hz and 1411 Hz in (a) cutting force direction and (b) feed force direction.

E. Sensor characterization

When cutting forces act on the tool tip during machining, the effect of the physical parameter strain can be induced in the tool shank and then sensed by the SAW strain sensor. Instrumentation with acoustic waves is based on measuring variations of the acoustic propagation velocity of the wave, or wave attenuation. These variations imply changes in wave properties (such as frequency for resonators) which can be translated into the corresponding change of the physical parameter measured. Any applied strain changes the resonant frequency of the SAW strain sensors, which can then be used to correlate to the corresponding change of the physical parameter measured. The relationship between this force and the strain is explained using equation (2); the tool shank is most likely to be deforming within the elastic region in machining applications, so a linear equation (3) is given in order to correlate the relationship between the strain the frequency change.

$$\varepsilon = -(h/2)\, F(L - X)/IE \qquad (2)$$

$$\Delta f = 2S_G \cdot \varepsilon \qquad (3)$$

Where h is the tool shank thickness, L is the length of the tool shank respectively, Δf is the natural frequency change of the SAW strain sensor, S_G is the calibration coefficients of the SAW, X is the distance between the SAW and the fixed end, E is the Young's modulus of the tool shank and I is the second moment of area.

Fig. 7 shows the frequency response of a pair of SAW strain sensors mounted onto the tool shank shown in Fig. 4. The two SAW strain sensors have their mounted centre frequency of 432.72 MHz and 433.38 MHz represented in X-axis. Moreover, the signal level was represented in Y-axis indicating the quality of the transmission signal. Each peak height should reach to at least 2000 in amplitude value in order to maintain an optimal link budget between the transceiver and the SAW strain sensors. The maximum sampling rate of the SAW strain sensors is 150 Hz (also known as a transmission frequency between the interrogation unit and the SAW strain sensors), and the interrogation distance is about 20 cm between the antenna and the interrogator.

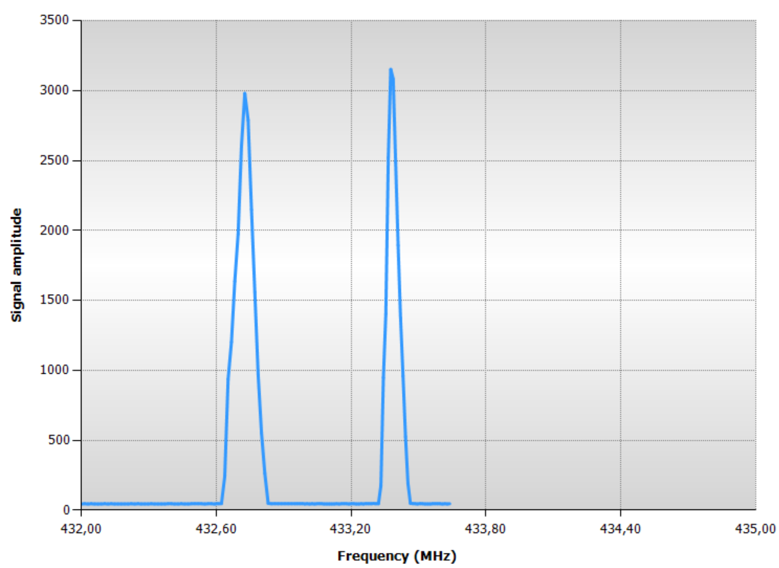


Fig. 7. Frequency response of a pair of SAW strain sensor.

F. Smart cutting tool calibration

A force signal generated from a turning process includes static and dynamic components. The static force components can be used to investigate cutting process performance and cutting tool condition to some extent. In order to use the SAW-based smart cutting tool device for force measurement in real machining, calibration was carried out to find the factor between strain and force. A known static force loading from 10 to 100 N, in steps of 10 N, is applied on the tool tip in order to produce a corresponding frequency change measured by the SAW. Fig. 8 and Fig. 9 shows a linear relationship between the force and the frequency output within the range from 0 to 100 N for the SAW strain sensor mounted on the top surface (namely SAW-Horizontal) and the device on the side surface of the tool shank (namely SAW-Vertical) respectively. This confirms that the tool shank is deforming in the elastic region [15]. Curve fitting has shown the exact equation for describing the relationship between the force and the frequency for each sensor, with a considerably high R-squared value of 0.999 and 0.998, respectively.

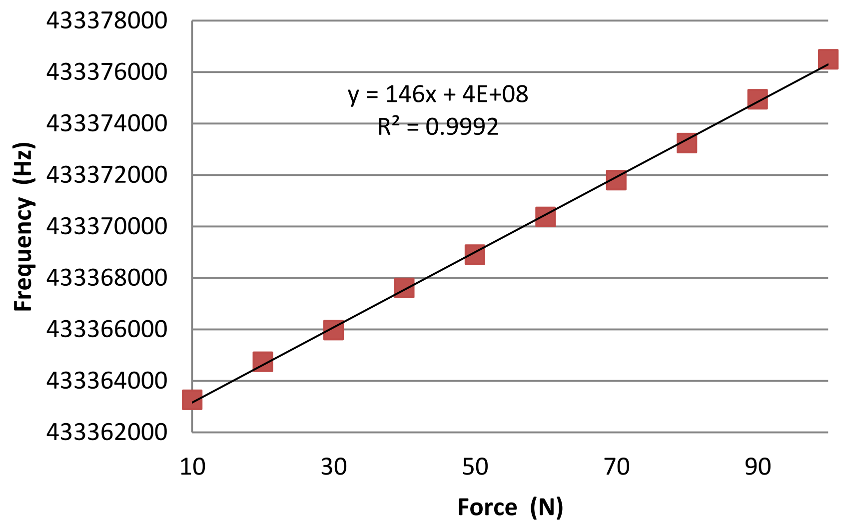


Fig. 8. SAW calibration on the SAW mounting onto the top surface of the tool shank.

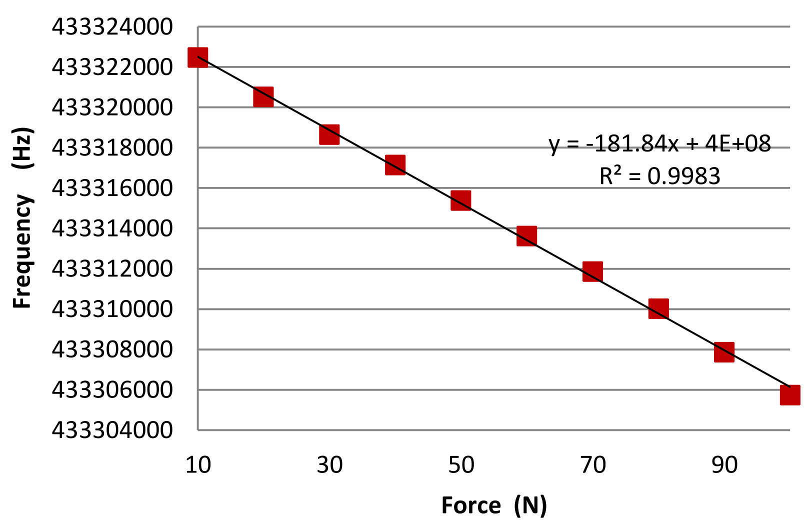
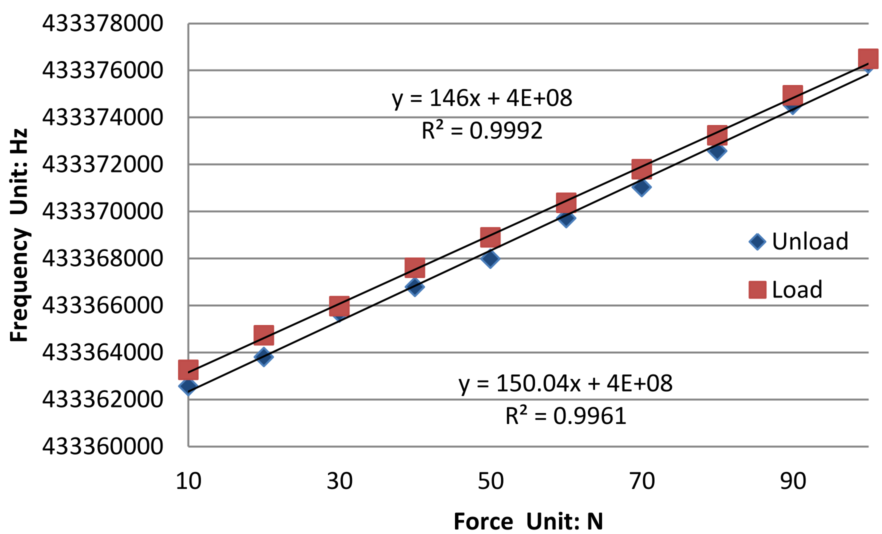


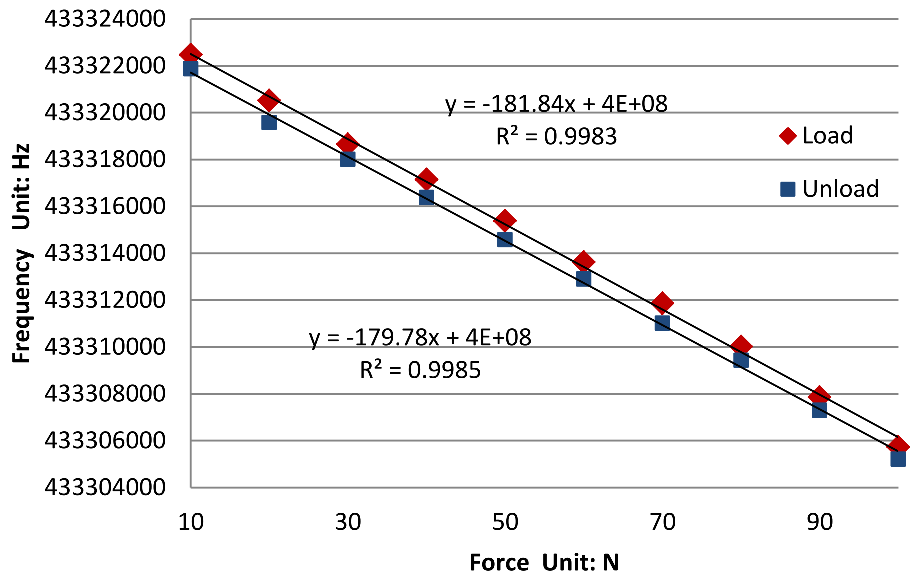
Fig. 9. SAW calibration on the SAW mounting onto the side surface of the tool shank.

G. Smart cutting tool assessment

In order to assess the SAW-based smart cutting tool, there are several technical data sets that need to be investigated, including sensitivity, hysteresis and cross talk effects. The sensitivities of both SAW horizontal and vertical sensors can be calculated to be 152 Hz/N and 185 Hz/N respectively from Fig. 8 and Fig. 9. The hysteresis of the SAW sensors is 7.3% and 4.7% calculated from Fig. 10 (a) and Fig. 10(b) respectively, with loading and unloading tests on the tool shank over the full range up to 100N. The impact hammer testing technique was employed to detect the cross talk in the proposed smart cutting tool. The tip of the cutting insert was impacted vertically and horizontally using the impact hammer. Both signal outputs of the impact from the impact hammer and the SAW sensors were converted from the time domain into the frequency domain. In the frequency domain, only the low frequency components from 0 to 75 Hz are considered, the responses were recorded from the SAW sensors and the impact hammer by applying a force in the vertical and horizontal directions respectively. The next procedure includes the technique to normalize the responses of the two impacts by dividing the dynamic response of the SAW sensors with the one from impact hammer. The technique was repeated three times for the three replications of the impact tests and the averages of the normalized values are denoted accordingly for the vertical and horizontal impacts. The cross talk effect of 20.3% and 13.2% associated with the SAW strain sensors was found by using the impact hammer testing technique. Table 2 lists all the mechanical aspects of the SAW-based smart cutting tool compared to a Kistler dynamometer model 9257b.



(a)



(b)

Fig. 10. Hysteresis calculation for (a) SAW-Horizontal and (b) SAW- Vertical with loading and unloading test.

TABLE II

TECHNICAL DATA OF THE SAW STRAIN SENSOR AND KISTLER DYNAMOMETER 9257b

SAW	**Sensitivity**	**Hysteresis**	**R^2**	**Bandwidth**	**Cross-talk**	**Dimension**	**Weight**
Cutting force	152 Hz/N	7.3%	0.999	150 Hz	20.3%	Negligible	Negligible
Feed force	185 Hz/N	4.7%	0.998	150 Hz	13.2%		
Kistler	**Sensitivity**	**Hysteresis**	**R^2**	**Bandwidth**	**Cross-talk**	**Dimension**	**Weight**
Cutting force	7.5 pc/N	0.5 %	0.999	2 kHz	2%	100x170 mm	7.4 kg
Feed force	3.7 pc/N	0.5 %	0.999	3.5 kHz	2%		

III. SMART MACHINING THROUGH THE SMART CUTTING TOOL

A. Smart machining conception and configuration

To make CNC machines smarter and address state of the art manufacturing requirements, smart machining is needed to satisfy every customer-specific request. Today's manufacturing processes need to satisfy smaller batch sizes, customer-specific variations of products, and the trend toward highly integrated products, which combine a lot of different functionality in one device. Machine requirements, with some levels of smartness, are defined below:

- Operate autonomously (intelligent)
  - High degree of flexibility
  - Awareness of machine and process parameters
- Avoid and correct processing errors (secured)
  - Monitoring and analysis capabilities
  - Quick modification of process plan and operation parameters
- Learn and anticipate (managed)
  - Model-based and adaptive control
  - Simulation capabilities
- Interact with other machines and systems (connected)
  - Time-sensitive and non-deterministic communication
  - Interconnected systems – “smart factory”

Smart machining, a subset of smart manufacturing, mainly focuses on the machining process, in order to improve process reliability and optimize machining performance through the integration of sensor, tool and machine-tool technology. The potential advantages are:

- minimization of the machining time;
- improvement of surface roughness;
- maximization of tool life;
- machining on special geometry workpieces with high precision and efficiency, such as slender shafts and thin-wall hollow cylinders;
- self-monitoring and process optimization;
- self-learning and performance improvement over time;
- awareness of the cutting process in dynamic real time, such as shear angle, chip formation, cutting forces and interaction within the cutting zone;
- plug-and-produce feature required for both the process and the machining system.

B. Material and cutting conditions

The use of composites and hybrid dissimilar materials has shown a vast increase in popularity amongst engineers and designers. Rotary Friction welding is a solid-state joining process; friction is developed at the interface of a rotating bar contacting a stationary bar of the same or dissimilar material. After sufficient heat is built the rotation is ceased and a large forging force is applied to join the materials. This process is particularly useful in joining dissimilar materials, creating hybrid dissimilar materials which can achieve superior performance for limited cost. A common application for such a hybrid material is used in the manufacture of IC engine valves. The valve head experiences high temperatures and stresses and so it is preferred to be constructed from high strength materials [25, 26]. The valve stem, however, is not put under the same high stresses and temperatures; so making this part out of one material would waste a large proportion of high strength, high cost material. This problem can be solved by friction welding a high strength nickel alloy to low cost carbon steel. Other applications include: pump shafts, spindle blanks, automotive stabilizer bars and oil/gas equipment. The issue with this best-of-both worlds approach is the shift in metal cutting procedures which is needed to compensate for a hybrid dissimilar material. The same cutting speeds, feeds and depths of cut and even tool types can be incompatible for the two or more materials which make up the workpiece.

For the test carried out in this paper, the workpiece material was a cylindrical, friction welded bar, consisting of a generic carbon steel joined to a nickel-copper, (Monel) alloy to form a dual material work-piece. The bar was mounted within an Alpha Series 1350X CNC lathe (with a Fanuc controller); with the steel end in the chuck. All cuts were made from the Monel end towards the steel end with the transition area roughly central. Additional instrumentation was applied to check the validity of the sensor feedback. All cuts were made in dry machining conditions using constant machining parameters: cutting speed- 80 m/min, feedrate- 0.15 mm/rev and depth of cut- 0.2 mm.

C. High precision smart cutting through constant cutting force

Maintaining constant cutting force throughout the high precision cutting process can reduce the tendency for cutting tool breakage and keep the geometry of the machined component within high accuracy. The basic block diagram of the ACC system used to achieve a constant cutting force in the high precision turning process is shown in Fig. 11. The cutting forces, captured from the smart cutting tool, need to be compared with a predefined cutting force range, before being fed into the adaptive control to adjust either spindle speed or feed rate. The objective of the adaptive control in machining the hybrid dissimilar material is to achieve a constant cutting force when machining from Monel to steel. The algorithm used to make this adjustment is based on machining trials as described in section 3.4.

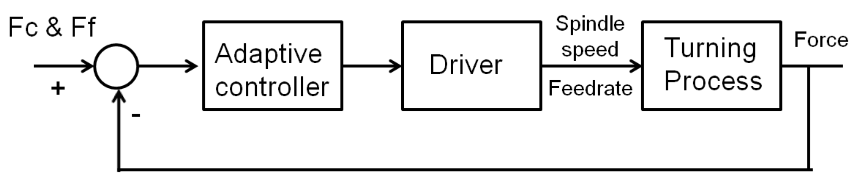


Fig. 11. Constant force control block diagram applied to high precision smart machining.

D. Smart machining control algorithms

In order to achieve the constant cutting force under dynamic conditions there is a need to implement a cutting trial to find the relationship between the feedrate and the cutting force. This relationship algorithm is embedded inside LabVIEW to compute the adapted parameters for the above requirements. Fig. 12 shows the relationship between the cutting force and the feedrate. Based on previous cutting trial results, adjusting the feedrate has a more significant influence on the cutting force [16]. For example, the cutting force increases by 105 N when adjusting the feedrate from 0.05 to 0.3 mm/rev. In order to keep the cutting force constant and to maintain high productivity, the adaptive control system must adjust the feedrate based on the formulae given below using the linear curve fitting technique. This formula is embedded inside LabVIEW and used to adapt the feedrate in application of constant cutting force.

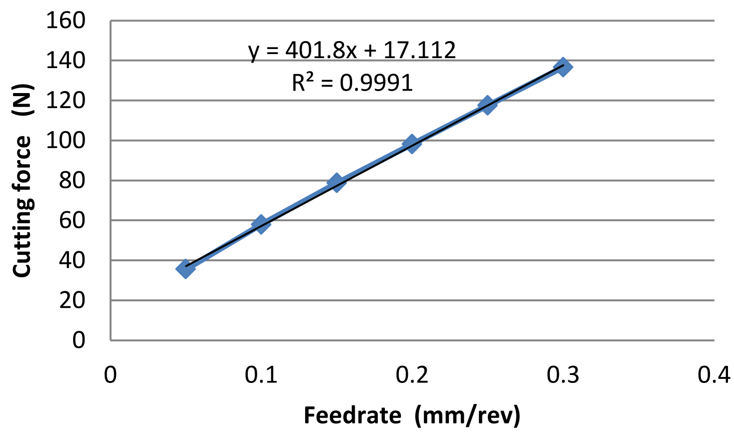


Fig. 12. The relationship between the cutting force and the feedrate.

E. LabVIEW user interface for communication and adaptive control on a CNC lathe

A block diagram of a CNC machine with adaptive control is shown in Fig. 13, where the adaptive control process is based on the smart tool measuring cutting force and includes a communication interface for extracting current cutting parameters. Also using LabVIEW, the user-interface program can perform self-monitoring and optimize these operations to determine whether the current cutting parameters are optimal and then provide optimal cutting parameters to operate the CNC lathe as necessary.

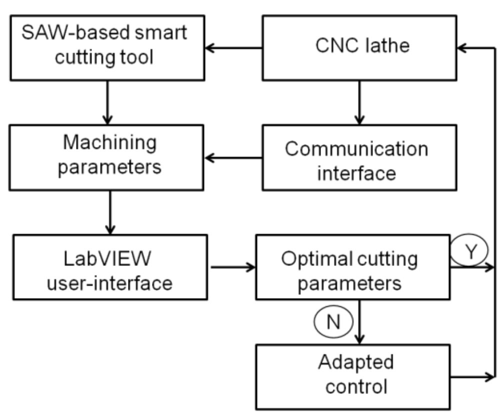


Fig. 13. Block diagram of a CNC machine with adaptive control.

A LabVIEW user-interface for communication and adaptive control has been developed, as shown in Fig. 14, to extract cutting parameter data, such as feedrate, constant surface speed, depth of cut, and spindle speed. The program would also record the main cutting force and feed force using the proposed SAW-based smart cutting tool signals obtained during the machining process. In order to extract the cutting parameters from a CNC lathe (ALPHA 1350XS), a C++ program was written and integrated into the LabVIEW interface. The function of the program is to manage the data transmit/receive sequence, based on IP addresses with the CNC lathe through Ethernet, and then to obtain the cutting parameters using proprietary coding provided from the Fanuc library [11]. In summary, four main steps need to be carried out before establishing the communication with the Fanuc CNC controller:

(1) Setting of TCP/IP on the personal computer side

(2) Setting of the Ethernet board and embedded Ethernet function on the CNC side

(3) Physical connection between personal computer and CNC machine tool

(4) Programming an application to call FOCAS (FANUC Open CNC API specifications) library

FOCAS enables the reading and writing of CNC data from the Fanuc controller via Ethernet. The sequence diagram of an application program for the communication with the Fanuc CNC controller is depicted in Fig. 15 [27].

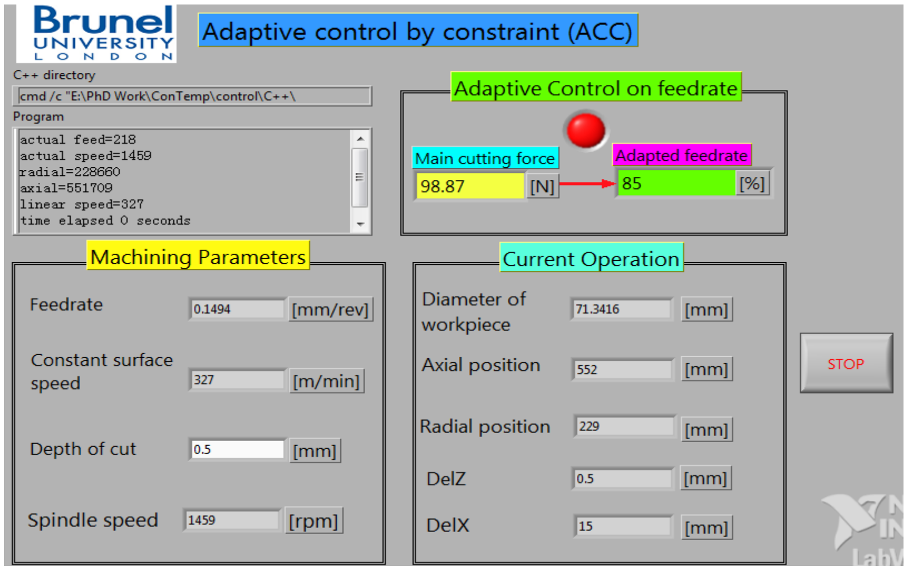


Fig. 14. LabVIEW user-interface and a screen copy of adaptive control on feedrate.

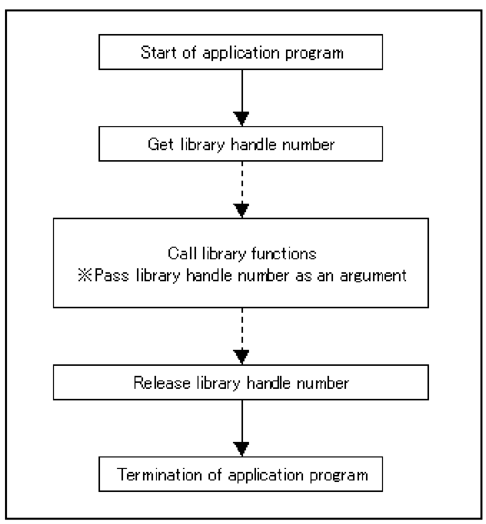


Fig. 15. Flow chart of the sequence in Fanuc controller communication program.

IV. MACHINING TRIALS, RESULTS AND DISCUSSIONS

The cutting trial was carried out on the CNC lathe (ALPHA 1350XS) based on the following cutting parameters: cutting speed: 80 m/min, Feedrate: 0.15 mm/rev and Depth of cut: 0.2 mm, under dry machining condition, as shown in Fig. 16. The cutting trial results, shown in Fig. 17 and Fig. 18, indicate the cutting force and the feed force measured by both Kistler dynamometer 9257b and the SAW-based smart cutting tool [28].

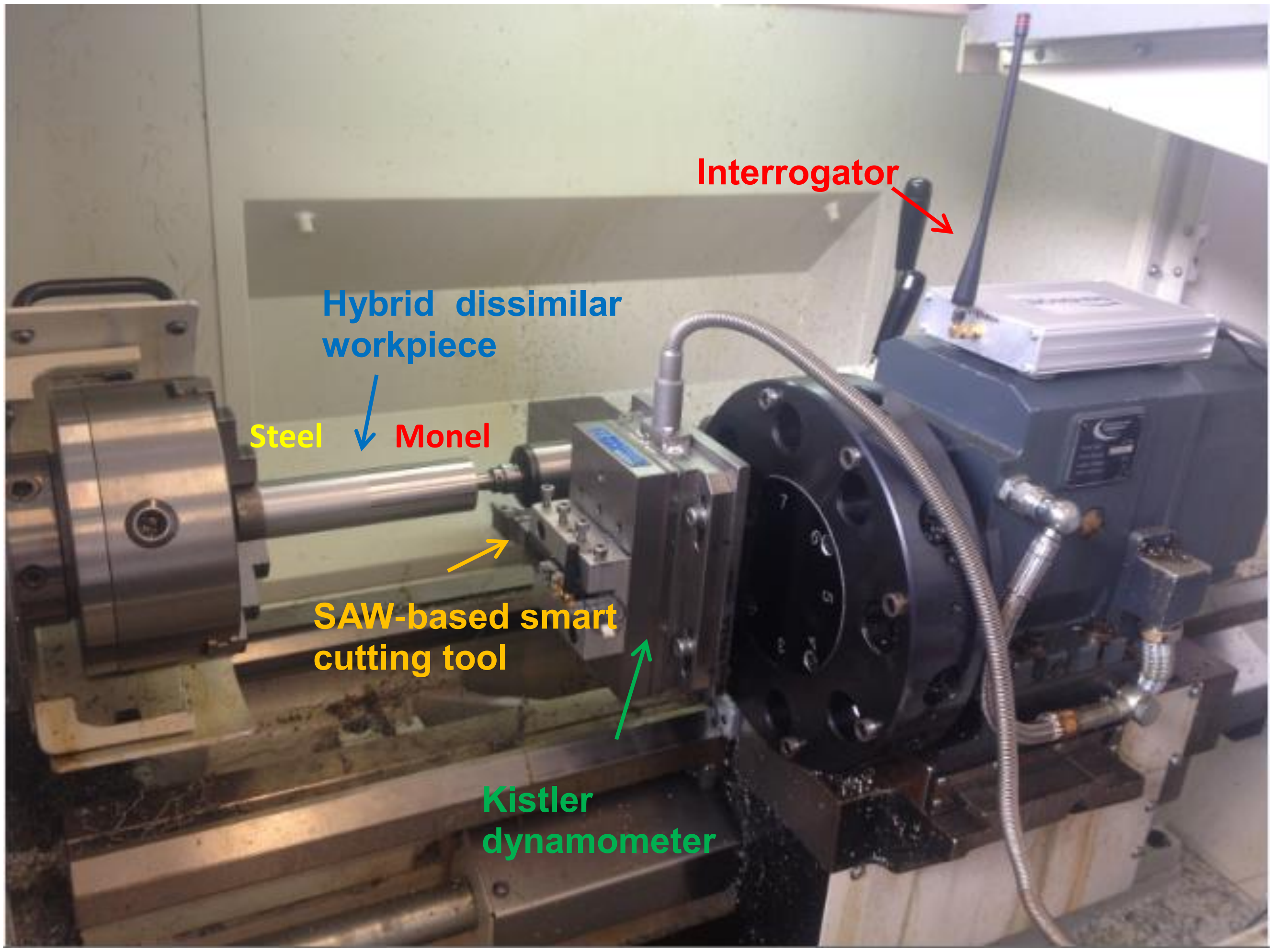


Fig. 16. Experimental setups including the SAW-based smart cutting tool, Kistler dynamometer, interrogator and hybrid dissimilar workpiece.

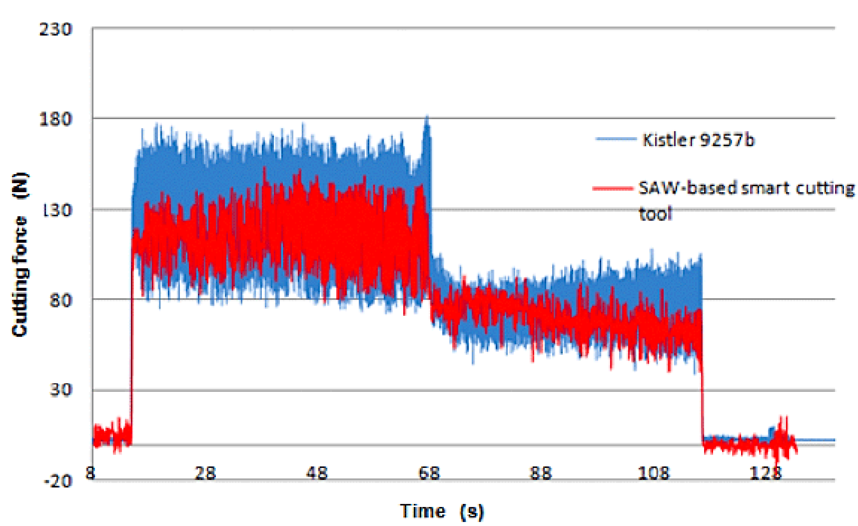


Fig. 17. Comparison between Kistler 9257b and SAW-based smart cutting tool on cutting force measurement in machining hybrid dissimilar material from monel to steel.

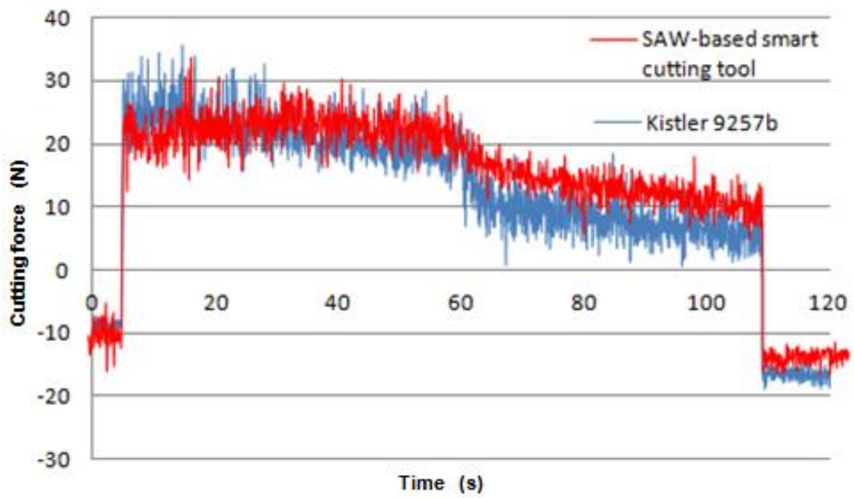


Fig. 18. Comparison between Kistler 9257b and SAW-based smart cutting tool on feed force measurement in machining hybrid material from Monel to steel.

These preliminary cutting trails have shown that the averaged cutting forces are 109.1N and 81.3N in machining from Monel to steel respectively, as shown in Fig. 17. In order to maintain the same cutting force magnitude level throughout the machining of the whole hybrid dissimilar workpiece, the feed rate needs to be adapted to be 153% (0.22 mm/rev) of the existing one (0.15mm/rev) in the transition area, using the formula given in Fig. 12. The adaptive control methodology was implemented and the result is depicted in Fig. 19, which shows that the cutting force is almost at the same level of magnitude throughout machining.

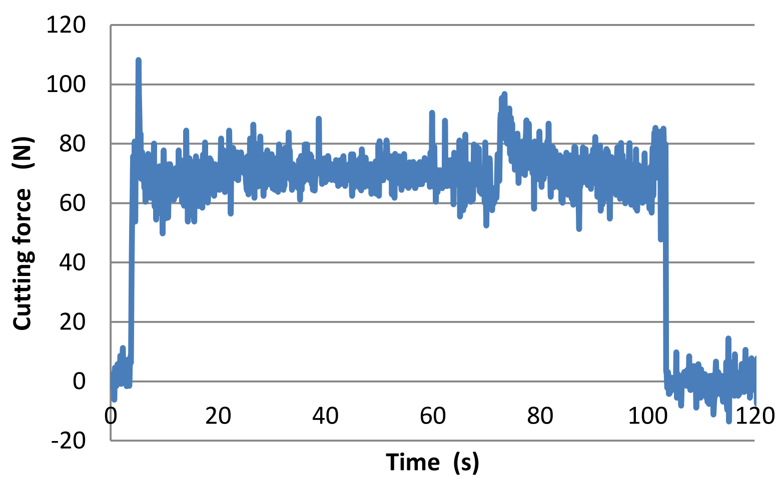


Fig. 19. Adaptation of feed rate to control cutting force in machining the hybrid dissimilar workpiece

A smart cutting tool, instrumented with SAW strain sensors, is proposed to measure the cutting force and the feed force in a real machining environment. The SAW-based smart cutting tool shows higher hysteresis of 7.3% and 4.7% than the commercially available Kistler dynamometer. Moreover, the cross-talk of 20.3% and 13.2% of the SAW device is also considerably high. The reason for this is mainly due to the position of the cutting tip; which is not located in the neutral axis of the tool shank. As a result, the cutting force and feed force generate unwanted torsion on the tool shank. Further investigation will therefore focus on cross-talk and hysteresis reduction based on optimization of the position of the cutting tip in order to achieve better cutting force measurements.

Both the cutting and feed forces were measured by the proposed SAW-based smart cutting tool and captured by customized LabVIEW user-interface in a real time. The results show that the SAW-based smart cutting tool demonstrated a strong correlation with the force signal response from Kistler dynamometer, as shown in Fig. 17 and Fig. 18. The SAW strain sensors also demonstrated the ability to pick up the dynamic cutting performance with maximum sampling rate of 150 Hz. Future work will also involve further optimization of the SAW instrumentation process in order to increase the SAW sampling rate.

Communication with the FANUC CNC machine controller can allow the operator to monitor the adapted feed rate online and in real-time. In practice the recommended feed rate value given by the supplier should constantly change when there are changes in machining conditions, such as different physical properties of the workpiece, different wear mechanisms formed on the tool and dynamics of the machine tool. Therefore, real-time communication with the machine tool can improve the adaptive control of the smart cutting tool, using the SAW-based smart cutting tool as the force measurement technique. Fig. 19 shows that by adapting the feed rate in real-time when machining a hybrid dissimilar workpiece, a constant cutting force can be achieved.

V. CONCLUSIONS

This paper presents the innovative design of a smart cutting tool, using SAW strain sensors as a sensing unit mounted onto the tool shank, to measure cutting force and feed force in the machining process in real time. The SAW-based smart cutting tool has been assessed to find its sensitivity, cross-talk and hysteresis parameters when it is calibrated with known conditions. The experimental results from real machining trials provide close agreement between the Kistler dynamometer and the SAW-based smart cutting tool, for both the cutting force and feed force measurements.

The paper also presents an innovative approach to smart machining using the SAW-based smart cutting tool as the cutting force measurement in the machining processes in real time, which is essential for high value added machining purposes, such as machining of difficult-to-cut materials (Titanium, Inconel and Si-based infrared devices) and hybrid dissimilar materials. Communication between the CNC lathe and the C++ program has been established to extract the relevant cutting parameters. Adaptive control system and CNC machining algorithms are developed based on feed rate adjustment and embedded into the LabVIEW user-interface, so as to achieve constant cutting force during the machining of a hybrid dissimilar workpiece.

ACKNOWLEDGMENTS

The authors would like to thank the UK Technology Strategy Board (TSB) for supporting this research (SEEM Project, contract No.: BD266E) and helpful discussions within the project consortium. Thanks are also extended to Mr Paul Yates and Dr Saiful Bin Che Ghani at Brunel University for their technical assistance.

REFERENCES

[1] J. Tlusty, and G. Andrews, “A critical review of sensors for unmanned machining,” Annals of the CIRP., vol. 32, no. 2, pp. 611–622, Feb. 1983.

[2] M. Weck, “Machine diagnostics in automated production,” *J. Manuf. Syst.,* vol. 2, no. 2, pp.101–106, 1983.

[3] A. Farhidzadeh, S. Salamone, B. Luna, and A. Whittaker, " Acoustic emission monitoring of a reinforced concrete shear wall by b- value based outlier analysis," *Structural Health Monitoring.*, vol.12, no.1, pp. 3-13, 2013.

[4] E. Dimla, and S. Dimla, "Sensor signals for tool-wear monitoring in metal cutting operations: a review of methods," *International Journal of Machine Tools & Manufacture.*, vol. 40, no.8, pp.1073–1098, Jun. 2000.

[5] J. L. Stein, and K. Huh. "Monitoring cutting forces in turning: A model: Base approach." *J. Manuf. Sci. Eng., Trans. ASME.*, vol. 124, no. 1, pp. 26-31, Aug. 2002.

[6] L. Holger, B. Ralf, B. Saskia, and S. Birte, "Thin film sensor for wear detection of cutting tools," *Sensors and Actuators A: Pysical.*, vol. 116, no. 1, pp.133-136, Oct. 2004.

[7] X. Sun, R. Bateman, K. Cheng, and S. C. Ghani, " Design and analysis of an internally cooled smart cutting tool for dry cutting," *Proc. IMechE, Part B: J. Engineering Manufacture*., vol. 227, no. 9, pp. 585-591, Nov. 2011.

[8] A. Binder, G. Bruckner, N. Schobernig, and D. Schmitt,"Wireless Surface Acoustic Wave Pressure and Temperature Sensor With Unique Identification Based on $LiNbO_3$," *IEEE Sensors Journal*, Vol. 13, pp. 1801-1805, May 2013.

[9] C.-M. Lin, Y.-Y. Chen, V. V. Felmetsger, W.-C. Lien, T. Riekkinen, D. G. Senesky, and A. P. Pisano, "Surface acoustic wave devices on AlN/3C-SiC/Si multilayer structures," *J. Micromech. Microeng.*, vol. 23, 025019, Feb. 2013.

[10] Y.-S. Huang, Y.-Y. Chen, and T.-T. Wu, "A passive wireless hydrogen surface acoustic wave sensor based on Pt-coated ZnO nanorods," *Nanotechnology*, vol. 21, 095503, 2010.

[11] W.-S. Wang, T.-T. Wu, T.-H. Chou and Y.-Y. Chen, "A ZnO-nanorod based SAW oscillator system for ultraviolet detection," *Nanotechnology*, Vol. 20, 135503, 2009.

[12] Y. Koren, and O. Masory, "Adaptive control with process estimation," *Annals of the CIRP*., vol. 30, no. 1, pp. 373-376, 1981.

[13] O. Masory, and Y. Koren, "Adaptive control system for turning." *Annals of the CIRP*., vol. 29, no. 1, pp. 281-284, 1980.

[14] T. Kim, and J. Kim, "Adaptive cutting force control for a machining center by using indirect cutting force measurements," *International Journal of Machine Tools & Manufacture*., vol. 36, no. 8, pp. 925-937, Aug. 1995.

[15] C. Wang, R. Rakowski, and K. Cheng, "Design and analysis of a piezoelectric film embedded smart cutting tool," *Proc. IMechE, Part B: J. Engineering Manufacture*., vol. 227, no. 9, pp. 254-260, Sep. 2013.

[16] C. Wang, S. C. Ghani, K. Cheng, and R. Rakowski, "Adaptive smart machining based on using constant cutting force and a smart cutting tool," *Proc. IMechE Part B: J. Engineering Manufacture.*, vol. 227, no. 2, pp. 249-253, Nov. 2013.

[17] M. Hoummady, A. Campitelli, and W. Wlodarski, "Acoustic wave sensors: design, sensing mechanisms and applications," *Smart Materials and Structures*., vol. 6, no. 6, pp. 647–657, Dec. 1997

[18] W. E. Bulst, G. Fischerauer, and L. Reindl, "State of the art in wireless sensing with surface acoustic waves," in *proc. 24th IECON*, 1998, pp. 2391-2396.

[19] G. Scholl, F. Schmidt, T. Ostertag, L. Reindl, H. Scherr, and U. Wolff, "Wireless passive SAW sensor systems for industrial and domestic applications," in *proc. IEEE International*, 1998, pp. 595-601.

[20] M. Hofer, N. Finger, G. Kovacs, J. Schoberl, S. Zaglmayr, U. Langer, and R. Lerch, "Finite-element simulation of wave propagation in periodic piezoelectric SAW structures," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*., vol. 53, no. 6, pp. 1192–1201, Jun. 2006.

[21] P. Alfred, "A review of wireless SAW Sensors," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*., vol. 47, no.2, pp. 317-322, Mar. 2000.

[22] B. Donohoe, D. Geraghty, and G. E. O'Donnell, "Wireless calibration of a surface acoustic wave resonator as a strain sensor," *IEEE Transactions on Sensors Journal.*, vol. 11, no. 4, pp.1026-1032, Feb. 2011.

[23] National Instrument, Bridgeview and LabVIEW-G Programming Reference Manual, http://www.ni.com/pdf/manuals/321296b.pdf [Accessed on 27/Nov/2013].

[24] R. Stoney, B. Donohoe, D. Geraghty, and G. E. O'Donnell, "The development of surface acoustic wave sensors (SAWs) for process monitoring," in *proc. 5th CIRP Conference on High Performance Cutting*, 2012, pp. 586 – 591.

[25] Friction welding satellite facings to valve seats, by A. Goloff. et al. (1967, Oct 9). Patent 3478411 [Online]. Available: http://www.google.com/patents/US3478411

[26] Friction welded valve seats, by L. V. Reatherford, and S. G. Russ. (1995, Oct 6). Patent 5653377 A [Online]. Available: https://www.google.com/patents/US5653377?pg=PA1&dq=US+Patent+no.++5653377+A.&hl=en&sa=X&ei=cGo4UpbHKIHKtQbap4GwBQ&ved=0CDkQ6AEwAA

[27] S. C. Ghani, "Design and analysis of the internally cooled smart cutting tools with the applications to adaptive machining," Ph.D. dissertation, Dept. AMEE., Brunel Univ., London, UK, 2013.

[28] C. Wang, K. Cheng, R. Rakowski, X. Chen, and M. Y. Cheng, M, "An investigation on the development of a smart cutting tool for precision machining using SAW-based force measurement," in *proc. 13th Precision Engineering & Nanotechnology (EUSPEN),* 2013, pp. 335-339.