

**Investigation of the use of power
ultrasound to improve
manufacturing processes in fluid
phase**

**A Thesis Submitted for the
Degree of Doctor of Philosophy**

By

Ahmed Teyeb

**Department of Electronic and
Electrical Engineering,
Brunel University London**

2026

DECLARATION OF AUTHORSHIP

I, Ahmed Teyeb, declare that this thesis titled, ‘Investigation of the use of power ultrasound to improve manufacturing processes in fluid phase’ and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all the main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Date: 14 March 2025

BRUNEL UNIVERSITY LONDON

Abstract

Advanced manufacturing techniques play a crucial role in ensuring the efficiency and reliability of electric vehicle (EV) battery packs. In particular, the assembly of busbars and connectors—key components for current distribution—relies on joining dissimilar metals like copper and Aluminum. Aluminium-Copper (Al-Cu) alloys are often selected as best choice due to the combination of lightweight and effective conductivity. However, conventional joining methods of these metals often lead to the formation of brittle intermetallic compounds, compromising electrical performance and mechanical integrity. Despite the progressive interest in ultrasonic vibration–assisted laser welding for joining dissimilar metals in EV busbars and connectors, there remains a restriction in foundational understanding of how ultrasonic frequency, amplitude, and energy coupling interact with laser–material dynamics to control melt pool physics, intermetallic compound formation, and joint integrity. There is a rare integration of systematic transducer design and tuning with welding process optimization by existing studies, leaving the relationship between transducer characteristics and weld quality largely unexplored. Consequently, there is a critical knowledge gap in establishing quantitative, process–structure–property relationships that link ultrasonic transducer parameters to mechanical, electrical, and metallurgical performance of dissimilar-metal laser welds in EV applications. Therefore, this study addresses the use of ultrasound vibration-assisted laser welding as a manufacturing technique, to join dissimilar metals such as Al-Cu, particularly for electric vehicles (EV) battery assembly. The research considers both theoretical and experimental approaches to the mechanism involved in formation of cavitation microbubbles and the effects of these agitated microbubbles on the process-structure-property relationship arising from the integration of high-power ultrasonic vibration technology with laser welding. Owing to optimal cavitation bubble formation at ultrasonic frequencies between 20 kHz and 40 kHz – ranges widely adopted in industry for both performance and safety – the study presents the design and development of

different transducer types operating at varying frequencies of 20, 28, and 40 kHz. Consideration of different experimental setups and varying sets of processing parameters, like transducer angle, transducer distance from metal plate, electrical impedance, and are put in place, to obtain optimal displacement and acceleration amplitudes.

The initial section of the work focuses on comprehensive review of metal joining processes; the advancements and challenges associated with EV batteries in recent times and introduces power ultrasound in industrial applications. Also, it delves into the theoretical modelling of formation and collapse of microbubbles caused by the introduction of ultrasonic waves into the solidifying phase of the weld pool. In addition, experimental investigation of structural vibration of lap and butt joints is discussed.

Furthermore, the latter section elucidates the mechanical and microstructural analyses of ultrasonic vibration-assisted laser welded joints. Results showed that the application of high-intensity ultrasound significantly disrupted epitaxial dendrite growth, refined grain structure, minimized plasma cloud formation, and altered the shape of intermetallic compounds from linear to spherical. The mechanical strength of vibration-assisted joints welded at 28 kHz and at welding speed of 40 mm/s showed a significant increase of 24.5% against the non-vibration-assisted counterpart. The application of high-intensity ultrasound significantly improved weld quality by straightening the weld profile, reducing differential weld width-to-root by 14 - 62%, refining grain structure, and reducing defects such as spatter and plasma cloud formation. Also, SEM results showed that the ultrasonic-assisted laser welded joint was characterized by smaller intermetallic formations and appeared mostly in the shape of spheres. Furthermore, it was observed that the volume density of the secondary phases within the grain boundaries reduced with the application of ultrasonic vibration. The pull test results indicated an approximate 10% increase in load capacity and a 27% increase in extension when vibration was introduced, compared to welds produced without vibration. This demonstrates that vibration-assisted welding enhances joint strength and ductility, contributing to improved mechanical performance and reliability of the weld.

Overall, the study provides an innovative methodology to address critical issues in industrial and manufacturing processing of dissimilar metals, mitigating the detrimental effects of the formation and presence of hard, brittle intermetallic compounds associated with Al-Cu alloys. This method is highly effective in contemporary material processing of busbars and connectors of EV batteries.

ACKNOWLEDGEMENTS

At the outset, I humbly express my profound gratitude to Allah Almighty, who has guided me to this pinnacle of academic achievement and smoothed the path towards it with His grace. It is with His blessings that I have navigated the rigors of this scholarly pursuit.

My deepest gratitude was extended to the cherished memories of my parents, whose blessings from above guided me steadfastly. To my beloved wife and siblings, whose encouragement, understanding, companionship, and love were my constant pillars of strength and comfort throughout this journey.

I extend my sincere appreciation to Professor Tat-Hean Gan, Director of the Brunel Innovation Centre (BIC), and Mr. Jamil Kanfoud, former Head of BIC, for the invaluable opportunity to be a part of the BIC team and for the unwavering support throughout my thesis endeavour.

My principal supervisor, Professor Wamadeva Balachandran, deserves special mention for accepting the task of guiding this work, offering unlimited advice, and providing relentless support that was essential to my progress.

I would also like to express my heartfelt thanks to Dr. Evelyne ElMasri, the current head of BIC, for all the resources and support made, especially during the final and critical phase of my PhD.

Special gratitude is owed to Dr. Makis Livadas, the Electronics Developments team manager at BIC, whose support and guidance were crucial in the effective production of the devices required for my research and for acting as the Research Degree Advisor (RDA) for my Ph.D.

To my colleagues—Dr. Mohamad Salimi, Maria Tyler, Ioanna Kampitaki, Dr. Shehane Lowe, Dr. Habiba Lais, and Mr. Sergio Malo—your infinite help and readiness to assist have been nothing short of extraordinary.

I would like to express my gratitude to all the staff at the Experimental Techniques Centre (ETC) at Brunel University for providing access to their microscopy facilities and for their invaluable support in training me to use the equipment effectively.

Additionally, my sincere appreciation goes to the dedicated team at The National Structural Integrity Research Centre (NSIRC) for their invaluable contributions and unwavering support, which have been pivotal in the advancement of my research and academic growth.

A special word of thanks goes to the entire team at Carrs Welding LTD, especially Phil Carr, John Silva, and Samiul Hoque, for their patience during trials and their willingness to accommodate last-minute access requests.

This journey has been a mosaic of support, mentorship, and collaboration, each piece as vital as the next, and for this, I am eternally grateful.

TABLE OF CONTENTS

Chapter 1	1
Introduction.....	1
1.1. Background and Motivation	1
1.2. Research Questions	5
1.3. Research Aim and Objectives	6
1.4. Research Outline	7
1.5. Contribution to New Knowledge in the Field	9
1.6. Impact of Research Outcome	10
1.7. List of Publications arising from the Doctorate	11
1.7.1. Journal publications.....	11
1.7.2. Conference papers	11
Chapter 2.....	13
Literature review	13
2.1. Introduction	13
2.2. Joining Processes of Metals.....	14
2.2.1. Metal joining processes	14
2.2.2. Industrial developments and challenges in liquid state joining processes	16
2.2.3. Laser welding process	17
2.2.4. Laser welding of similar and dissimilar metals: Recent developments and challenges.....	18
2.3. Electric Vehicle Batteries	22
2.3.1. EV battery packs - Recent advancements	23

2.3.2.	Laser welding of EV battery connectors: challenges and perspectives.....	29
2.3.3.	Criteria of performance and quality of the EV battery connectors	30
2.4.	Ultrasonic Vibration-assisted Material Processing with Fluid Phase.....	31
2.4.1.	Cavitation in molten metals.....	31
2.4.2.	Ultrasonic vibration-assisted laser welding of similar and dissimilar materials ...	33
2.4.3.	Power ultrasound and cavitation in liquids and molten materials	36
2.4.4.	Ultrasonic-assisted welding: mechanisms, cavitation effects, and microstructural improvements.....	36
2.4.5.	Ultrasonic assisted laser welding of similar materials (Aluminium alloys).....	38
2.4.6.	Ultrasonic assisted laser welding of dissimilar materials.....	39
2.5.	Research Approach.....	39
2.6.	Summary.....	40
Chapter 3.....		42
Microbubbles collapsing in a welding fusion pool.....		42
3.1.	Introduction	42
3.2.	Theoretical Modelling	43
3.2.1.	Ultrasonic plate vibration	44
3.2.2.	Coupling of the plate vibration and the fusion area pressure	48
3.2.3.	Cavitation dynamics	49
3.3.	Design and Simulation of Focused Ultrasonic Horns for use with Langevin Transducers in Contact and Contactless Modes	52
3.4.	Numerical Simulation of Vibration Transmission to the Molten Pool Area.....	56
3.5.	Summary.....	58
Chapter 4.....		60

Development of Ultrasonic Power Generation System for Improved Cavitation Microbubble Excitation	60
4.1. Introduction	60
4.2. Ultrasonic Wave Generation	61
4.2.1. System prototype development	61
4.2.2. Specification	62
4.2.3. Amplifier requirements and considerations.....	64
4.2.4. Amplifier tests	67
4.2.5. Signal testing	69
4.2.6. Thermal testing.....	70
4.3. Vibration Evaluation	73
4.3.1. Accelerometer measurement	73
4.3.2. 3D laser doppler vibrometer	73
4.4. Contactless Vibration of the Plate	74
4.5. Temperature Changes of the HPUT Horn	79
4.6. Effect of Tightening Torque on Ultrasonic Transducer: Impedance Testing.....	80
4.7. Summary.....	82
Chapter 5.....	84
Evaluation of microstructure and mechanical properties of ultrasonic vibration-assisted laser welded aluminium alloys	84
5.1. Introduction	84
5.1.1. Laser welding process	84
5.1.2. 6 series aluminium alloys	85
5.1.3. Ultrasonic vibration-assisted laser welding of aluminium alloys.....	87

5.2.1.	Ultrasonic vibration-assisted laser welding system.....	88
5.2.2.	Laser system parameters.....	90
5.3.	Sample Preparation.....	90
5.3.1.	Surface quality.....	90
5.3.2.	Weld geometry	91
5.3.3.	Grain structure	91
5.3.4.	Tensile strength	92
5.4.	Experimental Results and Discussions.....	92
5.4.1.	Plasma cloud.....	92
5.4.2.	Aspect ratio.....	93
5.4.3.	Examination of surface quality.....	95
5.4.4.	Microstructure analysis	97
5.4.5.	Grain structure analysis	98
5.4.6.	Relationship between theoretical modeling of cavitation effect and experimental results.....	100
5.4.7.	Tensile tests	101
5.5.	Mechanisms Involved in the Weldment Changes Induced by Ultrasonic Vibration.....	105
5.6.	Other Possible Effects of Ultrasonic Vibration on Weld Melts	107
5.7.	Summary.....	108
Chapter 6.....		109
	Ultrasound vibration assisted laser welding through generating low-intensity ultrasound cavitation.....	109
6.1.	Introduction	109

6.2.	Experimental Configuration for Ultrasonic Assistance Laser Welding	111
6.2.1.	Ultrasonic vibration assistance of laser welding	113
6.2.2.	Vibration measurements	113
6.2.3.	Pull test results using 20 kHz transducer	115
6.2.4.	Pull test results using 40 kHz transducer	117
6.3.	Ultrasonic Vibration Assistance of Laser Welding of Aluminium (Al1050) to Copper (Cu101)	119
6.4.	Microstructural Results	121
6.4.1.	Baseline microscopy results	121
6.4.2.	Ultrasonic assisted welding at 20 kHz.....	122
6.4.3.	Ultrasonic assisted welding at 40 kHz.....	124
6.5.	Summary.....	125
Chapter 7.....		126
Conclusions and Recommendations for Future Work.....		126
7.1.	Introduction	126
7.2.	Research Overview.....	126
7.3.	Key Findings	129
7.4.	Significance of Research	131
7.5.	Recommendations for Future Work	131
Bibliography		133
Appendix I		150
20 kHz transducers.....		150
28 kHz transducers.....		152

40 kHz transducers.....	153
20 kHz transducer	156
28 kHz transducer	158
40 kHz transducer	160
Appendix II	164
Lap joints	164
Holder for the plate welding	165
Butt joints.....	167
Appendix III.....	169
Contact and Contactless Ultrasonic Vibration.....	173
Shear test results for 20 kHz ultrasonic transducer.....	176
Shear test results for 28 kHz ultrasonic transducer.....	177
Shear pull results for 40 kHz ultrasonic transducer.....	178
Appendix IV	180

LIST OF FIGURES

Figure 2. 1: Laser Beam Welding Process.....	18
Figure 2. 2: Overview of battery packs indicating two constructions with (a) prismatic and (b) cylindrical cells. [64]	24
Figure 2. 3: Overview of different cell types used in automotive battery applications: (left) cylindrical cell, (middle) prismatic cell, (right) pouch cell. [64]	25
Figure 2. 4: Schematic Illustration of a Typical EV Battery Assembly [72].....	26
Figure 3. 1: Leakage of guided waves into the fluid. The meltpool agitates due to low local pressure which generates cavitation.....	44
Figure 3. 2: A clamped-plate vibration-mode shape subjected to unit force excitation at the (a) corner, (b) side and (c) centre of the plate at 20 kHz.....	46
Figure 3. 3: Plate subjected to ultrasonic excitation at three different locations a, b, and c. ...	46
Figure 3. 4: Plate vibration subjected to a unit force excitation at (a) corner (b) side (c) centre of the plate at 19 kHz.	47
Figure 3. 5: Exciting the plate from the side using a single transducer at (a) 20 kHz (b) 28 kHz and (c) 40 kHz.....	48
Figure 3. 6: Pressure variation in the molten pool with respect to the frequency.....	49
Figure 3. 7: Cavitation radius and threshold pressure with respect to the excitation frequency.	50
Figure 3. 8: Cavitation bubble (a) radius (b) wall velocity subjected to 20 kHz vibration.	51
Figure 3. 9: The piezoelectric component that generates vibration. (a) The back mass of a transducer where the horn screw (b) numerical simulation.	53
Figure 3. 10: Full modelling generates a vibration from the horn. (a) Meshed conical horn (b) Results from vibrated conical horn, excited by the piezoelectric	53
Figure 3. 11: Full modelling generates a vibration at. (a) 28 kHz (b) 40 kHz from vibrated conical horn, excited by the piezoelectric.....	54
Figure 3. 12: The transducer configuration (a) plan view (b) side view.....	55
Figure 3. 13: Fabricated Transducers and horns for 20, 28, and 40 kHz.....	56

Figure 3. 14: The model configuration and the location of the applied vibration: (a) the highlighted area is considered molten copper; (b) the same location is considered molten aluminium; and (c) the meshed model.....	56
Figure 3. 15: Application of ultrasonic vibration to the molten pool area at 20 kHz. (a) Acceleration amplitude, and (b) the acoustic pressure in the molten pool area.	58
Figure 4. 1: (a) Initial system floor plan highlighting input and output transformers (b) Block diagram outlining the old systems design built by BIC with additional transformer units	62
Figure 4. 2: Updated block diagram incorporating inline transformer units. Compared to the previous design, the transformer modules are now compact inline units.	64
Figure 4. 3: A Complete Ultrasonic Power System.....	66
Figure 4. 4: Inline Transformer Unit.....	66
Figure 4. 5: Wired with preliminary Test Setup	67
Figure 4. 6: System Block Diagram.....	67
Figure 4. 7: Test rig set up and diagram showing connection of test equipment	68
Figure 4. 8: Voltage readings from the N670C showing stable voltage output from a single amplifier module.....	68
Figure 4. 9: Complimentary current reading from the N6705C showing different stages on a no-load amplifier module first ramp up no signal input second ramp up signal input	69
Figure 4. 10: Amplifier a (yellow) output identical to amplifier b output (green) with the excitation which will be used by the transducer (purple) showing bridge mode configuration operation	69
Figure 4. 11: Maximum output from the amplifier using the 120Vp-p output from the N6705c power supply.....	70
Figure 4. 12: Left: closed thermal testing configuration. Right: Open thermal testing configuration showing transistors.....	70
Figure 4. 13: Idle operating temperature maximum amount recorded at 49.3 degrees after 24h in closed thermal testing configuration.....	71

Figure 4. 14: Comparison between 2 idle and 2 maximum output amplifier modules after 5 minutes of operation reaching a maximum temperature of 107.6 degrees in open thermal testing configuration	71
Figure 4. 15: Detailed assessment of single amplifier module after 25min of maximum output operation reaching a maximum temperature of 114.7°C in open thermal testing configuration	72
Figure 4. 16: Idle operation of the amplifier modules 2 minutes after 1h operation 48.5°C recorded in open thermal testing configuration	72
Figure 4. 17: A Dewesoft Acquisition Unit for Accelerometry	73
Figure 4. 18: (a) The Q55 transducer with the needle horn that can be screwed into the transducer, (b) the power amplifier.....	74
Figure 4. 19: The plate configuration, made of aluminium alloy 1050, for vibration measurement in the three orthogonal directions.	75
Figure 4. 20: The plate vibration in the vertical direction, the z-axis, increases the transducer angle from approximately 5 ° to 80 °.....	76
Figure 4. 21: The plate vibration in the horizontal direction, the x-axis, increases the transducer angle from approximately 5 ° to 80 °.....	77
Figure 4. 22: The plate vibration in the horizontal direction, the y-axis, by increasing the transducer angle from approximately 5 ° to 80 °.....	77
Figure 4. 23: The effect of the distance between the tip of the transducer horn and the structure on the contactless vibration specifically in the vertical direction, referred to as the z-axis. ...	78
Figure 4. 24: Experimental configuration to record temperature changes of the horn due to the operation of the laser welding device	80
Figure 4. 25: Graphical Plot of effect of Transducer Tightening Torque on Resonant Impedance	82
Figure 5. 1: Experimental set-up for laser welding with ultrasound assistance: (a) schematics and (b) physical set-up.....	88

Figure 5. 2: Plasma cloud captured by the monitoring camera during the welding process: (a) with no ultrasound used and (b) when ultrasound was used.....	92
Figure 5. 3: Aspect ratios of welds achieved at different configurations (T: plate thickness, WS: welding speed)	93
Figure 5. 4: Examination of the surface of the welds achieved without ultrasound at (a) 25 mm/sec and (b) 40 mm/sec and with ultrasound at (c) 28 kHz, 80 W, and 25 mm/s and (d) 40 kHz, 50 W, and 40 mm/s. The arrows point to the central line of the weld	96
Figure 5. 5: SEM analysis of cross sections of welds (2 mm thick plates) achieved at 25 mm/s (a) without ultrasound and (b) with ultrasound at 40 kHz and 50 W (spherical nature of the intermetallic structures).	97
Figure 5. 6: Reflected light microscopy images ($\times 200$ magnification) of cross sections of welds (2 mm thick plates) achieved at 40 mm/s (a) without ultrasound (arrows indicating some dendrites) and (b) with ultra-sound at 40 kHz and 50 W (arrows indicating some soli	99
Figure 5. 7: Load vs. extension (a) at 28 kHz, 40 mm/s, and (b) at 40 kHz, 40 mm/s. (c) Ultimate tensile strength at 40 mm/s.	102
Figure 5. 8: Load vs. extension (a) 28 kHz, 25 mm/s, (b) 40 kHz, 25 mm/s, and (c) ultimate tensile strength at 25 mm/s.	103
Figure 6. 1: Laser welding of a copper plate to a battery terminal. (a) The ultrasonic assistance laser welding configuration. (b) The final plate welded to the battery.....	111
Figure 6. 2: The simplified welding configuration. (a) The bottom holder, (b) fastened top holder to the bottom one, and (c) a picture showing the location of two plates, one at the top and the other at the bottom, along with the location of excitation from the tra.....	112
Figure 6. 3: The welding configuration includes (a) the utilisation of an ultrasound transducer with a focussed horn during laser welding and (b) the oval shape of the welding.	112
Figure 6. 4: The experimental configuration generates (a) contact and (b) contactless vibration at approximately 0 degrees and (c) contactless vibration at a 45-degree angle. (d) High-frequency accelerometer type 4397.	114

Figure 6. 5: The vibration output from the (a) contact, (b) contactless excitation at a 5-degree angle, and (c) contactless excitation at a 45-degree angle.	114
Figure 6. 6: Ultrasonic-vibration-assisted welding using a HPUT with a small end tip horn at (a) a 0-degree angle in contact, and (b) a 45-degree angle in contactless mode.....	115
Figure 6. 7: The 20 kHz HPUT used during the laser welding. Transducer configurations: (a) a large tip horn and (b) a small tip horn.....	116
Figure 6. 8: A Lloyd LR10K tensile tester used to conduct pull tests.	116
Figure 6. 9: The 40 kHz HPUT used during the laser welding. Transducer configurations: (a) large horn tip and (b) small horn tip.	118
Figure 6. 10: (a) The experimental configuration with the copper (Cu101) plate on top and the aluminium alloy 1050 plate on the bottom, and (b) the positioning of the transducer for ultrasonic assistance in welding.....	119
Figure 6. 11: The microscopy results associated with the non-ultrasonic welding: (a) 500 μm , explaining the aluminium and copper-rich regions, (b) 500 μm , (c) 100 μm , and (d) 5 μm	121
Figure 6. 12: Microscopy of the test associated with the 20 kHz transducer in the contactless mode: (a) 1000 μm , (b) 200 μm , (c) 100 μm , and (d) 20 μm	123
Figure 6. 13: Microscopy of the test associated with the 40 kHz transducer in the contactless mode: (a) 1000 μm , (b) 200 μm , (c) 100 μm , and (d) 20 μm	124
Figure A1. 1: Produced Transducer with a sensor fitted at the tip of the horn.....	150
Figure A1. 2: The spectrum of 20 kHz transducer with respect to the transducer configuration for the frequency range of 0-15 kHz, 15 kHz-30 kHz.	151
Figure A1. 3: The spectrum of 20 kHz transducer with respect to the transducer configuration for the frequency range 30 kHz to 45 kHz.....	151
Figure A1. 4: The spectrum of 28 kHz transducer with respect to the transducer configuration for the frequency range of 0-15 kHz, 15 kHz-30 kHz and 30- 45 kHz.	153
Figure A1. 5: The spectrum of 40 kHz transducer with respect to the transducer configuration for the frequency range of 0 – 30 kHz, and 30 – 60 kHz.....	154
Figure A1. 6: Locations of the vibration measurement along the plates.	155

Figure A1. 7: Vibration amplitude of transducer under pressure of 0.4 Nm	156
Figure A1. 8: Vibration amplitude of transducer under pressure of 0.8 Nm.	156
Figure A1. 9: Vibration amplitude of transducer under pressure of 1.6 Nm.	157
Figure A1. 10: Vibration amplitude of transducer under torque of 3.2 Nm.	157
Figure A1. 11: Vibration amplitude of transducer under torque of 0.4 Nm.	158
Figure A1. 12: Vibration amplitude of transducer under pressure of 0.8 Nm.	159
Figure A1. 13: Vibration amplitude of transducer under pressure of 1.6 Nm.	159
Figure A1. 14: Vibration amplitude of transducer under pressure of 3.2 Nm.	160
Figure A1. 15: Vibration amplitude of transducer under pressure of 0.4 Nm.	161
Figure A1. 16: Vibration amplitude of transducer under pressure of 0.8Nm.	161
Figure A1. 17: Vibration amplitude of transducer under pressure of 1.6 Nm.	162
Figure A1. 18: Vibration amplitude of transducer under pressure of 3.2 Nm.	162
Figure A2. 1: . Experimental setup for vibration analysis during ultrasonic vibration assisted laser welding process	164
Figure A2. 2: Plastic holder for welding the ‘L’ shape plates.	165
Figure A2. 3: Analysis of the lap joints vibration level for 0-100 % welding progress with a 28 kHz transducer.	166
Figure A2. 4: Analysis of the lap joints vibration level for 0-100 % welding progress with a 40 kHz transducer.	167
Figure A2. 5: Analysis of the butt joints vibration level for 0-100 % welding progress with a 28 kHz transducer.	167
Figure A2. 6: Analysis of the butt joints vibration level for 0-100 % welding progress with a 40 kHz transducer.	168
Figure A3. 1: The (a) battery plate holder used for connecting the plate to the battery head (b) the plate inside the battery head connector that will be welded to the battery head, (c) the top view from the battery head connector.....	169

Figure A3. 2: The 20 kHz transducer used for further investigation. (a) A Plain transducer, (b) transducer with an accelerometer attached to its end tip and (c) a high-frequency accelerometer, type 4397.....	170
Figure A3. 3: The spectrum of the transducer (a) without and (b) with a focused horn.....	171
Figure A3. 4: The experimental configuration generates (a) contact, (b) contactless vibration at approximately 0 degrees and (c) contactless vibration at 45 degrees.	171
Figure A3. 5: The vibration output from the contact, contactless excitation, and contactless excitation at a 45-degree angle.	172
Figure A3. 6: Ultrasound vibration-assisted welding using (a) shear, (b) compressional and (c) contactless vibration.....	172
Figure A3. 7: The transducer configuration (a) placing the bottom plate and (b) placing the top holder.	173
Figure A4. 1: The piezo electric that generates vibration. The back mass of a transducer where the horn	180

LIST OF TABLES

Table 2. 1: Features of Liquid-State Joining Processes	15
Table 2. 2: Examples of electric vehicle batteries (cell configuration: s – series-, p-parallel connection).....	26
Table 3. 1: Proposed dimensions for the horn length with different natural frequency	55
Table 3. 2: Material properties used in the simulation.....	57
Table 4. 1: General Specifications for Amplifier System.....	64
Table 4. 2: Characteristics of the Amplifier Modules.....	65
Table 4. 3: Final Specification of the System.....	65
Table 4. 4: Effect of Tightening Torque on Transducer Impedance.....	81
Table 5. 1: Aspect ratios of welds achieved at different configurations.....	94
Table 5. 2: The average difference between weld keyhole width and root depth in mm with different set-ups.	94
Table 6. 1: Pull test results associated with the 20 kHz HPUT with small and large horn tips without ultrasonic assistance.....	117
Table 6. 2: Pull test results associated with the 40 kHz HPUT with small & large horn end tips	118
Table 6. 3: Pull test results associated with the 20 kHz and 40 kHz HPUTs with the small horn end tip (focused horns).....	120
Table A3. 1: Pull Test Results for 20 kHz with Small and Large Tips comparing Contact and Contactless Modes	174
Table A3. 2: Pull Test Results for 20 kHz with Small and Large Tips comparing Contact and Contactless Modes	175
Table A3. 3: Shear test results associated with the 20 kHz with tapered and the industrial transducer.....	176
Table A3. 4: Shear test results associated with the 28 kHz with tapered and the focused horn	177

Table A3. 5: Shear Pull test results associated with the 40 kHz with tapered and the focused horn.	178
Table A4. 1: Proposed dimensions for the horn length with different natural frequencies ...	180

LIST OF SYMBOLS AND ABBREVIATIONS

<i>NIPD</i>	Non-Invasive Prenatal Diagnosis	<i>EV</i>	Electric Vehicle
<i>HIFU</i>	High Intensity Focused Ultrasound	<i>Al</i>	Aluminium metal
<i>HPUT</i>	High-Power Ultrasonic Transducer	<i>Cu</i>	Copper metal
<i>SEM</i>	Scanning Electron Microscope	<i>Ar</i>	Argon Gas
<i>FEA</i>	Finite Element Analysis	<i>Si</i>	Silicon
<i>PUVT</i>	Power Ultrasound Vibration Treatment	<i>Fe</i>	Iron
<i>BIC</i>	Brunel Innovation Centre	<i>Ti</i>	Titanium
<i>DAC</i>	Digital-to-Analog Converter	<i>Mg</i>	Magnesium
<i>PZT</i>	Piezoelectric Transducer	<i>Mn</i>	Manganese
<i>FSW</i>	Friction Stir Welding	<i>H₂O</i>	Water
<i>UGW</i>	Ultrasonic Guided Wave	<i>HNO₃</i>	Trioxonitrate (V) Acid
<i>PCB</i>	Printed Circuit Board	<i>HCl</i>	Hydrochloric Acid
<i>CLV</i>	Compact Laser Vibrometer	<i>AA</i>	Aluminium Alloy
<i>RMS</i>	Root Mean Square	<i>HAZ</i>	Heat Affected Zone
<i>3D</i>	Three-dimensional	<i>TAZ</i>	Thermally Affected Zone
<i>BVD</i>	Butter-Worth-Van Dyke Model	<i>UV-A</i>	Ultrasonic Vibration-assisted
<i>F₀</i>	Force Amplitude	<i>AM</i>	Additive Manufacturing
<i>B</i>	Bending Fitness	<i>IMC</i>	Intermetallic Compound
<i>E</i>	Young's Modulus	<i>ICE</i>	Internal Combustion Engine
<i>ν</i>	Poisson Ratio	<i>TIG</i>	Tungsten Inert Gas

P_0	Liquid Static Pressure	ρ_s	Plate Surface Density
P_v	Vapour Pressure of the Bubble	ω	Angular Velocity
σ	Melt Surface Tension Coefficient	θ_m	Bessel Function
R_0	Internal Radius of the Bubble	ζ_n	Hankel Function
γ	Specific Heat Capacity of the Fluid	$\xi(x, y)$	Steady-State Trans Displacement
f_r	Sound Field Frequency	ψ_{mn}	Natural Frequency
P_B	Actual Cavitation Threshold	B_m	Modulation Index
R	Bubble Radius	P_f	Internal Pressure
$\dot{R}$	Bubble Radius from 1st Derivative	W_l	Radial Displacement
$\ddot{R}$	Bubble Radius from 2nd Derivative	α	Bulk Modulus of Semi Fluid
μ	Viscosity of Melt	k_s	Wavenumber for the Plate
P_A	Sound Pressure	k_f	Wavenumber for the Semi Fluid

Chapter 1

Introduction

1.1. Background and Motivation

Advancements in materials processing have driven innovations across industries, enabling the creation of components with unique properties tailored to diverse applications [1]. Rising demand for high-performance materials has led to the development of techniques that improve their structural, mechanical, and thermal properties. These advancements are especially critical in sectors such as electronics, aerospace, biomedical engineering, and energy, where precision and reliability are paramount [2].

Metal manufacturing stands at the forefront of these innovations, serving as a cornerstone for modern industrial applications [3]. Its versatility supports the creation of components ranging from simple to highly complex geometries, meeting the rigorous demands of various engineering designs. The ability to optimize manufacturing processes ensures that metals perform reliably in challenging environments, addressing issues like wear, fatigue, and corrosion. This adaptability is enhanced by advanced methods such as forging, casting, extrusion, and welding, enabling the production of customized components with exceptional precision and efficiency. A central aspect of many metal manufacturing techniques is the solidification process, a critical phase where molten metal transitions into a solid state. This phase determines the material's microstructure and influences its overall performance. Factors such as cooling rate and composition play pivotal roles, underscoring the need for precise control during manufacturing.

This research explores the application of ultrasonic vibration to enhance material manufacturing processes during the solidification phase. By tackling key challenges and developing innovative methodologies, this study aims to advance materials processing technologies, with a focus on improving structural integrity and performance in critical applications.

Metal welding is one of the manufacturing processes that involve solidification process by melting and fusing of two metal parts together to form a single, solid piece [4,5], and used in a

variety of industries including construction [6], shipbuilding, and aerospace [7]. Unlike, its mechanical manufacturing counterparts, welding requires no additional parts or fasteners to hold metals together. The welded joints possess high strength, which may exhibit superior strength compared to their parent metals. Also, dissimilar metals can be welded together, and the technique is flexible enough to join parts with complex and intricate sections. However, during conventional welding process, the presence of micro- and macrostructural defects, such as cracks, pore formation, lack of penetration, slag inclusion, and stress corrosion cracking are unwanted features that are associated with most welded joints, which may lead to structural degradation, rejection of parts and assemblies, significant reduction in product functionality, and component failure during service [8]. These defects are strongly influenced by the behaviour of the molten weldment, such as heat transfer, fluid flow, phase change, and elemental evaporation, and can be significantly mitigated while the welding process is controlled by using a more effective approach [9, 10]. For instance, increasing the transverse flow of the molten pool can reduce the lack-of-fusion effect at sidewalls and improve the weld quality [11].

Laser welding is a very effective technique that has garnered attention over the last decade. It is a non-contact welding method that uses a laser beam to generate heat and join metal components together. It offers several advantages over traditional welding methods, including high precision: laser welding allows for precise control of the welding process, reducing the risk of defects or inaccuracies in the final product due to highly localized heat input and rapid solidification rates, creating thin layers of heat affected zones [12]; faster welding speeds: laser welding is typically faster than traditional welding methods, reducing the overall time needed to manufacture a product [13]; minimal heat-affected zone: it generates less heat than traditional welding methods, reducing the amount of material that is affected by the welding process [14, 15], and; improved material properties: it results in a stronger and more consistent weld, which can improve the overall durability and performance of the welded parts. It eradicates the susceptibility to re-melting, compared to arc welding. Laser welding is a highly efficient and precise process used in various industrial applications [16, 15]. It is commonly used in the automotive industry for welding parts such as exhaust systems, fuel filters, and body panels

[17]. The technique is also used in the aerospace industry for welding aircraft parts such as turbine blades and fuselage components [8]. In the medical industry, it is used for welding medical devices, such as surgical instruments and implants [18]. One of the most significant applications of laser welding is in the assembly of battery connectors and electric vehicle (EV) battery packs. Although, in general, laser welding is sensitive to materials, characterized by melt instability, and low penetration depth, which limits the technology to joining thin strips or components only, laser welding provides a clean and precise method for joining battery components, ensuring that the battery operates safely and efficiently [19]. Also, the technique provides high-strength welding for various material selections. Nowadays, it has a great potential to push the EV vehicle industry by providing robust and reliable battery connections [20]. However, there are several challenges associated with laser welding of EV battery connectors. Porosity and blowholes are major issues accompanying the use of laser welding on EV batteries. They arise because of bubbles being released from the molten pool during laser welding process [21, 22]. These defects primarily stem from the existence of residual substances, like stamping oil and cleaning solutions, on the fragile battery cell cover and explosion-proof valve. When subjected to the high intensity of the laser power, these liquids rapidly undergo vaporisation, resulting in splattering and blowhole formation on the welded surface [23]. Another key challenge is the difficulty of laser welding of aluminium alloys, which are commonly used in EV batteries [21]. Aluminium alloy represents a typical eutectic alloy, and welding can lead to the occurrence of hot cracks. These cracks encompass weld crystallisation cracks and heat-affected zone (HAZ) liquefaction cracks [24]. Due to elemental agglomeration within the welding area, eutectic segregation emerges, along with grain boundary melting. Liquefaction cracks tend to form at these grain boundaries, ultimately compromising the performance of welded joints [25]. A third limitation of employing laser welding to EV batteries is the formation of brittle and hard intermetallic compounds, such as Cu_3Al , Cu_4Al_3 , CuAl and CuAl_2 [20, 26, 27, 28]. For instance, tabs and busbars interconnectors of Li-ion EV batteries are majorly fabricated using Al and Cu [29]. However, laser welding of Al and Cu remains a limitation due to their significant differences in thermal and metallurgical properties, and the precipitation of these

brittle phases can significantly reduce the electrical contact resistance of EV battery connectors. Based on the above three problems encountered during manufacturing of EV battery connectors, it is of great importance to develop a high-performance and high-efficient manufacturing methodology to mitigate the limitations.

In recent times, studies have increased on the significant impact of ultrasonic vibration on manufacturing processes coupled with low equipment cost [30, 31]. This manufacturing-assisted approach has been widely adopted to improve manufacturing process efficiency. Ultrasonic waves propagate at wave frequencies that exceed 20 kHz, surpassing the maximum frequency humans can hear. This level of frequency is higher than other mechanical vibrations, therefore it propagates at a steadier rate which enhances the reliability of manufacturing processes without any additional low-frequency effects such as noise and machinery vibrations. Ultrasonic vibration possesses the ability to influence the outcome of a laser welded joint due to its acoustic cavitation effect. With respect to conventional welding, the base metal is heated and melted to form a molten pool. As the pool solidifies, without any additional cooling source, large grains are formed within the solidifying pool, leading to formation of metals and alloys with lower yield strength [32]. Thus, the size of the grains directly influences the mechanical properties and functionality of the welded joint. On the other hand, employing ultrasonic vibration in laser welding, the grain size is significantly refined. This refinement is largely attributed to the rapid bursting of the existing bubbles within the molten pool, generating an intensified shock wave throughout the molten pool and increasing the recoil pressure and rate of cooling. During solidification, ultrasonic vibration promotes two crucial phenomena: Firstly, it breaks large crystal grains to form finer crystal grains, and secondly, it speeds up the release of any trapped bubbles from the molten pool, reducing pore formation and presence of blowholes [33]. Therefore, during an ultrasonic vibration-assisted laser welding process, ultrasonic energy encourages the formation of equiaxed grains and enhances the mechanical properties of the weld [34].

In this thesis, ultrasonic vibration-assisted laser welding technique will be employed to enhance the efficiency of manufacturing process during liquid and solidification stages. The research

will particularly focus on the application of ultrasonic energy in laser welding of similar (Al-Al) and dissimilar metals (Al-Cu) in butt and lap joints respectively, investigating the influence of ultrasonic vibration in contact and contactless mode on improving the microstructure and mechanical properties of the laser welded joints.

1.2. Research Questions

- i. **Research Question 1:** Mitigation of Intermetallic Compound Formation in Ultrasonic Vibration-Assisted Laser Welding of EV Battery Connectors:

How does ultrasonic vibration-assisted laser welding impact the formation of hard and brittle intermetallic compounds in Al-Cu alloys during laser welding of similar and dissimilar EV battery busbars and connectors? What are the effects of processing parameters, such as horn mount distance, vibration frequency, transducer angle, and ultrasonic power, on the microstructure, mechanical performance, and electrical properties of the weld?

This question seeks to evaluate the effectiveness of ultrasonic vibrations in addressing the challenges posed by dissimilar metal welding, focusing on optimizing processing parameters to enhance weld quality and performance in EV battery connectors.

- ii. **Research Question 2:** Influence of Ultrasonic Vibration Frequencies and Transducer Setups on Microbubble Collapse and Grain Refinement:

How do ultrasonic vibration frequencies influence microbubble collapse and grain refinement in the welding of light alloys for EV battery packs? How does transducer configuration affect vibration efficiency and enhance the mechanical properties and reliability of welded zones?

This question explores the role of acoustic cavitation in promoting melt degassing and microstructural refinement, aiming to identify optimal vibration conditions and transducer configurations that enhance the mechanical properties and reliability of welded zones in EV battery packs.

- iii. **Research Question 3:** Optimization and Validation of Horn/Transducer Positioning and Ultrasonic Vibration Parameters for Enhanced Weld Quality:

What is the optimum horn/transducer positioning for achieving the maximum amplitude necessary to initiate cavitation within the fusion zone? How does this influence grain refinement, and to what extent do theoretical models align with experimental results in terms of microstructure, mechanical strength, and electrical properties of welded zones?

This question investigates the optimal positioning of the ultrasonic horn/transducer and the validation of theoretical models against experimental outcomes, aiming to refine practical techniques for optimizing weld quality in EV battery connectors.

1.3. Research Aim and Objectives

The goal is to develop innovative ultrasonic vibration-assisted laser welding technique to improve structural weld integrity for joint configurations, facilitating the adoption of ultrasonic technology in the industry. The study also aims to provide a deeper understanding of the materials processing field, contributing to the development of new and improved materials for various applications, with a particular focus on utilizing power ultrasonic technology for material refining and enhancing the properties of the final products.

The following specific objectives have been coined to satisfy the research aim:

- i. Examine the impact of varying ultrasonic vibration frequencies from approximately 20 kHz to 40 kHz on the rate of microbubble collapse and grain refinement during the welding of light alloys used in EV battery packs, aiming to improve the microstructure.
- ii. Determine the optimum positioning distance for the mounting of the horn/transducer in ultrasonic vibration-assisted laser welding to achieve the maximum amplitude necessary within the fusion zone and analyse its effect on grain refinement.
- iii. Develop an in-house power generation system to evaluate the efficiency of vibration performance in ultrasonic-assisted laser welding with different setups, including modifications to transducer types.
- iv. Explore the effects of combined processing parameters, such as laser power, laser speed, vibration frequency and ultrasonic power, on the microstructure and mechanical properties enhancement, during ultrasonic vibration-assisted laser welding. This objective is intended to achieve improved control of intermetallic compound formation and

near-zero porosity welding for stronger, lightweight EV battery connections. Furthermore, the investigations of this research will shrink the theory-practice divide which can lead to improved welding process precision and efficiency, enabling the automotive industry to meet the increasing demand for sustainable transportation solutions.

- v. Establish a correlation between theoretical modelling outcomes, specifically focusing on the interaction between ultrasonic vibration setup parameters and the maximum vibration amplitude experienced by the plates during the laser welding process, and practical results achieved in ultrasonic vibration-assisted laser welding, with an emphasis on microstructure refinement, mechanical strength enhancement, and electrical properties of the welded zone.
- vi. Synthesize research findings to advance the understanding of ultrasonic vibration-assisted laser welding techniques for joining similar and dissimilar EV battery connectors and light alloys in EV battery packs. This will be achieved by integrating, comparing and evaluating multiple factors such as system design, processing parameters, hardware orientation to develop a coherent understanding of the topic, ultimately contributing to improved materials performance and structural integrity in critical automotive applications.

1.4. Research Outline

The PhD thesis considers the entirety of the research work, sectioned into seven chapters. The first chapter introduces the background and motivation for the investigations undertaken in the research work, focusing on the progressive development of metal manufacturing techniques towards the need to achieve an effective innovative approach to mitigate the problems associated with welding processes used in achieving high-performance EV battery components. The chapter introduces the use of ultrasonic vibration-assisted laser welding process to improve structural integrity, process optimization, and develop durable materials for EV battery assembly, especially components like busbars and connectors.

The second chapter discusses the in-depth studies of recent developments and challenges encountered in metal manufacturing – joining processes of metals – which is hinged on laser welding of similar and dissimilar metals. The chapter proceeds with the current advancements

on EV battery technology, emphasising on EV battery packs and connectors. Furthermore, it highlights the principles and works conducted on ultrasonic vibration-assisted laser welding and provides key knowledge on the different components of a typical industrial power ultrasound setup.

With the objective to study the effects of ultrasonic vibration on microstructural behaviour during an ultrasonic vibration-assisted laser welding process, the third chapter delves into the theoretical modelling of interactions between the ultrasonic vibration processing parameters and factors influencing the collapse of microbubbles in a welding fusion pool. It initially investigates the application of remote ultrasonic vibration and identifies optimal plate mode orientation for maximum vibrational displacement. Furthermore, the chapter provides thorough theoretical analysis of cavitation dynamics and the relationship between optimised vibration frequencies and cavitation threshold values.

The fourth chapter evaluates ultrasonic vibrations and amplitudes generated by an ultrasonic-assisted laser system for butt joints of Al-Al grade 6 and lap joints of EV battery connectors. Also, the chapter introduces the use of a 3D laser vibrometer and vibration acquisition unit with an accelerometer to measure the vibration levels and displacement generated during the welding process.

The fifth chapter investigates the process of applying ultrasonic vibrations to the molten pool aluminium alloy AA6082 to improve both its microstructure and mechanical properties. Surface quality, microstructural evolution, grain structure analysis, and tensile tests were conducted on the samples. Also, investigations were conducted on conventional and ultrasonic-assisted laser welding processes to assess the ultrasonic vibration effect in the ultrasonic band 20–40 kHz. This was achieved to produce high-power ultrasonic vibration waves, improving the weldability of crack-sensitive aluminium alloys.

The sixth chapter demonstrates the impact of low-intensity ultrasonic vibration on enhancing weld quality in ultrasonic vibration-assisted laser welding. It evaluates the effects of contact and contactless vibration modes, transducer configurations, and optimized parameters—such as horn length, transducer positioning, and operating frequency on the microstructure, ductility,

and overall properties of welded joints. Key findings highlight the ability of ultrasonic vibrations to reduce intermetallic compound formation, improve material mixing, and refine microstructure, ultimately enhancing the reliability of welds in EV battery connectors.

Chapter seven wraps up the thesis by summarizing the study on using ultrasonic vibrations to improve welding for different metals, focusing on electric vehicle (EV) battery connections. It highlights the main findings, showing how ultrasonic vibrations help avoid hard and brittle compounds in welds, making the joints stronger. The chapter compares different welding tools and methods and suggests ideas for future research to make welding better and explore its use in various industries.

1.5. Contribution to New Knowledge in the Field

The key knowledge gap in studying ultrasonic vibration–assisted laser welding of dissimilar metals for EV busbars and connectors lies in the limited understanding of the coupled interaction between ultrasonic vibration, laser–material interaction, and dissimilar metal metallurgy, particularly under high-speed, industrially relevant conditions.

Specifically:

- i. There is insufficient scientific clarity on how ultrasonic vibration influences melt pool dynamics, intermetallic compound (IMC) formation, grain refinement, and defect suppression (e.g., porosity, spatter, cracking) when welding common EV dissimilar metal pairs such as Cu–Al.
- ii. Existing studies rarely address the frequency-dependent effects of ultrasonic excitation on weld stability, electrical conductivity, and mechanical reliability in busbars and connectors, which are critical for EV performance.
- iii. There is a lack of integrated research linking ultrasonic transducer design (frequency, power, coupling method, durability) with process outcomes in laser welding, making it unclear how transducer parameters should be optimized for industrial EV applications.

- iv. Additionally, the scalability, repeatability, and long-term reliability of vibration-assisted laser welds in high-current, thermally cycled EV environments remain underexplored

Therefore, the findings of the study provide adequate information on the interactions between ultrasound characteristics and metallurgical behaviour of weld joints, demonstrating how cavitation microbubble formation within the melt pool influences defect suppression and inclusion probability, thereby improving the predictability of the impact of processing parameters on material performance of EV battery components. The research shows the potential to improve the development and manufacture of EV batteries in the United Kingdom and the world at large. With the integration of ultrasound technology and laser welding, the study addresses the present demand for improved weld quality of EV battery components. Furthermore, the manufacturing approach advances the contemporary status of welding methods and improves the reliability and performance of EV batteries, highly beneficial to the automotive industry in the UK. Its novelty lies in its provision of qualitative and quantitative insights into the design and optimisation of transducers/horn, yielding the development of effective and precise tools suitable to advance the functionalities of ultrasound-assisted laser welding techniques. In addition, this study contributes to the progress of electric vehicle technology and pose wider implications for the advancement of efficient and reliable welding procedures in different industrial applications.

1.6.Impact of Research Outcome

The research in this dissertation, supported by Innovate UK through the UltraMAT (Ref. 102802) and Soni-Laser (Ref: 10018077) projects in collaboration with the Brunel Innovation Centre, UK, aimed at advancing EV battery manufacturing. The Centre's provision of vital equipment and facilities enabled exploration into ultrasonic-assisted laser welding techniques. This work, focusing on integrating Power Ultrasonic Technology (PUT) with laser welding, aimed to enhance battery cell interconnection efficiency and quality. Key areas of improvement

included manufacturing precision, contactless PUT innovation, battery module production automation, addressing manufacturing challenges, enhancing battery pack safety and energy density, and simplifying design and production processes. The impact of this research is evident in scientific publications and global conference discussions, highlighting its significance in the EV battery manufacturing industry.

1.7.List of Publications arising from the Doctorate

1.7.1. Journal publications

1. Teyeb, A.; Silva, J.; Kanfoud, J.; Carr, P.; Gan, T.-H.; Balachandran, W. Improvements in the Microstructure and Mechanical Properties of Aluminium Alloys Using Ultrasonic-Assisted Laser Welding. *Metals* 2022, 12, 1041. <https://doi.org/10.3390/met12061041>
2. Teyeb, A.; Salimi, M.; El Masri, E.; Balachandran, W.; Gan, T.-H. Analytical Simulation of the Microbubble Collapsing in a Welding Fusion Pool. *Materials* 2023, 16, 410. <https://doi.org/10.3390/ma16010410>
3. Salimi, M.; Livadas, M.; Teyeb, A.; El Masri, E.; Gan, T.-H. Biofouling Removal Using a Novel Electronic System for Driving an Array of High Power Marinised Transducers. *Appl. Sci.* 2023, 13, 3749. <https://doi.org/10.3390/app13063749>
4. Salimi, M.; Teyeb, A.; El Masri, E.; Hoque, S.; Carr, P.; Balachandran, W.; Gan, T.-H. Experimental and Numerical Investigation of the Use of Ultrasonic Waves to Assist Laser Welding. *Materials*, 17(11), p.2521. <https://doi.org/10.3390/ma17112521>

1.7.2. Conference papers

5. Teyeb, A.; Lowe, S.; Kanfoud, J.; Gan, T.H. 2018. Investigation on the Use of Power Ultrasonic to Improve the Laser Welding of Aluminium Alloys. In Proceedings of the ISER

396th International Conference on Nanoscience, Nanotechnology & Advanced Materials, Budapest, Hungary, 2018.

6. Teyeb, A.; Salimi, M.; El Masri, E.; Hoque, S.; Carr, P.; Balachandran, W.; Gan, T.H. On the Use of Low-Intensity Ultrasonic Vibration for Enhancing the Laser Welding. September 2023, Conference: ISTANBUL 25th International Conference on “Innovations in Engineering, Technology & Health Sciences” (IIETH-23).

Chapter 2

Literature review

2.1.Introduction

The preceding chapter outlined the background on metal manufacturing techniques and application laser welding in joining EV battery busbars and connectors, as well as the aim, objectives, significance, and structure of this research. Consequently, the knowledge gap of this study has been established. To consider recent studies undertaken, this chapter provides a comprehensive review of the existing literature related to the various processes involved in joining metals, laser welding technique, detailed literature on EV batteries, and the application of laser welding in EV batteries. The chapter also reviews the influences of ultrasonic vibration and cavitation bubble formation on the quality and integrity of weld joints in EV battery connectors. The manufacturing sector is persistently exploring methods to enhance their operations to cater to the demand for superior quality products. Metal joining processes are pivotal in the production of various components and assembling of engineering systems, including electric vehicle (EV) batteries. The inception of innovative joining techniques is crucial to augment the quality and efficiency of these components. Laser welding is a prevalent joining process in the industry, particularly for the assembly of EV battery connectors and packs. However, the process encounters several challenges, especially when welding dissimilar materials. One potential solution to these challenges is the application of ultrasonic technology. Ultrasonic vibration-assisted material processing has been shown to improve a variety of manufacturing processes, including additive manufacturing and laser welding. Power ultrasonic technology has demonstrated significant potential in refining materials and enhancing the mechanical strength and electrical impedance of the final products [35, 36]. This chapter reviews the state-of-the-art developments and challenges in liquid-state joining processes, laser welding of similar and dissimilar materials, and recent advancements in EV battery joining technologies. The chapter will also discuss the application of ultrasonic technology in material processing and propose

future research directions in ultrasonic-assisted laser welding of similar and dissimilar materials.

2.2.Joining Processes of Metals

2.2.1. Metal joining processes

Metal joining processes utilised in industry and fabrication can be categorised into liquid state joining and solid state joining. Liquid state joining refers to processes where the materials to be joined are melted or heated to their plastic state to facilitate bonding. Examples of liquid state joining methods include soldering, brazing,, which use filler materials that are melted and then allowed to flow into the joint, where they solidify and bond the materials together [37, 38]. These examples are listed in **Table 2.1** according to [39]. Soldering is a fusion technique employed for joining various metal by liquefying solder. Solder, which is typically composed of a tin and lead alloy, undergoes a phase change as it is melted by the application of a hot iron. The iron is heated to temperatures exceeding 315°C, and upon cooling, it forms a strong electrical connection. In electrical soldering, both solder wire and solder paste contain a flux. The flux serves the dual purpose of cleansing the soldering surfaces and preventing oxidation of the molten solder. The joining process can be classified into hard (occurs at temperatures above 450 °C) and soft soldering (which is conducted between 90 °C and 450 °C). Due to the low temperatures used in soft soldering, it poses the least thermal stress and mechanical strength, therefore it is not suitable for mechanical load-bearing applications. Furthermore, it is inappropriate to join components that are used in high-temperature applications because the soldered joint loses strength and melts. Soldering is a conventional method employed in the assembly of electrical components and wiring. While it finds application in various fields such as plumbing, sheet metal fabrication, or automotive radiator repair, its methodologies and materials diverge significantly from those utilized in electrical applications. Brazing is a type of soldering which is done at temperatures above 450 °C and uses a metal of a higher melting point compared to those used in hard and soft soldering. Conversely, similarly to hard soldering, the

metal to be fused is heated rather than being melted. When the joining materials are heated to a sufficient temperature, the soldering metal is placed between the joining materials which melts and serves as a bonding agent.

Table 2. 1: Features of Liquid-State Joining Processes

S/N	Category	Welding	Soldering	Brazing
1	Joint Strength	Welded joints are renowned for their exceptional load-bearing capabilities, often surpassing the inherent strength of the base metal.	Soldered joints are typically the least robust among the three types of joints and are not intended for load-bearing purposes. They are primarily employed to establish electrical connections.	Brazed joints are generally weaker than welding joints but offer greater strength compared to soldered joints. They are suitable for bearing loads to a certain extent.
2	Processing Temperature	The welding process necessitates a specific temperature, indicated as 3800°C	The soldering process requires a temperature range of up to 450 °C	The temperature in brazing joints can reach as high as 600 °C
3	Workpiece Heating	To join workpieces, they must be heated until they reach their melting point.	Heating of the workpieces is not required.	Workpieces are heated, but they are maintained below their melting point.
4	Mechanical Properties	The heating and cooling during the joining process can lead to alterations in the mechanical properties of the base metal at the joint.	The mechanical properties of the material remain unchanged after the joining process.	There may be a slight alteration in the mechanical properties of the joint, but it is nearly negligible.
5	Heat Cost	The process incurs heating expenses and demands a high level of skill.	The associated costs are minimal, and the skill requirements are quite low.	The costs involved and the level of skill required fall somewhere between the other two options.

6	Post-Heat Treatment	Typically, heat treatment is necessary to mitigate any adverse effects resulting from welding.	No heat treatment is required.	No heat treatment is required after brazing
7	Preheating of Work-piece	Preheating of the work-piece is not necessary before welding, as welding is conducted at high temperatures.	Preheating the workpieces before soldering is beneficial for achieving high-quality joints.	Preheating is advantageous for creating strong joints, especially because brazing is conducted at low temperatures.

On the other hand, solid state joining refers to processes where the materials to be joined are not melted but are, instead, deformed or interlocked to form a bond. These methods create a mechanical bond between the materials without melting them. Each type of joining process has its own advantages and disadvantages. Liquid state joining methods are often used when high strength and low porosity are desired. However, they also tend to generate a significant amount of heat, which can result in warping and other thermal stresses in the finished product. Solid state joining methods are often preferred for high-volume production and for applications where heat generation must be minimized. However, they may not be as strong as liquid state joining methods, and the joint strength may depend on the surface quality of the materials being joined [40]. For busbars and tab connections in EV batteries, liquid-state metal joining methods are highly required because of their thorough metallurgical continuity, extremely low electrical resistance and durability under elevated current and vibration conditions; such performance levels may not be achieved consistently with solid-state joining methods [29].

2.2.2. Industrial developments and challenges in liquid state joining processes

Most fluid phase manufacturing processes such as laser welding, fusion welding, direct metal deposition, and casting fundamentally rely on the phenomenon of total fusion of a material, followed by rapid solidification. Liquid-state joining processes require fusion and solidification of multi-materials which may be different in thermal properties, such as thermal conductivity

and thermal expansion, mechanical properties like strength, hardness, and ductility), and other characteristics (melting point, electrical properties). Consequently, the structure of the material in the final solidified state, as well as its mechanical and electrical properties, strongly depend on the solidification phase [35]. For instance, this is especially evident when the material consists of a metal alloy, or even a combination of two dissimilar materials, such as in the case of lap joining, by laser welding, of metallic connectors to battery cells, during the manufacturing of battery packs for electric vehicles [40]. The difference in melting points between several types of metals leads to the coexistence of liquid and solid phases at certain temperatures during solidification, and subsequently to the agglomeration of particles of similar composition, which ideally should be dispersed homogeneously throughout the liquid phase during solidification [37]. The presence of voids and gas bubbles, as well as the variability in grain size are phenomena frequently observed, and which cause the properties of the final material to deteriorate, leading to problems such as hot cracking and subsequently poor battery connection [38].

2.2.3. Laser welding process

Laser welding, different from traditional fusion welding techniques, exhibits unique characteristics pertaining to equipment and operational approach. In laser welding, a narrow but deep weld pool is achievable, characterized by a significant low heat input to the joint with respect to conventional techniques. This intrinsic feature makes laser welding suitable for specific applications requiring significant weld aspect ratios. Control over the penetration depth and weld width is achieved through optimization of processing parameters, including laser power modulation, beam focal position adjustments, welding speed modulation, energy transfer modes (pulsed or continuous), and shielding gas configurations. Such precise control empowers laser welding to facilitate the joining and fabrication of critical components with minimised risk. Laser welding presents multiple benefits, including reduced welding width, increased penetration depth, high speed, superior joint strength, minimal workpiece distortion, and the ability to fulfil requirements for lightweight, corrosion-resistant joints, aesthetic weld appearance, reduced electrode consumption, elimination of machining processes, and the capability to weld

in challenging-to-access areas. Consequently, this technology has garnered significant interest across various industries, such as aerospace, medical device, and automotive manufacturing. Two primary laser welding methods exist: the first involves rapid movement of the workpiece beneath the laser beam for continuous welding, while the second, more prevalent method, entails welding through the irradiation of a series of laser beams. Significantly, as a result of the immediate occurrence of solidification after melting during laser welding, minimal interactions take place between the molten material and the surrounding atmosphere. Consequently, the use of shielding gases is generally not required.

Figure 2.1 illustrates a schematic representation of the laser welding process, depicting the two primary welding methods.

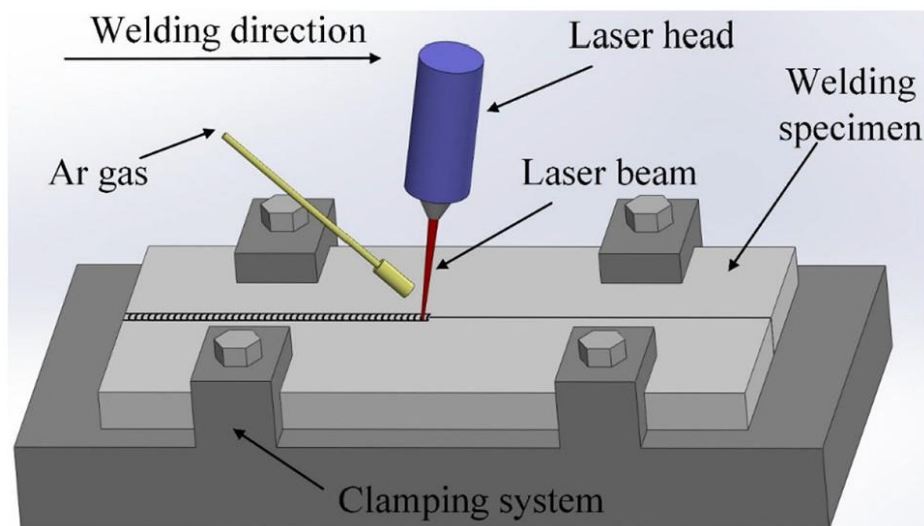


Figure 2. 1: Laser Beam Welding Process

2.2.4. Laser welding of similar and dissimilar metals: Recent developments and challenges

During laser welding of identical or similar materials, a strong metallurgical bond is established at the weld seam [41]. In other words, the fusion zone possesses the identical composition and, in an ideal situation, possessing the same mechanical properties (such as tensile strength, ductility, etc.) as the base material. In the automobile industry, the use of aluminium alloys is increasing due to its lightweight advantage [42, 43]. While aluminium alloys can be effectively

joined using conventional fusion welding methods, laser welding offers unique attributes that render it an optimal choice for aluminium alloy joining [44]. Laser welding exhibits exceptional compatibility with most strain-hardenable alloys, such as AA5182 and AA5754, enabling autogenous welding. However, it is worth noting that during laser welding, the introduction of filler metal is an option, either to provide reinforcement or to enhance joint strength and ductility as needed [45]. In the case of many heat-treatable alloys like AA6016, the risk of hot cracking during welding arises due to both their chemical composition and the thermal strains induced within the metal during the welding process [46]. To mitigate this issue and prevent hot cracking, the introduction of a filler metal is employed to tailor the composition of the weld bead, ensuring it falls outside the crack-sensitive range.

Practical experience in industry has demonstrated that the inclusion of an eutectic alloy, such as Al-Si, in the weld can effectively prevent hot cracking [47]. However, this approach does result in a shorter solidification interval. Nevertheless, the filler wire technique presents two significant drawbacks. Firstly, it leads to uncontrolled alterations in the macroscopic properties of the joint as a result of difficulty in achieving guaranteed process stability [48]. Secondly, due to the small size of the laser beam, there is occasional interference with the filler wire, resulting in inconsistent penetration and instability in the weld pool [49]. For instance, incorporating a 4043 Al-Si alloy wire into a 6061-alloy weld decreases its susceptibility to hot cracking. However, this also leads to a 50% reduction in both tensile and ultimate strengths. Consequently, there is a pressing need to optimize the process parameters to reduce sensitivity to cracking, particularly in the manufacturing of lightweight, high-strength components, especially for the transportation equipment industry.

Recent developments have shown the use of laser welding to achieve the joining of both similar and dissimilar materials with clean and narrow weld bead, and with the ability to weld difficult-to-reach areas [50, 51]. Over the past seven years, more than 200 scholarly articles have been published, specifically addressing the laser welding of dissimilar metals. The predominant focus has been on combinations like Al/Fe, Al/Ti, and Al/Cu. Notably, Al-Cu alloys have

emerged as a popular choice, particularly for applications in the electrical field, such as connectors for electric vehicle (EV) batteries [52].

Das et al. [53] investigated the electrical resistance and corresponding temperature change of a weld joint obtained by ultrasonic vibration-assisted welding of aluminium/copper-coated nickel cell tab with copper busbars. The results showed that when current was passed through the welded joint at room temperature, there was a temperature rise due to resistive heat loss at the joint. With respect to the current flow through the aluminium tab and the copper busbar joint, the temperatures recorded for a pulse current of 200 A and 250 A were 53.26°C and 73.25°C, respectively. On the other hand, the respective values for a copper tab to copper busbar joint were 39°C and 49°C respectively. The higher variation in temperature associated with the dissimilar metals was due to the difference in resistance of aluminium and copper. The authors concluded that the increased temperature exceeded the safe operating threshold temperature of most viable Li-ion battery cells, and this thermal rise may result in premature ageing of the battery. Huang et al. [54] studied the metal mixing mechanism in laser keyhole welding of dissimilar metals, Al (AA1100 Al plate) and Cu (nearly pure Cu plate), considering the results obtained through experimental and computational analyses. The experimental investigation was conducted to identify the influences of laser power, welding speed, and the heat input on the mixing process of the metals in the fusion region. The simulation aspect focused on the physics governing the heat transfer, fluid dynamics, and the metal mixing mechanism within the molten pool. The investigation showed that the recoil pressure from the laser effect on the molten pool contributed to an upward migration of copper from the bottom of the molten pool. On the other hand, the Marangoni effect led to a development of vortices at 2 sides and a backward flow within the molten pool, which promoted the metal mixing process. Thus, increased power laser resulted in increased recoil pressure and Marangoni stresses, thereby, causing an upward movement of a higher fraction of copper atoms to mix with aluminium. Furthermore, the authors revealed that an increase in welding speed shortened the lifespan of the molten pool and reduced the time required for appropriate metal mixing by the fluid flow.

Schmalen and Plapper [55] joined aluminium and copper using laser-based braze-welding process. The formation of brittle IMCs was significantly reduced with this technique by avoiding the intermixture of the dissimilar metals. The resultant joint was a tough, ductile joint with reduced electrical resistance.

The primary challenge that diminishes the mechanical and operational characteristics of welded joints between dissimilar alloys arises from the development of an intermetallic compound (IMC) layer [56, 57, 58]. When this intermetallic phase is uniformly dispersed within the metal matrix between grain boundaries, serving as a dispersed reinforcing agent that hinders dislocations or acts as a high-melting-point crystallization nucleus, however, it plays a beneficial role by enhancing mechanical properties [59]. Conversely, when the IMC exists as a continuous inclusion along the fusion line between two dissimilar metals, it creates a vulnerable zone. This is due to the gradient and non-uniformity in microstructure at the transition from the IMC to the metal, as IMCs exhibit elevated hardness and brittleness under these conditions [52]. It is important to note that the formation and behaviour of IMCs of Cu and Al are governed by the interdiffusion coefficients of Cu and Al in each IMC and they are different. Consequently, this leads to distinct growth rates of each IMC layer. Also, the dimension of the diffusion layer formed is related to both the diffusion time and number of IMC layers formed, where the IMC layers have a significant effect on the mechanical and electrical properties of Cu–Al, causing a discontinuity in material properties across the fusion zone towards the weld-substrate interface [60, 61]. Furthermore, different busbars exhibit variation in electrical conductivity stemming from the formation of different intermetallic compounds and grain size variations in the Al-Cu joints, although, electrical resistivity is obtained at higher amount of Cu content in these intermetallic compounds [62].

Advances in laser technology and welding techniques have improved the efficiency and quality of laser welding. However, there are still areas of improvement such as the consistency of material properties and ensuring proper control of the laser beam to avoid overheating and

damage to the material. Some other challenges include dealing with differences in thermal expansion and melting behaviour, ensuring a consistent weld, and avoiding cracking and porosity in the final joint [63, 64].

In conclusion, laser welding of both similar and dissimilar material continues to face challenges, but developments in laser technology and welding techniques hold promise for continued progress.

2.3. Electric Vehicle Batteries

The importance of the joining process in battery pack manufacturing is paramount, particularly in the context of Electric Vehicles (EVs), which are increasingly vital for mitigating transportation-related emissions and addressing climate change. EVs offer numerous advantages, including reduced greenhouse gas emissions, the ability to utilize renewable energy sources for charging, cost savings due to lower operating expenses, enhanced battery technology, and government incentives promoting their adoption. Lithium-ion solid-state batteries currently serve as the primary power source for a wide range of applications, from portable electronics to EVs. To prevent the use of larger batteries, increased consumption of rare-earth metals and achieve weight saving [65], EVs require the interconnection of several thousand cells in their battery systems to deliver the requisite power. Consequently, the cell-to-cell or module-level joining process assumes a central role in battery pack manufacturing, directly influencing battery capacity and, by extension, the performance of EVs in advancing environmental sustainability and energy independence.

The battery is the main component in an electric vehicle (EV). It stores the electrical energy that powers the vehicle's electric motor and is the source of its propulsion. The size, capacity, and performance of the battery determine the vehicle's range, acceleration, and overall driving experience. Also, the busbar is a key component in modern electric vehicles because it is essential not only for battery cell interconnection but also for power distribution and overheat resistance [66]. Improving battery technology is a key focus for the EV industry, as increasing

the range and the reliability, reducing the cost, and improving the charging time of batteries is crucial for widespread adoption of EVs.

During operational scenarios, there are several failures that can occur which are not limited to the interior sections of the battery but also to the battery management system, sensors, and connection components, each caused by different factors. According to research, over 400 fire incidents associated with electric vehicles have been reported in China between the years 2018 and 2021. Other than external causes, the chances of fires due to battery faults were recorded at about 85% of the entire incidents [67]. Operationally, manufacturing defects or acquired problems during service can subject the power battery to several failures and these failures can be widely classified as internal short circuit, capacity degradation, and leakage of electrolyte. Therefore, ensuring the structural integrity of components within the battery is essential to prevent possible failures that could result in high-risk conditions, even thermal runaway, electrical short circuits, or mechanical failure in service [68].

2.3.1. EV battery packs - Recent advancements

Electric Vehicles (EVs) are increasingly emerging as formidable contenders to traditional internal combustion engine (ICE) vehicles. Data from the International Energy Agency (IEA) indicates that in 2019, electric vehicles constituted 2.6% of global car sales. This figure experienced a noteworthy rise to 4% in 2020, surpassing the earlier projection of 3% provided by the IEA [69]. The contemporary advancements in battery technology have animated the development of electric vehicles (EVs). To compete with ICE vehicles, EVs still need to overcome some barriers, with a primary focus on enhancing battery technology. Lithium-ion (Li-ion) batteries are progressively finding applications in large-scale energy storage systems for grid-related purposes. Consequently, there is a substantial demand for battery manufacturing, where a multitude of individual cells must be interconnected, either in series or parallel, to meet the power and driving range requirements. For instance, the widely adopted pouch cell format relies on tab-to-busbar connections as the electrical interconnect. Based on the design of the

module, several pouch cells are interconnected within a module, and multiple modules are organized into a battery pack or storage unit [70, 71]. Definitions of these units are given as follows:

- Cells: the basic building blocks of an EV battery, responsible for storing energy and providing power to the vehicle.
- Modules: multiple cells are organized into modules to form a higher voltage and capacity unit.
- Packs: multiple modules are packaged into a battery pack, which serves as the main energy source for the vehicle. The pack includes control electronics and thermal management systems to ensure safe and efficient operation.

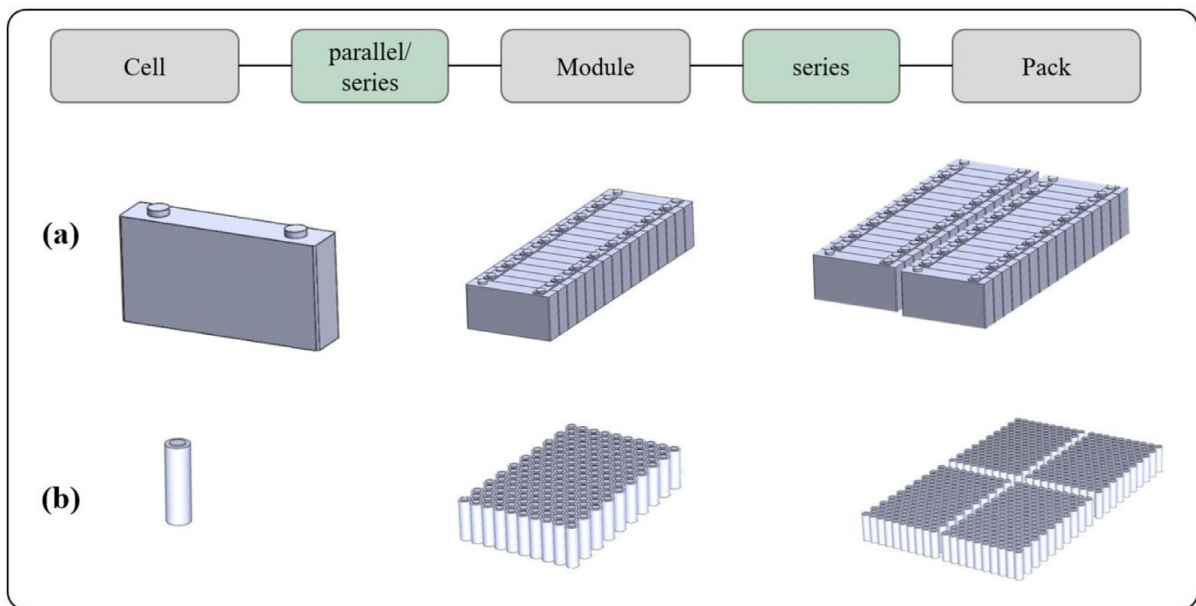


Figure 2. 2: Overview of battery packs indicating two constructions with (a) prismatic and (b) cylindrical cells. [64]

As shown in **Figure 2.3**, several types of cells that are commonly used include:

- **Prismatic cells**: A type of battery cell that has a flat, rectangular shape, with a metallic casing and a stacked construction. Prismatic cells are flexible in terms of design and can be easily incorporated into various battery pack configurations.

- **Cylindrical cells:** A type of battery cell that has a cylindrical shape, similar to a traditional AA battery. Cylindrical cells have a long history of use in consumer electronics and are also widely used in electric vehicles due to their stability and durability.
- **Pouch cells:** A type of battery cell that has a soft, flexible packaging, similar to a food pouch. Pouch cells are lightweight and can be easily shaped to fit into various battery pack configurations.
- **Flat cells:** A type of battery cell that has a flat, disk-like shape, with a thin profile. Flat cells are commonly used in applications where a low profile and high energy density are desired.

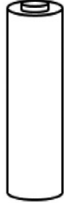
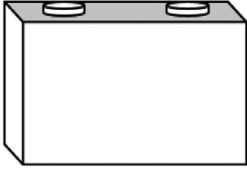
Cylindrical cell	Prismatic cell	Pouch cell
		
• Small size (e.g. 18650 type ($\varnothing$ 18 mm, height 650 mm)) • Hard casing • Low individual cell capacity • Build in safety features • Comparably cheap	• Hard casing • Large size • High individual cell capacity	• Soft casing • Large size • High individual cell capacity • Geometrical deformation during (dis-)charging

Figure 2. 3: Overview of different cell types used in automotive battery applications: (left) cylindrical cell, (middle) prismatic cell, (right) pouch cell. [64]

The specific type of cell used in an EV battery, which is illustrated in **Figure 2.4**, depends on various factors, such as the desired energy density, cost, safety, and thermal management requirements of the battery pack. The different types of cells have their own advantages and disadvantages, and the specific design choice depends on the specific requirements of the application.

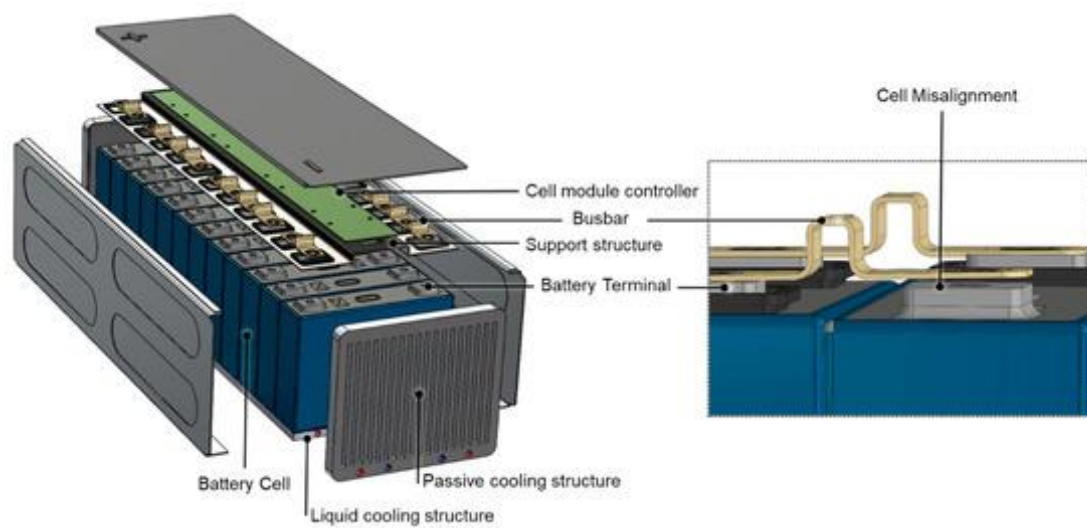


Figure 2. 4: Schematic Illustration of a Typical EV Battery Assembly [72]

While the composition of an electric vehicle (EV) battery may exhibit slight variations depending on the specific type of electric vehicle, it typically consists of three primary components: cells, modules, and a pack, which also possess different cell configurations and are assembled by using different joining processes [73]. **Table 2.2** presents a list of various examples of electric vehicles with their corresponding battery features, orientations and joining processes [40].

Table 2. 2: Examples of electric vehicle batteries (cell configuration: s – series-, p-parallel connection)

Vehicle	Tesla Model S 85 kW	Tesla Roadster	BMW i3	Nissan Leaf	Chevrolet Bolt EV Second generation	Volkswagen MEB – modular electric vehicle drive matrix (I.D. family models)
Modules	16	11	8	58	7	Up to 12
Cells per module	404	621	12	4	24 & 32	24
Cell configuration	74P6S16S	69p9s11s	1p12s8s	2p2s48s	96s2p	—

Total no. of cells	7104	6831	96	192	192	Up to 288
Cell Type	Cylindrical	Cylindrical	Prismatic	Pouch	Pouch (12.7 by 17.7-cm)	Prismatic or Pouch
	18,650	18,650				
Cell manufacturer	Panasonic	—	Samsung SDI	AESC	LG Chem	—
Joining technology	Wire bonding	—	Laser welding	Ultrasonic welding	Ultrasonic welding	—

It is essential to put the joining processes in high consideration due to their significant influence on key battery performance criteria such as electrical, thermal and mechanical factors [74].

There are several techniques that are used in the assembly of battery packs for electric vehicles (EVs), including:

- Spot welding: A welding process in which two metal parts are joined together by applying heat and pressure to specific points, creating a strong and reliable connection. Spot welding is commonly used to assemble battery cells into battery packs, as well as to connect the battery pack to other components in the EV.
- Glue bonding: A bonding process in which a bonding agent, such as a glue or adhesive, is used to bond two parts together. Glue bonding is commonly used to assemble battery cells into battery packs, as well as to secure the battery pack in place within the EV.
- Hot press bonding: A bonding process in which heat and pressure are applied to bond two parts together. Hot press bonding is commonly used to assemble battery cells into battery packs, as well as to bond the battery pack to other components in the EV.
- Screw and bolt fastening: A fastening process in which screws or bolts are used to secure two parts together. Screw and bolt fastening is commonly used to assemble battery cells into battery packs, as well as to secure the battery pack in place within the EV.
- Welding: Welding is commonly used to assemble battery cells into battery packs, as well as to connect the battery pack to other components in the EV.

The specific assembly technique used in a battery pack depends on various factors, such as the design requirements, cost, safety, and production volume of the battery pack. Therefore, choice of assembly technique is a key factor in the overall performance, reliability, and cost of the battery pack.

Limited literature exists concerning the preferences and associated challenges in the realm of joining processes, which can be summarized as follows [74]:

Electrical and Thermal Challenges:

- Low Electrical Resistance: Achieving joints with minimal electrical resistance is crucial, as reduced electrical resistance translates to lower energy loss, diminished heat generation, and subsequently, less temperature increases at the joint during charging and discharging processes.
- Low Thermal Input: Minimising thermal input is particularly vital, especially when employing fusion-type welding methods, as subjecting the cell to excessive heat could potentially lead to safety vent melting, seal compromise, or internal short-circuiting.
- High Thermal Fatigue Resistance: Ensuring that battery interconnects exhibit high thermal fatigue resistance is essential for long-term durability and reliable performance.

Material and Metallurgical Challenges:

- Compatibility for Dissimilar Materials Joining: Joining dissimilar materials may result in the formation of intermetallic layers, which are less desirable due to their elevated electrical resistance and brittle nature compared to the parent materials. Therefore, joints characterized by minimal intermetallic content are preferred.
- Variability of Materials and Surfaces: Overcoming challenges related to highly conductive and reflective materials, surface coatings or oxide layers, joint stack-ups (especially those involving varying thicknesses and/or multiple sheets), is imperative to ensure satisfactory joints.

Mechanical Challenges:

- Durable Joint Strength: It is essential that the joining methods can achieve joint areas or weld sizes that exhibit reliable strength with minimal variability.

- Avoiding Mechanical and Vibrational Damage during Joining: Excessive deformation or the transmission of vibrations into the cell during the joining process can potentially harm internal connections. Precautions must be taken to prevent such damage, as induced residual stress or vibrational energy may be released and lead to joint failure.

2.3.2. Laser welding of EV battery connectors: challenges and perspectives

Laser welding is often used to create lap joints in various applications, including the manufacture of battery packs for electric vehicles.

A lap joint is a type of joint in which two overlapping plates are joined together, typically with a weld. The overlapping plates provide increased strength and stability to the joint, making it ideal for high-stress applications. Laser welding is a precise and controlled welding process that is ideal for creating lap joints in thin materials, such as battery cell foils. The laser beam can be directed precisely to the joint, ensuring a strong and consistent weld. In addition to its precision and control, laser welding provides a clean and efficient welding process, with minimal material distortion and reduced risk of defects. This makes it an attractive option to produce high-quality and reliable lap joints in battery packs for electric vehicles. Furthermore, owing to the narrow welds and the rapid welding pace, this method generates minimal heat within the assembly during welding [75], a critical aspect when dealing with battery tab welding due to the sensitivity of the chemicals within the batteries to heat. In the typical scenario of welding a tab to a terminal, it is advisable for the tab to have a thinner profile compared to the battery cell casing terminal. Precise control over process parameters becomes imperative to achieve the desired balance between weld strength and conductivity without breaching the integrity of the battery enclosure. This welding technique also finds utility in various other applications, such as sealing the battery casing for prismatic cells and facilitating the joining of tab-to-bus bar and bus bar-to-bus bar connections [76]. Given the minuscule weld pool resulting from laser welding, it exhibits a very tight gap tolerance, necessitating, in certain cases, the clamping of the tab to the battery during the welding process [77].

Overall, laser welding is a versatile and effective technique for creating lap joints in a variety of applications, and it is increasingly being used in the manufacture of EV battery packs.

However, welding dissimilar metals, such as aluminium and nickel, can be challenging and result in poor joint quality. Some of the challenges in laser welding EV battery connectors include:

- Thermal mismatch: Different metals have different thermal expansion coefficients, which can cause thermal stress and cracking during the welding process.
- Melting and solidification behaviour: Dissimilar metals have different melting points, melting ranges, and solidification behaviours, which can affect the final joint quality.
- Joint geometries: Complex joint geometries and tight tolerance requirements can make it difficult to achieve consistent, high-quality welds.
- Surface contamination: Surface contaminants, such as oils, grease, or oxides, can interfere with the welding process and result in poor joint quality.

2.3.3. Criteria of performance and quality of the EV battery connectors

The performance and quality of an EV battery connector can be evaluated based on the following criteria:

- Electrical conductivity: A high-quality EV battery connector must provide low resistance and high electrical conductivity to ensure efficient transfer of electrical energy.
- Mechanical strength: The connector should have a robust mechanical design to withstand the high forces encountered in an EV battery system.
- Durability: The connector should be able to withstand the harsh environment of an EV battery system and should be designed for long-term reliability.
- Temperature resistance: The connector must be able to operate in a wide temperature range, from sub-zero temperatures to high temperatures encountered in the battery system.
- Safety: The connector should meet safety standards and should not pose any risk of fire or other hazards during normal operation.

Other parameters are obviously relevant to any products design such as ease of use, environmental compatibility and cost-effectiveness.

Despite all the challenges, laser welding remains a promising technology for welding EV battery connectors. There is a growing interest in developing new welding techniques and technologies that can improve joint quality, reduce welding time, and reduce costs. One promising approach is the use of hybrid laser welding techniques, which combine laser welding with other welding methods, such as arc welding [78] or friction stir welding [79], to overcome the limitations of laser welding alone [80]. Another approach is the use of advanced sensors and process monitoring techniques to improve the control and accuracy of the welding process.

Ultimately, the use of laser welding for EV battery connectors presents both challenges and opportunities. With continued research and development, it is likely that the quality and efficiency of laser welding for this application will continue to improve, leading to increased adoption and cost savings in the EV battery industry. The aim of this study is to investigate the potential of using ultrasonic waves to improve the laser welding of EV battery connectors.

2.4. Ultrasonic Vibration-assisted Material Processing with Fluid Phase

2.4.1. Cavitation in molten metals

Ultrasonic wave is a powerful phenomenon on promoting the melt microheterogeneity as well as the main processes of degassing and fine filtration in solidifying metals. When an ultrasonic vibration is applied to excite the solidifying phase of metallic joints during welding, cavitation bubbles are often formed at the solid-liquid interface within the molten pool. The acoustic cavitation that occurs in the molten pool contributes to the fragmentation and shaping of intermetallic compounds, acting as the main cause of degradation of the properties [79]. To activate the cavitation, enough acoustic energy should be introduced in the liquid metal to establish a pressure variation that initiates bubbles formation [81]. Ultrasonic wave in molten metals can improve the microstructure of the metal through both mechanical and thermal effects.

- Mechanical effects: The high-frequency ultrasonic waves generate high-intensity pressure waves in the liquid, leading to the creation of numerous small gas bubbles. The collapse of these bubbles produces shock waves that agitate the molten metal and promote solidification and crystallisation. This enhances the mixing and homogenization of the liquid, leading to improved microstructure and reduced defects.
- Thermal effects: The high-frequency ultrasonic waves also generate heat due to energy dissipation during bubble collapse. This additional heat input can improve the thermal history of the metal and promote material transport and homogenisation, leading to improved microstructure and reduced defects.

These effects of ultrasonic cavitation can lead to improved properties such as increased density, reduced porosity, improved mechanical strength, and enhanced surface quality in the final metal products.

The vibration can be transmitted to the molten pool in two ways: vibration of workpiece [36, 50, 63] and tool vibration [64, 80, 82]. The four mechanisms known as cavitation, acoustic flow, mechanical and thermal effects are produced in the fusion zone of the weld during the ultrasonic vibration. The development of cavitation in the molten metal is one of the remarkable applications of high-power ultrasound. This involves four mechanisms: acoustic streaming, microstreaming, microjets, and micro-streams.

The cavitation bubble expands and contracts in the molten pool until it is exposed to the high-pressure region from the ultrasound wave and implodes. The implosion of bubble generates a high-pressure acoustic wave called shock wave and a local hot spot at a very high temperature. The other mechanism such as acoustic streaming microstreaming, micro streamers and micro-jets are followed by the implosion of the cavitation.

The emission of the shock wave due to the collapse of cavitation bubble attached to a rigid wall is investigated by Brujan et al. [83]. Their results indicated that a major portion of the shock wave is dissipated within 100 mm of the bubble wall. Some of the cavitation burst under the compression of the ultrasound wave sooner than they fill with gas solved in the melt. Typically, the bubble threshold for collapsing increases as increasing the ultrasound frequency; 1.2 atm

at 20 kHz, 1.6 atm at 20 kHz, 1.6 atm at 140 kHz, 3 atm at 1 MHz, and 5.8 atm at 5 MHz [84, 85].

Ultrasonic vibration-assisted additive manufacturing (UVAM) is a 3D printing technique that combines ultrasonic vibration with traditional additive manufacturing processes. The addition of ultrasonic vibration can improve the quality and efficiency of the additive manufacturing process. This can be achieved in three specific ways: The ultrasonic vibration improves material distribution by reducing the formation of voids and ensuring a more uniform structure in the final product; ultrasonic vibration can also increase the build speed by promoting material flow and reducing the formation of unwanted defects such as voids, which can slow down the build process; and can also enhance the surface finish of the final product, reducing the need for post-processing and improving the quality of the final product.

Several researchers studied the effect of ultrasonic waves to improve AM process [86]. This research study investigated the potential of using high-intensity ultrasonic to control the solidification process and scaling up the system for directed-energy deposition additive manufacturing. The results show that ultrasonic can assist in refining the grain structure and reducing anomalies such as porosities. The study also found that ultrasonic can reduce hot cracks and potentially control grain orientation, providing new applications for ultrasonic-assisted additive manufacturing.

In conclusion, ultrasonic vibration-assisted manufacturing has the potential to improve the efficiency and quality of traditional additive manufacturing processes, making it a promising technique to produce high-quality and complex metal components.

2.4.2. Ultrasonic vibration-assisted laser welding of similar and dissimilar materials

Welding of dissimilar materials poses several challenges [54], which include material compatibility issues; melting point differences; thermal expansion mismatch; difficulties in welding processes; wettability concerns; and lack of filler metals.

These challenges can lead to decreased weld quality, reduced service life, and potential failure of the welded components. Effective strategies, such as using specialised filler metals, pre-

treatment, and multi-pass welding techniques, must be used to overcome these challenges and produce high-quality dissimilar material welds.

Ultrasonic vibration-assisted laser welding is a process that combines laser welding with ultrasonic vibration. Ultrasonic vibration addresses the limitations in laser welding by introducing high-frequency sound waves that improve the wettability of the material and promote better fusion between dissimilar materials [30]. This vibration mitigates the effects of thermal expansion mismatch and material compatibility issues by enhancing the flow and mixing of molten metal. It also lowers the effective melting point by reducing local thermal gradients and facilitates the welding process by minimising the need for filler metals and addressing difficulties in achieving a consistent weld.

- Similar materials: Ultrasonic vibration can help to enhance the penetration depth of the laser beam and improve the quality of the weld by reducing porosity and improving the uniformity of the weld bead.
- Dissimilar materials: In addition to enhancing penetration depth, ultrasonic vibration can also help to overcome the challenges associated with laser welding of dissimilar materials, such as high thermal conductivity differences, significant differences in melting points, and low wettability. The ultrasonic vibration helps to stir and mix the materials, promoting the formation of a more uniform and homogeneous weld.

Several studies were carried out to characterise the effect of ultrasonic wave on tungsten insert gas (TIG) welding [87] – [90]. It was shown by Sun et al. [87] that there is 300% increase in the penetration rate compared with the conventional TIG welding. The increase in penetration is owing to the increased arc push force via ultrasonic leading to the oscillation in the arc plasma. Ultrasonic assisted laser welding is studied by several scholars [91] – [101]. A finite element modelling and a laser Doppler vibrometer are used to estimate the ultrasonic energy propagation on the workpiece by Tarasov et al [91]. They have shown improvement in microstructure, microhardness, and tensile strength of the weld 321 stainless steel when ultrasonic vibration transmitted into the welding zone.

Declined to the weld porosity from 4.3 % to 0.9 with a reduction to its average size is reported by Lei et al [92]. Teyeb et al. [97] showed experimentally that the strength of weld increased by 26% when the laser welding assisted by an ultrasonic vibration. Deeper penetration is reported by Woizeschke et al. [98] and Radel [99] when laser welding is assisted by ultrasonic vibration, which is due to the heating effect of ultrasonic vibration.

The effect of using different ultrasound power on the porosity of a welding joint is experimentally investigated by Yin et al [100]. The results showed that appropriate ultrasonic power significantly increased grain state of grain in the weld. The tensile strength of a welded joint increased by approximately 12 % compared with the conventional welding. Increasing the ultrasonic power beyond the appropriate level can degrade the tensile strength.

Ultrasonic cavitation in molten metals can improve the microstructure through the following mechanisms:

- Mechanical stirring: The intense pressure waves generated by ultrasonic cavitation collapsing create mechanical stirring of the molten metal, leading to improved mixing and homogenisation of the metal.
- Thermal effects: The collapse of cavitation bubbles can release high-energy shock waves and heat, leading to local heating and cooling of the molten metal. This can promote solidification, modify the dendritic structure, and refine the grain size of the metal.
- Gas removal: The shock wave emission from the cavitation process can also help remove gas inclusions and other impurities, leading to an improvement in the microstructure and reduction of defects [50].

In conclusion, ultrasonic vibration-assisted laser welding has the potential to improve the efficiency and quality of laser welding for both similar and dissimilar materials, making it a promising technique for a variety of applications in the manufacturing and repair of metal components.

2.4.3. Power ultrasound and cavitation in liquids and molten materials

Power ultrasound refers to ultrasonic waves with high energy, which can be used in a variety of applications [102 - 105], including:

1. Medical: used for imaging, therapeutic purposes (such as breaking up kidney stones), and cleaning and sterilising medical instruments.
2. Industrial: used for cleaning, welding, and cutting materials, and for non-destructive testing and inspection.
3. Environmental: used for cleaning and purifying water, removing oil from contaminated water, and breaking down pollutants in wastewater.
4. Food processing: used for homogenising, emulsifying, and pasteurising food products.
5. Cosmetics: used to produce creams, gels, and other personal care products.
6. Textile: used for cleaning, degassing, and modifying the properties of textiles.
7. Materials science: used for synthesizing and modifying the structure of materials, such as ceramics and nanoparticles.

2.4.4. Ultrasonic-assisted welding: mechanisms, cavitation effects, and microstructural improvements

Most manufacturing processes, such as laser welding, additive manufacturing, and casting, are based on the phenomenon of total fusion of material, followed by rapid solidification. The material's structure in the final solidified state and its mechanical and electrical properties strongly depend on the solidification phase [36, 106]. This is especially evident when the material consists of an alloy of metals or even a combination of two dissimilar materials, such as in the case of lap joining (by laser welding) of specific connectors to battery cells, for the manufacturing of battery packs for electric vehicles [40]. The difference in melting points between different types of metals leads to the coexistence of liquid and solid phases and subsequently to the agglomeration of particles of similar nature, which ideally should be dispersed homogeneously throughout the liquid phase during solidification [37, 107].

The presence of voids and gas, and the grain size variability, are phenomena frequently observed that cause the final material's properties to deteriorate, leading to problems such as hot cracking and, subsequently, fragile connection [37]. Ultrasonic processing of molten materials is the primary technique that helps to improve the microstructure by grain refinement. The vibration can be transmitted to the molten pool in two ways: vibration of the workpiece [51, 63, 108] or tool vibration [64, 82, 109]. Four mechanisms, cavitation, acoustic flow, mechanical effect, and thermal effect are produced in the fusion zone during ultrasonic vibration. One of the remarkable applications of high-power ultrasound on molten metal is the creation of cavitation in the melt. Acoustic cavitation is a powerful phenomenon promoting melt micro-heterogeneity and the main processes of degassing and fine filtration in light alloys. The acoustic cavitation in the molten pool contributes to the fragmentation and shaping of intermetallic compounds, which is the leading cause for the degradation of the properties [50]. Four mechanisms are involved in acoustic cavitation: acoustic streaming, microstreaming, microjets, and micro-streams.

The associated phenomenon is described as follows. The cavitation bubble expands and contracts in the molten pool until it is exposed to the high-pressure region from the ultrasound wave and then implodes. The implosion of a bubble generates a high-pressure acoustic wave called a shock wave and a local hot spot at a very high temperature. The other mechanisms, such as acoustic streaming, microstreaming, micro-streamers, and microjets, are followed by the implosion of the cavitation [110].

The effect of vibration and waves on the creation of a cavitation bubble has been presented in several studies [39,40]. The emission of the shock wave due to the collapse of a cavitation bubble attached to a rigid wall was investigated by Brujan et al. [83]. Their results indicated that a significant portion of the shock wave is dissipated within 100 μm from the bubble wall. Ultrasound cavitation can burst under the compression of the ultrasound wave sooner than they fill with dissolved gas in the melt. Typically, the bubble threshold for collapsing increases as the frequency of ultrasound increases; 1.2 atm at 20 kHz, 1.8 atm at 140 kHz, 3 atm at 1 MHz, and 5.8 atm at 5 MHz [84, 85].

Several studies were carried out to characterise the effect of ultrasonic waves on inert tungsten gas (TIG) welding [87 – 90]. It was shown by Sun et al. [87] that there is a 300% increase in the penetration rate compared with conventional TIG welding. The increase in the penetration results from increased arc push force via ultrasound, leading to the oscillation in the plasma arc. Ultrasonic-assisted laser welding has been studied by several scholars [90 – 95], for example, finite element modelling and a laser Doppler vibrometer were used to estimate the ultrasonic energy propagation on the workpiece by Tarasov et al. [91]. An improvement in the microstructure, microhardness, and tensile strength of the 321 stainless steel weld was reported when ultrasonic vibration is transmitted into the welding zone. Lei et al. [96] reported that the weld porosity decreased from 4.3% to 0.9% with a reduction in its average size. Teyeb et al. [97] showed experimentally that weld strength increased by 26% when the laser welding was assisted by ultrasonic vibration. Deeper penetration is reported by Woizeschke et al. [98] and Radel [54] when laser welding is assisted by ultrasonic vibration, which is due to the heating effect of ultrasonic vibration.

The effect of using different ultrasound power on the porosity of a welding joint is experimentally investigated by Yin et al. [100]. The results showed that appropriate ultrasonic energy significantly increases the grain state of the weld. The tensile strength of a welded joint increased by approximately 12% compared with conventional welding. Increasing the ultrasonic power beyond the appropriate level can degrade the tensile strength. As the ultrasound melt treatment before solidification notably affects refining and solidification in light alloys, the welding can be called micro-casting.

2.4.5. Ultrasonic assisted laser welding of similar materials (Aluminium alloys)

The objective of this study is to investigate the potential benefits of using HPUTs as ultrasonic assistance for laser welding to improve the quality and efficiency of joining similar material, specifically butt joints using grade 6 aluminium alloys (6062 or 6083) and lap joints using grade 3 aluminium alloys 3003. By utilising ultrasonic technology during the welding process, the aim is to improve the mechanical properties of the weld joint, such as its tensile strength

and ductility. Additionally, the study will evaluate the effect of ultrasonic parameters, such as frequency, amplitude, and the operation time, on the welding quality of the resulting joint. The research findings will provide insights into the feasibility of implementing ultrasonic assisted laser welding in the manufacturing of aluminium components and structures and may have broader implications for the development of advanced welding techniques for other similar materials.

2.4.6. Ultrasonic assisted laser welding of dissimilar materials

The second objective of this research is to investigate the application of ultrasonic energy in the laser welding of dissimilar materials, such as copper to aluminium joints, and joints of different grades of aluminium. The joining of dissimilar materials presents unique challenges due to differences in their physical and metallurgical properties. The use of ultrasonic energy in conjunction with laser welding can potentially improve the quality and efficiency of the welding process for these materials [111].

This objective will be achieved through a series of experiments, including laser welding of copper to aluminium joints with and without ultrasonic vibration assistance. The effect of ultrasonic parameters such as amplitude, frequency, and duration on the weld quality and strength will be studied. Additionally, laser welding of different grades of aluminium, such as grade 6 Al alloy 6083 and grade 3 Al alloy 3003, will be conducted with and without ultrasonic vibration assistance. The resulting weld quality, microstructure, and mechanical properties will be analysed to determine the effectiveness of ultrasonic energy in improving the welding process for dissimilar materials.

2.5. Research Approach

The research aims to explore the effect of ultrasonic parameters on the process outcomes, such as joint strength and electrical impedance, and to optimize the welding process for improved performance. The proposed works involve designing and building an ultrasonic assistance sys-

tem and conducting experiments to evaluate the effectiveness of ultrasonic-assisted laser welding on aluminium alloys and dissimilar material joints. The experimental results will be analysed and compared with conventional laser welding to identify the advantages of ultrasonic-assisted laser welding. However, the state-of-the-art technique, specifically laser welding, has not been able to mitigate the formation of brittle Al-Cu intermetallic phases that are associated with Al-Cu alloys, nevertheless, these alloys show exceptional potential as EV battery busbars and connectors.

This work builds upon existing studies on ultrasonic vibration-assisted welding by extending the investigation beyond general process effectiveness to a more fundamental and systematic evaluation of ultrasonic energy delivery into the weld pool. While prior literature has primarily focused on demonstrating the qualitative benefits of ultrasonic assistance on weld quality, the present study establishes a direct relationship between the design and development of an ultrasonic power generator, transducer geometry, and the resulting vibration amplitudes required to initiate effective cavitation bubble formation within the weld pool. Furthermore, unlike most previous studies that consider a single mode of ultrasonic excitation, this work uniquely compares the use of contact and contactless transducers and evaluates their respective abilities to induce melt pool agitation. By examining the consequent effects on microstructural evolution and grain refinement in dissimilar Cu–Al welds, this study offers a more comprehensive and mechanistic understanding of how ultrasonic vibration influences weld behaviour, thereby advancing current knowledge in the field.

2.6.Summary

The electric vehicle (EV) battery industry has immense potential and is garnering attention from various stakeholders such as governments, non-governmental organisations, international bodies, associations, and funders. As the demand for EV batteries increases, significant efforts and development are being undertaken to improve and optimise the assembly process. However, there is still ample room for research and development to enhance the efficiency of

these processes. Ultrasonic techniques have shown promise in several manufacturing processes, but their potential for improving EV battery connector assembly has not been extensively studied. This research aims to fill this gap and contribute to the knowledge in the field. By exploring the use of ultrasonic vibration in laser welding of battery connectors, this study offers a novel approach to enhance the performance and quality of EV batteries, which will be of immense value to the industry and society. To address this gap, it is essential to investigate the theoretical models that describe the mechanisms governing cavitation collapse and the generation of ultrasonic shockwaves within the weld fusion pool, as well as the resulting effects on weld behaviour. Therefore, the next chapter (Chapter 3) examines these theoretical models, with particular focus on weld pool pressure distribution, plate vibration, and cavitation dynamics.

Chapter 3

Microbubbles collapsing in a welding fusion pool

3.1.Introduction

The previous chapter provided extensive review on existing studies on recent developments in the EV battery industry, laser welding of EV batteries connectors, laser welding of dissimilar metals and ultrasonic vibration assisted laser welding. While existing literatures have demonstrated the overall impact of ultrasonic vibration–assisted laser welding, a theoretical investigation and modeling of plate vibration distribution is essential to predict the optimal transducer locations that can deliver the most effective vibrational energy for enhancing laser-welded joints and the minimum cavitation threshold pressure that can initiate grain refinement in the weld zone. This present chapter explains the vibration distribution on a plate resulting from excitation applied at different locations and frequencies. Cavitation theory has been explored to confirm the initiation of cavitation and to study its dynamics within the molten pool area. During the vibration assisted laser welding; cavitation might be initiated which has shown in the literature that ultrasound cavitation improves microstructure morphology and refines the grain of the weld [112, 113]. In this work, the plates are excited through narrow-band high-power ultrasound transducers (HPUTs). Ultrasonic frequencies between 20 and 40 kHz have been selected due to their optimal cavitation bubble formation as adopted by industry standards for performance, safety, and process compatibility [114]. Therefore, a theoretical investigation is conducted to identify the plate-mode shapes resulting from ultrasonic vibrations, aligned with the frequency bandwidth of HPUTs at approximately 20 kHz, 29 kHz, and 40 kHz. It was shown that applying the excitation from the side of the clamped plate produces an order of 10^3 higher vibration displacement amplitude, compared with excitation from the corner. The forced vibration of cavitation and bursting time are studied to identify its dynamics, and the time required to generate and implode cavities, hence specifying the vibration-assisted welding time.

Thus, the proposed computational route enables efficient multi-parametric analysis of cavitation, initiated by remote ultrasound excitation, in the molten pool under welding.

In this chapter, the theoretical vibration of the plate coupled with cavitation vibration in the molten area is presented. As the HPUTs available in the marketplace can excite the plate in a region of narrow band frequency, a simulation study was carried out to understand the wave propagation and modes in the structures at the desired frequencies. An objective of this study is to find the optimum position to remotely vibrate the centre of the plate with the maximum amplitude and hence generate ultrasound cavitation in the molten pool area. The cavitation phenomenon that occurs during the solidifying phase is the origin of the microstructure improvements in the joints. Therefore, further theoretical investigations were conducted to find the cavitation vibration in the molten pool area, initiated and propagated by the remote excitation of the plate. Such a theoretical investigation can help to find the optimal position, frequency, and time for vibration-assisted welding.

3.2.Theoretical Modelling

This section provides theoretical explanations of the plate's vibration under ultrasonic-guided wave (UGW) propagation and its interactions with the ultrasound cavitation in the fusion zone. As shown in **Figure 3.1**, part of the ultrasound-guided wave (UGW) travelling in the plate leaks or refracts into the liquid. When the sound pressure of the UGW exceeds the cavitation threshold, several microbubbles are generated in the fluid close to the solid–fluid boundary. As the ultrasound excites the plate, the microbubbles are subjected to positive and negative pressure. They expand and contract under negative and positive pressure, respectively [101].

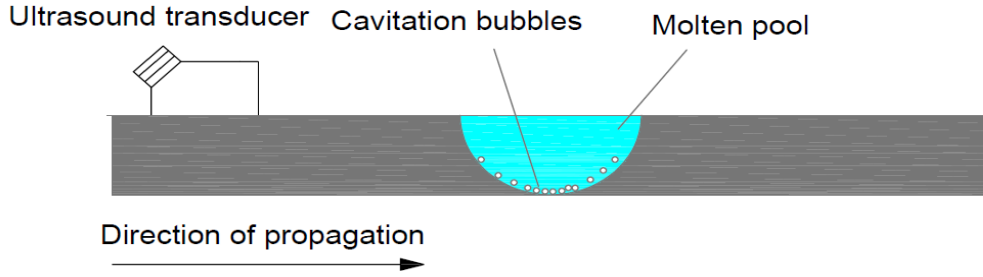


Figure 3. 1: Leakage of guided waves into the fluid. The melt pool agitates due to low local pressure which generates cavitation.

3.2.1. Ultrasonic plate vibration

In recent years several studies have been carried out to identify the plate response subjected to different types of excitement. The modelling of plate vibration has been studied extensively since 1787. Most of the relevant background theories on the free and forced plate vibration can be found in the work by Leisaa [115]. Due to the presence of the higher order matrices the virtual approach is suggested by Sung et.al [115, 116, 112] in a series of studies which make computationally less expensive to estimate the response of the plate. In this study the theoretical modelling from Vlasov [103] is used to obtain the mode shape of the plate at the desired frequency region. For a thin, fully clamped Kirchhoff–Love plate subjected to a harmonic point force excitation, the steady-state transverse displacement $\xi(x, y)$ is obtained from the forced plate vibration equation [115]. Generally, the steady state transverse displacement of the clamped plate influences the amplitude of the vibration [118], which in turn determines the acoustic pressure at the weld area [119]. If this pressure exceeds a critical threshold, then, cavitation occurs.

Equation 3.1 gives the expression of the steady state transverse displacement if the plate excites harmonically:

$$\xi(x, y, t) = \hat{\xi}(x, y)e^{i\omega t} \quad (3.1)$$

The normal velocity is according to equation 3.2:

$$v_n = \frac{\delta \xi}{\delta t} = i\omega \hat{\xi} \quad (3.2)$$

At the solid–liquid interface, that is the melt pool, this vibrating boundary generates a specific pressure in the melt pool estimated as:

$$p(x, y) \approx \rho_l c_l v_n = i \rho_l c_l \omega \xi(x, y) \quad (3.3)$$

where p is the pressure in the melt pool, ρ_l is the density of the molten metal, c_l is the sound speed through the molten metal, and ω is the ultrasonic angular frequency. Therefore, equation 3.3 shows that the pressure is directly proportional to the ultrasonic angular frequency and the amplitude of the vibration. Since cavitation occurs when the acoustic pressure exerted exceeds the cavitation threshold and typically in metals, cavitation pressure is approximately 0.1 – 1 MPa, therefore, substituting the cavitation pressure, we have equation 3.4:

$$i \rho_l c_l \omega \xi \geq p_{cavitation} \quad (3.4)$$

The minimum amplitude required to initiate cavitation within the melt pool is

$$\xi_{min} = \frac{p_{cavitation}}{i \rho_l c_l \omega} \quad (3.5)$$

Under resonant excitation, the displacement amplitude at the weld region can be sufficiently very large and when such vibration is propagated by a high-power ultrasound transducer (HPUT) operating within a narrow band frequency, it can generate significant ultrasonic compressional vibration at the weld interface effectively. It is advantageous to select the transducer to align with the resonance frequency of the plate that can generate the high-pressure acoustic wave in the fusion zone of the weld.

Figure 3.2 shows a 25 cm × 25 cm × 0.1 cm clamped aluminium alloy plate-mode shape with alloy density, $\rho_s = 2800 \text{ kg/m}^3$, Poisson ratio $\nu = 0.33$ and Young's modulus $E = 72.5 \text{ GPa}$, subjected to unit force at the locations illustrated in Figure 3.3. The plate dimension was selected to satisfy the assumptions of classical Kirchhoff–Love plate theory and provide a geometry large enough to support well-defined modal shapes without undermining the consideration for laboratory-scale ultrasonic excitation. Although in ultrasonic melting treatment different frequency bandwidths are employed to excite the plate, in this study the plate-mode shapes are plotted for the frequency 20 kHz, subjected to a unit force at the locations illustrated in **Figure 3.3**.

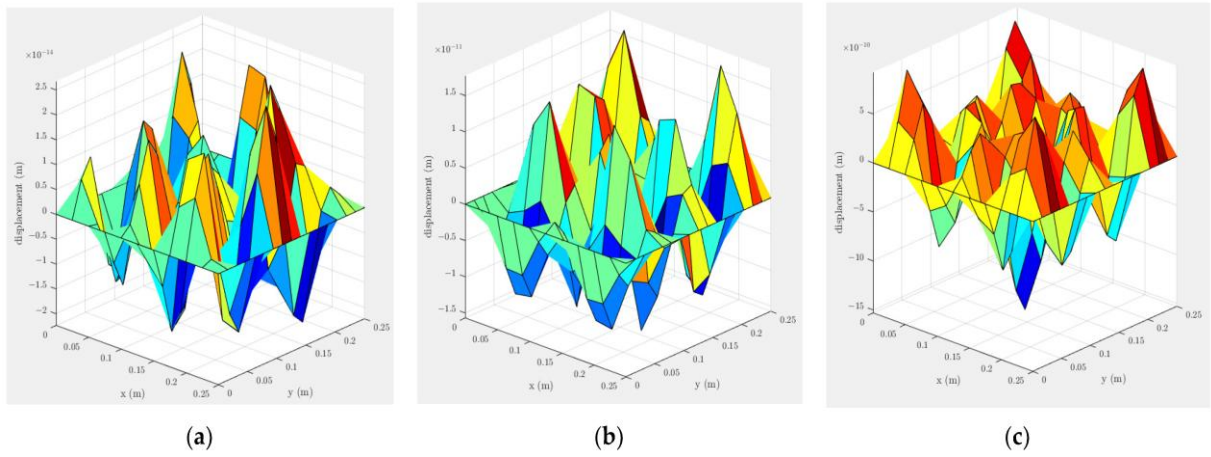


Figure 3. 2: A clamped-plate vibration-mode shape subjected to unit force excitation at the (a) corner, (b) side and (c) centre of the plate at 20 kHz.

The excitation locations are illustrated in **Figure 3.3**.

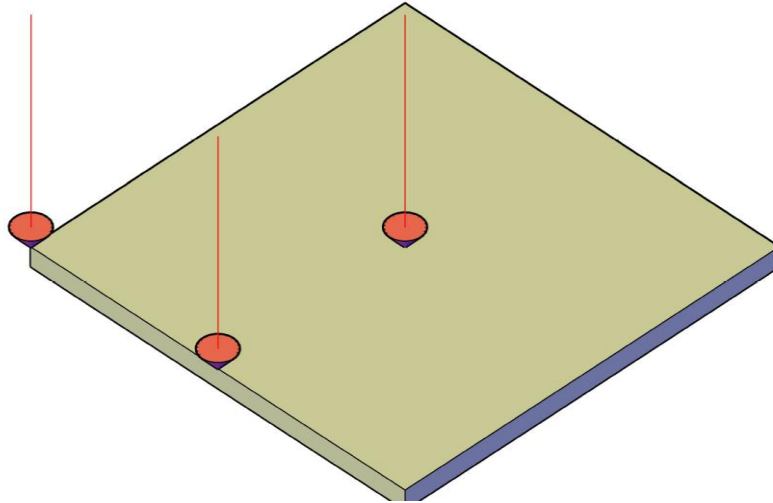


Figure 3. 3: Plate subjected to ultrasonic excitation at three different locations a, b, and c.

As illustrated in **Figure 3.2**, at the excitation point the displacement reaches its maximum value. Although using a vibration close to the tip of the laser head is preferable, it might not be practical to be very close to the laser head due to the heating produced in the welding zone area. Another approach is to use a fixed location for the ultrasound to vibrate the fusion zone area

remotely. As illustrated in **Figure 3.2(b) and (c)**, when the plate is subjected to excitation from the side, the displacement amplitude is an order of 10^3 higher compared to the corner excitation. Teyeb et al. [97] used an ultrasound transducer at the side of a plate to transmit the ultrasound vibration into the molten pool. In this study, the effect of a single transducer on the plate displacement is plotted at the frequencies used by Teyeb et al.: 19, 28 and 40 kHz. The excitation location is highlighted by a red arrow in **Figure 3.3**.

For the excited plates, shown in **Figure 3.4**, the plate subjected to ultrasonic vibration at the corner exhibited the minimum displacement amplitude compared with other locations. Also, the maximum displacement was associated with the same exciting plate at the corner.

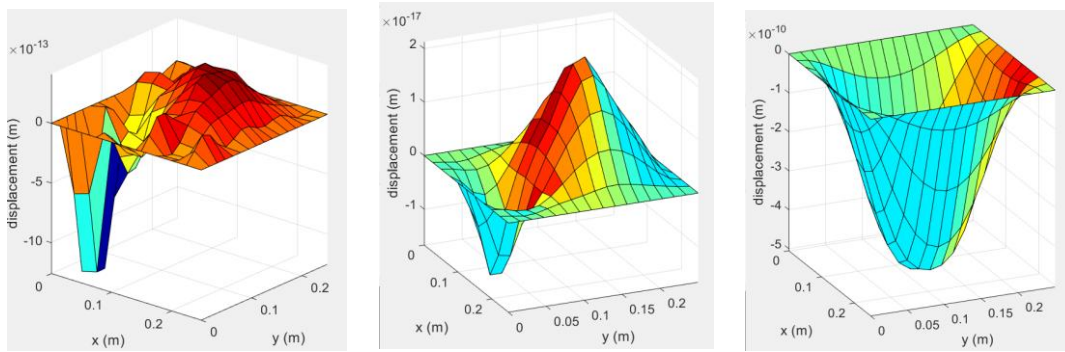


Figure 3. 4: Plate vibration subjected to a unit force excitation at (a) corner (b) side (c) centre of the plate at 19 kHz.

Although using a vibration close to the tip of the laser head is preferable, in practice it might not be practical to be very close to the laser head due to the heating produced in the welding zone area. Another approach is to use a fixed location for the ultrasound to remotely vibrate the fusion zone area. In a study conducted by Jian et al., [120], the impact of the excitation frequency on the microstructure and mechanical characteristics was examined. The researchers observed that there was a reduction in grain size with increasing frequency. Furthermore, there was a rise in tensile strength, elongation and hardness due to the introduction of ultrasonic vibration. In another work by Nothdurft et al. [121], the effect of the ultrasonic amplitude, at an ultrasonic frequency of 20 kHz, on the weld seam features were investigated. The magnitude of impact of localize excitation on the weld seam was also examined. It was found that relative

position of the weld directly influenced the localized excitation, and at higher vibration amplitudes and regions of excitation near the vibration anti-node displayed most improved grain refinement. Teyeb et al. [97] used a pair of transducers at the either side of a plate to transmit the ultrasound vibration into the molten pool. In **Figure 3.5**, the effect of single transducer on the displacement of plates is plotted at the frequencies.

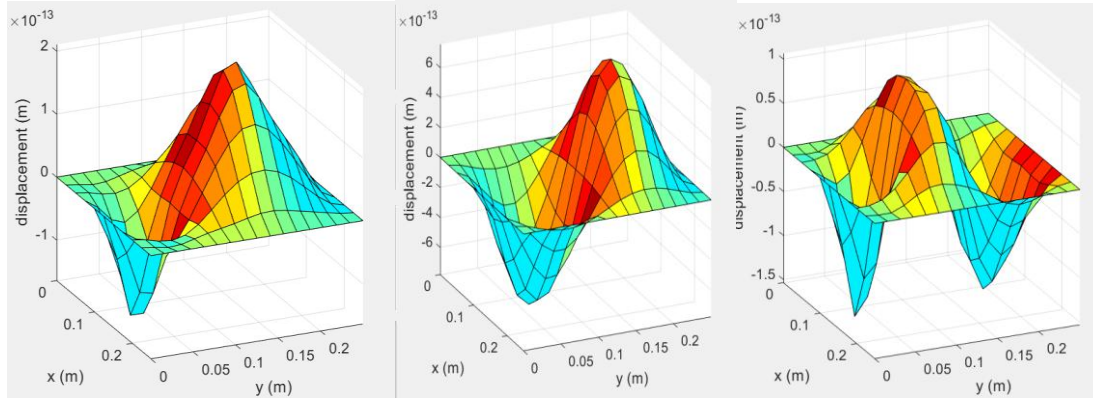


Figure 3. 5: Exciting the plate from the side using a single transducer at (a) 20 kHz (b) 28 kHz and (c) 40 kHz.

3.2.2. Coupling of the plate vibration and the fusion area pressure

To identify the pressure in the fusion zone, it is assumed that the vibration is applied to a semi-cylinder. The relation between internal pressure, P_f , and the pipe wall displacement, W_1 , can be expressed by [105]:

$$P_f = \frac{-2B}{1 - (\alpha_s - \alpha_f)^2} \frac{W_1}{a}, \quad (3.6)$$

where B and a is the bulk modulus of the semi fluid and the cylinder radius, respectively. The W_1 parameter is the radial displacement of the cylinder shape in the fusion area. The $\alpha_s = k_s a$ and $\alpha_f = k_f a$, where k_s and k_f are the wavenumber for the plate and the semifluid respectively.

The pressure variation in the molten pool is plotted in **Figure 3.6** using the displacement value associated with the centre of the plate shown in **Figure 3.4**. As illustrated in **Figure 3.6**, the optimum frequencies for exciting the plate are approximately 22 kHz and 32 kHz.

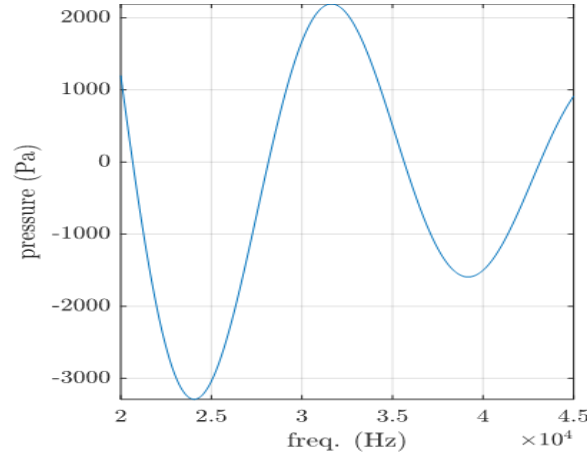


Figure 3. 6: Pressure variation in the molten pool with respect to the frequency

Although the plate displacement is maximum at 28 kHz, shown in **Figure 3.5**, the pressure in the molten area, shown in **Figure 3.6**, is not noticeable compared with the other frequencies. Considering the results shown in **Figure 3.4** and **Figure 3.5**, it is recommended to use either a 20 kHz or 40 kHz transducer.

3.2.3. Cavitation dynamics

Cavitation is referred to the generation of cavities and the subsequent oscillation behaviour due to exceeding the binding force between the melt molecules [111]. The cavitation threshold in terms of pressure, within the melt is given by [112]:

$$P_B = P_0 - P_v + \frac{2}{3\sqrt{3}} \left[\frac{\left(\frac{2\sigma}{R_0}\right)^3}{P_0 - P_v + \frac{2\sigma}{R_0}} \right]^{\frac{1}{2}}, \quad (3.7)$$

where P_0 is the liquid static pressure, P_v is the vapour pressure in the bubble, and σ is the surface tension coefficient of the melt. The R_0 parameter is the initial radius of the bubble. It should be emphasized that as a cavitation bubble grows from a small-sized nucleus to a greater size compared to its initial size, the bubble will start to collapse at a certain radius, that is the threshold radius, having a partial pressure, which is a small value. When considering a typical cavitating flow, the threshold radius could be in the order of 10^2 more than the initial nucleus radius, R_0 . Therefore, if the initial partial pressure of the gas within the nucleus was approximately 1 bar the value of P_{gm} at the onset of collapse would be about 10^{-6} bar. This shows that increasing cavitation radius may result to extremely high values of temperature and pressure within the melt. However, in practice, several factors mitigate this process, such as the diffusion of gas into the bubble and the effect of liquid compressibility [111].

The relationships between the initial radius of cavitation and the sound field frequency, f_r , can be expressed by [113]:

$$f_r = \frac{1}{2\pi R_0} \left[\frac{3\gamma}{\rho_f} \left(P_0 + \frac{2\sigma}{R_0} \right) - \frac{2\sigma}{\rho_f R_0} \right]^{\frac{1}{2}}, \quad (3.8)$$

where γ is the specific heat capacity of the fluid and ρ_f is the fluid density. By assuming the physical parameter of $P_v = 2000$ Pa, $\sigma = 0.910$ N/m, $P_0 = 0.101$ MPa, $R_0 = 10$ μ m, and actual cavitation threshold $P_B = 155,411$ Pa, Equations (3.7) and (3.8) are plotted in **Figure 3.7**. As seen in **Figure 3.7**, increasing the frequency gives a smaller cavity but requires a higher pressure to initiate it. The required pressure to initiate cavitation is 100 times higher than the maximum value illustrated in **Figure 3.6**. Hence it is recommended to use a mobile transducer close to the area where the welding operation is happening to achieve the desired displacement level as shown in **Figure 3.2 (c)**.

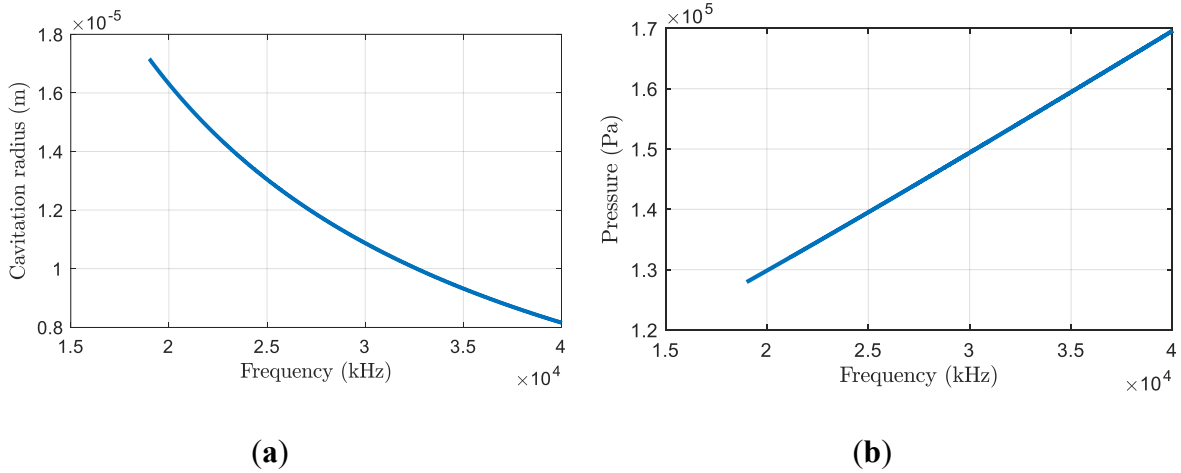


Figure 3. 7: Cavitation radius and threshold pressure with respect to the excitation frequency.

The behaviour of cavities has been extensively studied and is covered in several literature references [111, 113, 106]. In this study, the oscillation of a vapour-gas cavity in an incompressible liquid is governed by Nolting–Neppiras equation:

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 + 4\mu\frac{\dot{R}}{R} + \frac{2\sigma}{R} = (p_0 - P_v + \frac{2\sigma}{R_0})\left(\frac{R_0}{R}\right)^3 - p_0 + p_v + p_A \sin(\omega t) \quad (3.9)$$

where R , $\dot{R}$, $\ddot{R}$ are bubble radius, first and second derivative. The R_0, σ and μ terms are the initial radius of the cavity, the surface tension of the melt and the viscosity of the melt. The p_0, p_v and p_A parameters are ambient pressure, vapour pressure and sound pressure respectively.

The pressure relapsed by imploding the cavitation is proportional to the acoustic pressure of the melt. The higher the acoustic pressure of the melt, the higher the acoustic wave released by the cavitation. The critical radius can be estimated by:

$$Pg + P_v - P_0 = \frac{2\sigma}{R}, \quad (3.10)$$

where $Pg + P_v$ is the total pressure inside the bubble.

The pressure distribution around the cavitation bubble is studied by [106], and the results indicated that the pressure reaches its maximum value at about $1.58 R$ from the cavitation bubble. It was shown in reference work [107] that the weld's penetration and width increased when a pulsed ultrasound was employed.

Changes in the bubble radius as well as the wall velocity are plotted in **Figure 3.8**, using Equation (3.9). As seen from the plots, the bubble oscillation happens up to approximately 100 milliseconds. The bubble radius and the wall velocity can reach approximately 0.004 mm and 30 m/s respectively. Based on the results shown in **Figure 3.8**, the effect of the shock wave from each ultrasound cavitation would be approximately 6.3×10^{-3} mm in the molten pool area. Depending on the width and the depth of the fusion zone, different cavitation numbers should be initiated to have ultrasonic grain refining.

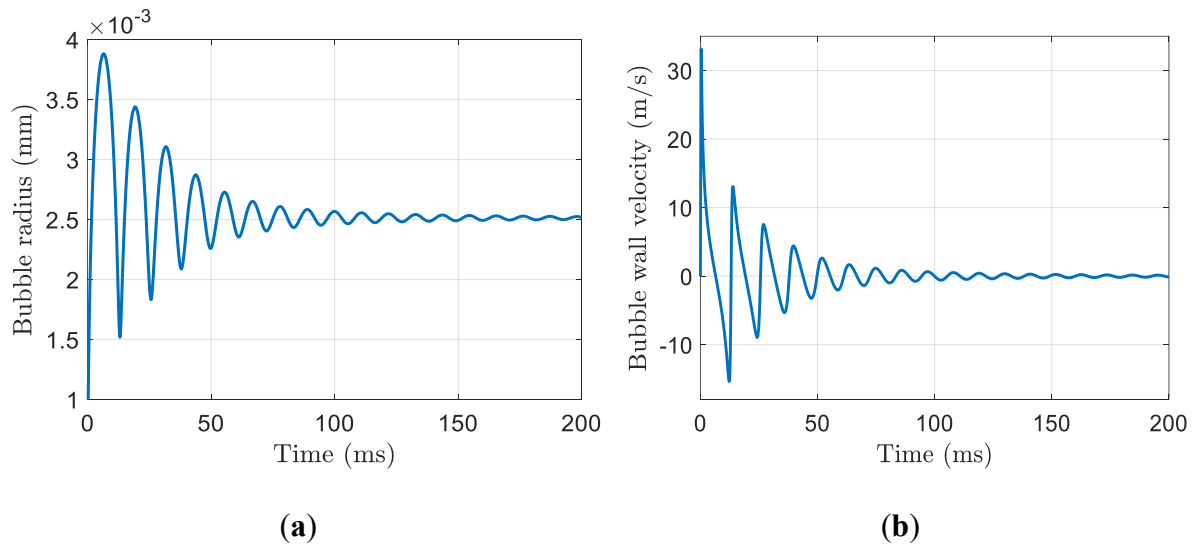


Figure 3. 8:Cavitation bubble (a) radius (b) wall velocity subjected to 20 kHz vibration.

3.3.Design and Simulation of Focused Ultrasonic Horns for use with Langevin Transducers in Contact and Contactless Modes

This section investigates on the vibration output from the transducer and its horn by using finite element analysis to model the transducer and simulate surface vibration characteristics. To make the vibration level at its optimum value, the horn length should be proportional to half of the wavelength associated with the transducer. The model integrates solid mechanics, and electrostatics, with relevant equations assigned to each respective medium. In the domain of electrostatics, the behaviour of piezoelectric ceramics is governed solely by the equations of solid mechanics. Free tetrahedral elements are employed, with the maximum mesh size considered to be one-sixth of the wavelength. In this study, the piezoelectric materials modelled were glass and zirconate titanate (PZT-4). All material properties were selected from the material library of COMSOL Multiphysics. The main body of the transducer is assumed to be made of steel, and aluminium material is selected for the horn.

To effectively simulate the vibrational energy of 22.8 kHz that passes through the transducer towards the front-end surface of the horn, it is essential to simulate the back mass of the transducer, which contains the piezoelectric material.

Figure 3.9 represents the back mass of the transducer to which the horn is screwed. From the surface simulation (Figure 4.28b), the topmost part of the back mass, located at a height of 45 mm above the base exhibits the highest displacement of 0.0008 to 0.0012 μm , compared to the mid-region of the back mass with vibration displacements less than 0.0004 μm . The uppermost portion of the transducer back mass exhibits the highest amplitude level because it is farther from the vibration node (typically near the centre of the back mass), resulting in greater displacement at the antinode during longitudinal resonance.

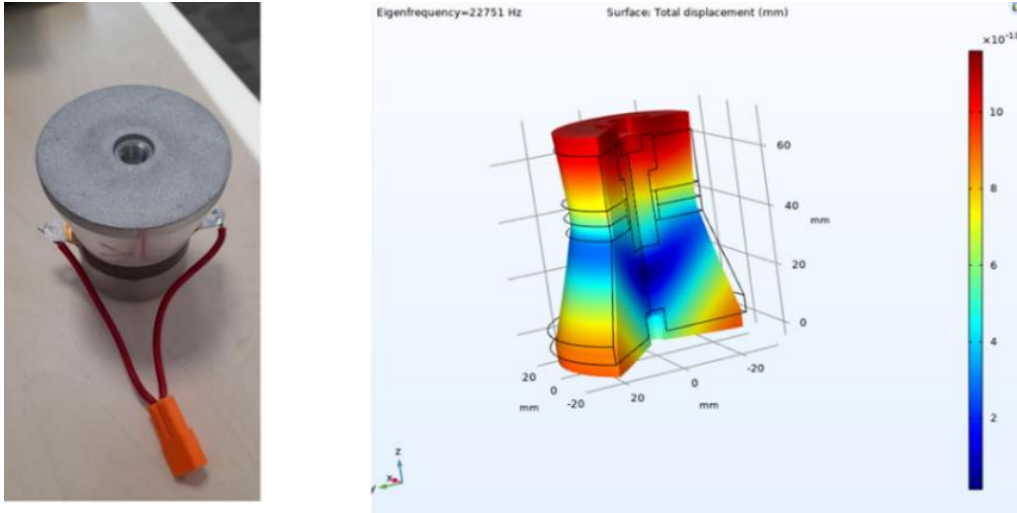


Figure 3. 9: The piezoelectric component that generates vibration. (a) The back mass of a transducer where the horn screw (b) numerical simulation.

At approximately 20 kHz the transducer generates high vibration which is then transmitted to the horn. Piezoelectric material can also be considered as a back mass for the horn. As shown in **Figure 3.10**, having a horn with a dimension of half of the natural frequency wavelength yields a high amplitude vibration at the transducer horn. Therefore, **Figure 3.10(a)** shows the meshing and surface vibration simulation of the transducer horn at an Eigen frequency of 20 kHz.

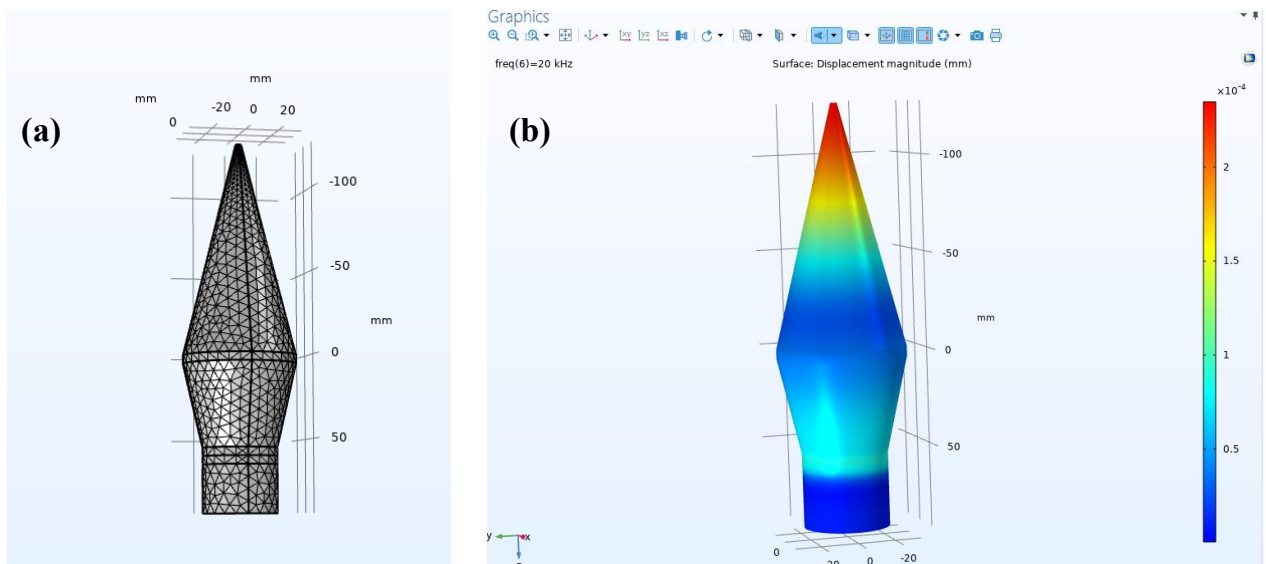


Figure 3. 10: Full modelling generates a vibration from the horn. (a) Meshed conical horn (b) Results from vibrated conical horn, excited by the piezoelectric

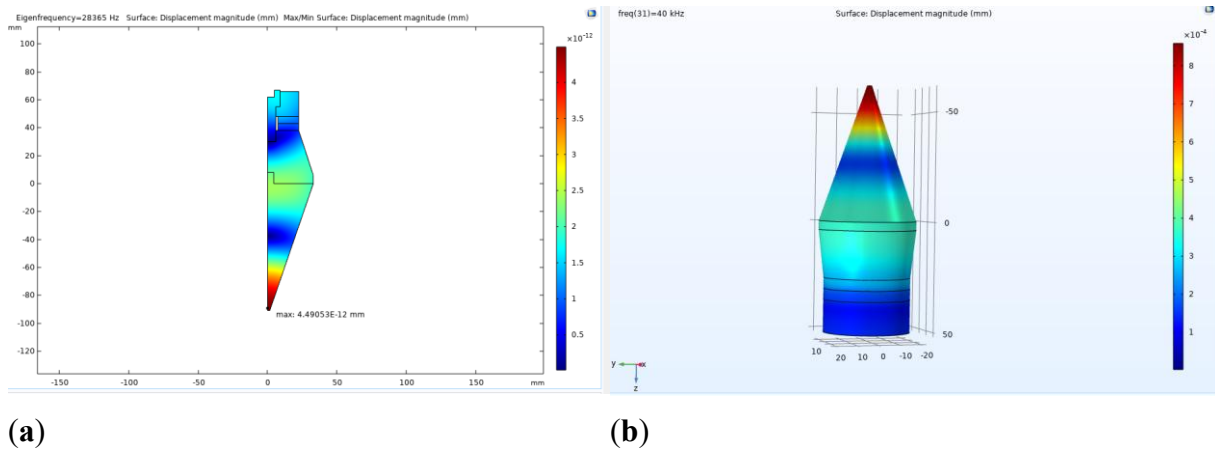


Figure 3. 11: Full modelling generates a vibration at. (a) 28 kHz (b) 40 kHz from vibrated conical horn, excited by the piezoelectric

From numerical simulation, the conical shaped horn vibrated at the highest amplitude compared to the designed cylindrical and the step horns [76]. Hence, it is recommended to use a conical shaped horn and depending on the performance of the transducer with the new design the effect of natural frequency on the printed product is considered. As shown in **Figure 3.11**, it is observed that the vibration level at the horn tip was the highest, vibrating at an amplitude of 2.5×10^{-4} mm, since the power output from the transducer is focused down on the smaller horn tip through the length of the horn. Different from the transducer, the horn is designed to have a heavy end where it is connected to the transducer while the other end (front-end surface tip) is lighter. When the horn vibrates in free space, the momentum of the two ends of the horn must be equal, therefore, the front-end surface tip of the horn operates at a higher velocity that balances the momentum at both ends of the horn [122].

Table 3.1 displays the dimensions of the designed horns for the three operation frequency levels. The length of the transducer is associated with having a horn dimension equal to half the wavelength at its natural frequency. The outer diameter matches that of the transducer itself, and the tip diameter is selected to maintain the conical shape of the transducer while providing sufficient space for laser operation.

Table 3. 1: Proposed dimensions for the horn length with different natural frequency

Transducer Fre- quency [kHz]	Length L [mm]	Outer diameter OD [mm]	Tip Diameter TD [mm]
20	127	66	3.3
28	91	66	3.3
40	62	45	2.25

The projection of the designed transducer is shown in **Figure 3.12**. The figure displays the dimensions of the back screw, top and tail diameters, and the length of the transducer from the plan and side views.

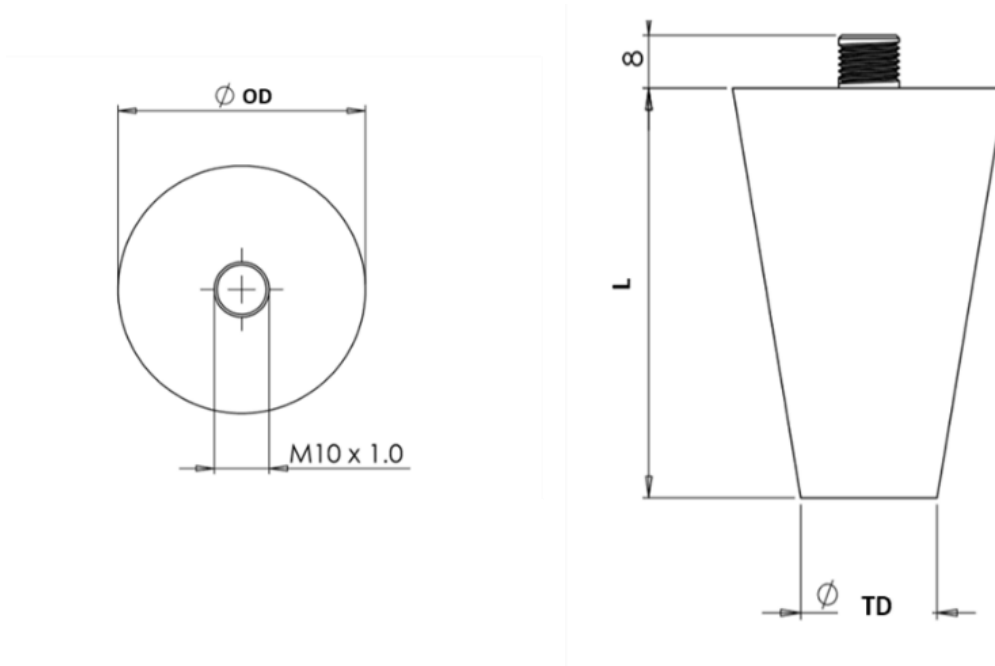


Figure 3. 12: The transducer configuration (a) plan view (b) side view.

The fabricated transducer with its horn is shown in **Figure 3.13**. The characteristics of the horn, in terms of its sensitivity to the resonance frequency of the transducer, are measured experimentally in Appendix I.



Figure 3. 13: Fabricated Transducers and horns for 20, 28, and 40 kHz.

3.4. Numerical Simulation of Vibration Transmission to the Molten Pool Area

This section aims to provide an estimation regarding the pressure transmission into the molten pool area, with the configurations illustrated in **Figure 3.14**.

To simplify the model, it is assumed that the tip of the transducer is in contact with the centre of the oval-shaped weld, as shown in **Figure 3.14**. The top oval shape highlighted in **Figure 6.14 (a)** is assumed to be molten copper (Cu101), which melts at approximately 1080 °C, while the bottom one is aluminium (Al1050), which becomes molten at 660 °C.

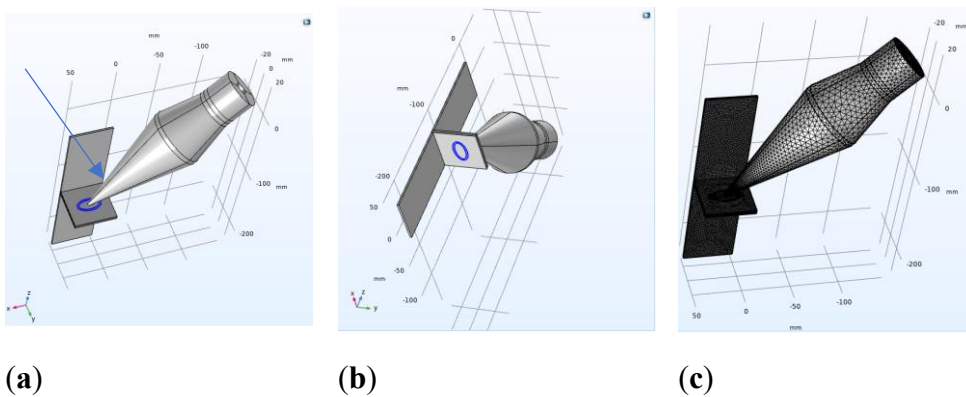


Figure 3. 14: The model configuration and the location of the applied vibration: (a) the highlighted area is considered molten copper; (b) the same location is considered molten aluminium; and (c) the meshed model.

The model integrates pressure acoustics, solid mechanics, and electrostatics, with relevant equations assigned to each respective medium. In the solid mechanics domain, reflective boundaries are applied at the area of the welding molten pool. In the domain of electrostatics, the behaviour of piezoelectric ceramics is governed solely by the equations of solid mechanics. Free tetrahedral elements are employed, with the maximum mesh size considered to be one-sixth of the wavelength [104]. In this study, the piezoelectric materials modelled were glass and zirconate titanate (PZT-4) and the piezoelectric excitation of the PZT-4 ceramics was simulated using a Frequency Domain study and resolved via a direct solver. Selection was based on the material library of COMSOL Multiphysics. The main body of the transducer is assumed to be made of steel, and aluminium material is selected for the horn. The material properties used in this simulation are given in **Table 3.2**.

Table 3. 2: Material properties used in the simulation.

Properties	Young's Modulus (Pa)	Density (kg/m ³)	Loss Factor	Wave Speed (m/s)
Aluminium (Al1050)	7×10^9	2700	0.003	5120
Copper (Cu101)	110×10^9	8960	0.005	3810
Steel	203×10^9	7850	0.0006	5950
Lead Zirconate Titanate	245×10^9	7600	0.02	-
Molten aluminium (Al1050)	-	2375	-	-
Molten copper (Cu101)	-	8020	-	-

The acceleration value shown in **Figure 3.15 (a)** is similar to the one shown in **Figure 5** in the paper. The obtained value shown in **Figure 3.15(b)** indicates that an acoustic pressure of approximately 0.1 Pa appears in the molten pool area. According to the theoretical results by Teyeb et al. [104], specifically elaborated using **Figure 4** in that paper, no ultrasound cavitation will develop in the molten pool area as the threshold for the cavitation at a frequency of 20 kHz is approximately 10^5 Pa.

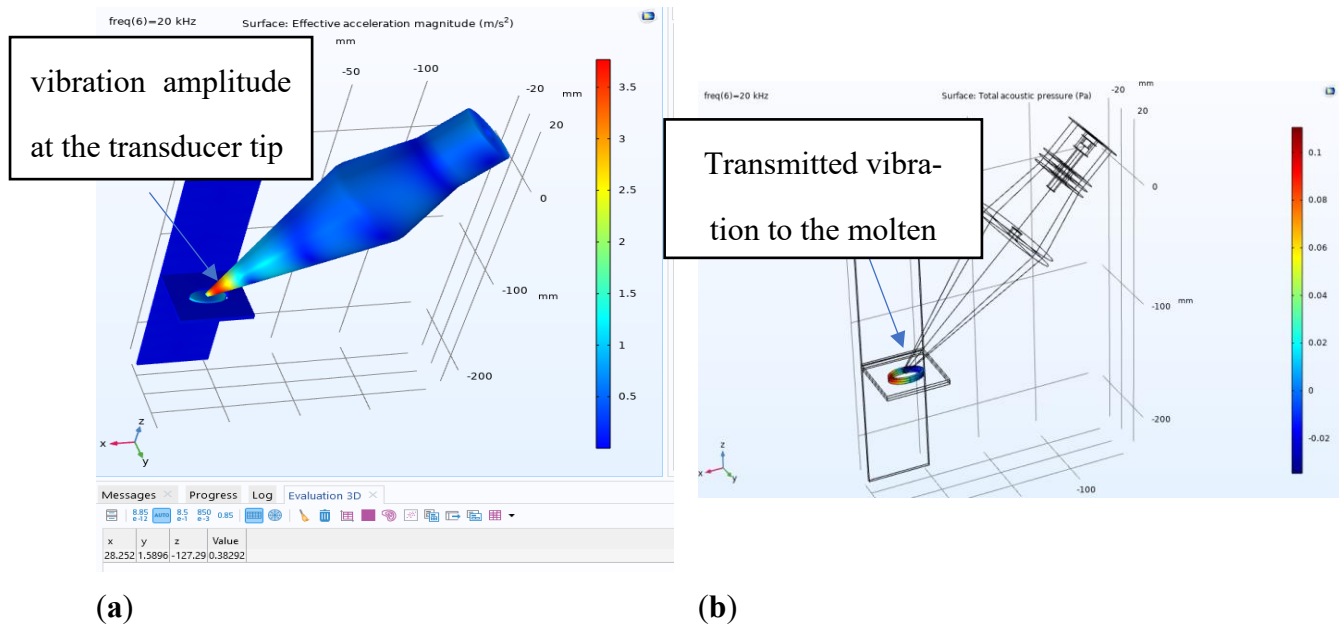


Figure 3. 15: Application of ultrasonic vibration to the molten pool area at 20 kHz. (a) Acceleration amplitude, and (b) the acoustic pressure in the molten pool area.

3.5.Summary

In this chapter, the theory associated with clamped plate vibrations and ultrasonic cavitation is explored to analyse the forced vibration of cavitation within the weld pool. The proposed method provided an accurate tool for predicting the minimum pressure required to initiate cavitation bubbles within the molten pool during ultrasonic assisted laser welding. The aim of this work was to investigate the use of narrow band ultrasonic waves to improve the laser welding process of EV battery connectors. Therefore, a theoretical study was conducted to understand the waves propagation and modes in the structures made and to the cavitation phenomenon that occurs during solidifying phase, which is at the origin of the microstructure improvements of the welded joints. A theoretical investigation allowed to evaluate the displacement and the energy levels for bursting of microbubbles in the fusion zone.

Time and frequency domain studies showed that for respective frequencies of 20 kHz, 28 kHz and 40 kHz, the displacement obtained in contact mode reached, at least a level of 9 nm which can excite the semifluid in the fusion zone and collapse the microbubbles. The pressure wave emitted from bursting of microbubbles was estimated to reach 470 MPa which has been confirmed in literature to be sufficient for creating a new grain within the microstructure. The

duration of solidifying phase should be around 0.01 s, which corresponds to 200 cycles of ultrasound at 20 kHz. In theory this is a sufficient time to make the bubbles expands and collapse in the melt. Hence, fragmentation of dendrites, grain refinement and an improved orientation of intermetallic formations can be achieved.

Thus, the control of ultrasonic power and displacement is essential for optimising the cavitation effect in ultrasonic vibration-assisted laser welding. The next chapter discusses the development and manufacturing of ultrasonic power generator, experimental design and arrangement of ultrasonic power transducers, amplifiers and thermal testing of these tools which were used to generate the required displacement and excite the welded pool. The goal of the chapter is to produce a prototype of the system, focusing on necessary optimizations to enhance manufacturability and modularity. Consequently, this ensures the ease of manufacture and modularity which is essential to making the system sustainably scalable while maintaining a consistent level.

Chapter 4

Development of Ultrasonic Power Generation System for Improved Cavitation Microbubble Excitation

4.1.Introduction

The previous chapter introduced existing theoretical models that have been employed to explain the interdependence between wave propagation by the introduction of ultrasonic vibration into a weld pool, the weld pool behaviour and cavitation dynamics. In accordance with this study, it is necessary to also examine the nature of power generator and ultrasonic transducers with corresponding parameters that can generate the minimum amplitude to effectively initiate cavitation during welding. Accordingly, this chapter begins by describing the experimental setup and the characterization of the ultrasonic power generator used to drive the transducers. The chapter also investigates the influence of the ultrasonic vibration on the microstructure morphology and refinement of grains of the weld.

The preceding chapter presented established theoretical models used to explain the interdependence between ultrasonic wave propagation within the weld pool, weld pool behaviour, and cavitation dynamics. Building on this foundation, it is also necessary to examine the parameters that govern the minimum vibration amplitude required to effectively initiate cavitation during welding. Accordingly, this chapter investigates the influence of ultrasonic vibration on weld microstructure morphology and grain refinement. The chapter begins by describing the experimental setup and the characterization of the ultrasonic power generator used to drive the transducers.

Three different focused horns, for 20 kHz, 28 kHz and 40 kHz, are designed and characterised to find the optimum distance and tightening torque for vibrating the plates under welding with the maximum amplitude. Similarly, a focused industrial transducer is characterised, and its

results are compared with the designed 20 kHz transducer. The chapter reports on results and findings from the following analyses: Effect of the tightening torque on the vibration output from transducer (theory with experiment); Effect of the welding on the vibration amplitude of the plate (theory with experiment); and COMSOL modelling of the transducer design.

In this chapter, an experimental design of power ultrasonic transducer with horns operated at frequencies of 20, 28, and 40 kHz was achieved to evaluate the optimal vibrational output sufficient to build up cavitations in a weld joint during laser assisted welding.

4.2. Ultrasonic Wave Generation

4.2.1. System prototype development

The aim of this section is to manufacture a prototype of the system which will provide necessary optimisations for ease of manufacture and modularity. The ease of manufacture and modularity is important to ensure the system is sustainably scalable while upholding comparable reliability we achieved in systems built before

The prototype consists of 4 major sections listed below:

1. Control – A Windows or Linux operating system-based machine with the required packages installed to interface with an STM32 microcontroller and BIC property “Sendwave” software which is used to interface with a signal generator capable of variable signal generation.
2. Signal Generator – an STM32 based microcontroller system which will receive instructions from the control which then will relay desired signal output to a pre-amplification module. The pre-amplification module will adjust the microcontroller output to match the requirements for high voltage amplification which may involve biasing, buffering and amplification.

3. High Power Amplifier – multiple modular units capable of adequately exciting eight (8) 150W Langevin transducers at their respective resonance frequencies which are projected to operate between 20 kHz to 100 kHz therefore flexibility would need to be considered.

4. Transducer Array- The system will be required to operate 8 150W Langevin transducers. The scope of the development is focused on the design and manufacturing aspects of the Signal Generator and High-Power Amplifier. These aspects are the key areas where ease of manufacture and modularity could be applied.

4.2.2. Specification

To specify the system, the general requirement was the ability to operate the Transducer array and effectively transmit ultrasonic energy. **Figure 4.1(a)** shows the initial system floor plan indicating the output and input transformers. Before, the development of the systems developed at Brunel Innovation Centre adopted the input and output transformer formats which significantly improved the complexity as seen in Figure 4.1 and in the block diagram in Figure 4.2. Therefore, there was a need to simplify this design and opt for less dependency on bulky transformers in the system.

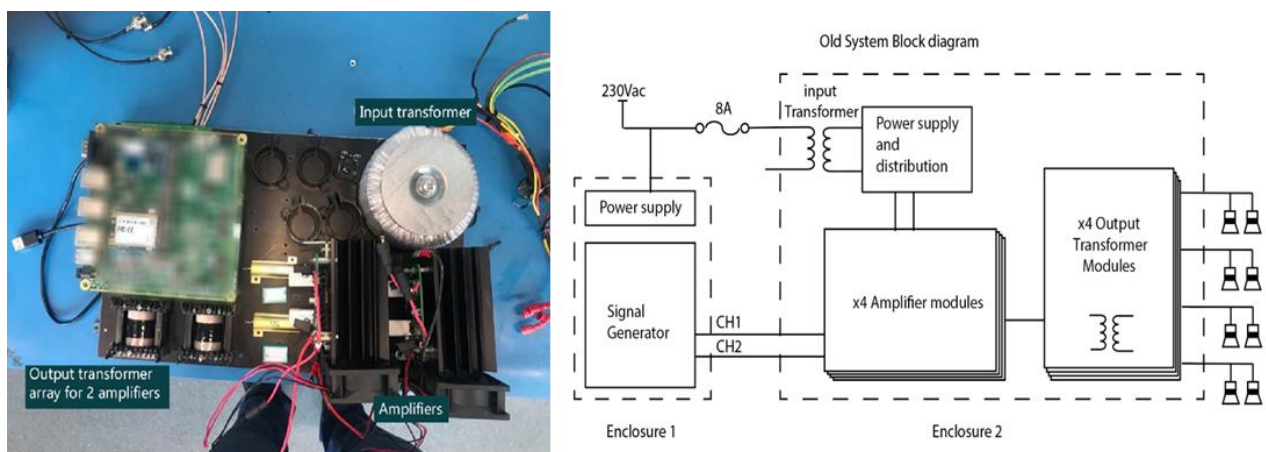


Figure 4. 1: (a) Initial system floor plan highlighting input and output transformers (b) Block diagram outlining the old systems design built by BIC with additional transformer units

As seen in **Figure 4.1(b)**, there are a variety of disparate components which all require purchasing wiring and testing. Furthermore, the input transformer would usually take up 30% of the mass of the system, however, reducing the component volume would greatly benefit the design.

To achieve this component reduction, the following steps were taken:

1. Eliminating the input transformer, the system produced an operating input voltage of 110Vac 60Hz/50Hz with a centre tapped input. Although this is not the UK standard mains supply, 230Vac 60Hz/50Hz, there are usually 110VAC supply in industrial and construction settings. Therefore, based on the case used, it was expected most positions would have the required input. On the other hand, If the required power supply is unavailable, there are portable site transformers which can step down the UK mains voltage to the required operating voltage. Therefore, operating at 110VAC was favoured.
2. By taking the output transformer array out, a bridge mode design was implemented which was an alternative to the initial transformer design. The bridge mode would double the amplifier size; however, it would be capable of doubling the transducer drive capability, producing comparable voltage levels to the transformer design.
3. The signal generator Power supply would be integrated on the printed circuit board.

With the modified design, the main elements of the system required 3 different types of Printed Circuit Boards (PCBs), and all the modules were self-contained. The modified block diagram is illustrated in **Figure 4.2**.

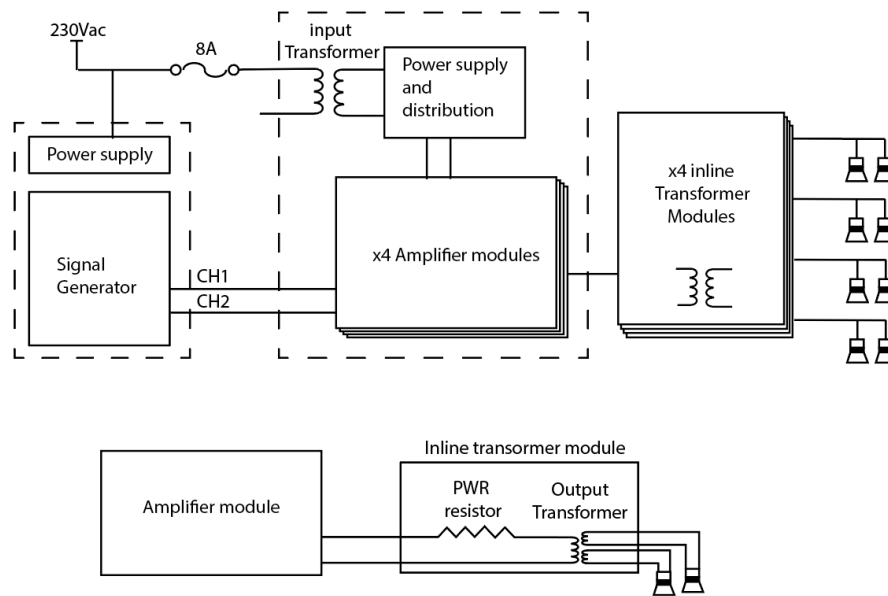


Figure 4. 2: Updated block diagram incorporating inline transformer units. Compared to the previous design, the transformer modules are now compact inline units.

Following the re-evaluation of the impedance changes after tightening the transducers, it was concluded that the output transformer component was required to cater for the change in impedance encountered.

With the general block diagram established, more detailed design concepts would be essential for the signal generator and the amplifier. The requirements and considerations for these units are expounded further in the following sections.

4.2.3. Amplifier requirements and considerations

The general specification developed for the amplifier system can be seen in Table 4.1.

Table 4. 1: General Specifications for Amplifier System

Number of Langevin transducers Supported	8
Number of amplifier modules	4
Number of power supply distribution boards	1
Max Power consumption	1500W
Input	110VAC CTE
Dimension (L x W x H)	600mmx200mmx200mm
Weight	15kg

Amplification of the signal required four (4) amplifier modules and a power distribution system in place. Internally the amplifier had a fused 600W capable power distribution system which powered 2 passive fans and 2 amplifier modules. Each amplifier module possessed a signal inverter and two 120W capable class AB amplifiers connected in an ion bridge mode.

The requirements for power distribution are detailed below:

1. 1500W capable power supply required with 110VAC with 4 fused outputs
 - X6 8200uF 80V Capacitors
 - X1 bridge rectifier (3.15A capacity)

The system consisted of 4-amplifier modules; each amplifier module contained two class-AB amplifiers connected in a bridge mode via the signal inverter. Each amplifier had the following individual characteristics shown in Table 4.2:

Table 4. 2: Characteristics of the Amplifier Modules

Voltage supply	Minimum +70V -70V supply
Output	98V _{rms} (132.2V _{pp})
Output power	150W
Frequency response	5kHz – 100kHz
Weight	2.5Kgs

Table 4. 3: Final Specification of the System

Values extrapolated from single 28kHz 100W stainless steel Langevin transducer		
	w/o Transformer module	W/ Transformer module
Number of channels	8	8
Inline output transformer units	N/A	4
Maximum output Voltage peak to peak	250V _{p-p}	720 V _{p-p}
Maximum output Voltage rms	88.3 V _{rms}	256V _{rms}
Maximum single transducer single amplifier module output power (rms)	30W*	200W
Maximum power to a single transducer when 2 transducers are connected to an amplifier module in parallel (rms)	15W*	100W
Maximum system power consumption	1200W	1800W
Single channel max power out	300W	450W
Efficiency resonant transducer	N/A	65%
Output signal stability at constant load	1%	1%
Storage temperature	-40 to +85°C	-40 to +85°C

System weight	19kgs	22kgs
System dimensions (LxWxH)	900mm × 300mm × 700mm	900mm × 300mm × 700mm

The completed power system is shown in **Figure 4.3** below.



Figure 4. 3: A Complete Ultrasonic Power System



Figure 4. 4: Inline Transformer Unit

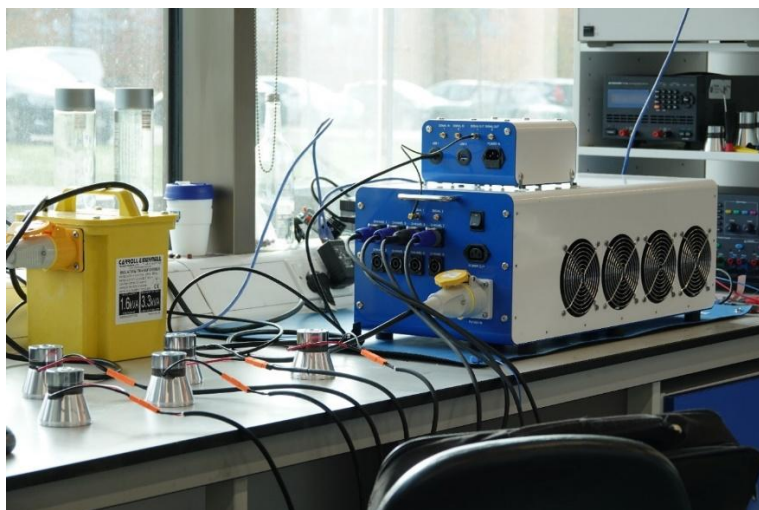


Figure 4. 5: Wired with preliminary Test Setup

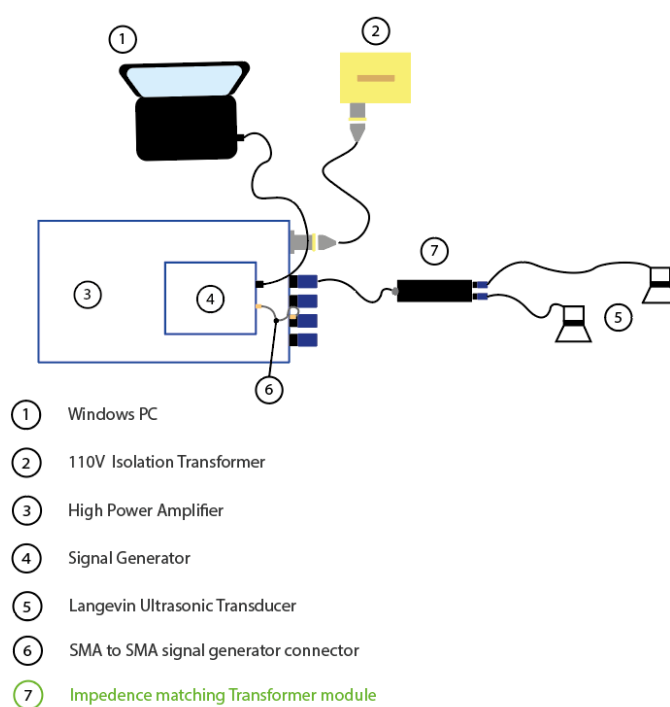


Figure 4. 6: System Block Diagram

4.2.4. Amplifier tests

Testing was done using a Keysight DSO x 2014A oscilloscope to assess the signal, a Keysight N6705c with two 300W 60V units to measure current and voltage supply and a FLIR A35 thermal camera to assess thermal properties as seen in **Figure 4.7**.

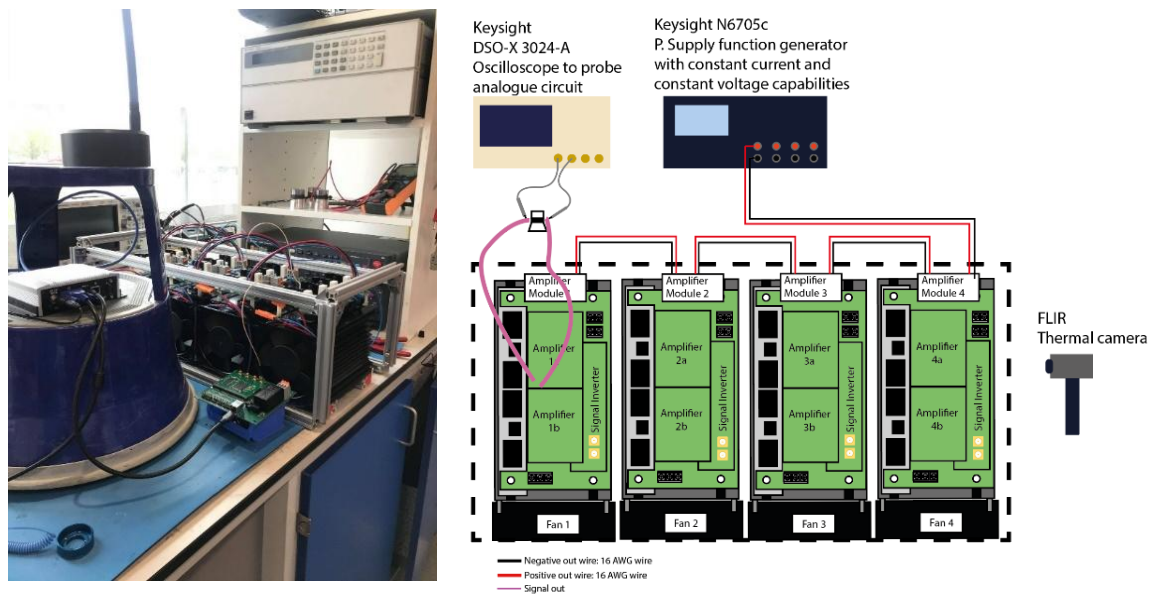


Figure 4. 7: Test rig set up and diagram showing connection of test equipment

The voltage and current output on a single amplifier without load can be seen in **Figures 4.8 and 4.9**, respectively. The idle current draws on a single amplifier module when idle was recorded at approximately 0.1A at 120Vp-p and can be seen to ramp up to 0.3A when signal is applied. No transients observed and the voltage supply remains identical and stable on the +60(volt avg1) and -60 (Volt avg 2) which have been serially connected. Further testing with 60W transducers showed that the amplifiers could run 2 60W transducers and this can be seen in the thermal testing section.

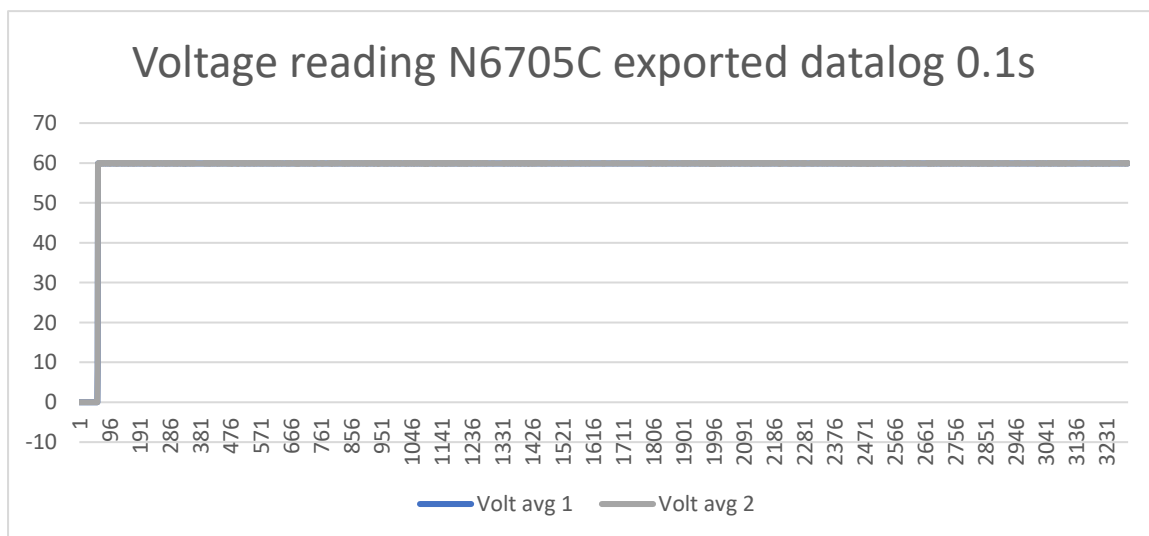


Figure 4. 8: Voltage readings from the N670C showing stable voltage output from a single amplifier module

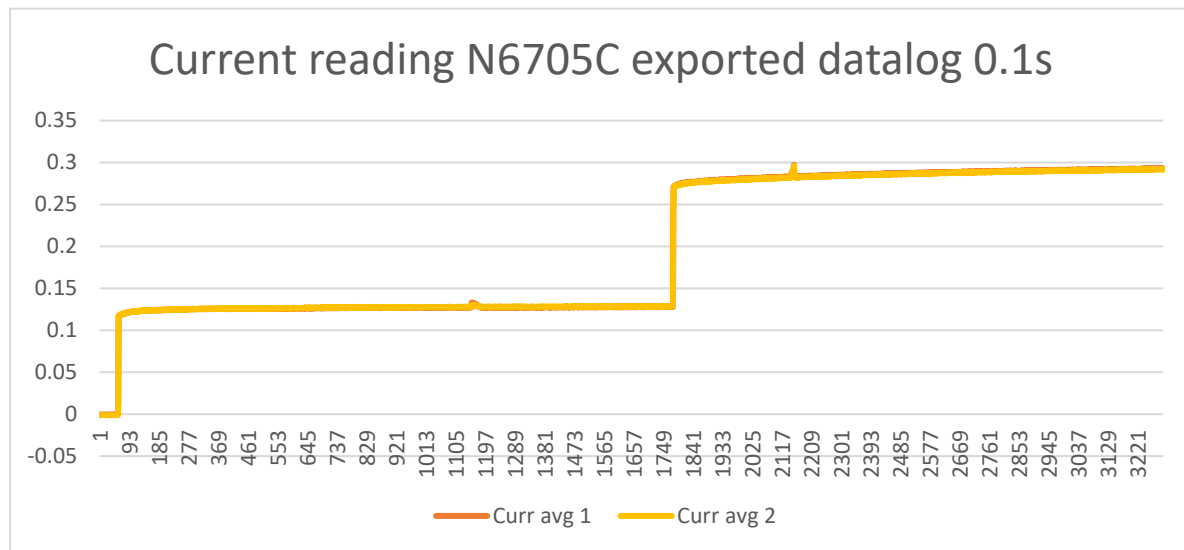


Figure 4. 9: Complimentary current reading from the N6705C showing different stages on a no-load amplifier module first ramp up no signal input second ramp up signal input

4.2.5. Signal testing

The signal output from the bridge mode was as expected as seen in **Figure 4.10** where the two outputs from the amplifiers produced a 283V output square wave seen in **Figure 4.11** from a 120Vp-p input. The predicted output using the power distribution board which supplies 150Vp-p can be extrapolated from this information with an average peak to peak voltage of 353.75Vp-p output with no load. The signal and current results can be seen in the following pages.

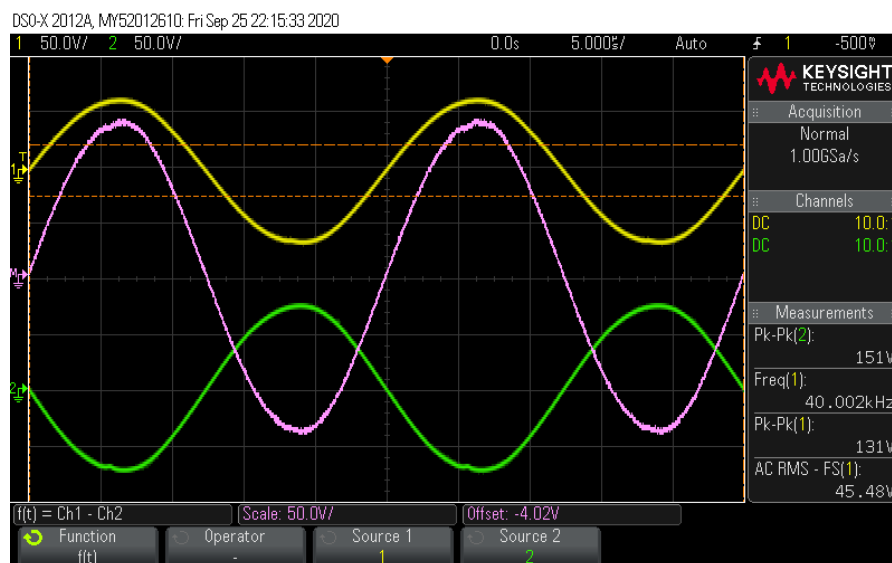


Figure 4. 10: Amplifier a (yellow) output identical to amplifier b output (green) with the excitation which will be used by the transducer (purple) showing bridge mode configuration operation

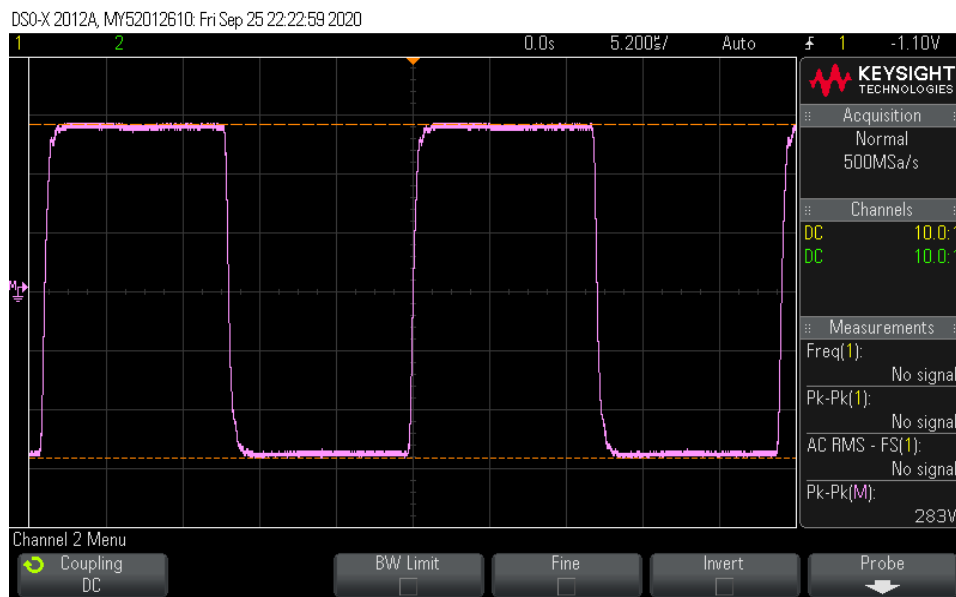


Figure 4. 11: Maximum output from the amplifier using the 120Vp-p output from the N6705c power supply

4.2.6. Thermal testing

Thermal testing was conducted using the signal generator and the final wired system using 6 Langevin transducers to compare the idle and active temperature of components on the PCB.

Figure 4.12 shows the thermal testing configuration at both left and right sides.

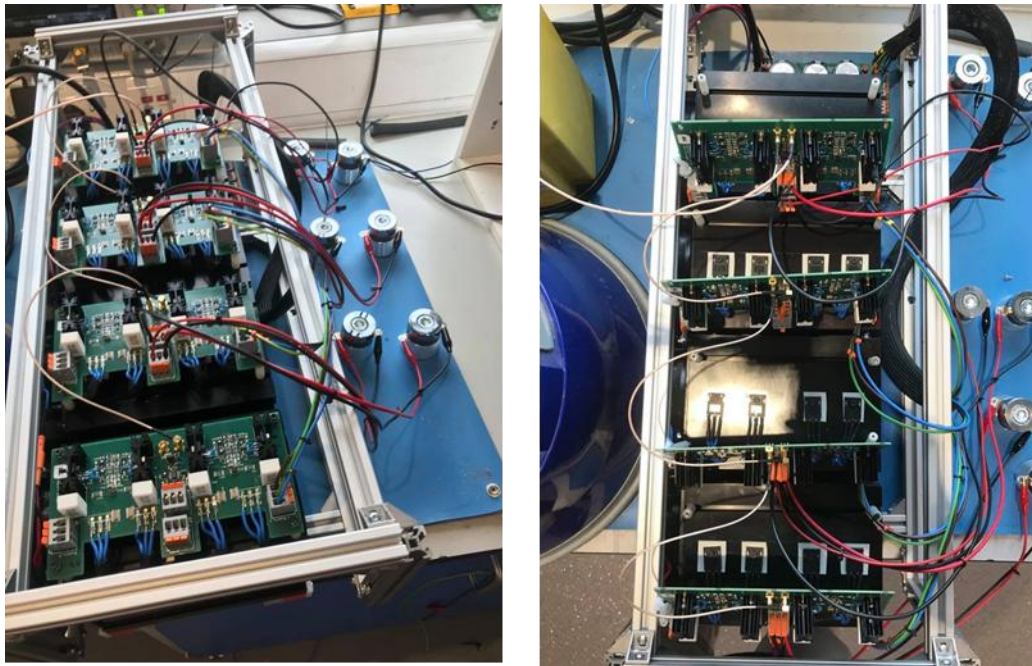


Figure 4. 12: Left: closed thermal testing configuration. Right: Open thermal testing configuration showing transistors

The maximum operating temperature of the amplifier transistors is 150°C and therefore in the open and closed thermal testing configuration seen in **Figure 4.13** the temperatures should not exceed that value. **Figure 4.14** represents the thermal variation of the PCB components as the transducer was operating at a maximum temperature of 107.6°C after operating for 5 minutes in open thermal testing configuration..

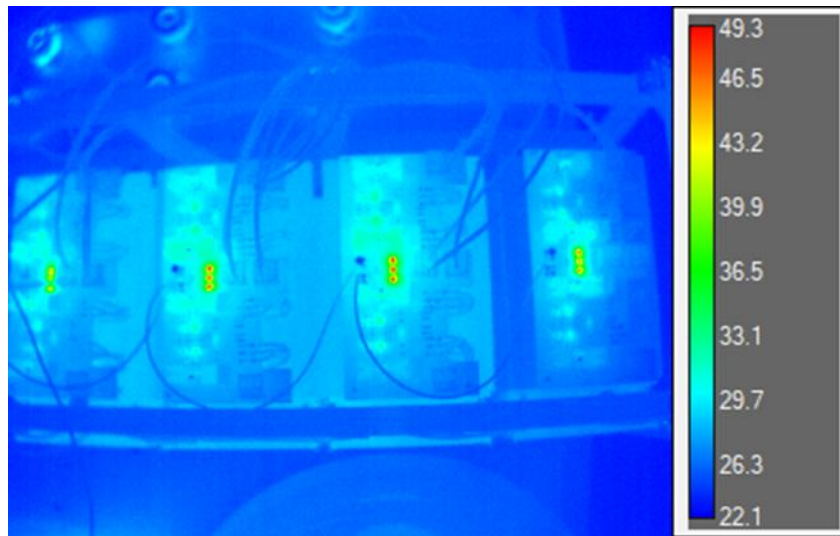


Figure 4. 13: Idle operating temperature maximum amount recorded at 49.3 degrees after 24h in closed thermal testing configuration

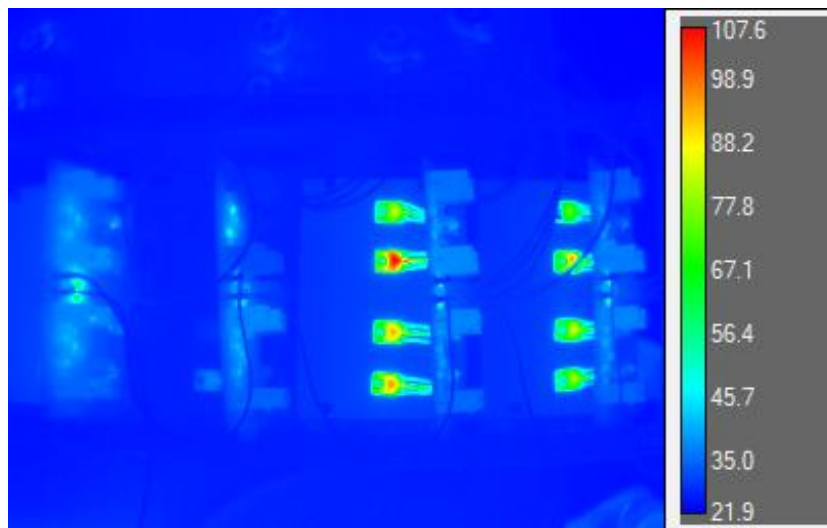


Figure 4. 14: Comparison between 2 idle and 2 maximum output amplifier modules after 5 minutes of operation reaching a maximum temperature of 107.6 degrees in open thermal testing configuration

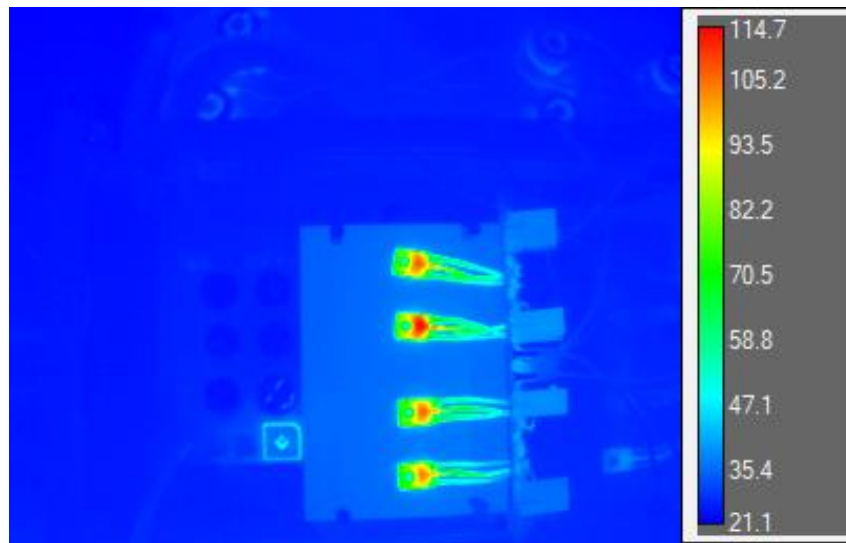


Figure 4. 15: Detailed assessment of single amplifier module after 25min of maximum output operation reaching a maximum temperature of 114.7°C in open thermal testing configuration

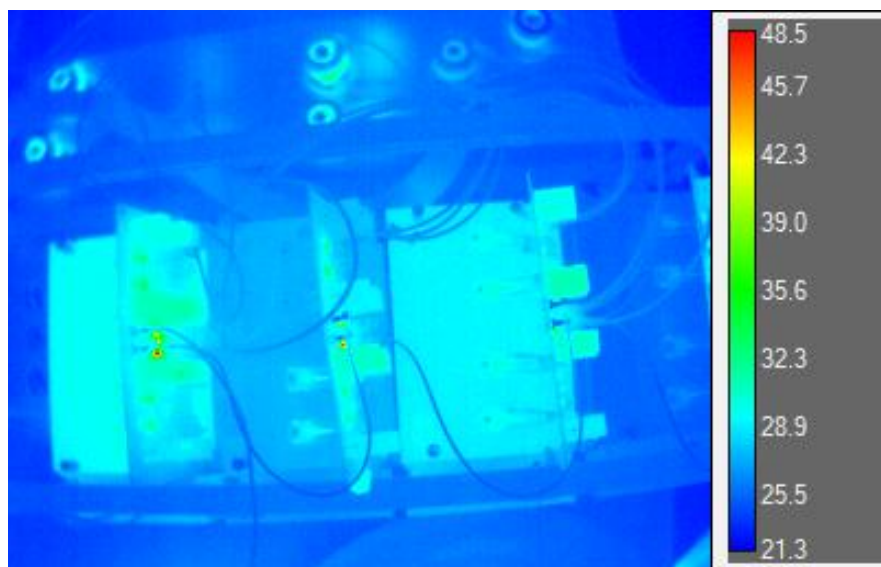


Figure 4. 16: Idle operation of the amplifier modules 2 minutes after 1h operation 48.5°C recorded in open thermal testing configuration

The thermal performance of the amplifiers was below the critical limit of 150°C on all the components. The test was successful. Further performance testing will be done during the life and operation of the system.

Temporal plots of the average temperature around an active transducer and amplifier were recorded over a 1hr period.

4.3. Vibration Evaluation

4.3.1. Accelerometer measurement

A Dewesoft acquisition unit, shown in **Figure 4.19**, is the device used to measure vibration. This type of acquisition unit is compatible with any piezoelectric sensors, such as the accelerometer used to detect the acceleration of the plate under vibration. The Dewesoft software is used to process and analyse the acceleration data, providing graphical and numerical representations of the data that can be used to identify trends, patterns, and other important information. This type of system is commonly used in various applications such as automotive testing, machinery monitoring, and vibration analysis. The system was purchased from Dewesoft and align with high-sensitive sensors which were connected to the surface of the vibrated plates, it was employed to measure the surface acceleration at a specific frequency. In this case, the frequencies considered were 20 kHz, 28 kHz, and 40 kHz.



Figure 4. 17: A Dewesoft Acquisition Unit for Accelerometry

4.3.2. 3D laser doppler vibrometer

3D laser doppler vibrometer is a non-contact measurement technique used to analyse mechanical vibrations and surface displacement of objects. It works by shining a laser beam onto a surface and measuring the velocity and frequency of the reflected light caused by the surface vibration. This measurement is then used to calculate the amplitude and phase of the vibration,

allowing for the analysis of structural dynamics and identification of potential structural problems. The 3D aspect refers to the capability of measuring vibrations in three dimensions, providing a more comprehensive view of the behaviour of the object [108].

The Vibrometer used in this study is a Polytec 3D-CLV that can measure 2 type of displacements which are average (FFT method) and Peak to Peak (Time domain method). The displacements were taken at 20, 30, 40 and 50 cm distance from the transducer mounting position.

4.4. Contactless Vibration of the Plate

This section focuses on the characterisation of an industrial High-Power Ultrasonic Transducer (HPUT) named Q55, aiming to determine the optimal output of contactless vibration from this device. The transducer is comprised of a long-focused horn, which is conveniently connected to the transducer itself through a user-friendly amplifier (see **Figure 4.18(a)**). The Q55 is an ultrasonic processor that offers a compact and affordable solution, taking up minimal bench space. It is particularly suitable for standard cell disruption and various small volume applications. The transducer associated with this model has a power rating of 55 watts, as shown in **Figure 4.18**, operates at a frequency of 20 kHz, and has dimensions of 203mm × 190mm × 146mm (width × length × height). The accompanying horn for this transducer features a tip diameter of 2mm and a maximum displacement of 200 µm.



(a)



(b)

Figure 4. 18: (a) The Q55 transducer with the needle horn that can be screwed into the transducer, (b) the power amplifier.

In this study, the objective is to weld two L-shaped plates together. To achieve this, it is beneficial to position the HPUT at an angle that can generate the highest vibration amplitude on the plate. By doing so, the maximum vibration amplitude can be transmitted to the molten pool area, enhancing the welding quality. To characterise the transducer, the vibration it generates is applied to an L-shaped plate at various angles ranging from 5 degrees to 80 degrees. This range of angles allows for a comprehensive assessment of the transducer's performance and its impact on the plate's response. The plate was made of aluminum alloy 1050 and has a thickness of 2 mm. To measure the response of the plate, a 3D laser vibrometer is employed, as depicted in **Figure 4.19**. The response of the plate is collected in three perpendicular directions: 1) the out-of-plane displacement along the z-direction, 2) the in-plane vibration along the x-direction, and 3) the in-plane vibration along the y-direction. While the L plate remains fixed and firmly attached to its base, the position of the transducer can be adjusted accordingly.

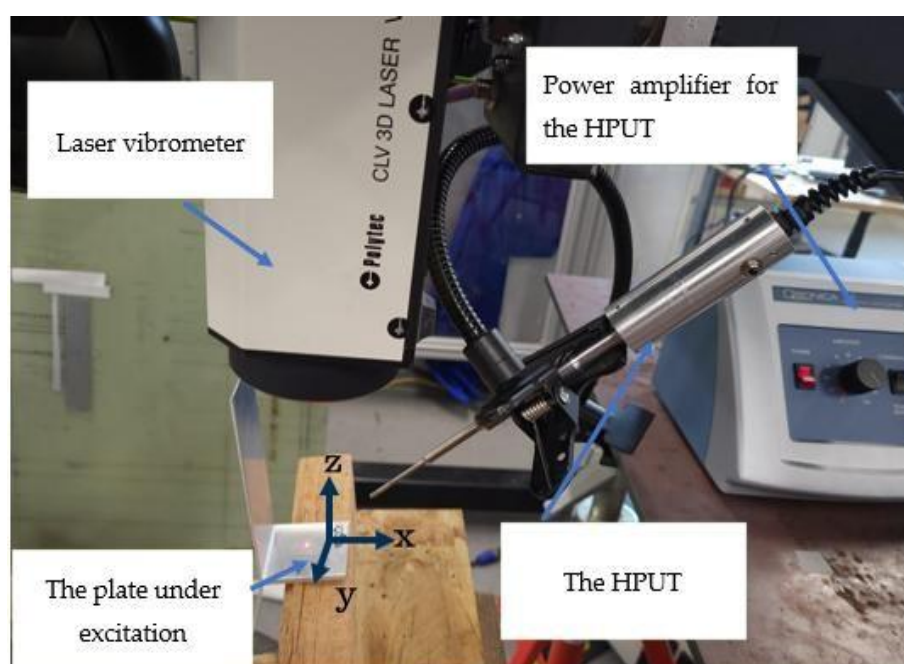


Figure 4. 19: The plate configuration, made of aluminium alloy 1050, for vibration measurement in the three orthogonal directions.

The out-of-plane vibration of the plate (the z-axis) is illustrated in **Figure 4.20**. The maximum vibration level from the plate was recorded at 60 degrees and the minimum at 5 degrees. The observed amplification of vibration at a 60-degree angle could potentially be attributed to the reflection of contactless vibration from the first plate to the second plate. This reflection results in a higher overall vibration compared to the 80degree angle configuration. Some of the additional frequency components present in the output signal apart from the fundamental frequency

are referred to as harmonics which are integer multiples of the fundamental frequency. The rest arise due to factors such as non-linearities, mechanical resonances, and impedance mismatches.

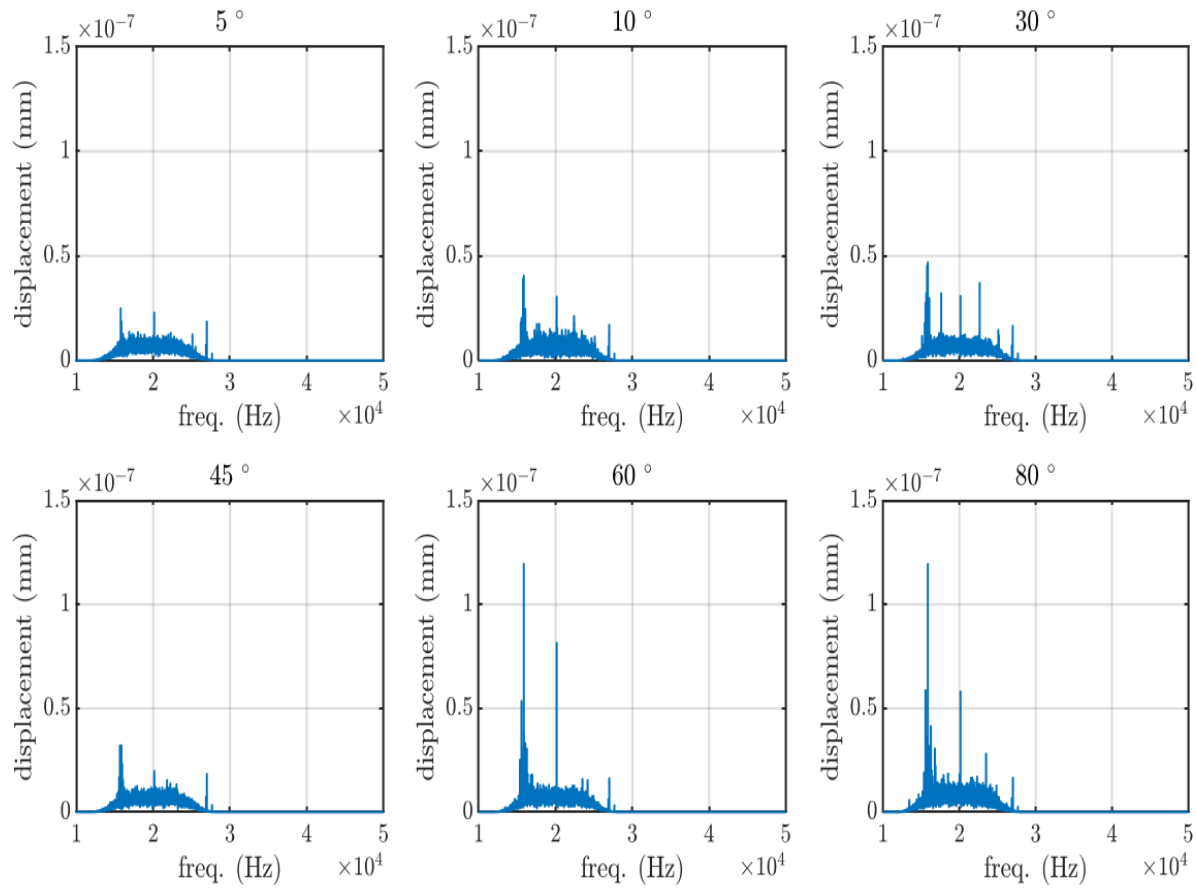


Figure 4. 20: The plate vibration in the vertical direction, the z-axis, increases the transducer angle from approximately 5 ° to 80 °.

The plate response under the contactless excitation for the x-axis, parallel to the direction of excitation, is plotted in **Figure 4.21**. The maximum vibration level from the plate was recorded at 60 degrees and the minimum at 5 degrees. Similar to previous findings, the maximum vibration level occurs at a 60-degree angle. This phenomenon is likely due to the reflection of vibrations from the first plate to the second, resulting in increased overall in-plane vibration compared to the configuration at a 5-degree angle.

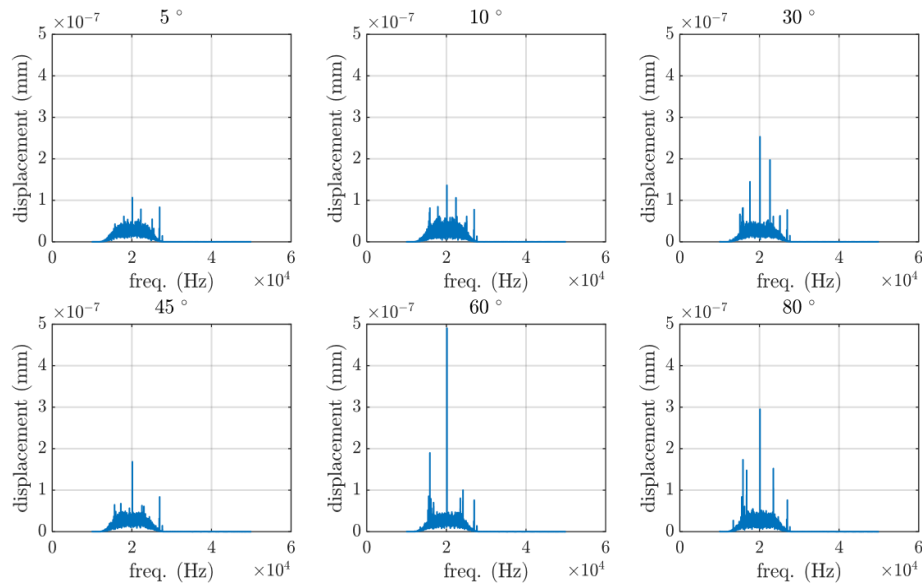


Figure 4. 21: The plate vibration in the horizontal direction, the x-axis, increases the transducer angle from approximately 5 ° to 80 °.

In-plane vibration of the plate in the perpendicular direction to the direction of excitation, the y-axis, is plotted in **Figure 4.22**. As in the previous directions, the highest level of vibration occurs at a 60-degree angle. This could be attributed to the reflection of vibrations from the first plate to the second plate, resulting in an increased overall in-plane vibration compared to the configuration with a 5-degree angle.

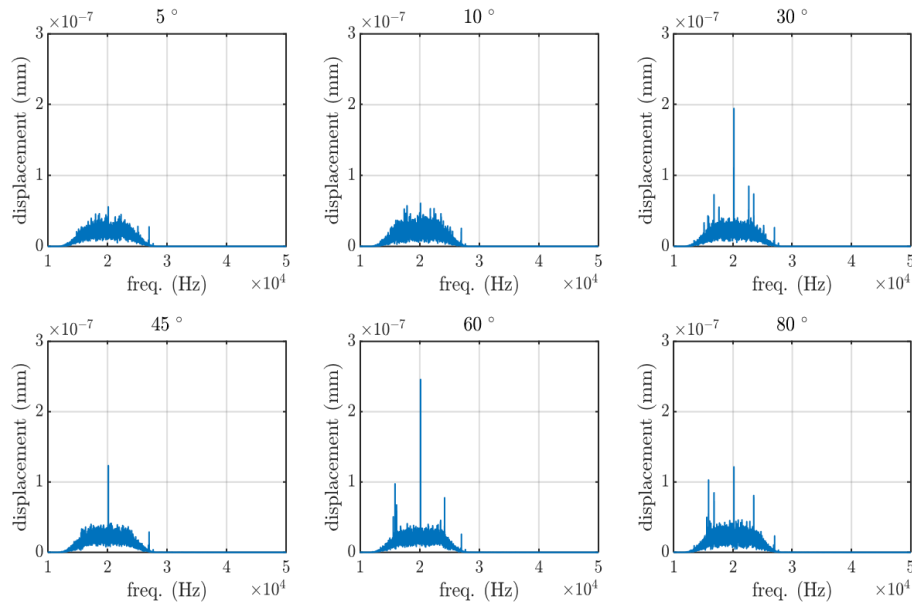


Figure 4. 22: The plate vibration in the horizontal direction, the y-axis, by increasing the transducer angle from approximately 5 ° to 80 °.

In addition, this study aimed to determine the optimal distance between the tip of the transducer horn and the desired structure, which would result in the highest contactless vibration. To assess this objective, the effect of varying distances between the two was measured, and the results are presented in **Figure 4.23**. It was found that the vibration level reached its peak when the gap between the structure and the tip of the transducer horn was 20 mm. Subsequently, as the gap increased to 25 mm, the vibration amplitude decreased by half. These findings highlight the importance of the distance between the transducer and the structure in achieving the desired vibration levels.

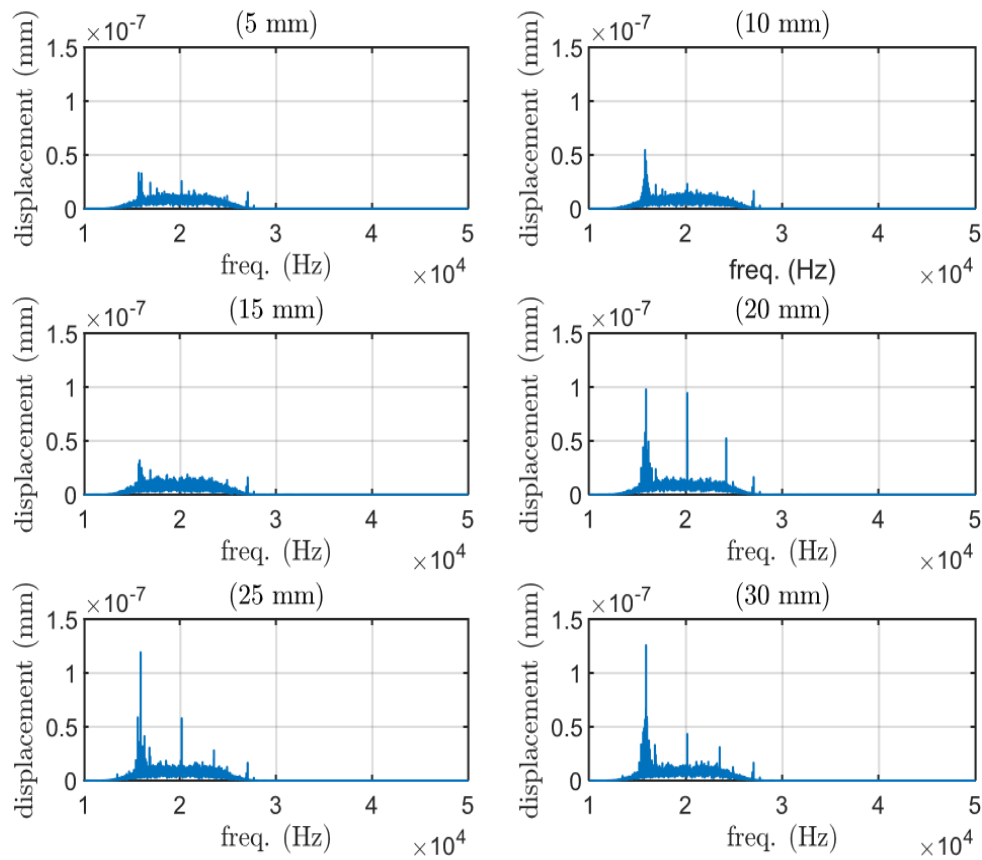


Figure 4. 23: The effect of the distance between the tip of the transducer horn and the structure on the contactless vibration specifically in the vertical direction, referred to as the z-axis.

Depending on the length of the gap, there will be resonance or standing wave field. For this case, the wavelength, λ , in the dry air can be estimated by $\lambda = c/f$, where c is the wave speed (343 m/s) and f is the frequency (20 kHz). Resonance occurs at every $(2n-1)\lambda/4$ distance, where n is an integer number. Consequently, the distances of 4.3 mm, 12.9 mm, 21.5 mm, and so on are expected to yield the highest vibration amplitudes. These distances correspond to the intervals determined by the resonance condition mentioned earlier, where the vibration amplitudes are likely to be maximised.

4.5. Temperature Changes of the HPUT Horn

This study aims to integrate the transducer with the laser welding system and generate contactless vibration during welding while measuring the effect of the laser temperature. Therefore, an experimental study was carried out to find the temperature changes during the laser operation. In ultrasonic-assisted laser welding, the prolonged contact between the tool head and the weld results in the high temperature of the weld transferring to the ultrasonic system. Particularly, the high energy from the laser beam can raise the temperature of the ultrasonic transducer during the process. This elevated temperature, in turn, causes a shift in the Eigen frequency of the ultrasonic oscillator and leads to unstable energy output. Therefore, addressing this issue is of utmost importance and urgency [109]. While the transducer horn does not physically touch the plate in contactless vibration, it is necessary to investigate its overall temperature during the laser operation. Therefore, the transducer was instrumented with a thermocouple and placed at the desired angle and distance from the area under welding. An IPG Photonics high-power multimode Ytterbium Fiber Laser system (YLS6000) is used in this experiment (shown in **Figure 4.26**). The maximum power is 6000 W and has a fixed wavelength of 1030 nm. The diameter of the fibre is 100 μm , using a multi-axis system with a bed that moves in the y direction and the laser head in the x and z direction, which allows trials to be conducted in a 3D plane. The laser optic is an IPG D50 wobble beam with a lens focal length of 200 mm, a collimation focal length of 200 mm and a spot size of 100 μm . For this experiment, the wobbling system was not activated. The parameters of the laser system (power and speed) are adjusted according to the requirements of the weld profile. For this investigation, 2 strips of AL1050 were used. The shape of the plates was flat and 2mm thick, with a width and length of 50 mm $\times$ 120 mm. The two plates were placed on each other with an overlap at 50mm, and the weld path would be in the centre. The Gaussian laser beam is focused on the plate and travels along the x-direction of the workpiece, forming an oval shape commonly used in the industry. The focus would be consistent across all trials; attached to the laser head is a camera with the same focal length as the laser.

Using 2kW travelling at 2000mm/min a known laser setting to penetrate through the first layer of 2mm Aluminium and then partial penetration through the second layer. The partial penetration is seen across many welds in the industry so as to not damage any components. It was found that for a single measurement, the temperature would not go beyond 41 °C. In practice, the laser might be operating for hours. However, the maximum temperature should still be the same as found by this investigation. The piezoelectric of the transducer itself might get hot if

it is set for continuous operation. A solution is given by Salimi et al. [110] to avoid the transducer heating up due to its non-stop operation.

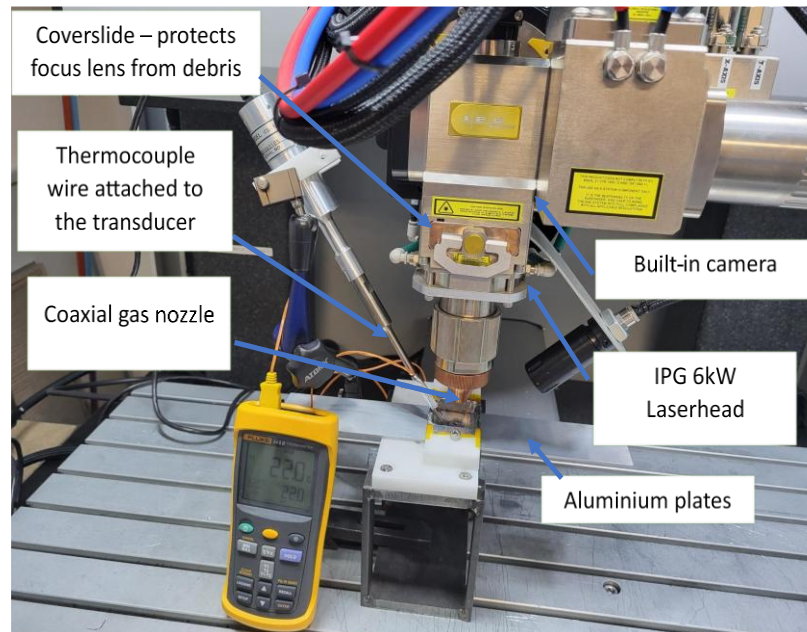


Figure 4. 24: Experimental configuration to record temperature changes of the horn due to the operation of the laser welding device

4.6.Effect of Tightening Torque on Ultrasonic Transducer: Impedance Testing

In this section, the aim of this study is to evaluate the effect of tightening torque on the performance of the transducer. For this purpose, several tests were carried out on high-power ultrasound transducers with resonance frequencies of 20 kHz, 28 kHz and 40 kHz.

The transducer is stimulated with a sinusoidal voltage at a specific operating frequency, facilitating the conversion of electrical voltage into mechanical vibrations. Structurally, the transducer forms an electrical-mechanical resonant circuit, longitudinally oscillating at half the wavelength of its resonance frequency. In its basic configuration, it comprises a stack of piezoelectric ceramics situated between two metal blocks. These metal blocks serve the dual purpose of securing and compressing the ceramics via a prestress bolt, as well as facilitating the transmission and amplification of the mechanical vibrations generated by the ceramics. An integral component of the transducer is the acoustic amplifier, or horn, which plays a crucial role in enhancing the amplitude of the mechanical vibrations generated by the transducer.

These vibrations are then dispersed across a broad area of the vibrating plate, with the aim of reducing the acoustic impedance of the plate upon which the acoustic energy is directed [123]. To achieve an effective transducer performance, there is an optimal tightening force, referred to as the tightening torque, which differs from transducer to transducer. Therefore, it is a challenge to determine a generic set of parametric values to obtain an optimal tightening force using any transducer. However, transducers can be designed with respect to an equivalent electric circuit, where the resonance resistance, known as the impedance of the transducer, is measured as an equivalent of the energy loss when the transducer vibrates. Ideally, when the transducer is excited with a sinusoidal voltage, by the ultrasonic generator, at a certain operation frequency an electric voltage is converted to a mechanical vibration. Using the lab's HP Agilent 5328a Universal analyzer, the impedance analysis of the transducers resonating was run at frequencies of 20, 28, and 40 kHz, respectively. The piezoelectric ceramic within the transducer is tightened to an optimal tightening torque to produce a stable vibration at lowest energy losses, and vibrational energy is concentrated towards the front-end surface [124, 125]. The value of the impedance varies as the tightening torque is increased or reduced, and this impedance can be captured via an impedance analyser. **Table 4.4** and **Figure 4.25** show the impedance of the transducer as a function of tightening torque.

With an increase in the tightening torque, there was a corresponding increase in the electrical impedance of the transducer. This relationship shows a general interaction between the tightening torque and the impedance of the transducer.

Table 4. 4: Effect of Tightening Torque on Transducer Impedance

Torque (Nm)	Transducer impedance (Ω)
0	5.7
0.5	17.3
1	23.8
1.5	35.4
2	49.6
2.5	63.4
3	71.4
3.5	72

According to Peng et al. [126], experiments were undertaken to investigate the changes in electrical impedance and vibration velocity in relation to the pre-tightening force using the Butterworth-Van Dyke (BVD) model. The findings illustrate that alterations in the pre-tightening force significantly affect the spurious resonance observed in the electrical impedance.

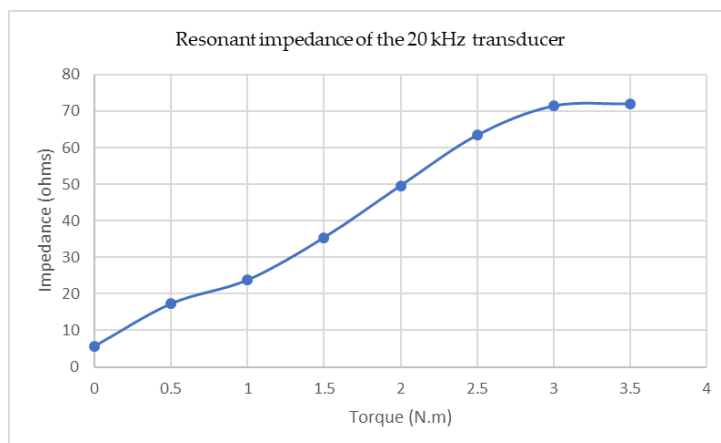


Figure 4. 25: Graphical Plot of effect of Transducer Tightening Torque on Resonant Impedance

4.7.Summary

The chapter discusses the characteristics of the ultrasound transducer used in this study, its vibration output, and the design of its horn.

Initially, the evaluation of transducer performance in terms of tightening torque, displacement amplitude and acceleration amplitude was conducted. This evaluation was carried out to test the performances of three different focused transducers with natural frequencies of 20, 28, and 40 kHz designed with lengths half their wavelengths.

It was found that the electrical impedance of the transducer increased with increasing tightening torque of the piezoelectric ceramic that produces vibration energy within the transducer. Further experiment was conducted to determine the optimal tightening torque that will produce the maximum vibration displacement at the front-end surface (tip) of the horn. The transducer was positioned at 5 different locations, employing tightening torques of 0.4, 0.8, 1.6, and 3.2 Nm and vibrating at three different operation frequencies (20, 28, and 40 kHz). Results revealed that that the highest vibration amplitudes were recorded under tightening torques from 0.4 to

1.6 Nm. At 3.2 Nm, the amplitude dropped to a lower displacement, indicating that the optimal tightening torque range for the produced transducer is 0.4 – 1.6 Nm. The power generated directly influenced the performance of the transducer by supplying sufficient energy to achieve the optimal vibration amplitude required for cavitation bubble excitation. Higher power output allowed for stronger generation of ultrasonic waves, resulting in higher displacements that may enhance the formation and collapse of cavitation bubbles, and improve material mixing and weld quality. Precise control of the generated power is critical for maintaining the transducer's efficiency and achieving consistent cavitation effects in the molten pool.

Finite element analysis was used to evaluate the surface vibration displacement at varying eigenfrequencies. It was observed that the designed conical-shaped horn produced maximum vibration at the specified tips of the horn.

Furthermore, with the use of an accelerometer, acceleration amplitudes were recorded for different states of the transducer, that is, with and without a horn, as well as with a focused horn. The focused horn showed the maximum acceleration, exhibiting its high-performance efficiency for industrial applications. The application of the focused transducer to ultrasonic vibration-assisted laser welding of both lap and butt joints revealed that acceleration amplitudes increased as the welding progressed from 0% to 100% at 25% interval.

To study the metallurgical impact of the structural vibration on the quality of weld joint, the next chapter discusses the effect of ultrasonic vibration on the microstructural evolution, grain structure, surface quality, weld geometry and the mechanical performance of a welded zone in aluminium alloy. The chapter also elucidates on the mechanisms involved in weldment changes by an ultrasound and other possible effect on the weld melt.

Chapter 5

Evaluation of microstructure and mechanical properties of ultrasonic vibration-assisted laser welded aluminium alloys

5.1.Introduction

Transducers can possess significant impact on the structural integrity of ultrasonic vibration-assisted welded joints, and different types of transducers and their corresponding properties were experimentally analysed and computationally simulated in the previous chapter. The vibrational energy transferred from the transducer to the plates might initiate ultrasound cavitation in the weld region. Welding high-strength aluminium alloys is generally a delicate operation due to the degradation of mechanical properties in the thermally affected zone (TAZ) and the presence of porosities in the molten metal. Furthermore, aluminium alloys contain compounds that solidify prior solidification of the bulk of the base alloy, therefore acting as stress concentration points that lead to the phenomenon of hot cracking. This chapter investigates the process of applying ultrasonic vibrations to the molten pool aluminium alloy AA6082 to improve both its microstructure and mechanical properties. Conventional and ultrasonic-assisted laser welding processes were analysed to assess the ultrasonic vibration effect in the ultrasonic band 20–40 kHz. Several tests were used to compare ultrasonically processed samples to baseline samples. The tensile and weld yield strengths of the welded joint within the aluminium plates were increased by 26% due to the power ultrasonic irradiation on the welds under optimum ultrasonic variable values during welding. It is estimated that the ultrasound intensity in the weld melt, using a maximum power of 160 W from a pair of 28 kHz transducers, is 35.5 W/cm² as a spatial average and 142 W/cm² at the antinodes.

5.1.1. Laser welding process

Cavitation activity was significant and sometimes, a main contributor to the achieved improvements in weld quality. In laser beam welding, a pulsed laser beam is used to weld thin materials (with a thickness of less than 1 mm), whereas a continuous beam is used to obtain deep welds [127]. It is, therefore, not necessary to chamfer the parts beforehand to widen access, as is commonly done in conventional welding. In addition, the use of a lasers improves the stability of the welding pool. This technique is often used to achieve significant production volumes in

the automotive and aerospace industries. For instance, the introduction of disk and fibre lasers achieved laser power ceiling scales of up to 16 and 100 kW, respectively [128 - 131]. The main parameters arising in a conventional continuous laser welding process are laser power, laser collimation (vertical position of the beam waist relative to the workpiece), welding speed, the type of shielding and/or root gas, and the flow rate of the gas. These parameters affect different aspects of the weld; for instance, an increase in laser power will lead to an increase in the power density, whilst a variation in the welding speed will increase or decrease the interaction time (i.e., the time the laser beam impinges on the same area) [132]. First, laser welding depends on the light coupling effect between the laser beam and workpiece, making the technology extremely reliant on the reflectivity of the material to be welded. Secondly, the laser can provide a concentrated heat source. However, materials with high thermal conductivity tend to partially disperse the heat and affect the profile of the resulting weld, (i.e., shallow welds are formed). Materials such as aluminium and its alloys pose additional challenges, as they have a strong tendency to form cracks due to several characteristics such as an extensive solidification range, a high thermal expansion coefficient, and large solidification shrinkage.

To mitigate the challenges, a new technique called oscillating laser welding has recently been developed to improve the weldability of materials with novel high-performance mechanical properties. However, the materials are difficult to weld. The technique depends on the weaving of a narrow laser beam as it travels along the weld joint [131]. Nevertheless, the use of vibration-assisted laser welding [133] to weld objects supported on a mechanically vibrated platform, demonstrates that grain refinement can be achieved during solidification. It is necessary to note that the solidification of cast moulds occurs at a much slower rate when compared to welding processes such as laser welding. Furthermore, the objective of recent studies has been to identify grain refinement at faster cooling rates [134].

5.1.2. 6 series aluminium alloys

The utilisation of hard aluminium alloy as a lightweight structural material is widely acknowledged for its exceptional attributes, encompassing remarkable strength, hardness, and a low-density profile. This alloy finds extensive applications across various sectors, including aerospace, automotive manufacturing, and rail transit. Nonetheless, the remarkable thermal conductivity exhibited by aluminium alloys necessitates substantial heat input during the welding process. Consequently, the fusion zone of the weld undergoes recrystallization, while the heat-affected zone experiences over-aging softening, thereby leading to a substantial reduction in

the strength coefficient of the welded joint [135]. In heat-treated aluminium, the microstructural morphology of the weld zone's centre line exhibits equiaxed grains and the grain boundary is characterised by the secondary phase. Usually, segregation occurs due to differential chemical composition within the weld zone with softened grains observed at the heat affected zone and recrystallized microstructure near the weld zone. Thus, the strength of the weld does not surpass a third-fifth of the base metal [136].

Another consideration in welding these series of aluminium alloy is that molten liquid tends to display reduced viscosity, leading to an unstable equilibrium between the capillary pressure within the keyhole and the gravitational force exerted by the molten pool. Consequently, the keyhole has a greater tendency to collapse, resulting in voids within the solidified weld [137]. Furthermore, weld cracking in 6xxx aluminium alloys, despite being extensively studied, continues to pose a significant challenge in welding processes. The modelling and characterisation of weld cracking have garnered considerable attention within the laser welding community. Various approaches, including both theoretical and data-driven methods, have been put forth to address this issue [138]. A prevailing consensus suggests that the introduction of silicon (Si) content in Al-Mg-Si alloys expands the critical solidification temperature range [139]. This extension plays a crucial role in mitigating the impact of thermal strain during the rapid cooling phase that follows welding, ultimately enhancing material ductility and reducing the likelihood of weld cracking.

Generally, the main alloying elements in 6xxx aluminium alloys are Si and Mg, despite their minute contents that do not exceed weight percentages of 1.2 and 1.5, respectively. The alloys gain strength from the formation of Mg_2Si precipitates formed in the grain boundaries. Mostly, the ratio of Mg to Si, by weight, falls on approximate values to 1.73. Si addition increases the strength of the weld joint; however, this is achieved at the expense of its corrosion resistance. On the other hand, increasing the Mg content will increase its resistance to corrosion but weaken the joint and reduce formability. There is trade-off to be considered to maximise the formation of the Mg_2Si precipitate. Therefore, a value lower than 1.73 indicates an increase in

Si content, resulting to increased strength and reduced corrosion resistance, while a value beyond 1.73 indicates otherwise [138].

5.1.3. Ultrasonic vibration-assisted laser welding of aluminium alloys

Concerning the studies on vibration-assisted laser welding, a larger fraction of these studies applies vibrations either in the infrasound band (<20 Hz) or the audible sound band (20 Hz to 20 kHz). It is possible to implement the former in an industrial environment, but it is very difficult to implement the latter due to its impact on the human auditory system and the need for additional personal protective equipment (PPE) [132].

Recent studies have shown that ultrasonic waves applied during welding operations, including laser melting, can limit the growth of grain structures and promote grain multiplication due to the effects of vibration, shocks, or fluid flows acting as new nuclei [139 – 143]. This phenomenon is called ultrasonic grain refinement. Grain refinement is an essential tool used to improve material tensile and yield strengths, as implied by the well-known Hall–Petch equation, relating yield strength to mean grain size under assumed spherical grains, which is a good approximation for well-refined grain structures [144].

Welding high-strength aluminium alloys is generally a delicate operation due to the degradation of the mechanical properties in the thermally affected zone (TAZ) and the presence of porosities in the molten metal. In the TAZ, tensile and yield strengths can be reduced by up to 50% compared to nominal values, depending on the welded alloy and the process used [140]. Furthermore, during the laser welding of aluminium alloy 6XXX, the formation and agglomeration of magnesium silicates (with a higher melting point than aluminium) provoke weld cracking during the solidification process. The aluminium alloy AA6082 (Al with 0.7–1.3% Si, 0.0–0.5% Fe, 0.0–0.1% Cu, 0.4–1.0% Mn, 0.6–1.2% Mg, and $<0.15\%$ of other elements) is highly crack-sensitive due to its composition of approximately 1% of magnesium silicide (Mg_2Si) [9]. Furthermore, susceptibility to hot cracking is influenced by the chemistry of the base alloy and the joint design [145]. To temper these effects, slower speeds can be used in conjunction with lower power, but this reduces one of laser welding's major advantages—its speed [146 – 148]. Also, it is recommended to monitor the heat input, during the liquefaction

stage because of heating beyond the eutectic temperature, and pre-heat the weld joint to mitigate tensile stress buildup during welding and solidification processes [149]. However, pre-heating practices during oscillating welding and cooling processes is complex. As a result, there are significant economic impacts (rejected welded materials and a loss of raw material, energy, and time) which prevent laser welding from being used in highly-sensitive applications such as those within aerospace [150 – 153].

5.2. Experimental Setup

5.2.1. Ultrasonic vibration-assisted laser welding system

The experimental set-up is shown in **Figure 5.1**. Two ultrasound transmission transducers, centrally located on the two parallel plates to be welded on opposite sides of and equidistant from the weld line, were used, i.e., the transducers did not move during our experiments relative to the plates, and both were always stationary in the laboratory frame of reference. This arrangement was chosen to maximise the scope of our research as follows. The arrangement, which involved a set of nodes and antinodes along the plate-weld line interfaces, led to quasi-standing waves in the plate.

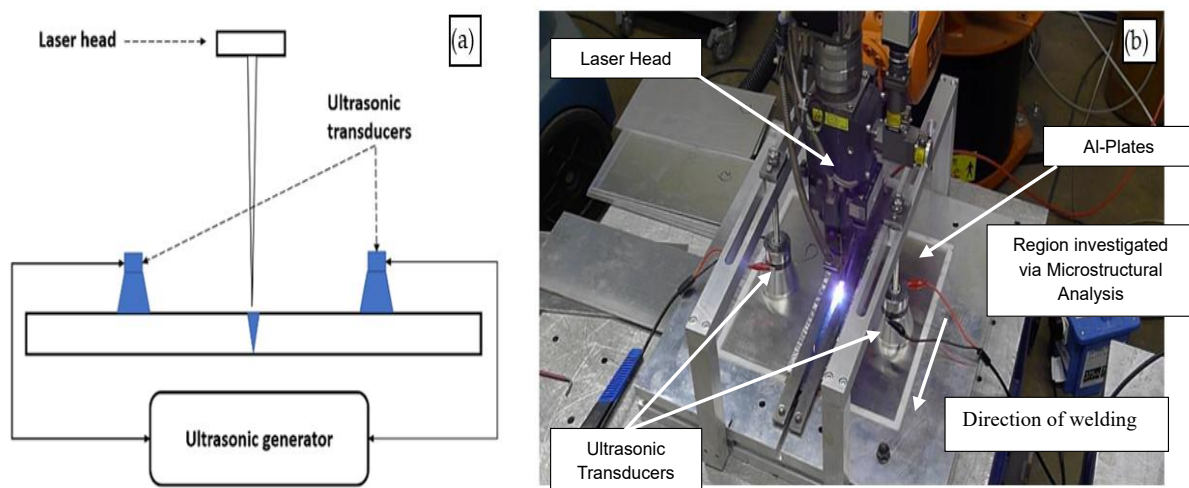


Figure 5. 1: Experimental set-up for laser welding with ultrasound assistance: (a) schematics and (b) physical set-up.

Therefore, during a single pass of the laser along the weld line and using a single power output setting of the transducers, by taking samples for microstructural analysis at distributed locations along the weld line, data was collected on the effect of ultrasound intensity on the weld microstructure over a continuous intensity range from the antinode level down to the nodal level. This is a fast and convenient method of collecting data to discover the optimum values of ultrasonic variables for weld improvement. When the optimum conditions are identified, to obtain a commercialised ultrasonically assisted laser welding system, the transducers are placed close to the weld line and moved along the weld line synchronously, with the laser spot positioned such that the spot always experiences the same field.

The laser beam source used for the experiments was a high-power solid-state disk laser (TruDisk 6002) from Trumpf (Ditzingen, Germany), with a maximum power of 6 kW and a set wavelength of 1030 nm. The fibre diameter was 400 μm , coupled to a Kuka Kr16 6-axis robotic arm. The laser optic was a D70 Laser head also from Trumpf (Ditzingen, Germany), with a 200 mm focal length of collimation and a lens with a focal length of 200 mm. The selected laser collimation was -2 mm in the z-direction, i.e., the laser beam waist was focused 2 mm below the surface of the plates to be welded. This beam position has been reported to achieve 100% welding depth, that is, the optimal weld depth for such practice [154]. The laser parameters were modified directly on the laser source console whilst the Kuka robotic arm controlled the linear welding speed. As shown in **Figure 5.1b**, to protect the bulk of the parent metal plates from excessive heating, two metal strips were rested on top of the plates on either side of the weld line and laser spot.

In the present study, a bespoke ultrasonic generator was developed to drive commercially available, high-power ultrasonic transducers (Piezoelectric Ultrasonic Cleaning Transducer (PZT-4) of Beijing Ultrasonic Co. Ltd, Beijing, China, with a diameter of approximately 7.5 cm at selected processing parameters, i.e., power and frequency. The system can output sine, square, sweep, barker code, and custom imported wave types. The material chosen for the welding trials was AA6082-T651 in the shape of flat plates. The plates all had a length and a width equal to 300 and 150 mm, respectively. However, their thicknesses varied throughout the trials,

as one objective of this study was to identify the effect of the ultrasonic waves on different material thicknesses. The chosen plate thicknesses were 1.5, 2, and 4 mm. A constant laser parameter setting was used for all the trial sets to minimise the effect of the laser parameters on the experiments. The tests were segregated by the thickness of the aluminium plates being welded, and each plate received designated laser settings.

5.2.2. Laser system parameters

The key laser welding parameters primarily encompass pulse energy, pulse duration, pulse repetition rate, welding velocity, and defocus distance. The selection of optimized welding parameters is essential to achieve a superior weld joint characterized by a flat surface and the absence of noticeable defects. The laser power was kept constant for each plate thickness; for the 1.5- and 2-mm plates, 2 kW was used, and 3 kW was used for the 4 mm plates. The main reason for this variance was to assure that a full penetration weld occurred during the trials.

Two values of laser travel speed were used, 0.025 and 0.040 m/sec, for every set of trials. This weld speed range was deemed to be within the no-hot-cracking window specified [141], and it is the range generally used when autogenously welding 6082-grade aluminium. The beam waist position was kept fixed for every trial at -2 mm, to achieve 100% welding efficiency. The chosen shielding gas was argon (99.99%), with a flow rate of 14 L/min. Throughout the experiments, 28 kHz-100 W (68 mm diameter) and 40 kHz-60 W (48 mm diameter) transducers (a pair of each) were used at 50% and 80% of the maximum power.

5.3. Sample Preparation

5.3.1. Surface quality

Using an Optimax Evo Cam II, several pictures were taken and compared with the top surface of the trial plates. The surface quality of welded joint can be affected by the properties of the materials welded, the thermal history during solidification and the spatial distribution of heat sink paths [155]. It has been reported that ultrasonic vibrations can improve the surface quality of weld joints because there is adequate melt flow during welding processes aided by the acoustic vibration [156, 157]. The surface condition of weld joints can be critical to the structural

performance of the joint. If the surface roughness is large to an extent, it may lead to the formation of preferential stress concentration sites, where fatigue damage may occur, reducing the fatigue strength of the whole welded alloy [100].

5.3.2. Weld geometry

To evaluate the weld geometry, every trial plate was sectioned (transversal cut) at the same locations (75, 150, and 225 mm) using an industrial metal saw (MetCut 300) and hot-mounted using a black epoxy resin and an automatic mounting press (OmegaPress EVO). Subsequently, the samples were polished on a metallurgical polisher (OmegaPol Twin 200 mm) using different wet/dry sandpapers (grit sizes: 240, 320, 400, 600, 800, 1000, and 1200) and water-cooled. The colouring of the weld zone was achieved by immersion in Keller's reagent (190 mL of H₂O, 5 mL of HNO₃, 3 mL of HCL, and 2 mL of HF) for 5 min. Finally, the macroanalyses were obtained by reflected light microscopy using a video microscope (Optimax Live Camera).

5.3.3. Grain structure

Keller's reagent, used to evaluate the weld geometry, is not ideal for grain analysis. The samples were repolished using different wet/dry sandpapers (1200, 2000, and 2500 grit) and finalised with a diamond suspension emulsion (particle size of 3 µm). The chosen etching method was Barker's reagent with electrolytically anodised samples (25 V and 0.1 A for 60 s) examined under polarised light. Finally, the microanalyses were obtained by reflected light microscopy using a video microscope (Optimax Live Camera). Scanning electron microscopy was used to produce images by scanning the surface of a sample with a focused beam of electrons. The addition of an EDX system (an energy dispersive X-ray analysis system) coupled with the SEM allowed for the identification of the elemental composition of the samples (and inclusions). The machine used was a Zeiss Supra 35VP with EDS, at the Experimental Techniques Centre (ETC) of Brunel University, London, with magnifications of up to 10,000×. The software used was the TEAM™ EDS Analysis System.

5.3.4. Tensile strength

To evaluate the mechanical properties of the welded joints, transverse weld specimens were prepared in strict accordance with the BS EN ISO 4136 standard at an independent UKAS accredited laboratory. The specimens were precision-cut to standard geometric dimensions, featuring an overall length of 150 mm and a width of 30 mm. The sectioning was performed such that the weld axis remained centered within the parallel length of the test specimen. To ensure statistical reliability and account for measurement uncertainty across the different parameter sets, five independent samples ($N = 5$) were fabricated and tested for each specific welding configuration. The samples were subjected to continuous tensile loading until rupture at room temperature.

5.4. Experimental Results and Discussions

5.4.1. Plasma cloud

The first noticeable improvement when the ultrasonic wave was used during laser welding was the visible reduction of the plasma cloud, as shown in **Figure 5.2**.

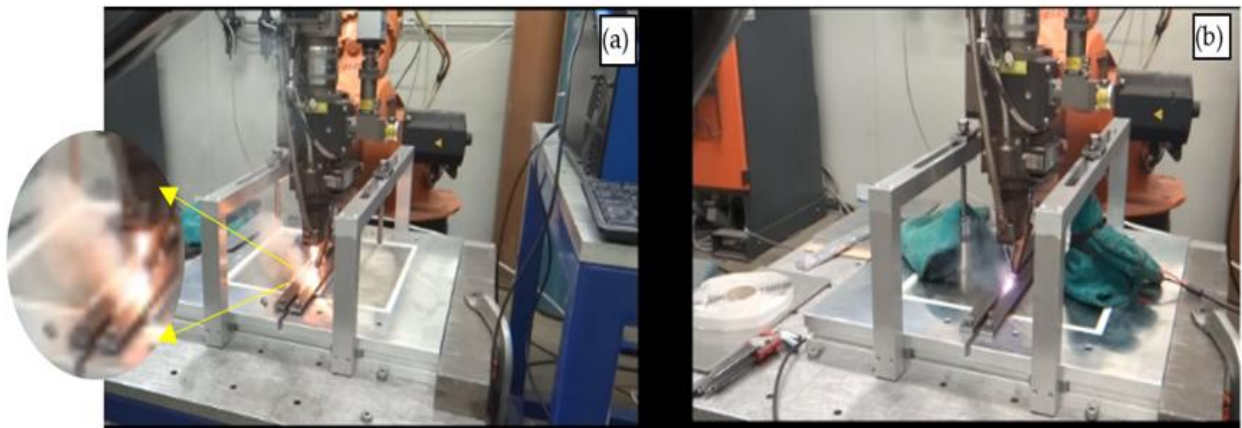


Figure 5. 2: Plasma cloud captured by the monitoring camera during the welding process: (a) with no ultrasound used and (b) when ultrasound was used.

This was noted in every ultrasonic-assisted trial compared to the baseline (laser welding without ultrasound). The ultrasonic waves enhanced the balance and stability of the keyhole, which minimised the pressure build-up and halted material ejections. Thus, plasma cloud was reduced due to lower pressure build-up.

5.4.2. Aspect ratio

The effect of the ultrasonic waves led to variations in weld aspect ratios (i.e., the ratio of weld root depth to its surface weld width), as summarised in the various images captured in **Figure 5.3** and reported in **Table 5.1**. Generally, it is worth noting that, with the thinner plates (1.5 and 2 mm), the use of the 40 kHz transducers led to smaller aspect ratios, whilst on thicker plates (4 mm), the converse was observed. At this frequency, there was an increase in horizontal surface area of the weld, leading to a drop in aspect ratio for both conditions under vibration (**Figure 5.3b and c**).

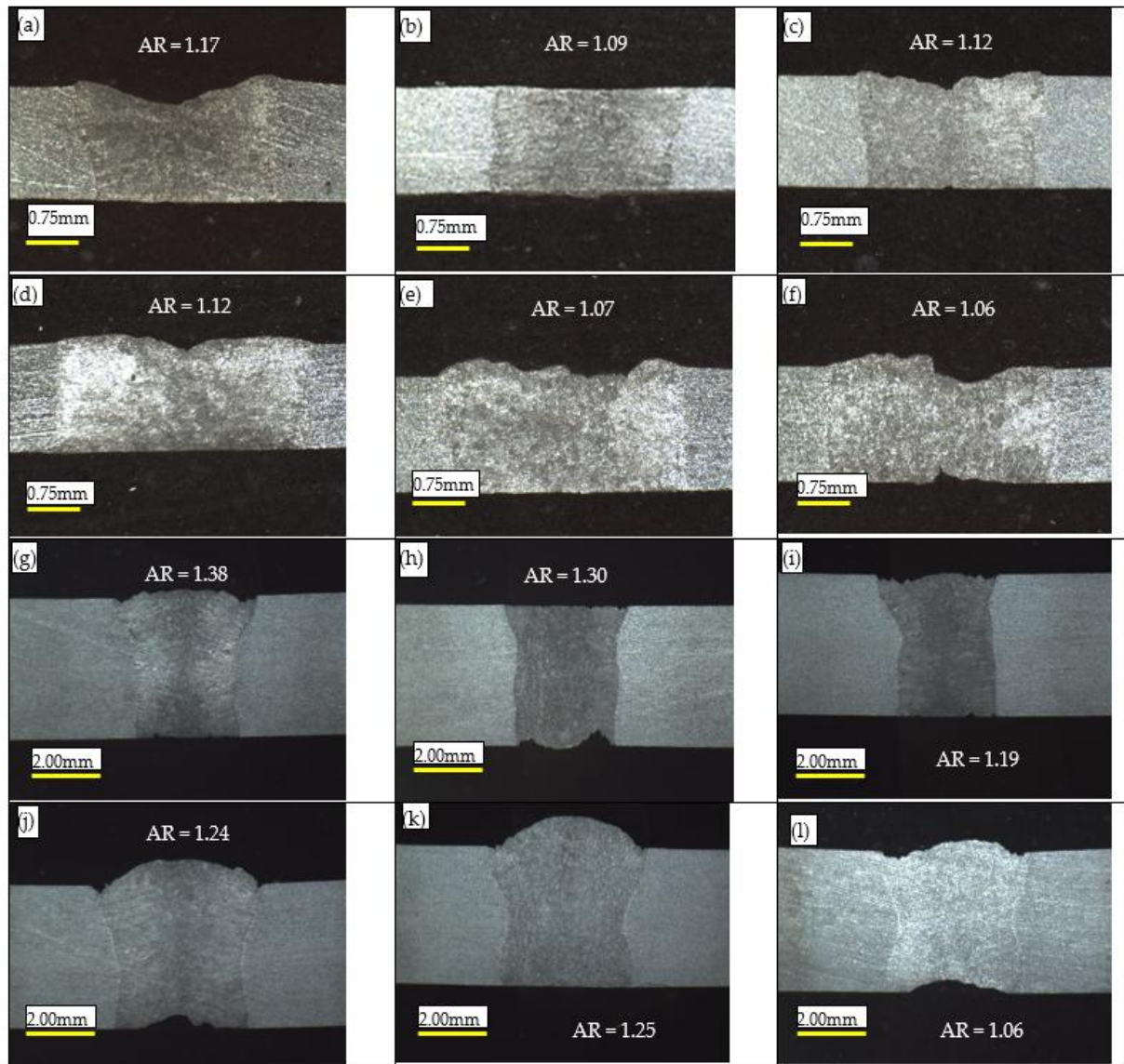


Figure 5. 3: Aspect ratios of welds achieved at different configurations (T: plate thickness, WS: welding speed)

Table 5. 1: Aspect ratios of welds achieved at different configurations

	No Ultra. Vibration	2 x 40 kHz / 30W	2 x 40 kHz / 50W
T=1.5 mm; WS=40 mm/s	1.17	1.09	1.12
T=1.5 mm; WS=25 mm/s	1.12	1.07	1.06
	No Ultra. Vibration	2 x 40 kHz / 50W	2 x 28 kHz / 80W
T=4 mm; WS=40 mm/s	1.36	1.30	1.19
T=4 mm; WS=25 mm/s	1.24	1.25	1.06

At a transducer power of 30 W, the surface exhibited a smooth profile with an aspect ratio of 1.09, which indicates a 6.8% reduction. When the transducer power was increased to 50 W, there was a slight increase in the aspect ratio to a value of 1.12 with a rougher surface profile. The wave penetration decreased along the axis of the plate thickness with increasing frequency because both wave absorption and scattering in the weld melt increased with frequency. Thus, to achieve complete coverage of the weld joint, the frequency must be reduced commensurately with increasing plate thickness.

With the plates that were 4 mm thick (**Figure 5.3 (g)–(k)**), the use of ultrasound at 28 kHz decreased the aspect ratio even further by 62%. However, 40 kHz ultrasound led to a reduction of only 14% when compared to the baseline. Compared with the thinner plates, the 28 kHz transducer achieved smaller aspect ratios on the thicker plates.

Table 5. 2: The average difference between weld keyhole width and root depth in mm with different set-ups.

Thickness	Baseline	28 kHz	40 kHz
1.5 mm	0.375	0.340	0.215
4 mm	0.965	0.365	0.830

It is important to note that the effect of ultrasonic assistance reduced the aspect ratio in both thinner and thicker plates. The exception is observed in the weld joint formed on a 4-mm plate at a welding speed of 25 mm/s, vibration frequency of 40 kHz, and transducer power of 50 W (**Figure 5.3k**). For thicker plates, although, the contact angle of the weld bead reduced with ultrasonic vibration, however, the weld depth was reduced due to the rapid solidification in-

duced by the vibration. This is in line with the work of Tian et al [158], stating that the decreased spreading due to rapid cooling experienced by the weld pool with ultrasonic vibration would be responsible for the decrease in contact angles. We used two fixed transducers, and the wave was stronger at the parts closest to the transducers and tended to be attenuated in the parts of the weld joint that were farther from the transducers. Whilst there were still noticeable improvements in weldability and surface quality, the weld profile (Keller's etchant) in the baseline trials (without ultrasound, see **Figure 5.3 (a), (d), (g), and (j)**) was nearly identical to the ultrasonic-assisted laser welding. Despite a noticeable benefit derived from the use of ultrasound assistance, it was also noted that, to be more effective, the ultrasonic contribution should be modulated to the size of the workpiece to be welded. For instance, whilst 40 kHz ultrasound improved weld profiles on the thinner plates (1.5 mm), the opposite was observed on thicker plates (4 mm), where the use of 28 kHz ultrasound generated more minor variations in the surface and root width. Applying vibration to alloy melt is one of the effective methods to improve the internal structure and microstructure of metal materials [136]. According to the work conducted by Zhang et al. [159] on the influence of ultrasonic vibration on current density and keyhole capability of plasma arc, the authors found that the integration of ultrasonic vibration and the controlled pulse current waveform could ensure the open keyhole establishment and complete penetration at lower peak current or higher welding speed.

5.4.3. Examination of surface quality

Examination of the surface quality of the welds confirmed the overall effectiveness of using ultrasonic power during the welding process. In **Figure 5.4 a, b**, concerning baseline samples, microcracks that are likely to be a crack initiation zone can be easily identified and spotted across the weld line. However, in **Figure 5.4c, d**, when ultrasound was used, the weld line completely disappeared, and an improvement in grain arrangement was noted.

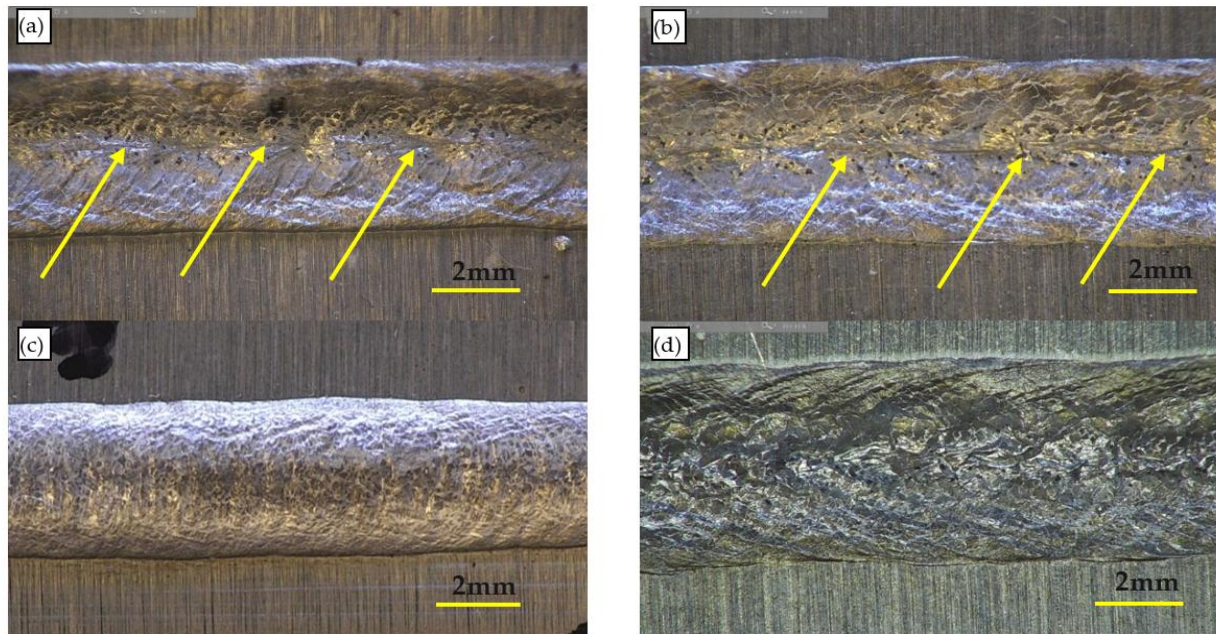


Figure 5. 4: Examination of the surface of the welds achieved without ultrasound at (a) 25 mm/sec and (b) 40 mm/sec and with ultrasound at (c) 28 kHz, 80 W, and 25 mm/s and (d) 40 kHz, 50 W, and 40 mm/s. The arrows point to the central line of the weld

The yellow arrows indicate the direction of weld fronts as the molten pool is created by the laser beam. Similarly, Krajewski et al. [160] analysed the effects of the ultrasonic vibrations applied to the melted metal pool by vibrating the substrates. The authors observed that the weld grains did not display the directionality observed when the welding process was conducted without the participation of ultrasonic vibrations, compared to the baseline weld structure.

The weld profiles of the ultrasonic vibration-assisted samples appeared more uniform and smoother than the baseline samples. Due to the ultrasonic energy, there was increased distribution of material within the weld line with minimal defects. In the work of Lei et al. [92], the authors explained that the laser energy density can be high enough that the heat input per unit area becomes large to cause coarsening of grains within the weld region and the inclusion of porosity that can limit the comprehensive properties of the joint. However, the introduction of ultrasonic streaming into the pool, grains can be refined and eliminate weld porosity and inclusion defect.

5.4.4. Microstructure analysis

As shown in **Figure 5.5a**, no agglomerations were noted in the SEM analysis without ultrasonic vibration. The grain boundaries are characterised with secondary phases (white coloured patterns and dark spots). During the cooling process immediately after welding, the temperature drops to temperatures lower than the solidus temperature of solute-rich phases. These phases tend to form before the solidus line of the low-melting eutectic phase is reached. As a result of the rapid solidification associated with laser welding, there is less sufficient time for the formation of eutectic phases to form, leaving the solute-rich phases (secondary phases) to form and occupy the grain boundaries. According to Chen et al [161], the solute-rich phase forms a continuous liquefied grain boundary that can immensely decrease the bond strength between adjacent grains to aid the crack propagation in a case where crack is initiated macroscopically. Thus, the grain boundaries become highly sensitive to cracks. These secondary phases are more likely to act as hot crack initiators when compared to the spherical nature of the intermetallic structures seen in the second sample shown in **Figure 5.5b**, where ultrasound was used. In that case, no agglomerations were observed throughout the SEM analysis, and intermetallic formations were smaller and appeared mostly in the shape of spheres. z

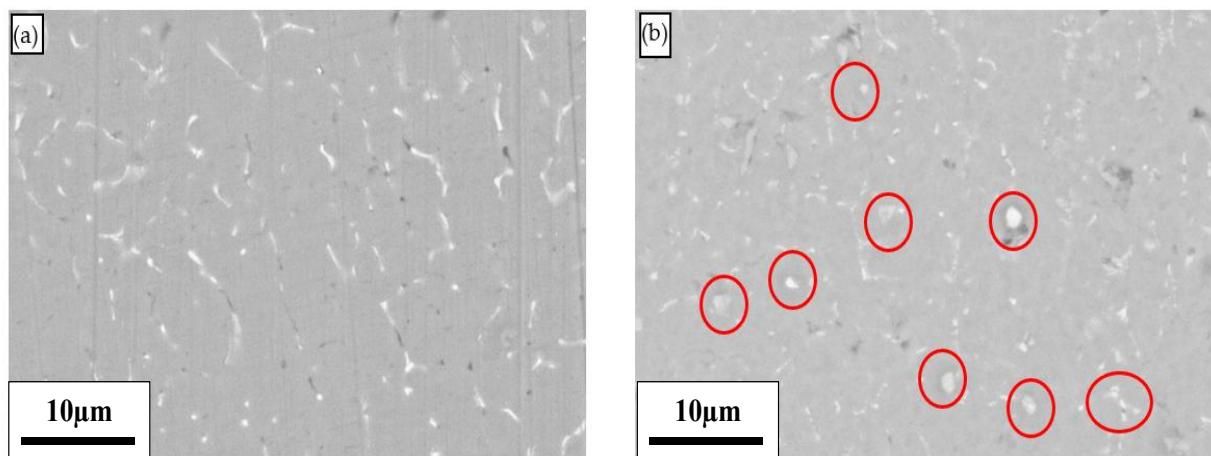


Figure 5. 5: SEM analysis of cross sections of welds (2 mm thick plates) achieved at 25 mm/s (a) without ultrasound and (b) with ultrasound at 40 kHz and 50 W (spherical nature of the intermetallic structures).

The visual data presented in the high-magnification SEM and EDS analyses in Figure 5.5, specifically concerning the radical morphological transformation of the intermetallic compounds,

can be logically deduced to represent the physical fragmentation and subsequent thermodynamic spheroidization of highly coarse magnesium silicide (Mg_2Si) eutectic networks and their highly likely associated, brittle monoclinic Beta- Al_5FeSi phases.

According to the study conducted by Sui et al. [137], it was found that the precipitate types formed during solidification remained the same with and without ultrasonic vibration, however, the distribution of the precipitates differs due to the application of ultrasonic vibration. The authors used an ultrasonic output power of 800 W for their analysis. The analysis showed that most of the precipitates were distributed along the grain boundary. By applying the ultrasonic vibration. The precipitates were more evenly distributed but not concentrated only along the grain boundary but also within the grains. They also reported that the presence of Mg supported the strengthening effect observed, which formed a strengthening phase that enhanced the welded joint. Furthermore, the contents of Mg and Al had the largest fraction within the weld matrix, where Mg not only formed precipitates, but was dispersed within the weld matrix, promoting intra-crystalline strengthening effect. In the work of Tzanakis et al [162], the authors reported that the introduction of ultrasonic vibrations into a melt pool resulted in removal of gases which led to decrease in porosity; refinement of grains and primary phases; improved nucleation characterized by substrates activation via wetting and grain multiplication due to dendrite fragmentation; reduced clustering of materials due to substantial acoustic pressures exerted during cavitation bubble collapse, and; effective distribution of solid or distinct phases through convection and acoustic micro-streaming.

5.4.5. Grain structure analysis

The reflected light microscopy images of the samples produced with and without ultrasound are shown in **Figure 6**. Without ultrasound, dendritic growth is evident (i.e., a tree-like structure in **Figure 5.6a**) in several locations throughout the weld zone. An unevenly distributed grain structure can also be seen. When ultrasound was used (**Figure 5.6b**), no agglomerations were noted in the analysis. The grain structure appears evenly distributed. However, a higher concentration of grains can be seen in the zones where different solidification fronts meet.

Without ultrasound, the number of grains per area appeared lower than that obtained with ultrasound. It was also possible to identify dendritic growths and an increased concentration of grains around these growths. In the trials with ultrasound, the grain structure appeared to be more homogenised and evenly distributed, and it was also possible to identify a boundary with different grain sizes (solidification front).

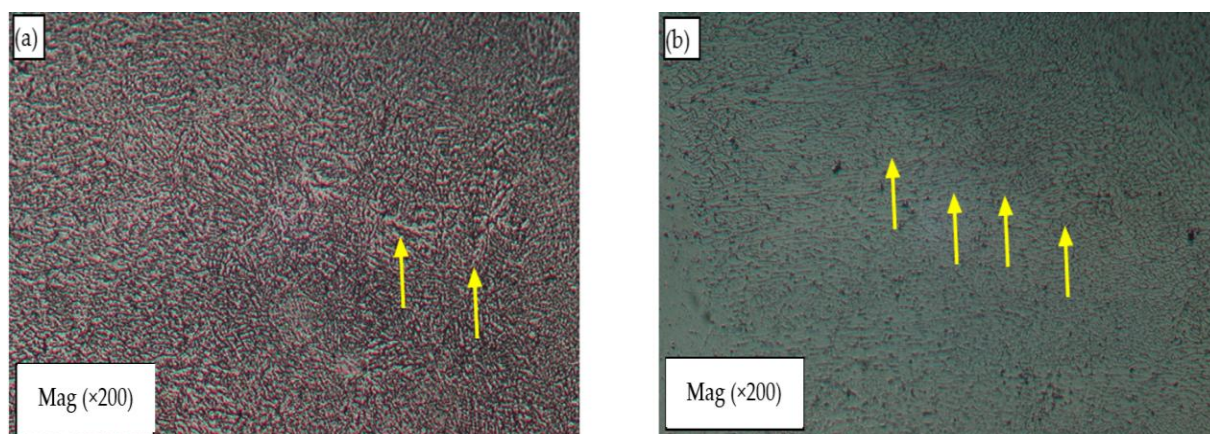


Figure 5. 6: Reflected light microscopy images ($\times 200$ magnification) of cross sections of welds (2 mm thick plates) achieved at 40 mm/s (a) without ultrasound (arrows indicating some dendrites) and (b) with ultra-sound at 40 kHz and 50 W (arrows indicating some soli

The work of Sui et al. [137] showed that increasing the ultrasonic output power influenced the grain size within the weld zone. The grain size decreased gradually till a certain output power was reached. At this power, the inverse relationship was not obeyed. It was reported that ultrasonic power caused grain refinement, however, there was a discontinuity with increasing output power. With the application of ultrasonic vibration during the cooling and the solidification process, heterogeneous nucleation and rapid nucleation of solid phases were promoted, thus increasing the rate of nucleation. This behaviour was also reported by other studies [163, 63]. Formation of larger grains was disrupted, creating smaller nucleating particle localized at the centre of the molten pool. This increased the number of smaller grains formed. The authors concluded that ultrasonic vibration inhibited grain growth during solidification. Ultrasonic vibrations possess substantial penetrating power, and they can potentially induce cavitation effects, typically manifesting when the acoustic pressure amplitude surpasses the Blake threshold [164]. In practice, aluminium alloy welding frequently results in pore formation due to the presence of multiple small bubbles and impurities within the molten pool. These factors disrupt

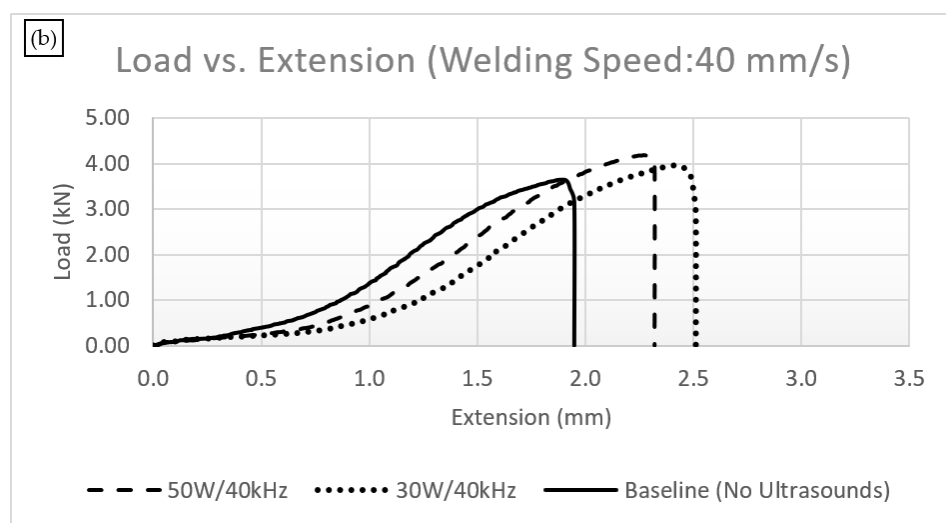
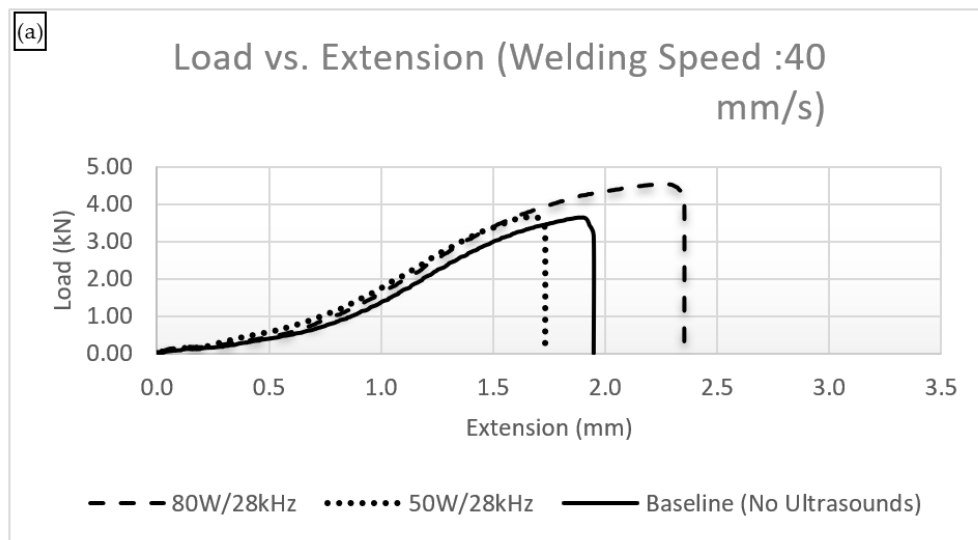
liquid continuity and can serve as cavitation nuclei, significantly lowering the cavitation threshold within the molten pool. Therefore, cavitation can manifest under the influence of relatively modest ultrasonic energy. Furthermore, this lowered cavitation threshold within the molten pool has a profound impact on the grain size of the aluminium alloy weld joint. The localized cavitation caused by ultrasonic vibration induces intense stirring and agitation within the molten metal, promoting rapid cooling and solidification. This rapid cooling process results in finer grain structures within the weld.

5.4.6. Relationship between theoretical modeling of cavitation effect and experimental results

The combined effect and dynamics of cavitation bubbles and acoustic streaming in ultrasonic vibration-assisted laser welding proves significant implications for the grain refinement observed in the experimental results (Fig. 5). As established in the theoretical explanation presented in Chapter 3, increasing ultrasonic frequency results in elevated melt pool pressure and a corresponding reduction in cavitation bubble radius, although the maximum shock intensity was discussed to be achieved at an approximate critical radius of $1.58R$ immediately prior to bubble collapse. The grain refinement mechanism evident in Fig. 5 unequivocally confirms the effectiveness of the incorporation of ultrasonic vibrations with the fusion area during the process of laser beam welding. The theoretical model previously explained traces the formation, evolution, and collapse mechanisms of the cavitation bubbles developed within the melt pool area during the weld solidification process, which modifies the grain structure by developing high-pressure shockwaves and micro-jets within the melt pool. Furthermore, the work of Ramirez et al. [165] showed that bubble collapse was due to the cavitation effect, whereby the newly formed dendritic structures are fractured by the generated impact wave. Consequently, fragmented dendrites may act as new nucleation sites. Another effect that was reported in the work was that the introduction of ultrasonic vibration resulted in reduced undercooling. Therefore, these combined effects were claimed to promote the formation of equiaxed grains.

5.4.7. Tensile tests

Tensile tests were performed on 1.5 mm thick samples, exclusively with smaller aspect ratios, and superior surface quality was attained at this thickness. The samples were prepared at laser scan speeds of 25 and 40 mm/s, resulting in the division of results into two distinct groups. Ultrasonic vibration was carried out using 28 kHz transducers (at 50 W and 80 W) and 40 kHz transducers (at 30 W and 50 W). Additionally, baseline trials without ultrasonic vibration underwent tensile testing to evaluate the effect of ultrasonic vibration in comparison to conventional laser beam welding. **Figures 5.7 and 5.8** show the load vs. extension and the ultimate tensile strength of the welds at 40 mm/s and 25mm/s, respectively.



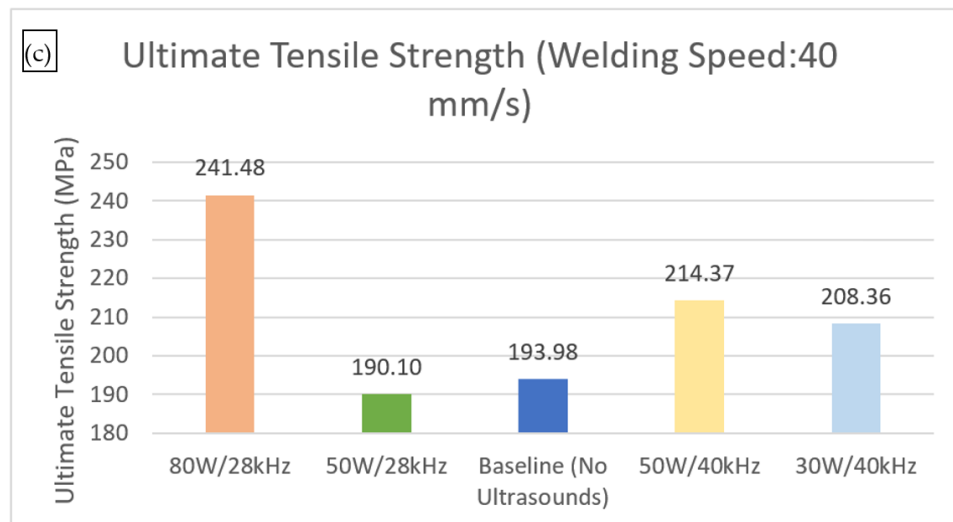
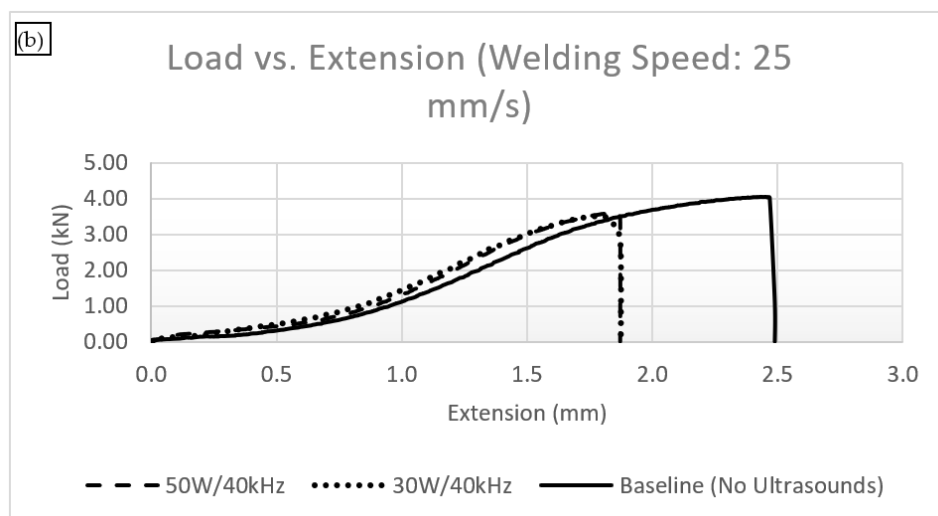
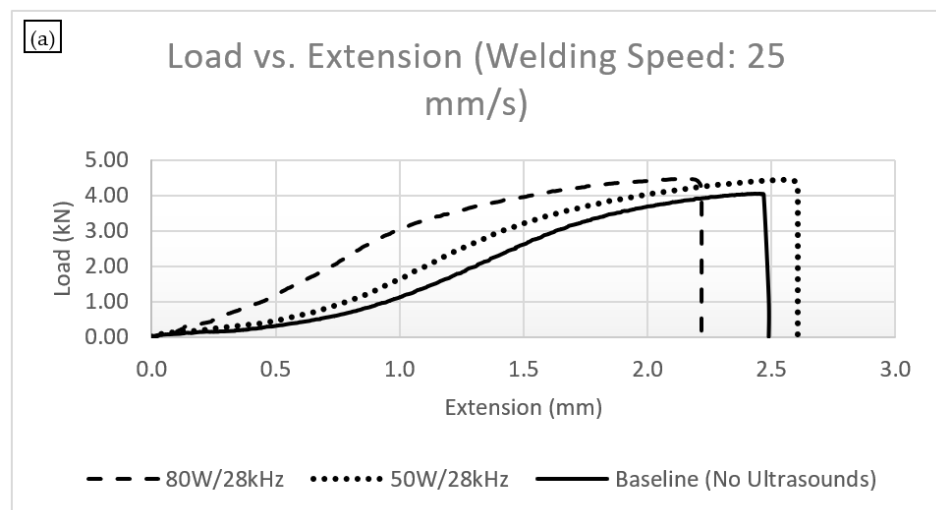


Figure 5. 7: Load vs. extension (a) at 28 kHz, 40 mm/s, and (b) at 40 kHz, 40 mm/s. (c) Ultimate tensile strength at 40 mm/s.



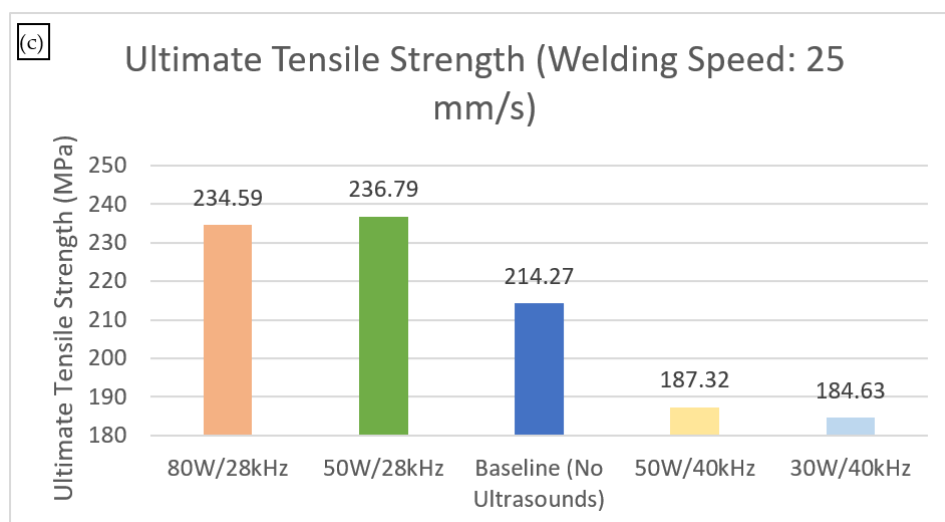


Figure 5. 8: Load vs. extension (a) 28 kHz, 25 mm/s, (b) 40 kHz, 25 mm/s, and (c) ultimate tensile strength at 25 mm/s.

In **Figure 5.7a**, the graph displays the load against extension for the weld samples fabricated at an ultrasonic frequency of 28 kHz. The dotted line represents the weld sample formed with an ultrasonic output power of 50 W, the broken line represents the sample welded at an output power of 80W, and the continuous line shows the tensile result for the control (no ultrasonic vibration). Prior to an extension level of 0.5 mm, the sample behaved in a similar manner. Beyond the 0.5-mm mark, there was an apparent differentiation between the ultrasonic vibration-assisted samples and the baseline. The tensile strengths of the ultrasonic vibration-assisted samples at 28 kHz showed higher values than the baseline sample. Eventually, the 28 kHz/80 W sample exhibited the most elongation and experienced the largest force to deform, while the 28 kHz/50 W and baseline samples showed similar force limits with the baseline extending more than the 28 kHz/50 W sample. At 40 kHz (**Figure 5.7b**), the 40 kHz/50 W displayed the highest resistance to tensile stress, however, the 40 kHz/30 W sample was most ductile of the three samples. The ultimate tensile strength results in **Figure 5.7c** showed that the strongest amongst the samples welded at a speed of 40 mm/s was the 28 kHz/80 W sample with an ultimate tensile strength of 241.48 MPa. In **Figure 5.8a**, showing the load vs extension plot for samples welded at a welding speed of 25 mm/s and ultrasonic frequency of 28 kHz, the 28 kHz/50 W sample displayed the highest elongation, and resisted a similar level of stress as the 28 kHz/80 W sample. The baseline sample showed the highest stress resistance and elongation

compared to the ultrasonic vibration-assisted samples in **Figure 5.8b**. The ultimate tensile strength chart showed that the 28 kHz/50 W possessed the highest ultimate tensile strength of 236.79 MPa. This indicates that there was a combined effect of the ultrasonic frequency, welding speed, and the ultrasonic output power on the mechanical strength of the weld joint. A 24.49% increase in ultimate tensile strength was recorded at a welding speed of 40 mm/s while an increase of 10.51% was realized at a welding speed of 25 mm/s, compared to the samples with no ultrasonic vibration. It can also be seen in **Figure 5.8** that, when ultrasound was used, we achieved an average increase of 10% in both ultimate tensile strength and the load required for failure. The maximum values were achieved at a frequency of 28 kHz. An interpretation of this result is suggested in Chapter 3, where we estimate the ultrasound intensity in the melt in relation to cavitation thresholds.

Despite the inevitable decrease in local strength due to the fusion process, in a trial with a power of 80 W, a frequency of 28 kHz, and a welding speed of 40 mm/s, the ultimate tensile strength was approximately 25% higher than the baseline trial. This increase could be explained by the homogenisation of the molten pool and the consequent reduction in crack initiation zones (e.g., dendritic growths). In the work of Yin et al. [166] the authors studied ultrasonic regulation of the welding performance and defects of 7A52 aluminium alloy plate. The authors observed that the average tensile strength of the ultrasonic vibration-assisted welded joint was approximately 84% higher than the weld with no ultrasonic input. This phenomenon arises from the regulatory influence of acoustic streaming and cavitation effects generated by ultrasonic waves on the grain state and joint defects. Moreover, as ultrasonic waves propagate, they enhance the fluidity of the melt and modify the heat transfer environment within the molten pool. Consequently, the internal temperature of the molten pool attains greater uniformity, the temperature gradient during weld solidification decelerates, leading to a reduction in thermal residual stress, and ultimately, an enhancement in the tensile strength of the sample is achieved.

5.5. Mechanisms Involved in the Weldment Changes Induced by Ultrasonic Vibration

This section reviews the possible ultrasonic mechanisms that may have been the cause of the improvements we observed in the structure of the laser welds formed in the presence of power ultrasound.

The strongest mechanism of ultrasonic action on fluid phase materials, especially grain refinement, is cavitation. In cavitation, enormous local forces, large enough to rupture chemical bonds and raise local temperatures up to 10,000 K, acting on solid particulates in a melt, are generated by its collapsing [167]. These forces are many orders of magnitude greater than the secondary ultrasound radiation forces between the nearest neighbouring melt particulates, generated by ultrasound scattered by the particulates and the primary ultrasound radiation beam forces acting directly on the melt particulates. These forces (also called Bjerknes forces) combine to help keep the particles apart and hence reduce the tendency towards agglomeration and porosity formation and promote the spatial uniformity of particle distribution; however, the process is prolonged due to the low level of these forces [168]. Thus, they can be effective in metal melts that exist for a long time, e.g., in a furnace or when continuously heated by a laser. However, it is unlikely that they would be very effective in laser spot welding, where the molten period at any point along the weld line lasts for only around a second.

Only cavitation forces are strong enough to break up the large and agglomerated grains in melts into smaller structures, and such structures will usually appear accidentally during melt cooling [169]. The times for bubble growth and subsequent collapse to release cavitation forces are ~ 1 ms and 150 μ s, respectively, so these forces can be effective in weld melts produced by rapidly moving laser spots.

The cavitation threshold intensity for aluminium melts has been published in the literature as 100 W/cm² [147]. It was not possible to determine whether cavitation forces were present in our experiments via the direct visual observation of bubbles in the melt because the melt was opaque, and our visual examination of the weld surfaces showed no surface emergence of bubbles. Thus, the likelihood of cavitation presence requires a calculation of the ultrasound power entering the melt. To accurately determine whether cavitation could have been present, we

would need to compute the ultrasonic field in the entire weld-plate structure. This field is complex, consisting of quasi-standing waves, and requires modelling for an accurate prediction of the intensity levels achieved in the weld melt for a given transducer output power, which we will perform in future work. However, a rough calculation of this intensity can be readily performed as follows.

With the knowledge that the compressional wave velocity in the aluminium plates is 6000 m/s [160], the wavelengths would be 21.4 cm and 15 cm at 28 and 40 kHz, respectively, which are larger than the cross section of the transducer interface. Therefore, the vibration from the transducers will not travel along the cross-section direction of the plates. The absorption in the plates outside the melt region will be negligible at such long wavelengths and low frequencies.

Thus, with the highest power used, 80% of the power of two transducers (160 W) will cross the weld line–plate interface. The area of the interface for the 1.5 mm thick and 30 cm long plates used for the tensile testing experiments was, therefore, 4.5 cm². In addition, the spatially averaged intensity was $160 \text{ W}/4.5 \text{ cm}^2 = 35.5 \text{ W/cm}^2$. Assuming a compressional wave velocity in the weld melt of 2000 m/s, the wavelength in the melt at 28 kHz was around 7 cm. Therefore, a set of around 6 antinodes and nodes would have been present along the 30 cm long weld line. At the antinodes, the wave intensity would be four times the average, i.e., 142 W/cm². Therefore, we conclude that the cavitation threshold was well exceeded at the antinodes and cavitation, thus making a significant or even dominant contribution to the ultrasonically improved ultimate tensile strength of the welds. We noted in Section 3.6 that the same improvement in ultimate tensile strength arose when transducer power outputs were reduced from 80 W to 50 W. For two 50 W transducers, the intensity in the melt at the antinodes would have been 89 W/cm², according to our calculation in Section 3.7, which is very close to the published cavitation threshold of 100 W/cm² referenced earlier in this subsection. One simple possible explanation is that far exceeding the threshold does not significantly increase bubble growth and collapse activity.

In a future publication, we will apply the Hall–Petch equation to our yield strength and grain size data to confirm that yield strength improvement stems from ultrasonic grain refinement in our welding process.

5.6. Other Possible Effects of Ultrasonic Vibration on Weld Melts

High-power ultrasonic waves are known to disperse alloying compounds, such as magnesium silicide, towards the weld boundary, thereby minimising the risk of cooling residual stresses, leading to the hot cracking phenomenon. Additionally, ultrasonic waves improve weld quality by reducing overall imperfections due to porosities and oxide formation. It is possible that high-power ultrasound forces could mitigate the negative effect of Marangoni flow. Marangoni forces arise from surface tension gradients and can adversely affect weld strength by introducing spatial variations in the microstructure [168].

Ultrasonic vibration could agitate the flow of the liquid melt at different solidification phases. This would result in an even heat distribution. Ultrasonic vibrations produce acoustic streaming into the liquid phase as it propagates across the solid-liquid interface to develop a turbulence within the molten pool. Following this, an acoustic pressure gradient is initiated due to the energy lost from the propagation of the ultrasonic wave into the liquid phase. This effect may promote the plastic flow of the metal and evenly distribute micro materials within the pool. In addition, rates of reactions between substances can be catalysed by the introduction of ultrasonic waves, and these waves can streamline the environmental conditions necessary for chemical reactions, initiate complex reactions, enhance product yield of reactions, and reduce reaction induction period.

The impact of ultrasonic vibration on precipitated phases can be characterised in two distinct stages. Initially, it serves to augment the quantity of precipitated phases. This is attributed to the improved molten pool fluidity induced by ultrasonic vibration, which facilitates the migration of alloy elements from the base metal to the weld, consequently increasing the number of precipitated phases. Subsequently, the focus shifts to altering the distribution of precipitates. In this stage, the stirring effect of ultrasonic vibration within the molten pool ensures a more

even dispersion of the second phase, which tends to form along grain boundaries and aggregate, ultimately leading to more uniform distribution within the crystal structure. As a result, as ultrasonic power levels rise, there is a gradual intensification of alloying elements from the base metal passing through the weld, resulting in a progressive increase in the number of precipitates formed within the weld, along with their more uniform distribution [137].

5.7. Summary

The mechanical analysis and tensile testing identified the parameters that led to an average increase in the ultimate tensile strength of 10%. The best trial of the study improved the ultimate tensile strength by 25% compared to the baseline, where no ultrasound was used. The weld profile became straighter when ultrasound was used, with the difference between weld width and root width being reduced by 14–62%, depending on the set of parameters used.

The use of high-intensity ultrasound effectively disrupted the epitaxial growth of the dendrites, refined the grain structure, reduced the plasma cloud, and transformed the shape of the inter-metallic compounds from linear to spherical. It also improved weld stabilisation and decreased the spatter levels, which are critical to weld quality and weld strength.

The resistance to crack propagation–crack initiation due to grain refinement and disruption of the epitaxial growth of dendrites is linked to the increase in ultimate tensile strength and the load required for failure. A noticeable improvement was observed during the trials using high-intensity ultrasound. The next chapter considers the introduction of ultrasound vibration to laser welding, generating low-intensity cavitation and studying its effect on the quality of the weld. This will be achieved by evaluating the impact of contactless ultrasonic vibrations during laser welding.

Chapter 6

Ultrasound vibration assisted laser welding through generating low-intensity ultrasound cavitation

6.1.Introduction

Nowadays, several manufacturing processes such as laser welding, additive manufacturing and casting are based on the total fusion of material, followed by rapid solidification [170, 171]. The material's structure in the final phase and its mechanical and electrical properties strongly depend on the solidification phase [172]. This is especially seen when the material consists of an alloy of metals or even a combination of two dissimilar materials, such as in the case of lap joining (by laser welding) of specific connectors to battery cells for the manufacture of battery packs for electric vehicles [173, 174].

The difference in melting temperature between different types of metals leads to the coexistence of liquid and solid phases. In other words, the agglomeration of particles of similar nature occurs in the molten pool area [175], which ideally should be dispersed homogeneously throughout the liquid phase during solidification [176]. The presence of voids and gas, as well as the grain size variability are phenomena frequently observed. These phenomena cause the final properties of the material to deteriorate [177, 178], leading to problems such as hot cracking [179]. Therefore, the battery connectors might be fragile and have a high electrical impedance which causes energy loss and temperature elevation in the battery packs [180, 181].

Ultrasonic processing of molten materials is a main technique that helps reduce residual stresses and improve the microstructure by grain refinement [182 – 184]. Ultrasound corresponds to waves with frequencies more than those audible to the human ear, greater than approximately 20 kHz [185]. The ultrasound cavitation in the molten pool contributes to the fragmentation and shaping of intermetallic compounds [104]. The ultrasonic energy can propagate

both in solid and fluid media. Cavitation can be defined as tiny gas bubbles being grown, oscillating, and collapsing in a fluid while subjected to ultrasound excitation [186]. Ultrasound cavitation can be initiated due to the leakage or refraction of the ultrasonic-guided wave from a solid to a fluid medium [187, 188]. Ultrasonic-guided waves, for instance, Rayleigh surface waves [189, 190], Lamb waves [191, 192], and Stonely waves [193] at an interface between two materials, can propagate in a finite medium [194 – 196].

The challenge of enhancing both micro and macro structural properties is often linked to improving the weldability of materials, which has traditionally been a key focus. A review of the existing literature on this subject reveal that most of the research involving mechanical vibrations primarily concentrates on the resulting effects. In many cases, these vibrations lead to grain fragmentation and the transformation of grain shapes into more balanced forms, resulting in improved mechanical properties like strength, impact resistance, or hardness. However, relatively few of these studies give significant attention to the technical aspects related to effectively applying vibrations, including their specific characteristics such as frequency, amplitude, or phase. Utilizing carriers unrelated to the base material to transmit vibrations offers an opportunity to circumvent issues associated with the proximity of the heat source and simplifies the technical aspects of introducing vibrations. Consequently, it is crucial to present a method for introducing vibrations that does not necessitate direct contact with the base material [197]. The focus of this study is centred on the use of contactless vibration to improve welding quality in terms of impedance value. For this purpose, a focused ultrasound that can be integrated with a laser welding system has been characterised in terms of the angle and the distance to produce the maximum vibration. The result from the non-ultrasound and contactless vibration assistance welding are analysed and the data indicated a reduction in the impedance of the welding when contactless vibration was employed. Usually, vibration assistance welding is carried out by HPUTs to generate out-of-plane displacement for the plate under welding. In this study, further investigation was carried out to find the difference in the impedance of the weld when the transducer was placed to deliver shear waves. Furthermore, the transducer was positioned

to produce a compressional wave, and their results are compared to the contactless system that has been designed.

6.2.Experimental Configuration for Ultrasonic Assistance Laser Welding

In the welding process, a battery is enclosed within a white plastic cover, as depicted in **Figure 6.1a**. A small copper (Cu101) plate, as shown in **Figure 6.1b**, is then welded to one of the battery terminals.

The current battery holder has limited space to record the vibration transmission to the little plate terminal, and even using a laser vibrometer, the data were erratic.

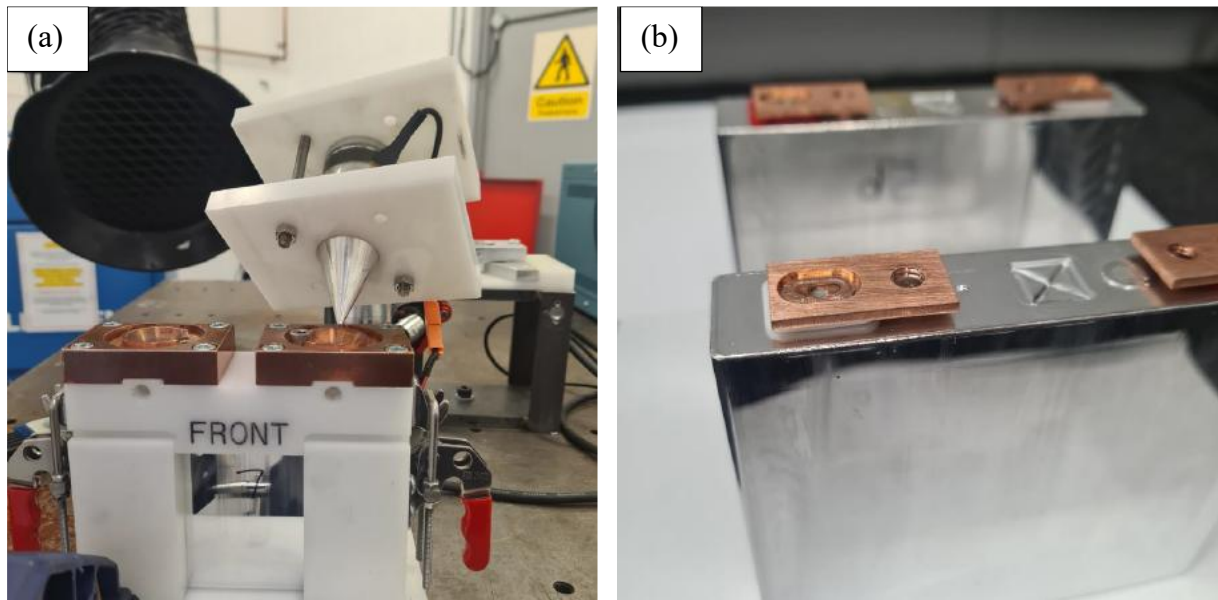


Figure 6. 1: Laser welding of a copper plate to a battery terminal. (a) The ultrasonic assistance laser welding configuration. (b) The final plate welded to the battery.

Furthermore, by welding the plate to the battery head, it is difficult to analyse the welding in terms of the pull test and microscopy. Therefore, a simplified setup is considered to replicate the welding of the plates to the battery terminal, as illustrated in **Figure 6.2**.

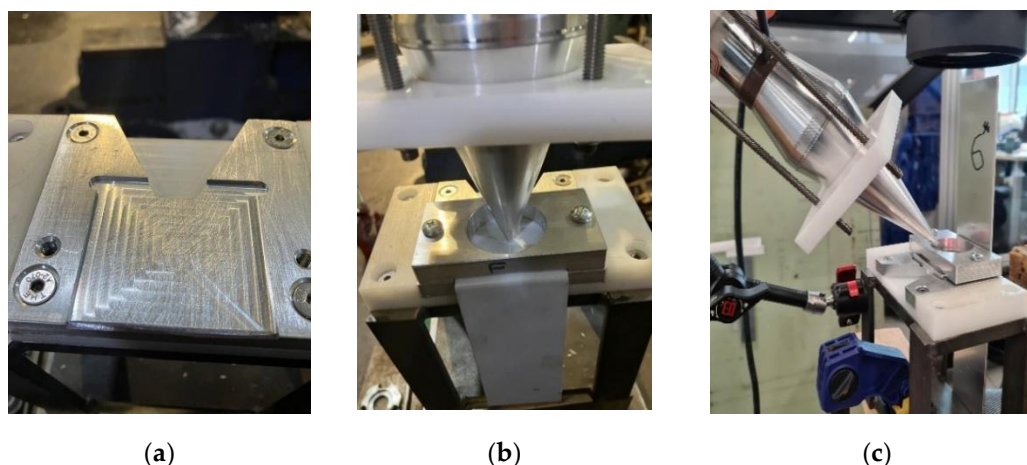


Figure 6. 2: The simplified welding configuration. (a) The bottom holder, (b) fastened top holder to the bottom one, and (c) a picture showing the location of two plates, one at the top and the other at the bottom, along with the location of excitation from the tra

As illustrated in **Figure 6.2 (b) and (c)**, a holder fastens two L-shaped plates, one at the top and the other at the bottom. This simplification allows for the recording of the transmitted vibration in the area where welding will take place. The utilisation of contactless vibration could present a viable solution for ultrasonic-assisted laser welding, particularly when encountering restricted space, as illustrated in **Figure 6.3**.

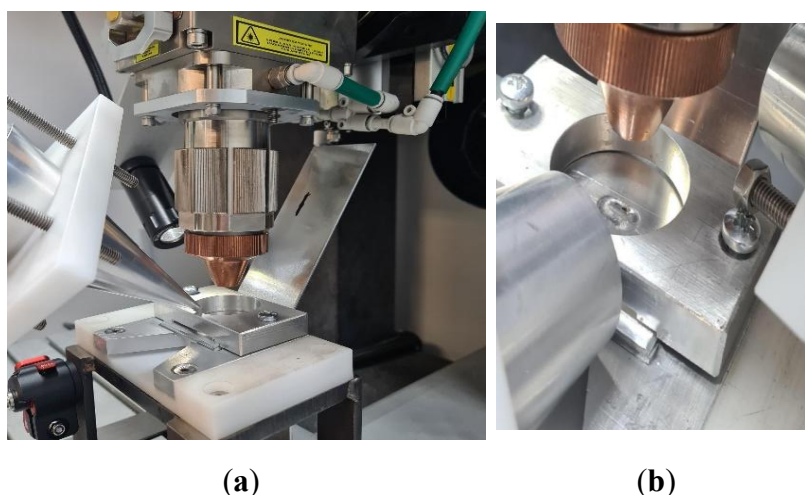


Figure 6. 3: The welding configuration includes (a) the utilisation of an ultrasound transducer with a focussed horn during laser welding and (b) the oval shape of the welding.

As seen in **Figure 6.3**, the final laser weld of the plate has an oval shape. The lasers used in this study are IPG Photonics high-power multimode Ytterbium Fibre Laser systems and their country of origin is the USA. The laser power utilised was 2000 W. The laser head operated at a speed of 2750 mm/min, with a wobble width of 0.7 mm and a frequency of 250 Hz. All the

plates used in this study have an L shape with dimensions of 50×50 mm at the welded bottom part and 100×50 mm at the top section. Throughout the trials, certain parameters were kept constant. This included the thickness of the plates being welded, which was 0.9 mm for copper and 2 mm for aluminium. All the measurements in this study were conducted with High-Power Ultrasound Transducers (HPUTs) at 20 kHz and 40 kHz, operating at 70% power. It is not recommended to increase the power amplification of the industrial horn as it tends to overheat and produce low amplitude noise instead of the desired signal. The 20 kHz transducer features a horn length of 127 mm, with the large tip having a diameter of 33 mm and the small tip a diameter of 3.3 mm. The 40 kHz transducer has a length of 62 mm, with the large tip having a diameter of 22.5 mm and the small tip a diameter of 2.25 mm.

6.2.1. Ultrasonic vibration assistance of laser welding

This section investigates the use of contact and contactless vibration methods to enhance laser welding quality by employing 20 kHz and 40 kHz HPUTs with small and large end tip horns, as illustrated in **Figures 6.2** and **6.3**.

Salimi et al. [110] characterised an industrial HPUT to determine the optimal distance and angle for contactless excitation. To make the vibration level at its optimum value, the horn length should be proportional to half of the wavelength associated with the transducer. To mitigate potential heating of the piezoelectric component in a similar transducer used in this study and the amplifier setup during continuous operation, a frequency sweep can be used [131]. This technique indirectly protects the transducer and power generator from potential damage. By varying the operating conditions through a frequency sweep, excessive heat accumulation is prevented, thus preserving the integrity of both the transducer and the power generator.

6.2.2. Vibration measurements

Prior to conducting ultrasonic-assisted laser welding, vibration tests are carried out to determine the vibration levels of the plates under welding in both contact and contactless excitation modes. The experimental vibration measurements involve a 20 kHz HPUT with a small horn end tip. The contact and contactless vibration output from the HPUT were measured on the

plates, made of aluminium alloy 1050, as shown in **Figure 6.4 (a)–(c)**. To find the vibration level associated with each measurement, a high-frequency accelerometer type 4397 is used, see **Figure 6.4 (d)**, to evaluate plate response.

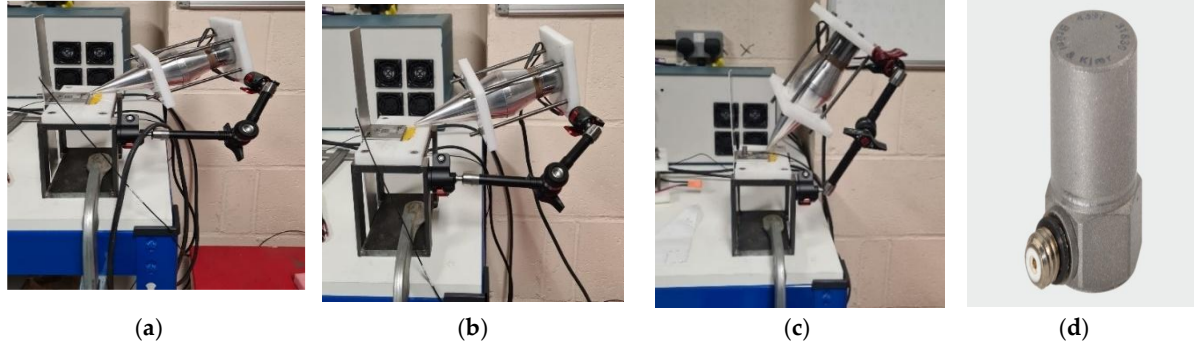


Figure 6. 4: The experimental configuration generates (a) contact and (b) contactless vibration at approximately 0 degrees and (c) contactless vibration at a 45-degree angle. (d) High-frequency accelerometer type 4397.

The accelerometer is operating on a single axis; hence, to record the plate vibration for the in-plane and out-of-plane excitation, the accelerometer should be oriented in the desired direction. It is expected that the vibration at a zero-degree angle generates an in-plane motion to the plate in the contact and the contactless excitation modes. From previous assessments using the same configuration with a 20 kHz HPUT [110], it was found that maximum vibration occurs when the transducer is positioned at a 60-degree angle, 20 mm away from the end tip of the horn and the plate. Although the 60-degree angle is optimal, a 45-degree angle has been chosen because using the 60-degree angle would result in a clash between the laser machine head and the HPUT.

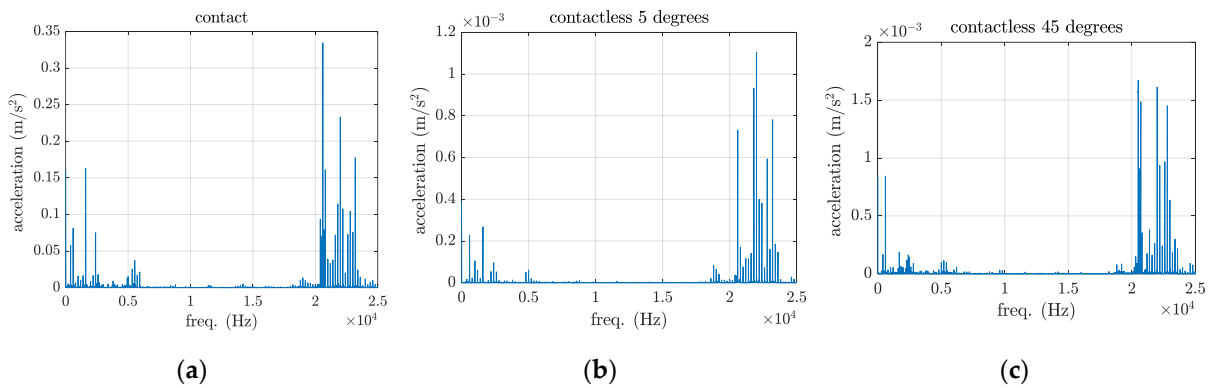


Figure 6. 5: The vibration output from the (a) contact, (b) contactless excitation at a 5-degree angle, and (c) contactless excitation at a 45-degree angle.

As illustrated in **Figure 6.5**, the vibration level from the contact excitation is more than 1000 times higher in acceleration amplitude compared to the contactless excitation.

6.2.3. Pull test results using 20 kHz transducer

An HPUT with a focused ultrasound horn operating at 20 kHz is used. To assess the mechanical integrity of the dissimilar metal lap joints, peel tests were conducted utilizing the L-shaped plate configurations. The test specimens consisted of 2 mm L-shaped plates fastened in an overlapping joint geometry. This configuration was specifically designed to facilitate peel testing, allowing the universal testing machine grips to pull the vertical arms of the plates apart at a constant speed, thereby measuring the maximum load required to separate the bonded interface. To guarantee statistical significance and allow for the calculation of standard deviations for each orientation (horn type/diameter), five replicate samples ($N = 5$) were tested for each transducer configuration and the average values and standard deviations for both load and final extension were recorded. A comprehensive summary of these results is presented in Appendix III. Both contact and contactless modes are employed to transmit ultrasonic waves into the molten pool area. **Figure 6.6** illustrates the different HPUT positions at a 0-degree angle in contact mode, and at a 45-degree angle in contactless mode. The vibration for contactless excitation was performed with a 20 mm distance from the molten pool area.

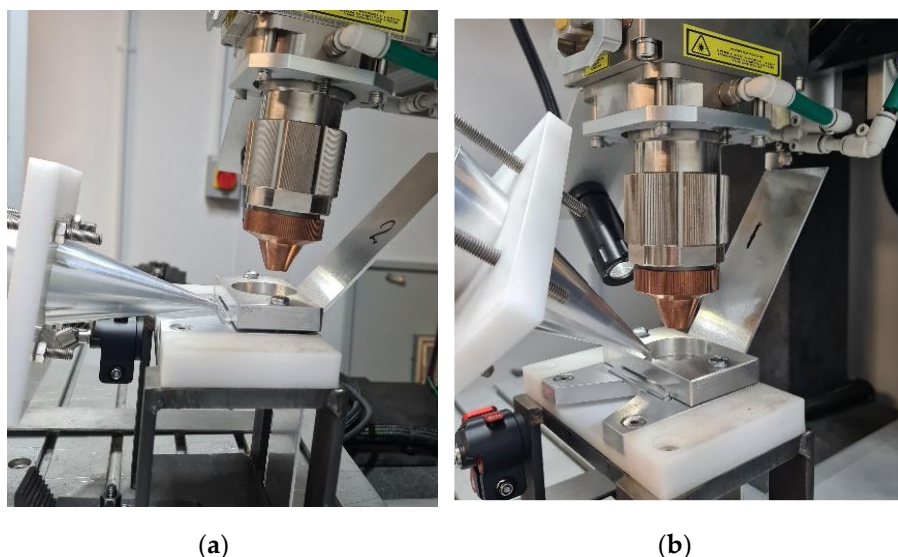


Figure 6. 6: Ultrasonic-vibration-assisted welding using a HPUT with a small end tip horn at (a) a 0-degree angle in contact, and (b) a 45-degree angle in contactless mode.

The 20 kHz HPUT used in this study is depicted in **Figure 6.7**. The HPUT, featuring a larger horn tip as shown in **Figure 6.7 (a)**, transmits greater overall pressure waves to the molten pool

area. Conversely, the HPUT with a smaller horn tip, illustrated in **Figure 6.7 (b)**, offers enhanced usability in the constrained spaces typically encountered during welding.

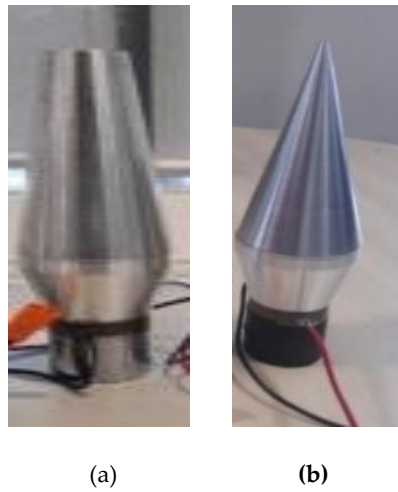


Figure 6. 7: The 20 kHz HPUT used during the laser welding. Transducer configurations: (a) a large tip horn and (b) a small tip horn.

The pull tests were conducted based on ISO 4136:2022, ISO 6892-1:2020 and ISO 9018:2015 standards. Tensile tests were performed at room temperature, which is set at 20 °C with a 50% relative humidity. A Lloyd LR10K tensile tester, manufactured by Lloyd Instruments Ltd. at their head office in West Sussex, UK, illustrated in **Figure 6.8**, was used to perform these tests, ensuring consistent and reliable measurement in accordance with the specified international standards.



Figure 6. 8: A Lloyd LR10K tensile tester used to conduct pull tests.

The results from pull tests are summarised in **Table 6.1**. A noticeable improvement in contactless mode indicates that low-intensity ultrasonic vibration is more effective in enhancing the mechanical properties of the weld than contact vibration.

Table 6. 1: Pull test results associated with the 20 kHz HPUT with small and large horn tips without ultrasonic assistance.

Horn Type/Diameter (mm)	Excitation mode/Angle	Average Load (N)	Average Final Extension (mm)
Small tip/3.3	Contactless/45°	561.0	14.0
Large tip/33	Contact/0°	530.7	10.7
Large tip/33	Contactless/ 45°	533.1	13.2
No ultrasonic assistance	N/A	509.0	11.0

The use of the HPUT with the small horn tip in the contactless position demonstrated approximately a 10% increase in load and a 27% increase in final extension compared to the non-ultrasonic case. When comparing contactless and contact setups, the HPUT with the small horn tip in the contactless configuration exhibited about a 6% higher load and a 31% greater extension than the large horn tip in a contact configuration. The use of the HPUT with the large horn tip in the contactless position resulted in roughly a 1% increase in load and a 23% increase in extension over the contact position. Similarly, He et al. (2024) applied ultrasonic-assisted resistance spot welding technique to join AA6061 aluminum alloy to Ti6Al4V titanium alloy. The authors used a 20 kHz ultrasonic generator to excite resistance spot welding and investigated the microstructure and mechanical performance of the joints. They reported that the application of ultrasonic vibration increased the maximum load by 43% and increased the final extension to twice the value of the joint without ultrasonic vibration assistance.

6.2.4. Pull test results using 40 kHz transducer

In this section, the welding process was carried out using a 40 kHz HPUT with the same methodology described in section 6.2.3. The transducer, characterised by a large and a small horn tip, is illustrated in **Figure 6.9(a)** and **(b)**, respectively.

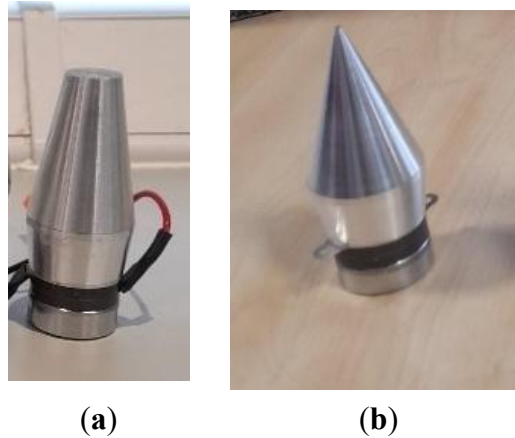


Figure 6. 9: The 40 kHz HPUT used during the laser welding. Transducer configurations: (a) large horn tip and (b) small horn tip.

The outcomes of the pull tests, corresponding to the use of the 40 kHz transducer in both contact and contactless modes, are depicted in **Table 6.2**. Better welding strength was achieved compared to welds made without ultrasonic assistance.

Table 6. 2: Pull test results associated with the 40 kHz HPUT with small & large horn end tips

Horn Type/Diameter (mm)	Excitation mode/Angle	Average Load (N)	Average Final Extension (mm)
Small Tip/2.25	Contactless/45°	527.0	12.7
Large Tip/22.5	Contact/0°	516.0	9.7
Large Tip/22.5	Contactless/45°	520.4	13.0
No ultrasonic assistance	N/A	509.0	11.0

The HPUT with the small tip horn in contactless mode at 40 kHz showed approximately a 4% increase in load and a 16% increase in extension compared to the non-ultrasonic method. The contactless versus contact at 40 kHz with the large tip showed approximately a 1% increase in load and a 34% increase in extension. Comparing 40 kHz to 20 kHz, the best performance with 40 kHz (small tip contactless) fell short by approximately 6.4% in load and 9.3% in extension compared to the 20 kHz small tip contactless mode. The average final extension from the contact mode with the 40 kHz transducer is less than the non-ultrasonic welding results shown in **Table 6.1**. This suggests that a high-power ultrasonic vibration level at such a frequency would

make the welding less ductile. The 20 kHz transducer outperformed the 40 kHz in all comparable configurations, both in terms of load and extension. The performance difference was particularly notable in contactless setups, where the 20 kHz consistently achieved better results than the 40 kHz, emphasising the efficiency of the lower frequency in this specific welding context. Ductile fracture was observed in every tested sample, where they underwent considerable plastic deformation (necking).

6.3. Ultrasonic Vibration Assistance of Laser Welding of Aluminium (Al1050) to Copper (Cu101)

In this section, the HPUTs at 20 kHz and 40 kHz, equipped with small horn tips, operated at 70% power for ultrasonic vibration assistance in laser welding. This investigation explores the use of ultrasonic vibration assistance in the laser welding of dissimilar materials, specifically welding copper (Cu101) and aluminium alloy 1050 plates, as shown in **Figure 10a**. The method aims to overcome the challenge of forming brittle intermetallic compounds (IMCs) in dissimilar material welds. Both transducers were in contactless mode and positioned at a 45-degree angle towards the weld, as illustrated in **Figure 6.10b**. The welding machine used in this section employs the same types of lasers (multi-mode fibre lasers) and utilises identical weld settings and welding fixtures as those described in Section 6.2.

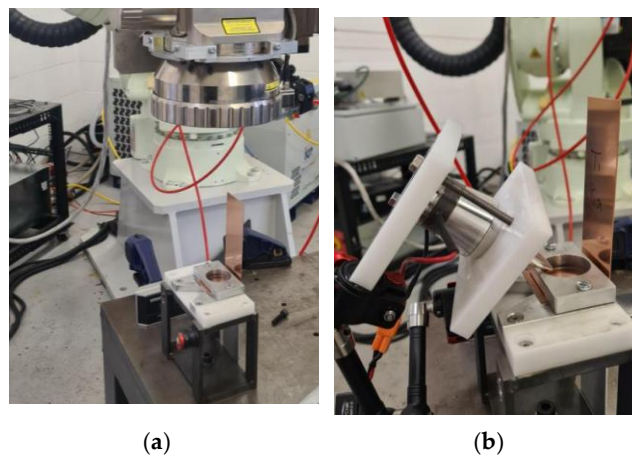


Figure 6. 10: (a) The experimental configuration with the copper (Cu101) plate on top and the aluminium alloy 1050 plate on the bottom, and (b) the positioning of the transducer for ultrasonic assistance in welding.

The same standards and the device, as explained in Section 6.2 and shown in **Figure 6.8**, were used to perform the pull tests, and the results are shown in **Table 6.3**. This table effectively presents comparative data illustrating the benefits of ultrasonic frequency variations in improving weld strength and ductility. Specifically, the 20 kHz transducer achieved a 45% higher load and a 94% greater extension than the 40 kHz transducer. These results underline the significant advantage of using lower-frequency ultrasonic assistance in enhancing the mechanical properties of the welds, both in terms of strength and ductility.

Table 6. 3: Pull test results associated with the 20 kHz and 40 kHz HPUTs with the small horn end tip (focused horns).

Frequency (kHz)	Excitation mode/Angle	Average load (N)	Average Final Extension (mm)
20	Contactless/45°	246.8	20.8
40	Contactless/45°	170.1	10.7
No ultrasonic as- sistance	N/A	110.0	4.8

The tests for ultrasonic laser-assisted welding of the dissimilar materials were repeated, and samples were collected for Scanning Electron Microscopy (SEM) analysis. The inspection was conducted using a Tescan Vega 3 SEM. The analysis focused on identifying features and characteristics of the welds through direct SEM imaging. Microstructure inspection adhered to the ISO 17639:2022 standard and was performed by Loughborough Surface Analysis Limited in Essex, UK.

To reveal the internal structure of the welds, the samples were transversely cut through the centre using a metallurgical abrasive cutting machine, specifically the MetCut 300. Subsequently, to prepare the samples for examination, they were mounted in a 40 mm carbon conductive black resin mount, named CitoPress-15, ensuring secure positioning for accurate observation. For achieving a smooth and polished surface, the Omega-Pol Twin 200 mm manual polishing system was employed. The polishing process involved using sandpaper with grit sizes of 240 and 1200, with the polishing machine set at a speed of 300 rpm. To further refine the surface, colloidal silica and a 3 µm diamond suspension were applied to a polishing cloth with the machine running at 150 rpm.

6.4. Microstructural Results

6.4.1. Baseline microscopy results

In this section, ultrasonic technology was not employed during the welding process. In the SEM images, different gradients represent variations in the material composition. In this case, copper and aluminium are dissimilar metals which have different atomic numbers, and thus they backscatter electrons at different rates. Metals with a higher atomic number backscatter more electrons than those with a lower atomic number, which is why copper appears brighter in SEM images. Thus, transitions or mixtures between different metals can appear as gradients of colour or brightness. **Figure 6.11** highlights the different intermetallic compounds for welding without ultrasonic vibration. It is important to note that these compounds appear scattered mainly on the copper–aluminium side richer in aluminium due to the higher density of copper.

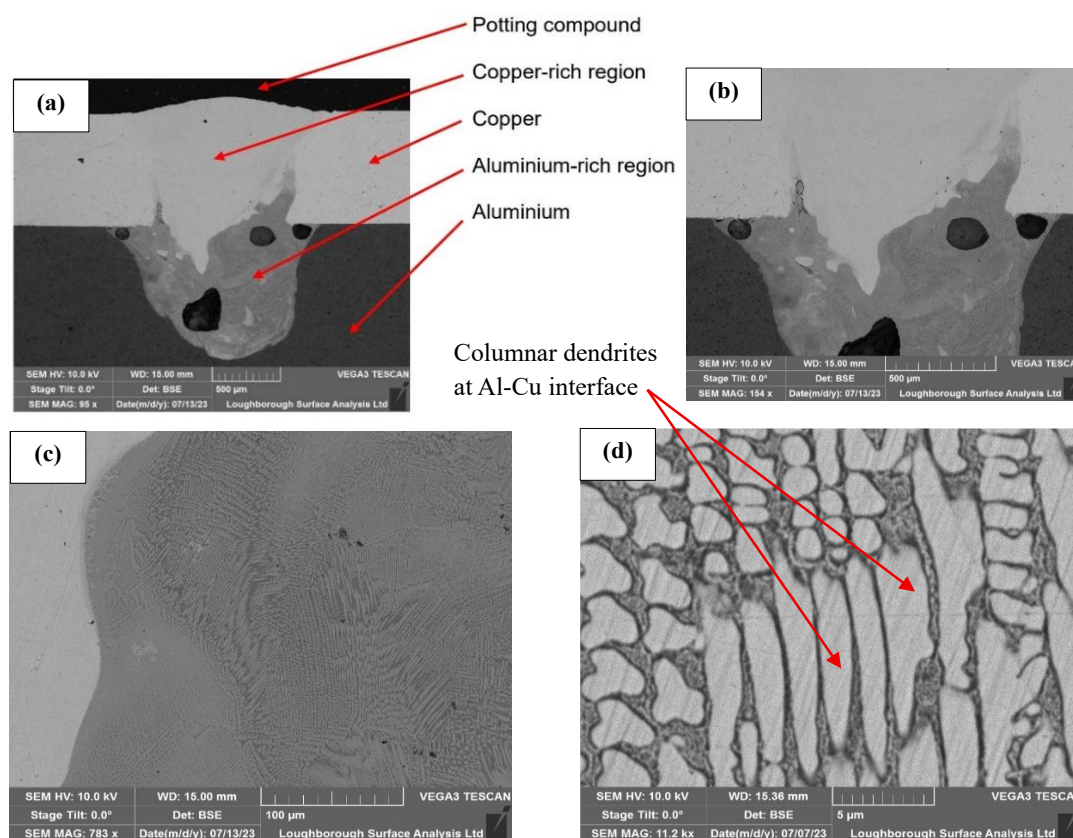


Figure 6. 11: The microscopy results associated with the non-ultrasonic welding: (a) 500 μm, explaining the aluminium and copper-rich regions, (b) 500 μm, (c) 100 μm, and (d) 5 μm.

The absence of ultrasonic vibrations indicates the formation of intermetallic compounds (IMCs), which is supported by the difference in brightness, particularly in the aluminium-rich region. This may be attributed to a certain degree of interdiffusion of atoms across the interface of copper and aluminium. The dark, spherical features within the same region may be related to solidification inclusions or blowholes. Due to the localized interaction volume of the laser welding process, extreme heat input is concentrated in a small interaction zone to rapidly increase the temperature without impacting the surrounding region. Under such extreme conditions, the temperature may be sufficient to locally melt the copper, resulting in the formation of brittle Cu-Al IMCs. During the solidification of the weld pool, the presence of such brittle compounds in the interfacial layer may compromise the integrity of the interface and therefore the strength of the joint.

6.4.2. Ultrasonic assisted welding at 20 kHz

In this section, a 20 kHz HPUT in contactless mode was used during the laser welding. **Figure 6.12** shows the effect of the ultrasound treatment on the intermetallic mentioned in Section 4.1, where, instead of scattered throughout the copper (Cu101)–aluminium (Al1050) mix, they instead appear mainly in the interface area between both materials. The intermetallic compounds form at the joint interface under all welding conditions, both with and without the use of ultrasonic vibrations. However, as shown in **Figure 6.12**, the application of ultrasonic vibrations successfully thins the layer of these intermetallic compounds at the interface, which in turn enhances the mechanical properties of the joints [197]. The presence of ultrasonic vibrations at 20 kHz has resulted in an extremely finer Al-rich region microstructure. It is deduced that this is due to the increase in the various physical phenomena contributed by the applied sound waves. The frequency of the applied sound wave is adequate for producing cavitation and acoustic streaming. Cavitation involves the application of extremely high-pressure shock fronts with excellent potential to refine a weld microstructure. Acoustic streaming promotes thorough stirring of the melt and effectively hinders the development of coarse grains and intermetallic compounds; this results in an increase in nucleation sites by virtue of frequent nuclei created

due to cavitation. In addition, this microstructure is associated with excellent homogenization phenomena that hinder the growth of columnar grains. On this basis, it may be established that the introduction of this frequency favours the development of an equiaxed and finer microstructure with respect to Al-based materials. This may be verified by the observation that frequency refinement has resulted in excellent uniformity and minimization of several undesirable phase formations within the interface region.

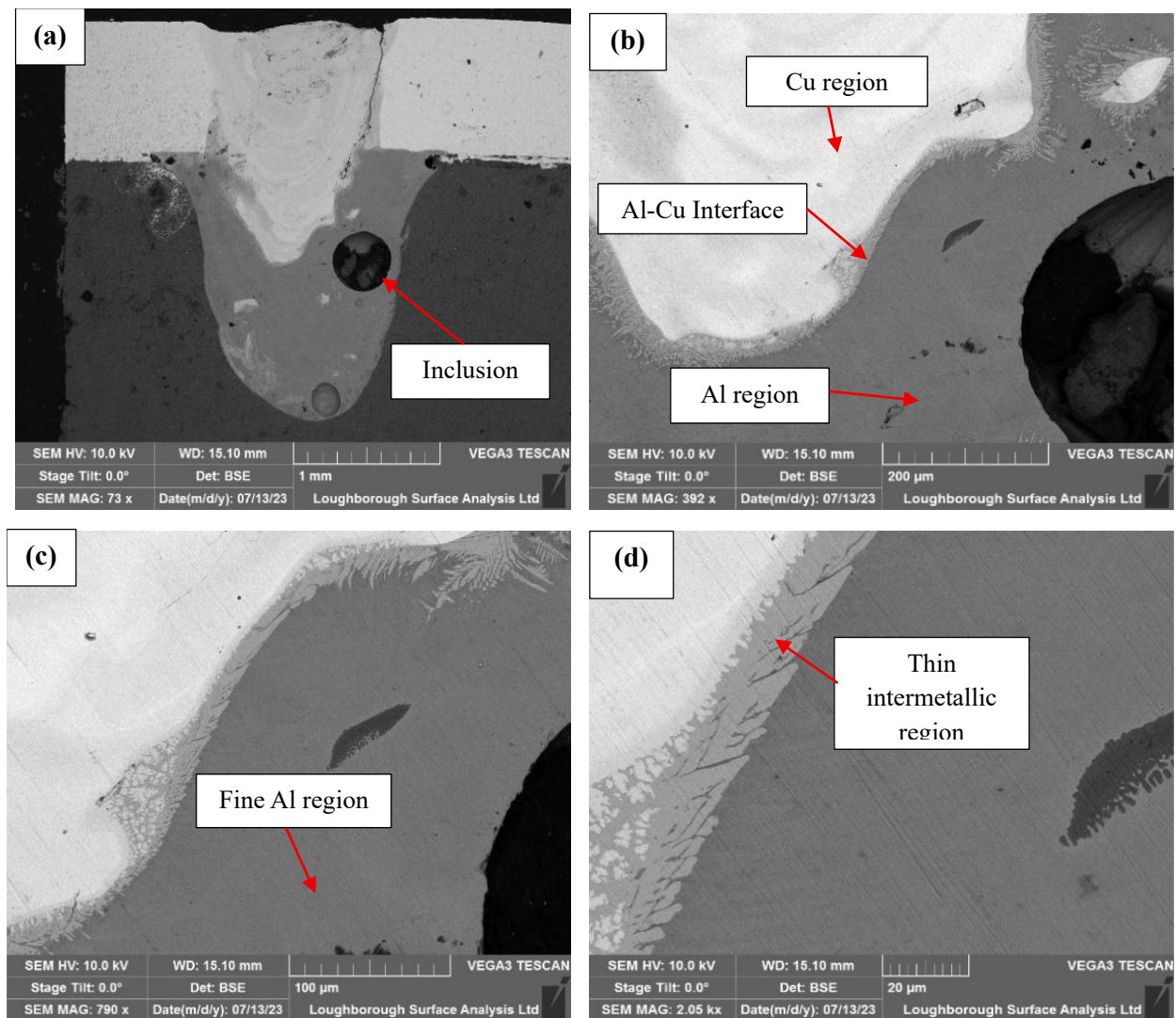


Figure 6. 12: Microscopy of the test associated with the 20 kHz transducer in the contactless mode: (a) 1000 μm, (b) 200 μm, (c) 100 μm, and (d) 20 μm.

6.4.3. Ultrasonic assisted welding at 40 kHz

In this section, the laser welding process involved ultrasonic assistance from a 40 kHz HPUT. As shown in **Figure 6.13**, the ultrasound treatment with a 40 kHz HPUT influences the intermetallic compounds, preventing their dispersion throughout the mixture of the two metals. Ultrasonic assistance, as shown in **Figure 6.13**, effectively controls the placement and reduces the spread of intermetallic compounds compared to the non-assisted method shown in **Figure 6.11**. The microstructural improvements evident in **Figure 6.13**, achieved through ultrasonic assistance, correlate with enhanced mechanical properties, such as increased tensile strength and ductility, as detailed in **Table 6.3**.

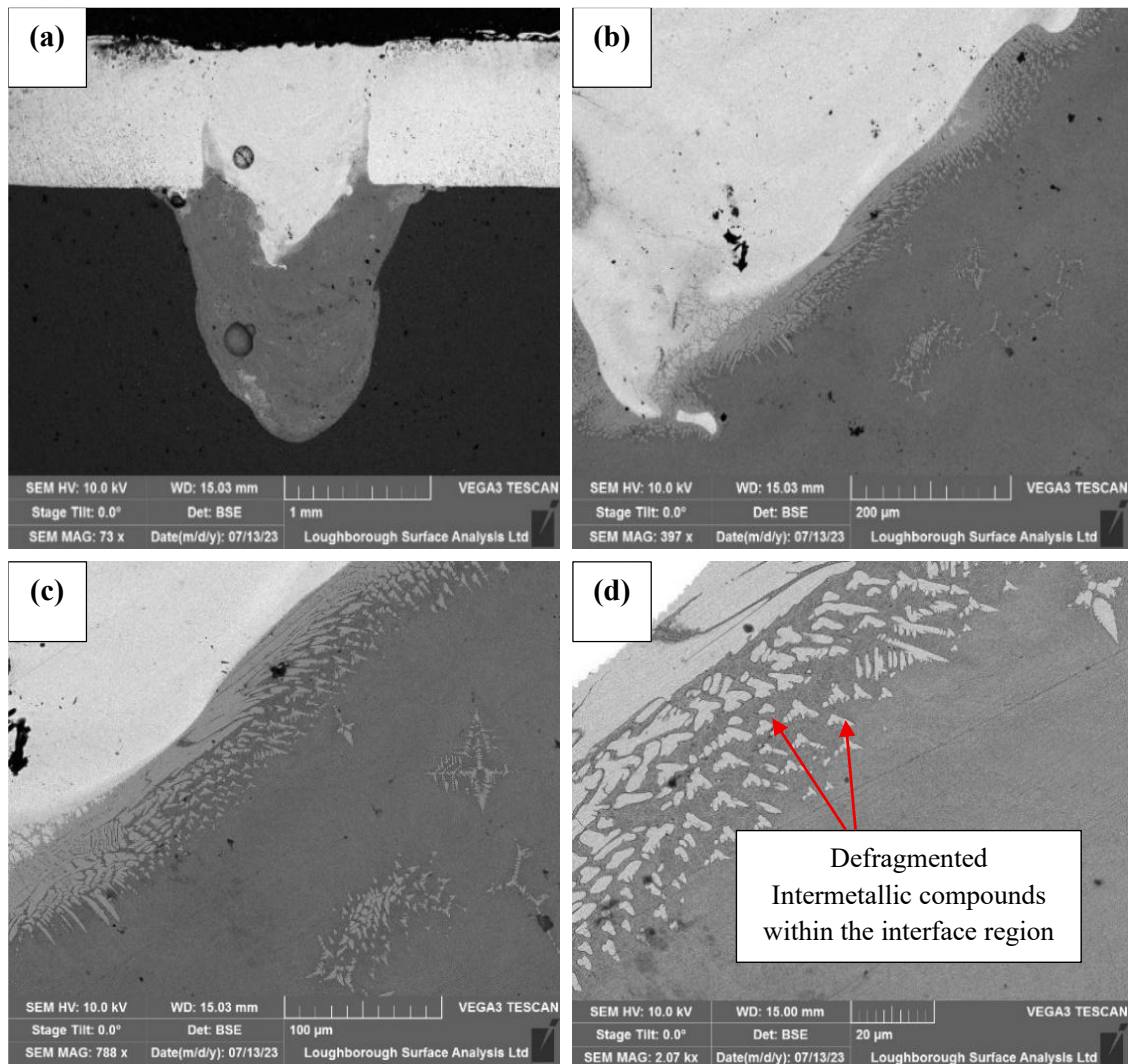


Figure 6. 13: Microscopy of the test associated with the 40 kHz transducer in the contactless mode: (a) 1000 μm , (b) 200 μm , (c) 100 μm , and (d) 20 μm .

6.5.Summary

In this chapter, the ultrasonic vibration-assisted laser welding at low intensities was studied with the aim of improving the weld quality of aluminium lap joints for EV batteries. The chapter discussed the impact of contactless vibrations employed to enhance the quality of the weld joint. This was evaluated by subjecting the welded joints to shear pull tests at varying test loads, transducer type and operating frequency, testing for ductility. At 20 kHz, the trend indicated that weld joints produced using industrial transducers exhibited greater ductility compared to those created using tapered transducers. No significant trend was observed with respect to the difference in ductility of the welded joints fabricated at 40 kHz.

Furthermore, a microstructural examination was conducted on the ultrasonic vibration-assisted weld joints. The SEM images revealed that the joints were largely characterised by keyholes and blowholes due to the limited solubility of the metals in each other in solid state. It was observed that crack initiation could be motivated by the formation and presence of intermetallic compounds that are hard and brittle, which then act as crack-prone sites. Considering the welded joint fabricated at 40 kHz, the intermetallic layer formed at the Al-Cu interface within the fusion zone appeared thin and densely structured. The proportion of intermetallic phases formed was diminished compared to samples where ultrasonic vibration was not applied. At 20 kHz, it could be plausible that the frequency generated by the transducer might have been insufficient to induce adequate material mixing during solidification. The formation of the intermetallic layer was observed within the fusion zone at the boundary between the copper-rich and aluminium-rich zones. Notably, the intermetallic layer seemed denser compared to samples where ultrasonic vibration was not employed.

The vibration levels recorded within the transducer and horn was modelled at BIC, United Kingdom. A key finding to this study was that, to optimize the vibration level, the length of the horn should be proportionate to half the wavelength corresponding to the transducer.

Chapter 7

Conclusions and Recommendations for Future Work

7.1.Introduction

The chapter concludes and summarises the key observations in the development of innovative ultrasonic vibration-assisted laser welding techniques to improve the welding of dissimilar metals particularly for butt and lap joints in EV battery applications. Also, it considers the modification of transducer types and comparison between the effect of ultrasonic vibrations on welded joints in contact and contactless modes. Furthermore, the chapter provides recommendations for the viability of these modified techniques in various industries, improving the manufacturing readiness level of ultrasonic vibration-assisted laser welding.

7.2.Research Overview

In recent years, there has been a surge in the significance of material processing in various industries, driven by the need for innovative materials with excellent properties. Processing or manufacturing techniques play a vital role in determining the final characteristics of materials, having key impact on industries such as electronics, energy, aerospace, and automobile. Metal manufacturing techniques provide a wide variety of benefits, enabling the production of complex shapes and achieving pre-determined material properties that meet standards, with an overall objective of reducing processing time and improving the quality of the product. Welding is outstanding out of these manufacturing techniques, especially in industrial fields such as aerospace and automobiles, where it offers increased strength for joints without the aid of additional fasteners. However, traditional welding processes usually result in defects, animating the exploration of more effective methods like ultrasonic vibration assisted laser welding. This innovative approach has been increasingly studied based on its low cost and the method lever-

ages on the ability of ultrasonic vibration to refine grain size, reduce internal defects, and improve mechanical properties, providing a potential solution for industrial applications requiring high-performance welding with enhanced efficiency.

Chapter 2 provided an overview of the current landscape and limitations in metal joining processes, with a comprehensive and focused analysis on laser welding of both similar and dissimilar metals. Furthermore, recent developments and advancements in electric vehicle (EV) battery technology, especially with respect to battery packs and connectors, were discussed. The increasing need for high-performance EV batteries outlines the essence of innovative solutions to improve efficiency and quality in manufacturing. The research objectives underscored in the chapter was aimed at exploring the application of ultrasonic-assisted laser welding for similar and dissimilar metals, highlighting the metallurgical limitations in joining dissimilar metals, and seeking to pioneer new techniques that optimise manufacturing processes. Overall, Chapter 2 served as a foundation for further evaluation and development of ultrasonic-assisted laser welding, providing promising potential for its execution across various industrial fields.

In Chapter 3, the concept of bubble cavitation is studied, which is responsible for the propagation of acoustic waves through the metal melt (weld zone) before solidification during ultrasonic-assisted laser welding. A synergistic modelling approach, integrating the plate vibration method with the cavitation oscillation method, was employed to analyse the force vibration induced by cavitation within the welding pool. The methodology is an accurate tool for forecasting the minimum pressure threshold needed for the initiation of cavitation bubbles within the melt pool during ultrasonic-assisted laser welding. In the study, it was found that at operating frequencies of 20, 28, and 40 kHz, the displacement in contact mode attained a minimum value of 9 nm, which was sufficient to excite the solidifying phase within the fusion zone and initiating ultrasound cavitation during time and frequency domain analyses. The resultant pressure wave generated by the collapse of ultrasound cavitation was computed to reach a value of 470 MPa, confirmed in existing literature as adequate for influencing grain microstructure formation. Moreover, it was observed that the time frame at 20 kHz, theoretically allowed ample

time for cavitation expansion and collapse within the solidifying phase to facilitate grain refinement and enhancing weld quality.

The fourth chapter discussed the experimental investigations on the structural vibration of lap and butt joints, starting with an examination of transducer performance across various parameters, such as electrical impedance, tightening torque, displacement amplitude and acceleration amplitude. Results showed that there was a correlation between tightening torque and electrical impedance of the transducer, with optimal torque identified to produce maximum vibrational displacement. Three horn designs were considered and implemented via computational modelling, with conical horns exhibiting excellent performance. In addition, accelerometer measurements revealed that focused horns offered the highest acceleration amplitudes, indicating adequate efficiency for industrial applications. The use of focused transducers in ultrasonic vibration-assisted laser welding demonstrated increasing acceleration amplitudes with welding progression.

Mechanical analysis and tensile testing, which were discussed in Chapter 5, revealed that certain parameters contributed to an average increase in ultimate tensile strength of 10%. The most successful trial of the study showed an outstanding 25% enhancement in ultimate tensile strength when compared to the baseline results, if ultrasound was not utilized. However, the application of ultrasound resulted in a superior uniform weld profile, reducing the difference between weld width and root width by a percentage of 14–62% across different parameter groups. The use of high-intensity ultrasound significantly disrupted epitaxial dendrite growth, refined grain structure, minimised plasma cloud formation, and altered the shape of intermetallic compounds from linear to spherical. Additionally, it improved weld integrity and reduced spatter levels, crucial factors affecting weld quality and strength. The resultant resistance to crack propagation and initiation, attributed to grain refinement and disruption of dendrite growth, correlated with the increase in ultimate tensile strength and load capacity for failure. Interestingly, significant improvements were recorded during tests using high-intensity ultrasound.

Chapter 6 illustrated the efficiency of low-intensity ultrasound vibration in improving the quality of the weld, especially highlighting the effect on impedance values. Characterisation of an HPUT (High Power Ultrasonic Transducer) integrated into the laser welding system was conducted to identify the optimal distance and angle for maximum contactless vibration. The experimental results showed an optimal excitation distance of 20 mm and an angle of 60 degrees for out-of-plane and in-plane displacements. While this angle may maximize vibration output from the piezoelectric inside the transducer, it may not be ideal for propagating shear and compressional waves in an efficient manner. Investigation into the effect of different wave types on laser welding revealed a negligible difference in welding improvement in impedance values between contact and contactless vibration methods. Ultrasonic-assisted welding with compressional waves exhibited the lowest impedance values, attributed to the inability of pure fluid to support shear wave propagation. The chapter also covers the shear pull test results and microstructural examination of weld joints under operating frequencies of 20 and 40 kHz, in comparison with the baseline result.

SEM images revealed that the joints predominantly exhibited keyholes and blowholes, attributed to the limited solubility of metals in each other in the solid state to form intermetallic compounds (IMCs). The presence of hard and brittle intermetallic compounds was found to initiate crack formation within the joints. In welds fabricated at 40 kHz, the intermetallic layer at the Al-Cu interface exhibited a thin and dense structure, with fewer intermetallic phases compared to samples without ultrasonic vibration. At 20 kHz, inadequate material mixing during solidification may have resulted from insufficient frequency generated by the transducer, leading to the formation of a dense intermetallic layer at the boundary between copper-rich and aluminium-rich zones; this proves the significance of ultrasonic vibration in mitigating the formation of intermetallic compounds.

7.3.Key Findings

From the experimental results, it is worth addressing the main research questions considered in Chapter 1. The following provides precise responses to the research questions accordingly:

- The application of ultrasonic vibration-assisted laser welding technique to achieve excellent weld integrity in butt and lap joints in dissimilar metals proved to be effective by mitigating the formation of hard and brittle intermetallic compounds, which are prone-sites for crack initiation.
- Increasing the operating frequency had a significant effect on the rates of rise and collapse of microbubbles in cavitation formation. This was detailed in Chapter 3.
- Based on the operating frequencies, there was a corresponding positioning of the transducer that produced optimal vibration level sufficient to collapse the cavitation microbubbles, sending in shock waves within the weld zone to significantly promote adequate mixing of the constituent elements. The optimal position of the transducer was 20 mm from the excited plate and an angle of 60 degrees for out-of-plane and in-plane displacements.
- Based on FEA modelled and designed transducers and horns, focused conical transducers produced optimal vibration to excite the welded plates. This type of transducer matches the requirements of an effective industrial transducer.
- Joints welded under the influence of ultrasonic vibration at a laser speed of 50W and frequency of 28 kHz gave an average ultimate tensile strength of 236.79 MPa compared to the welded joints with no ultrasonic vibration, which gave an average ultimate tensile strength of 214.27 MPa.
- The introduction of ultrasonic vibration-assisted laser welding led to discontinuity in epitaxial dendrite growth, increased grain refinement, reduced plasma cloud formation during welding, and converted linear-shaped IMCs to spherical form.

The study provides innovative solutions to minimise the formation of hard and brittle intermetallic compounds commonly formed in Al-Cu joints, particularly in EV batteries. Therefore, the work has addressed the aim of the research, although the work paves way for further considerations that can be recommended to advance its scope.

7.4. Significance of Research

The research offers the potential to bridge the knowledge gap existing in the welding process of EV battery connectors to obtain highly efficient battery performance, crucial to the automotive industry. With the rapid shift towards electrification in the automotive sector, ascertaining the structural integrity and material performance of light alloys used in EV battery assembly packs is paramount. The integration of ultrasonic vibration-assisted to contemporary laser welding practice offers a novel methodology to address prolonged challenges typical of conventional welding methods, such as porosity, formation of hard and brittle intermetallic compound formed from joining dissimilar metals, and presence of hot cracks, offering valuable understanding of the potential of ultrasonic vibration-assisted laser welding for various applications, where the combination of dissimilar materials demands precision, structural integrity, and performance optimization is needed. The research is tailored to provide qualitative insights into the mechanisms and necessary optimisations for this advanced method to improve the microstructure, mechanical properties, and electrical characteristics of welded regions. Consequently, the achievement of such enhancements will contribute to the development of more efficient, reliable, and durable EV batteries, which are critical for the widespread adoption of electric vehicles and the reduction of greenhouse gas emissions.

7.5. Recommendations for Future Work

These recommendations provide a pathway for future research endeavours projected towards progressing the body of knowledge and application of ultrasonic-assisted laser welding technology:

1. **Further Investigation of Ultrasonic Vibration Parameters:** It is essential to consider the potential of conducting additional research to examine the influence of varying ultrasonic parameters such as frequency, power, amplitude, and topological ranges of different test pieces (thickness, shape, curvature, etc.), and duration on weld quality and properties.

2. **Optimisation of Welding Parameters:** The research may progress by continuing the studies aimed at optimising welding parameters, including laser power, welding speed, and focal point position, to enhance weld strength and quality.
3. **Evaluation of Different Material Combinations:** The inclusion of other engineering materials can be considered to extend research efforts, examining the effects of ultrasonic-assisted laser welding on different material combinations, including dissimilar metals and composite materials.
4. **Development of Advanced Welding Techniques:** The study may proceed to explore the potential for integrating ultrasonic-assisted laser welding with other advanced welding techniques, such as electron beam welding, to further enhance weld quality and performance.
5. **Investigation of Industrial Applications:** With respect to the manufacturing readiness of the technique, conducting studies to evaluate the applicability and effectiveness of ultrasonic-assisted laser welding in various industrial sectors, including automotive, aerospace, and electronics manufacturing may be worth exploring its potential.
6. **Evaluation of further quantitative analysis of the present data using the Hall–Petch equation,** relating equiaxed grain size to yield strength and related models. Future work should seek to broaden the range of values of the ultrasonic vibration parameters (frequency and power) and the topological ranges of different test pieces (thickness, shape, curvature, etc.) to determine the optimum values, i.e., those that maximise weld improvement for a prescribed cost/energy expenditure.
7. **Modelling of radiation field in the plates and across the weld melt–plate interfaces** to confirm that cavitation was a significant contributor to weld quality improvement in the experiments reported in this work. Such a model will reveal the locations of the nodes and antinodes in the weld melt line such that, by comparing microstructure samples cut from both node and antinode regions, cavitation effects on weld quality improvement can be directly revealed.

Bibliography

- [1] Sanusi, K.O., Malatji, N., Jeje, S.O., Kanyane, L.R. and Shongwe, M.B., 2025. Advancements in Fabrication Techniques and their Impact on the Properties of Titanium-Based Medium Entropy Alloys for Extreme Environment Applications: A Review. *Metals and Materials International*, pp.1-33.
- [2] Park, M., 2024. Materials Processing Techniques: A Comprehensive Overview. *J Mater Sci Nanomater*, 8(165).
- [3] Salo, J.T., 2010. Innovation in the Metal Manufacturing Industry: Facilitating Innovation with Electronic Business Applications. *International Journal of Electronic Business Management*, 8(2).
- [4] Wu, F., Falch, K.V., Drakopoulos, M. and Mirihanage, W.U., 2023. Effects of melt pool flow on porosity levels in arc welding. In *IOP Conference Series: Materials Science and Engineering* (Vol. 1274, No. 1, p. 012011). IOP Publishing.
- [5] Zitouni, A.H., Spiteri, P., Aissani, M. and Benkheda, Y., 2020. Thermal and fluid flow modeling of the molten pool behavior during TIG welding by stream vorticity method. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 14, pp.173-188.
- [6] Mazur, M., 2017. Assessment of the construction welding process. *Procedia engineering*, 192, pp.580-585.
- [7] Zavadski, A., 2018. Advanced welding technologies used in aerospace industry.
- [8] Muthukumaran Malarvel, Harjeet Singh (2021) An autonomous technique for weld defects detection and classification using multi-class support vector machine in X-radiography image, *Optik*, 231, 166342
- [9] Wu, S., Zhao, F., Wang, P., Gong, S. and Wu, Z., 2025. Study on Molten Pool Flow and Porosity Defects in Laser–Tungsten Inert Gas (TIG) Welding of 4J36 Invar Steel. *Materials*, 18(8), p.1824.
- [10] Ma, M., 2025. A numerical study of dynamic behavior of the molten pool in laser welding of aluminum alloy. *Manufacturing Review*, 12, p.30.
- [11] Han, S., Liu, G., Tang, X., Xu, L., Cui, H. and Shao, C., 2022. Effect of molten pool behaviors on welding defects in tandem NG-GMAW based on CFD simulation. *International Journal of Heat and Mass Transfer*, 195, p.123165
- [12] Kumar, N., Kumar, P., Upadhyaya, R., Kumar, S. and Panday, C., 2023. Assessment of the Structural Integrity of a Laser Weld Joint of Inconel 718 and ASS 304L. *Sustainability* 2023, 15, 3903 [online]

- [13] Parchegani, S., Piili, H., Ganvir, A. and Salminen, A., 2023, December. Laser welding of additively manufactured parts-A review. In IOP Conference Series: Materials Science and Engineering (Vol. 1296, No. 1, p. 012030). IOP Publishing.
- [14] Gao, X., 2025. Laser Welding Technology. Metals, 15(1), p.86.
- [15] Katayama, S., 2020. Fundamentals and details of laser welding. Singapore:: Springer Singapore.
- [16] Ye, Z., Wang, S. and Zhou, S., 2024, December. Research and application of laser welding process and automatic welding equipment for high strength steel plates. In 7th International Conference on Advanced High Strength Steel and Press Hardening (ICHSU 2024) (pp. 617-625). Atlantis Press.
- [17] Biswas, A.R., Banerjee, N., Sen, A. and Maity, S.R., 2023. Applications of laser beam welding in automotive sector-a review. Advances in Additive Manufacturing and Metal Joining: Proceedings of AIMTDR 2021, pp.43-57
- [18] Gomes, D.F., Galvão, I. and Loja, M.A.R., 2019. Overview on the evolution of laser welding of vascular and nervous tissues. Applied Sciences, 9(10), p.2157
- [19] Kim, M., Bang, H., Hyun, S., Yi, S. and Kim, C., 2023. Review on Ultrasonic and Laser Welding Technologies of Multi-Layer Thin Foils for the Lithium-Ion Pouch Cell Manufacturing. Journal of Welding and Joining, 41(6), pp.462-474.
- [20] Feng, J., Zhang, P., Yan, H., Shi, H., Lu, Q., Liu, Z., Wu, D., Sun, T., Li, R. and Wang, Q., 2023. Application of laser welding in electric vehicle battery manufacturing: a review. Coatings, 13(8), p.1313.
- [21] Ali, S. and Shin, J., 2022. In-depth characterization of laser-welded aluminum-and-copper dissimilar joint for electric vehicle battery connections. Materials, 15(21), p.7463.
- [22] Harati, E. and Kah, P., 2022. Laser welding of aluminum battery tab to variable Al/Cu busbars in Li-ion battery joint. AIMS Materials Science, 9(6), pp.884-918.
- [23] Mandal, N.R., 2016. Welding defects. In Ship construction and welding (pp. 283-292). Singapore: Springer Singapore.
- [24] Kah, P., Hiltunen, E. and Martikainen, J., 2010, July. Investigation of hot cracking in the welding of aluminium alloys (6005 & 6082). In Proceedings of the 63rd Annual Assembly & International Conference of the International Institute of Welding, Istanbul, Turkey (pp. 11-17).
- [25] de Haas, M., Van Scherpenzeel, S.M. and de Hosson, J.T., 2006, July. Grain boundary segregation and precipitation in aluminium alloy AA6061. In Materials science forum (Vol. 519, pp. 467-472). Trans Tech Publications Ltd

- [26] Lee, S.J., Nakamura, H., Kawahito, Y. and Katayama, S., 2014. Effect of welding speed on microstructural and mechanical properties of laser lap weld joints in dissimilar Al and Cu sheets. *Science and Technology of Welding and Joining*, 19(2), pp.111-118
- [27] Heideman, R., Johnson, C. and Kou, S., 2010. Metallurgical analysis of Al/Cu friction stir spot welding. *Science and Technology of Welding and Joining*, 15(7), pp.597-604.
- [28] Guo, Y., Qiao, G., Jian, W. and Zhi, X., 2010. Microstructure and tensile behavior of Cu–Al multi-layered composites prepared by plasma activated sintering. *Materials Science and Engineering: A*, 527(20), pp.5234-5240.
- [29] Choi, S., Lim, S., Shan, A., Lee, J., Yun, T.G. and Hwang, B., 2025. Tab-to-Busbar Interconnections in EV Battery Packs: An Introductory Review of Typical Welding Methods. *Micromachines*, 17(1), p.2
- [30] Zhou, S., Ma, G., Dongjiang, W., Chai, D. and Lei, M., 2018. Ultrasonic vibration assisted laser welding of nickel-based alloy and Austenite stainless steel. *Journal of Manufacturing Processes*, 31, pp.759-767
- [31] Liang, H., Shi, X. and Li, Y., 2025. Effect of Ultrasonic Assistance on Properties of Ultra-High-Strength Steel in Laser-Arc Hybrid Welding. *Coatings*, 15(4), p.389
- [32] Shuai, L., Yinlei, G., Dongdong, L., Ziyue, L., Yunli, F. and Fucheng, Z., 2023. Unusual grain-size effects on tensile deformation behavior of twinning-induced plasticity steel with low Mn content. *Journal of Materials Research and Technology*, 24, pp.586-594
- [33] Ji, F., Hu, Z., Qin, X., Yin, F., Ni, M. and Xiong, X., 2023. Grain refinement and mechanism of steel in ultrasound assisted wire and arc additive manufacturing. *International Communications in Heat and Mass Transfer*, 143, p.106724
- [34] For Ultrasonic laser welding: Liu et al., (2022) Design Optimization and Eigen frequency Tuning of Ultrasonic Oscillator of One-dimensional Longitudinal Vibration at High Temperature for Laser Welding, *The International Journal of Advanced Manufacturing Technology*
- [35] H. L. Wei, J. Mazumder, and T. DebRoy, “Evolution of solidification texture during additive manufacturing,” *Sci Rep*, vol. 5, no. 1, pp. 1–7, 2015.
- [36] Y. Li and K. Shen, “The effect of melt vibration on polystyrene melt flowing behavior during extrusion,” *Journal of Macromolecular Science, Part B*, vol. 47, no. 6, pp. 1228–1235, 2008
- [37] D. Favez, J.-D. Wagniere, and M. Rappaz, “Au–Fe alloy solidification and solid-state transformations,” *Acta Mater*, vol. 58, no. 3, pp. 1016–1025, 2010.
- [38] O. Mypati, S. Sahu, S. K. Pal, and P. Srirangam, “An investigation of mechanical and electrical properties of friction stir welded Al and Cu busbar for battery pack applications,” *Mater Chem Phys*, p. 126373, 2022

- [39] Scribd. (n.d). Differences Between Welding. Retrieved from <https://www.scribd.com/document/341776647/Differences-Between-Welding>
- [40] M. F. R. Zwicker, M. Moghadam, W. Zhang, and C. v. Nielsen, "Automotive battery pack manufacturing – a review of battery to tab joining," *Journal of Advanced Joining Processes*, vol. 1, Mar. 2020, doi: 10.1016/j.jajp.2020.100017.
- [41] Wang, H., Liu, D., Lippold, J.C. and Daehn, G.S., 2020. Laser impact welding for joining similar and dissimilar metal combinations with various target configurations. *Journal of Materials Processing Technology*, 278, p.116498
- [42] Tolun, F., 2019, December. Use of aluminum alloys in automotive industry. In *Congress Proceedings Series* (p. 63).
- [43] Zhang, W. and Xu, J., 2022. Advanced lightweight materials for Automobiles: A review. *Materials & Design*, 221, p.110994.
- [44] Mu, H., Luo, S., Wang, L., Li, Z., Chen, M., Wang, X., Nagaumi, H. and Hu, Z., 2024. Microstructure and mechanical properties of aluminum alloy laser welded joint assisted by alternating magnetic field. *Journal of Materials Research and Technology*, 33, pp.6842-6852.
- [45] Abbaschian, L. and Lima, M.S.F.D., 2003. Cracking susceptibility of aluminum alloys during laser welding. *Materials Research*, 6, pp.273-278.
- [46] Rakhi, K., Kang, S. and Shin, J., 2023. Hot-cracking mechanism of laser welding of aluminum alloy 6061 in lap joint configuration. *Materials*, 16(19), p.6426.
- [47] Zhang, F., Liang, S., Zhang, C., Chen, S., Lv, D., Cao, W. and Kou, S., 2021. Prediction of cracking susceptibility of commercial aluminum alloys during solidification. *Metals*, 11(9), p.1479.
- [48] Huang, W., Chen, S., Xiao, J., Jiang, X. and Jia, Y., 2021. Investigation of filler wire melting and transfer behaviors in laser welding with filler wire. *Optics & Laser Technology*, 134, p.106589
- [49] Tao, W., Yang, Z., Chen, Y., Li, L., Jiang, Z. and Zhang, Y., 2013. Double-sided fiber laser beam welding process of T-joints for aluminum aircraft fuselage panels: Filler wire melting behavior, process stability, and their effects on porosity defects. *Optics & Laser Technology*, 52, pp.1-9
- [50] M. Khavari, A. Priyadarshi, A. Hurrell, K. Pericleous, D. Eskin, and I. Tzanakis, "Characterization of shock waves in power ultrasound," *J Fluid Mech*, vol. 915, 2021.
- [51] J. Bast, J. Hübner, and C. Dommaschk, "Influence of vibration during solidification of molten metals on structure and casting properties," *Adv Eng Mater*, vol. 6, no. 7, pp. 550–554, 2004

- [52] S. Kuryntsev, "A review: Laser welding of dissimilar materials (Al/Fe, Al/Ti, Al/Cu)—Methods and techniques, microstructure and properties," *Materials*, vol. 15, no. 1, p. 122, 2021.
- [53] A. Das, T.R. Ashwin, and A. Barai, "Modelling and characterisation of ultrasonic joints for Li-ion batteries to evaluate the impact on electrical resistance and temperature raise," *J Energy Storage*, vol. 22, pp. 239-248, 2019
- [54] W. Huang, H. Wang, T. Rinker, and W. Tan, "Investigation of metal mixing in laser key-hole welding of dissimilar metals," *Mat & Des*, vol. 195, p. 109056, 2020.
- [55] P. Schmalen and P. Plapper, "Resistance measurement of laser-welded dissimilar Al/Cu joints," *J Las Micro Nano-eng*, vol. 12, no. 3, pp. 189-194, 2017.
- [56] Yiwen, R.E.N., Junhui, T.A.O., Jie, L.I., Xinqi, C.H.E.N., Chuanhui, W.A.N.G., Haiqin, J.I.N., Hongyan, Q.I., Zhuo, W.A.N.G., Xing, X.I.E. and Jie, P.A.N., 2023. Mechanical Properties of Laser Welded Joint of Copper and Steel Dissimilar Metals. *Wuhan University Journal of Natural Sciences*, 28(1), pp.68-76.
- [57] Zhu, Z., Guo, Y., Wang, X., Zhang, L., Yin, C. and Song, H., 2024. Changes in intermetallic compounds and mechanical performance of steel/aluminum welded joints containing nano TiC during isothermal aging. *ACS Applied Nano Materials*, 7(20), pp.24132-24140.
- [58] Kah P, Vimalraj C, Martikainen J, Suoranta R. Factors influencing Al-Cu weld properties by intermetallic compound formation. *International Journal of Mechanical and Materials Engineering*. 2015 Dec;10(1):10.
- [59] A.O. Soto, A.S. Salgado, and E.B. Niño, "Thermodynamic analysis of high entropy alloys and their mechanical behavior in high and low-temperature conditions with a microstructural approach-A review," *Intermetallics*, vol. 124, p. 106850, 2020.
- [60] Zhao, D., Guo, W., Shang, Z., Xu, C., Gao, X. and Wang, X., 2024. The growth behavior and kinetics of intermetallic compounds in Cu–Al interface at 600° C–800° C. *Intermetallics*, 168, p.108244.
- [61] Kim, D., Kim, K. and Kwon, H., 2021. Investigation of formation behaviour of Al–Cu intermetallic compounds in Al–50vol% Cu composites prepared by spark plasma sintering under high pressure. *Materials*, 14(2), p.266.
- [62] Mypati, O., Anwaar, T., Mitra, D., Pal, S.K. and Srirangam, P., 2023. Characterization and modelling of Al and Cu busbar during charging and discharging of Li-ion battery for electric vehicles. *Applied Thermal Engineering*, 218, p.119239.
- [63] K. B. Nie, X. J. Wang, K. Wu, X. S. Hu, M. Y. Zheng, and L. Xu, "Microstructure and tensile properties of micro-SiC particles reinforced magnesium matrix composites produced by semisolid stirring assisted ultrasonic vibration," *Materials Science and Engineering: A*, vol. 528, no. 29–30, pp. 8709–8714, 2011.

- [64] Z. Huang, M. Lucas, and M. J. Adams, "Influence of ultrasonics on upsetting of a model paste," *Ultrasonics*, vol. 40, no. 1–8, pp. 43–48, 2002.
- [65] M.J. Brand, E.I. Kolp, P. Berg, T. Bach, P. Schmidt, and A. Jossen, "Electrical resistances of soldered battery cell connections," *Journal of Energy Storage*, vol. 12, pp. 45–54, 2017.
- [66] Pragana, J.P.M., Baptista, R.J.S., Bragança, I.M.F., Silva, C.M.A., Alves, L.M. and Martins, P.A.F., 2020. Manufacturing hybrid busbars through joining by forming. *Journal of Materials Processing Technology*, 279, p.116574.s
- [67] 18. Zhang, Z., Cao, R., Gao, X., Yu, H., Jin, Y., Sun, Y., Liu, X. and Yang, S., 2025. Research progress on typical failure mode diagnosis and early warning of power battery for NEVs. *Next Energy*, 9, p.100390
- [68] da Silva, B.F.A., Kasaei, M.M., Akhavan-Safar, A., Carbas, R.J.C., Marques, E.A.S. and da Silva, L.F.M., 2025. Failure analysis of novel hybrid busbars made by hole hemming for electric vehicle applications. *Archives of Civil and Mechanical Engineering*, 25(2), p.107.
- [69] IEA EV Outlook, 2020 - <https://www.iea.org/reports/global-ev-outlook-2020>
- [70] A. Das, D. Li, D. Williams, and D. Greenwood, "Weldability and shear strength feasibility study for automotive electric vehicle battery tab interconnects," *J Brazilian Soc Mech Sci and Eng*, vol. 41, pp. 1–14, 2019.
- [71] A. Das, A. Barai, I. Masters, and D. Williams, "Comparison of tab-to-busbar ultrasonic joints for electric vehicle Li-ion battery applications," *World Elect Vehicle J*, vol. 10, no. 3, p. 55, 2019.
- [72] H. Saariluoma, A. Piironen, A. Unt, J. Hakanen, T. Rautava, and A. Salminen, "Overview of optical digital measuring challenges and technologies in laser-welded components in EV battery module design and manufacturing," *Batteries*, vol. 6, no. 3, p. 47, 2020
- [73] N. Nembhard, "Safe, sustainable discharge of electric vehicle batteries as a pre-treatment step to crushing in the recycling process" (Master's thesis, Universitat Politècnica de Catalunya, 2020).
- [74] A. Das, D. Li, D. Williams, and D. Greenwood, "Joining technologies for automotive battery systems manufacturing," *World Electric Vehicle Journal*, vol. 9, no. 2, p. 22, 2018.
- [75] W.M. Steen and J. Mazumder, "Laser Material Processing," Springer Science & Business Media, 2010.
- [76] P. Schmalen, P. Plapper, and W. Cai, "Process robustness of laser braze-welded Al/Cu connectors," *SAE International Journal of Alternative Powertrains*, vol. 5, no. 1, pp. 195–204, 2016.

- [77] M.J. Brand, P.A. Schmidt, M.F. Zaeh, and A. Jossen, "Welding techniques for battery cells and resulting electrical contact resistances," *Journal of Energy Storage*, vol. 1, pp. 7-14, 2015.
- [78] . Zhou, T.T. Zhang, H.L. Tsai, and P.C. Wang, "Hybrid laser-arc welding in aerospace engineering," in *Welding and Joining of Aerospace Materials*, pp. 123-156, Woodhead Publishing, 2021.
- [79] Y. Huang, Z. Lv, L. Wan, J. Shen, and J.F. dos Santos, "A new method of hybrid friction stir welding assisted by friction surfacing for joining dissimilar Ti/Al alloy," *Mat Lett*, vol. 207, pp. 172-175, 2017.
- [80] H. Liu, W. Lin, and M. Hong, "Hybrid laser precision engineering of transparent hard materials: challenges, solutions, and applications," *Light: Science & Applications*, vol. 10, no. 1, p. 162, 2021.
- [81] Xu, W.W., Tzanakis, I., Srirangam, P., Mirihanage, W.U., Eskin, D.G., Bodey, A.J. and Lee, P.D., 2016. Synchrotron quantification of ultrasound cavitation and bubble dynamics in Al–10Cu melts. *Ultrasonics sonochemistry*, 31, pp.355-361.
- [82] G. S. Prihandana, M. Mahardika, M. Hamdi, Y. S. Wong, and K. Mitsui, "Effect of micro-powder suspension and ultrasonic vibration of dielectric fluid in micro-EDM processes—Taguchi approach," *Int J Mach Tools Manuf*, vol. 49, no. 12–13, pp. 1035–1041, 2009
- [83] E. A. Brujan, T. Ikeda, and Y. Matsumoto, "On the pressure of cavitation bubbles," *Exp Therm Fluid Sci*, vol. 32, no. 5, pp. 1188–1191, 2008
- [84] R. E. Apfel and C. K. Holland, "Gauging the likelihood of cavitation from short-pulse, low-duty cycle diagnostic ultrasound," *Ultrasound Med Biol*, vol. 17, no. 2, pp. 179–185, 1991.
- [85] K. Yasui, "Influence of ultrasonic frequency on multibubble sonoluminescence," *J Acoust Soc Am*, vol. 112, no. 4, pp. 1405–1413, 2002
- [86] P. S. Lowe, X. Honey, J. Crossley, K. Karunaratne, C. Kannangara, and S. Jones, "Scaling-up ultrasonic vibration assisted additive manufacturing to build 316 L 3 m3 waste container flange," *J Manuf Process*, vol. 83, pp. 97–104, Nov. 2022, doi: 10.1016/j.jmapro.2022.08.053
- [87] Q. J. Sun, S. B. Lin, C. L. Yang, and G. Q. Zhao, "Penetration increase of AISI 304 using ultrasonic assisted tungsten inert gas welding," *Science and Technology of Welding and Joining*, vol. 14, no. 8, pp. 765–767, 2009.
- [88] X. Chen, Z. Shen, J. Wang, J. Chen, Y. Lei, and Q. Huang, "Effects of an ultrasonically excited TIG arc on CLAM steel weld joints," *The International Journal of Advanced Manufacturing Technology*, vol. 60, no. 5, pp. 537–544, 2012, doi: 10.1007/s00170-011-3611-0.

- [89] H. Lan, X. Gong, S. Zhang, L. Wang, B. Wang, and L. Nie, "Ultrasonic vibration assisted tungsten inert gas welding of dissimilar metals 316L and L415," *International Journal of Minerals, Metallurgy and Materials*, vol. 27, no. 7, pp. 943–953, 2020.
- [90] F. Yang, J. Zhou, and R. Ding, "Ultrasonic vibration assisted tungsten inert gas welding of dissimilar magnesium alloys," *J Mater Sci Technol*, vol. 34, no. 12, pp. 2240–2245, 2018.
- [91] S. Y. Tarasov, A. v Vorontsov, S. v Fortuna, V. E. Rubtsov, V. A. Krasnoveikin, and E. A. Kolubaev, "Ultrasonic-assisted laser welding on AISI 321 stainless steel," *Welding in the World*, vol. 63, no. 3, pp. 875–886, 2019.
- [92] Z. Lei, J. Bi, P. Li, T. Guo, Y. Zhao, and D. Zhang, "Analysis on welding characteristics of ultrasonic assisted laser welding of AZ31B magnesium alloy," *Opt Laser Technol*, vol. 105, pp. 15–22, 2018.
- [93] A. v Kolubaev, O. v Sizova, S. v Fortuna, A. v Vorontsov, A. N. Ivanov, and E. A. Kolu-baev, "Weld structure of low-carbon structural steel formed by ultrasonic-assisted laser welding," *J Constr Steel Res*, vol. 172, p. 106190, 2020.
- [94] A. I. Gorunov, O. A. Nyukhlaev, and A. K. Gilmudinov, "Investigation of microstructure and properties of low-carbon steel during ultrasonic-assisted laser welding and cladding," *The International Journal of Advanced Manufacturing Technology*, vol. 99, no. 9, pp. 2467–2479, 2018.
- [95] J. Liu, H. Zhu, Z. Li, W. Cui, and Y. Shi, "Effect of ultrasonic power on porosity, micro-structure, mechanical properties of the aluminum alloy joint by ultrasonic assisted laser-MIG hybrid welding," *Opt Laser Technol*, vol. 119, p. 105619, 2019.
- [96] Z. Lei, J. Bi, P. Li, Q. Li, Y. Chen, and D. Zhang, "Melt flow and grain refining in ultrasonic vibration assisted laser welding process of AZ31B magnesium alloy," *Opt Laser Technol*, vol. 108, pp. 409–417, 2018.
- [97] A. Teyeb, J. Silva, J. Kanfoud, P. Carr, T.-H. Gan, and W. Balachandran, "Improvements in the Microstructure and Mechanical Properties of Aluminium Alloys Using Ultrasonic-Assisted Laser Welding," *Metals (Basel)*, vol. 12, no. 6, p. 1041, 2022.
- [98] P. Woizeschke, T. Radel, P. Nicolay, and F. Vollertsen, "Laser deep penetration welding of an aluminum alloy with simultaneously applied vibrations," *Lasers in Manufacturing and Materials Processing*, vol. 4, no. 1, pp. 1–12, 2017.
- [99] T. Radel, "Thermal impacts in vibration-assisted laser deep penetration welding of aluminum," *Phys Procedia*, vol. 89, pp. 131–138, 2017.
- [100] P. Yin, C. Xu, Q. Pan, W. Zhang, and X. Jiang, "Effect of Different Ultrasonic Power on the Properties of RHA Steel Welded Joints," *Materials*, vol. 15, no. 3, p. 768, 2022.
- [101] Prosperetti, A. Vapor Bubbles. *Annu. Rev. Fluid Mech.* 2017, 49, 221–248.

- [102] Sung, C.-C.; Jan, C.T. Active Control of Structurally Radiated Sound from Plates. *J. Acoust. Soc. Am.* 1997, 102, 370–381.
- [103] Vlasov, V.S. *Some New Problems on Shells and Thin Structures*; Naca Tech: Washington, DC, USA, 1949.
- [104] Teyeb, A.; Salimi, M.; El Masri, E.; Balachandran, W.; Gan, T.-H. Analytical Simulation of the Microbubble Collapsing in a Welding Fusion Pool. *Materials* 2023, 16, 410.
- [105] Pinnington, R.J.; Briscoe, A.R. Externally Applied Sensor for Axisymmetric Waves in a Fluid Filled Pipe. *J. Sound Vib.* 1994, 173, 503–516.
- [106] Ashokkumar, M. The Characterization of Acoustic Cavitation Bubbles—An Over-view. *Ultrason Sonochem.* 2011, 18, 864–872
- [107] Chen, C.; Fan, C.; Cai, X.; Lin, S.; Liu, Z.; Fan, Q.; Yang, C. Investigation of Formation and Microstructure of Ti-6Al-4V Weld Bead during Pulse Ultrasound Assisted TIG Welding. *J. Manuf. Process.* 2019, 46, 241–247
- [108] Chen, D.M. and Zhu, W.D., 2021. Investigation of three-dimensional vibration measurement by three scanning laser Doppler vibrometers in a continuously and synchronously scanning mode. *Journal of Sound and Vibration*, 498, p.115950
- [109] Liu, Z., Jin, X., Zhang, J., Hao, Z. and Li, J., 2022. Design optimization and eigenfrequency tuning of ultrasonic oscillator of one-dimensional longitudinal vibration at high temperature for laser welding. *The International Journal of Advanced Manufacturing Technology*, pp.1-19
- [110] Salimi, M.; Livadas, M.; Teyeb, A.; El Masri, E.; Gan, T.-H. Biofouling Removal Using a Novel Electronic System for Driving an Array of High-Power Marine Transducers. *Applied Sciences* 2023, 13, 3749, doi:10.3390/app13063749
- [111] Louisnard, O.; González-García, J. Acoustic Cavitation. In *Ultrasound Technologies for Food and Bioprocessing*; Springer: Berlin/Heidelberg, Germany, 2011; pp. 13–64.
- [112] Jamshidi, R.; Brenner, G. Dissipation of Ultrasonic Wave Propagation in Bubbly Liquids Considering the Effect of Compressibility to the First Order of Acoustical Mach Number. *Ultrasonics* 2013, 53, 842–848.
- [113] Brennen, C.E. *Cavitation and Bubble Dynamics*; Cambridge University Press: Cambridge, UK, 2014; ISBN 1107644763
- [114] Shi, Z., Wang, Z., Yang, B. and Liu, L., 2025. Insights into cavitation enhancement: Numerical simulation and spectrum analysis of a novel dual-frequency octagonal ultrasonic reactor. *Ultrasonics Sonochemistry*, 112, p.107197.
- [115] Leissa, A.W. *Vibration of Plates*; Scientific and Technical Information Division, National Aeronautics and Space Administration: Washington, DC, USA, 1969; Volume 160

- [116] Sung, C.-C.; Chiu, C.-Y. Control of Sound Transmission through Thin Plate. *J. Sound Vib.* 1998, 218, 605–618.
- [117] Sung, C.-C.; Jan, J.T. The Response of and Sound Power Radiated by a Clamped Rectangular Plate. *J. Sound Vib.* 1997, 207, 301–317.
- [118] Huang, C.L. and Sandman, B.E., 1971. Large amplitude vibrations of a rigidly clamped circular plate. *International Journal of non-linear Mechanics*, 6(4), pp.451-468
- [119] Hu, Z., Hua, L., Qin, X., Ni, M., Ji, F. and Wu, M., 2021. Molten pool behaviors and forming appearance of robotic GMAW on complex surface with various welding positions. *Journal of Manufacturing Processes*, 64, pp.1359-1376
- [120] Jiang, W., Chen, X., Wang, B., Fan, Z. and Wu, H., 2016. Effects of vibration frequency on microstructure, mechanical properties, and fracture behavior of A356 aluminum alloy obtained by expendable pattern shell casting. *The International Journal of Advanced Manufacturing Technology*, 83(1), pp.167-175
- [121] Nothdurft, S., Ohrdes, H., Twiefel, J., Wallaschek, J., Mildebrath, M., Maier, H.J., Hassel, T., Overmeyer, L. and Kaierle, S., 2019. Influence of ultrasonic amplitude and position in the vibration distribution on the microstructure of a laser beam welded aluminum alloy. *Journal of Laser Applications*, 31(2).
- [122] DeAngelis, D.A., Schulze, G.W. and Wong, K.S., 2015. Optimizing piezoelectric stack preload bolts in ultrasonic transducers. *Physics Procedia*, 63, pp.11-20.
- [123] Pérez-Sánchez, A., Segura, J.A., Rubio-Gonzalez, C., Baldenegro-Pérez, L.A. and So-to-Cajiga, J.A., 2020. Numerical design and analysis of a langevin power ultrasonic transducer for acoustic cavitation generation. *Sensors and Actuators A: Physical*, 311, p.112035
- [124] Zhang, J.G., Long, Z.L., Ma, W.J., Hu, G.H. and Li, Y.M., 2019. Electromechanical dynamics model of ultrasonic transducer in ultrasonic machining based on equivalent circuit approach. *Sensors*, 19(6), p.1405.
- [125] Lais, H., 2019. The generation of cavitation for the removal of fouling on submerged structures using high power ultrasonic transducers (Doctoral dissertation, Brunel University London)
- [126] Peng, X., Hu, L., Liu, W. and Fu, X., 2020. Model-based analysis and regulating approach of air-coupled transducers with spurious resonance. *Sensors*, 20(21), p.6184
- [127] Williams, D., 2017. Understanding, calculating, and measuring total harmonic distortion (THD). *All About Circuits*, 20.
- [128] Bishoyi, B., 2014. Laser beam welding of commercially pure titanium sheets (Doctoral dissertation).

- [129] Fathi, H.; Närhi, M.; Gumenyuk, R. Towards Ultimate High-Power Scaling: Coherent Beam Combining of Fiber Lasers. *Photonics* 2021, 8, 566. <https://doi.org/10.3390/photonics8120566>.
- [130] Katayama, S. *Handbook of Laser Welding Technologies*; Woodhead Publishing: Sawston, UK, 2013.
- [131] Teyeb, A.; Lowe, P.S.; Kanfoud, J.; Gan, T.H. Investigation of the use of power ultrasonic to improve the laser welding of Aluminium alloys. *Int. J. Mech. Prod. Eng.* 2018, 6, 51–54.
- [132] Fathi, H.; Närhi, M.; Gumenyuk, R. Towards Ultimate High-Power Scaling: Coherent Beam Combining of Fiber Lasers. *Photonics* 2021, 8, 566. <https://doi.org/10.3390/photonics8120566>
- [133] Oladimeji, O.; Taban, E. Trend and innovations in laser beam welding of wrought aluminium alloys. *Weld World* 2016, 60, 415–457. <https://doi.org/10.1007/s40194-016-0317-9>
- [134] Gallego-Juárez, J.A.; Rodriguez, G.; Acosta, V.; Riera, E. Power ultrasonic transducers with extensive radiators for industrial processing. *Ultrasonic. Sonochemistry* 2009, 17, 953–964
- [135] Hagenlocher, C.; Fetzer, F.; Weller, D.; Weber, R.; Graf, T. Explicit analytical expressions for the influence of welding parameters on the grain structure of laser beam welds in aluminium alloys. *Mater. Des.* 2019, 174, 107791.
- [136] Huang, H.Y., Kuo, I.C. and Zhang, C.W., 2018. Friction-stir welding of aluminium alloy with an iron-based metal as reinforcing material. *Science and Engineering of Composite Materials*, 25(1), pp.123-131
- [137] Sui, C., Liu, Z., Ai, X., Liu, C. and Zou, Z., 2022. Effect of ultrasonic vibration on grain size and precipitated phase distribution of 6061 aluminium alloy welded joint. *Crystals*, 12(2), p.240
- [138] Sun, T., Franciosa, P., Sokolov, M. and Ceglarek, D., 2020. Challenges and opportunities in laser welding of 6xxx high strength aluminium extrusions in automotive battery tray construction. *Procedia CIRP*, 94, pp.565-570
- [139] Zhang, F., Liang, S., Zhang, C., Chen, S., Lv, D., Cao, W. and Kou, S., 2021. Prediction of cracking susceptibility of commercial aluminium alloys during solidification. *Metals*, 11(9), p.1479
- [140] Eskin, D.G. Ultrasonic processing of molten and solidifying aluminium alloys: Overview and outlook. *Mater. Sci. Technol.* 2016, 33, 636–645.
- [141] Dubey, A.K.; Yadava, V. Laser beam machining—A review. *Int. J. Mach. Tools Manuf.* 2008, 48, 609–628.
- [142] Silva, J. *Laser Welding of Aluminium Rings*. Mastery Thesis, Instituto Superior Técnico, Universidade Técnica de Lisboa, Lisboa, Portugal, 2011.

- [143] Todaro, C.J.; Easton, M.A.; Qiu, D.; Zhang, D.; Bermingham, M.J.; Lui, E.W.; Brandt, M.; StJohn, D.H.; Qian, M. Grain structure control during metal 3D printing by high intensity ultrasound. *Nat. Commun.* 2020, 11, 142, <https://doi.org/10.1038/s41467-019-13874-z>
- [144] Puga, H.; Costa, S.; Barbosa, J.; Ribeiro, S.; Prokic, M. Influence of ultrasonic melt treatment on microstructure and mechanical properties of AlSi9Cu3 alloy. *J. Mater. Process. Technol.* 2011, 211, 1729–1735
- [145] Masuda, T., Sauvage, X., Hirose, S. and Horita, Z., 2020. Achieving highly strengthened Al–Cu–Mg alloy by grain refinement and grain boundary segregation. *Materials Science and Engineering: A*, 793, p.139668
- [146] Singh, S., Kadoi, K., Ojo, O., Alexandrov, B. and Andersson, J., 2023. The effects of chemistry variations on hot cracking susceptibility of Haynes® 282® for aerospace applications. *Materials & Design*, 228, p.111853.
- [147] Leong, T.S.; Martin, G.J.; Ashokkumar, M. Ultrasonic encapsulation—A review. *Ultrason. Sonochemistry* 2016, 35, 605–614.
- [148] Ali Naderi Bakhtiyari, Zhiwen Wang, Liyong Wang, Hongyu Zheng, A review on applications of artificial intelligence in modeling and optimization of laser beam machining, *Optics & Laser Technology*, Volume 135, 2021, 106721, ISSN 0030-3992
- [149] [98] Yuan, D.; Shao, S.; Guo, C.; Jiang, F.; Wang, J. Refining of Ti-6Al-4V alloy fabricated by laser and wire additive manufacturing assisted with ultrasonic vibration. *Ultrason. Sonochemistry* 2021, 73, 105472
- [150] Rojas, H., Molina, A., Valdez, S., Campillo, B., Martínez, H., Sedano, A. and Serna, S., 2020. The impact of heat input on the microstructures, fatigue behaviours, and stress lives of TIG-welded 6061-T6 alloy joints. *Materials Research Express*, 7(12), p.126512.
- [151] Franco, E.E.; Meza, J.M.; Buiochi, F. Measurement of elastic properties of materials by the ultrasonic through-transmission technique. *Dyna* 2011, 78, 58–64.
- [152] Available online: <Http://www.sonicsystems.co.uk/userfiles/downloads/9/P100-20%20Equipment%20Specification.pdf> (accessed on 10 January 2022).
- [153] Leitner, M.; Leitner, T.; Schmon, A.; Aziz, K.; Pottlacher, G. Thermophysical Properties of Liquid Aluminium. *Metall. Mater. Trans. A* 2017, 48, 3036–3045. <https://doi.org/10.1007/s11661-017-4053-6>.
- [154] [103] Jeong, I.L.; Jung, K.J.; Lee, K.; Kim, J.; Hoon, C.H.O. Experiment and Modeling to Assess Ultrasonic Attenuation Factor in Molten Aluminium Alloy. In *Proceedings of the Symposium on Ultrasonic Electronics*, Pukyong National University, Busan, South Korea, 16–18 November 2016; Volume 37

- [155] Thiel, C., Weber, R., Johannsen, J. and Graf, T., 2013. Stabilization of a laser welding process against focal shift effects using beam manipulation. *Physics Procedia*, 41, pp.209-215.
- [156] Hu, S., Zheng, D., Zhao, G., Li, G. and Tang, H., 2018. The effect of welded joint properties on the surface characteristics of laser-welded 2205 duplex stainless steel. *Advances in Mechanical Engineering*, 10(9), p.1687814018797449.
- [157] Zhang, Z., He, C., Li, Y., Yu, L., Zhao, S. and Zhao, X., 2020. Effects of ultrasonic assisted friction stir welding on flow behaviour, microstructure and mechanical properties of 7N01-T4 aluminium alloy joints. *Journal of Materials Science & Technology*, 43, pp.1-13.
- [158] Tian, Y., Shen, J., Hu, S., Wang, Z. and Gou, J., 2018. Effects of ultrasonic vibration in the CMT process on welded joints of Al alloy. *Journal of Materials Processing Technology*, 259, pp.282-291.
- [159] Zhang, C., Wu, C. and Tian, S., 2020. Effect of ultrasonic vibration on current density and keyholing capability of plasma arc. *Science and Technology of Welding and Joining*, 25(5), pp.422-430
- [160] Krajewski, A., Włosiński, W., Chmielewski, T. and Kołodziejczak, P., 2012. Ultrasonic-vibration assisted arc-welding of aluminium alloys. *Bulletin of the Polish Academy of Sciences. Technical Sciences*, 60(4), pp.841-852.
- [161] Chen, L., Wang, C., Xiong, L., Zhang, X. and Mi, G., 2020. Microstructural, porosity and mechanical properties of lap joint laser welding for 5182 and 6061 dissimilar aluminium alloys under different place configurations. *Materials & Design*, 191, p.108625.
- [162] Tzanakis, I., Lebon, G.S.B., Eskin, D.G. and Pericleous, K., 2016. Investigation of the factors influencing cavitation intensity during the ultrasonic treatment of molten aluminium. *Materials & Design*, 90, pp.979-983.
- [163] Atamanenko, T.V., Eskin, D.G., Zhang, L. and Katgerman, L., 2010. Criteria of grain refinement induced by ultrasonic melt treatment of aluminium alloys containing Zr and Ti. *Metallurgical and Materials Transactions A*, 41, pp.2056-2066.
- [164] Tonry, C.E.H., Djambazov, G., Dybalska, A., Griffiths, W.D., Beckwith, C., Bojarevics, V. and Pericleous, K.A., 2020. Acoustic resonance for contactless ultrasonic cavitation in alloy melts. *Ultrasonics sonochemistry*, 63, p.104959.
- [165] Ramirez, A., Qian, M., Davis, B., Wilks, T. and StJohn, D.H., 2008. Potency of high-intensity ultrasonic treatment for grain refinement of magnesium alloys. *Scripta Materialia*, 59(1), pp.19-22
- [166] Yin, P., Xu, C., Pan, Q., Zhang, W. and Jiang, X., 2022. Study on ultrasonic regulation of the welding performance and defects of 7A52 aluminium alloy plate. *AIP Advances*, 12(4).

- [167] Pandit, A.V., Sarvothaman, V.P. and Ranade, V.V., 2021. Estimation of chemical and physical effects of cavitation by analysis of cavitating single bubble dynamics. *Ultrasonics Sonochemistry*, 77, p.105677
- [168] Mutswatiwa, L., Katch, L., Kizer, N.J., Todd, J.A., Sun, T., Clark, S.J., Fezzaa, K., Lum, J.S., Stobbe, D.M., Jones, G. and Meinert Jr, K.C., 2024. High-speed synchrotron X-ray imaging of melt pool dynamics during ultrasonic melt processing of Al6061. *Communications Materials*, 5(1), p.143
- [169] Leung, C.L.A., Marussi, S., Atwood, R.C., Towrie, M., Withers, P.J. and Lee, P.D., 2018. In situ X-ray imaging of defect and molten pool dynamics in laser additive manufacturing. *Nature communications*, 9(1), p.1355.
- [170] Sargent, N.; Jones, M.; Otis, R.; Shapiro, A.A.; Delplanque, J.-P.; Xiong, W. Integration of Processing and Microstructure Models for Non-Equilibrium Solidification in Additive Manufacturing. *Metals (Basel)* 2021, 11, 570
- [171] Yuan, L. Solidification Defects in Additive Manufactured Materials. *Jom* 2019, 71, 3221–3222
- [172] Manvatkar, V.; De, A.; DebRoy, T. Spatial Variation of Melt Pool Geometry, Peak Temperature and Solidification Parameters during Laser Assisted Additive Manufacturing Process. *Materials Science and Technology* 2015, 31, 924–930.
- [173] Wei, H.L.; Elmer, J.W.; DebRoy, T. Origin of Grain Orientation during Solidification of an Aluminum Alloy. *Acta Mater* 2016, 115, 123–131.
- [174] Sun, T.; Franciosa, P.; Liu, C.; Pierro, F.; Ceglarek, D. Effect of Micro Solidification Crack on Mechanical Performance of Remote Laser Welded AA6063-T6 Fillet Lap Joint in Automotive Battery Tray Construction. *Applied Sciences* 2021, 11, 4522
- [175] Casalino, G. Advances in Welding Metal Alloys, Dissimilar Metals and Additively Manufactured Parts. *Metals (Basel)* 2017, 7, 32.
- [176] Wang, P.; Chen, X.; Pan, Q.; Madigan, B.; Long, J. Laser Welding Dissimilar Materials of Aluminum to Steel: An Overview. *The International Journal of Advanced Manufacturing Technology* 2016, 87, 3081–3090.
- [177] Kolařík, L.; Janovec, J.; Kolaříková, M.; Nachtnebl, P. Influence of Diffusion Welding Time on Homogenous Steel Joints. *Procedia Eng* 2015, 100, 1678–1685.
- [178] Tathgir, S.; Rathod, D.W.; Batish, A. A-TIG Welding Process for Enhanced Penetration in Duplex Stainless-Steel: Effect of Activated Fluxes. *Materials and Manufacturing Processes* 2019, 34, 1659–1670.
- [179] Kah, P.; Rajan, R.; Martikainen, J.; Suoranta, R. Investigation of Weld Defects in Friction Stir Welding and Fusion Welding of Aluminium Alloys. *International Journal of Mechanical and Materials Engineering* 2015, 10, 1–10.

- [180] Manitsas, D.; Andersson, J. Hot Cracking Mechanisms in Welding Metallurgy: A Re-view of Theoretical Approaches. In Proceedings of the MATEC Web of Conferences; EDP Sciences, 2018; Vol. 188, p. 03018.
- [181] Yin, L.; Zhu, C.; Xu, J.; Zhao, H.; Qiu, J.; Wang, H.; Liu, K. Dynamic Impedance Analysis of Intestinal Anastomosis during High-Frequency Electric Field Welding Process. *Sensors* 2022, 22, 4101.
- [182] Wang, Z.; Gao, J.; Bilal, H.M.; Luo, J.; Li, X. Impedance Compensation of the Welding Area of the RF Connector and Microstrip Line. In Proceedings of the 2018 10th International Conference on Communications, Circuits and Systems (ICCCAS); IEEE, 2018; pp. 190–194.
- [183] Kumar, S.; Wu, C.; Shi, L. Intermetallic Diminution during Friction Stir Welding of Dissimilar Al/Mg Alloys in Lap Configuration via Ultrasonic Assistance. *Metallurgical and Materials Transactions A* 2020, 51, 5725–5742.
- [184] Kumar, S.; Wu, C. Suppression of Intermetallic Reaction Layer by Ultrasonic Assistance during Friction Stir Welding of Al and Mg Based Alloys. *J Alloys Compd* 2020, 827, 154343.
- [185] Kumar, S.; Wu, C.S.; Padhy, G.K.; Ding, W. Application of ultrasonic vibrations in welding and metal processing: A status review. *J. Manuf. Process.* 2017, 26, 295–322.
- [186] Zuo, Y.Y.; Gong, P.; Ji, S.D.; Li, Q.H.; Ma, Z.W.; Lv, Z. Ultrasound-Assisted Friction Stir Transient Liquid Phase Spot Welded Dissimilar Copper-Aluminum Joint. *J Manuf Process* 2021, 62, 58–66.
- [187] Shahidian, A.; Afshar, H.; Habibi, M.R.; Ghassemi, M. Therapeutic Nanostructures: Application of Mechanical Engineering in Drug Delivery. *Nanoarchitectonics for smart delivery and drug targeting* 2016, 1.
- [188] Izadifar, Z.; Babyn, P.; Chapman, D. Ultrasound Cavitation/Microbubble Detection and Medical Applications. *J Med Biol Eng* 2019, 39, 259–276.
- [189] Qu, Z.; Jin, S.; Wu, L.; An, Y.; Liu, Y.; Fang, R.; Yang, J. Influence of Water Flow Velocity on Fouling Removal for Pipeline Based on Eco-Friendly Ultrasonic Guided Wave Technology. *J Clean Prod* 2019, 240, 118173.
- [190] Mi, B.; Xia, J.; Shen, C.; Wang, L. Dispersion Energy Analysis of Rayleigh and Love Waves in the Presence of Low-Velocity Layers in near-Surface Seismic Surveys. *Surv Geophys* 2018, 39, 271–288.
- [191] Every, A.G.; Mathe, B.A.; Comins, J.D. The Study of Guided Waves in Surfaces and Thin Supported Films Using Surface Brillouin Scattering and Acoustic Microscopy. *Ultrasonics* 2006, 44, e929–e934.

- [192] Li, W.; Deng, M.; Hu, N.; Xiang, Y. Theoretical Analysis and Experimental Observation of Frequency Mixing Response of Ultrasonic Lamb Waves. *J Appl Phys* 2018, 124, 044901.
- [193] Li, W.; Xu, Y.; Hu, N.; Deng, M. Numerical and Experimental Investigations on Second-Order Combined Harmonic Generation of Lamb Wave Mixing. *AIP Adv* 2020, 10, 045119.
- [194] Abd-Alla, A.M.; Abo-Dahab, S.M.; Al-Thamali, T.A.; Mahmoud, S.R. Influence of the Rotation and Gravity Field on Stonely Waves in a Non-Homogeneous Orthotropic Elastic Medium. *J Comput Theor Nanosci* 2013, 10, 297–305.
- [195] Lissenden, C.J. Nonlinear Ultrasonic Guided Waves—Principles for Nondestructive Evaluation. *J Appl Phys* 2021, 129, 021101.
- [196] Li, W.-B.; Deng, M.-X.; Xiang, Y.-X. Review on Second-Harmonic Generation of Ultrasonic Guided Waves in Solid Media (I): Theoretical Analyses. *Chinese Physics B* 2017, 26, 114302.
- [197] Jiang, C.; Li, W.; Deng, M.; Ng, C.-T. Quasistatic Pulse Generation of Ultrasonic Guided Waves Propagation in Composites. *J Sound Vib* 2022, 524, 116764. Zhao, J., Wu, C.S. and Su, H., 2021. Ultrasonic effect on thickness variations of intermetallic compound layers in friction stir welding of aluminium/magnesium alloys. *Journal of Manufacturing Processes*, 62, pp.388-402.
- [198] Hollatz, S., Kremer, S., Ünlübayir, C., Sauer, D.U., Olowinsky, A. and Gillner, A., 2020. Electrical modelling and investigation of laser beam welded joints for lithium-ion batteries. *Batteries*, 6(2), p.24.
- [199] Baù, M.; Ferrari, V.; Marioli, D.; Sardini, E.; Serpelloni, M.; Taroni, A. Contactless Excitation and Readout of Passive Sensing Elements Made by Miniaturized Mechanical Resonators. In *Proceedings of the SENSORS, 2007 IEEE*; IEEE, 2007; pp. 36–39
- [200] Yamashita, T.; Ando, K. Low-Intensity Ultrasound Induced Cavitation and Streaming in Oxygen-Supersaturated Water: Role of Cavitation Bubbles as Physical Cleaning Agents. *Ultrason Sonochem* 2019, 52, 268–279.
- [201] Wood, A.K.W.; Sehgal, C.M. A Review of Low-Intensity Ultrasound for Cancer Therapy. *Ultrasound Med Biol* 2015, 41, 905–928.
- [202] de Oliveira, R.F.; Oliveira, D.A.A.P.; Soares, C.P. Effect of Low-Intensity Pulsed Ultrasound on L929 Fibroblasts. *Archives of Medical Science* 2011, 7, 224–229.
- [203] Yamashita, T.; Ando, K. Low-Intensity Ultrasound Induced Cavitation and Streaming in Oxygen-Supersaturated Water: Role of Cavitation Bubbles as Physical Cleaning Agents. *Ultrason Sonochem* 2019, 52, 268–279.
- [204] Lauterborn, W.; Thomas, K.; Mettin, R.; Philipp, K.; Kroeninger, D.; Schanz, D. Acoustic Cavitation and Bubble Dynamics. *Archives of Acoustics* 2008, 33, 609–617.

-
- [205] Lentacker, I.; De Cock, I.; Deckers, R.; De Smedt, S.C.; Moonen, C.T.W. Understanding Ultrasound Induced Sonoporation: Definitions and Underlying Mechanisms. *Adv Drug Deliv Rev* 2014, 72, 49–64.
- [206] <https://www.twi-global.com/what-we-do/research-and-technology/technologies/welding-joining-and-cutting/lasers/laser-welding>

Appendix I

Vibration Output from the HPUTs

In Chapter 4, the transducer horn was designed with the aim of being used during laser welding. This appendix provides further details on the characterisation of the horn, which was done experimentally.

The measured vibration is captured by a high-frequency accelerometer mounted into the experimental setup at the horn tip (**Figure A1.1**). The transducer performance is evaluated with and without horn, as well as the transducer with the focused horn.



Figure A1. 1: Produced Transducer with a sensor fitted at the tip of the horn

20 kHz transducers

Figure 2 shows the acceleration amplitude versus frequency plots for the 20 kHz transducer between frequencies of 0 – 15 kHz (**Figure A1.2 (a)**) and 15 – 30 kHz (**Figure A1.2(b)**).

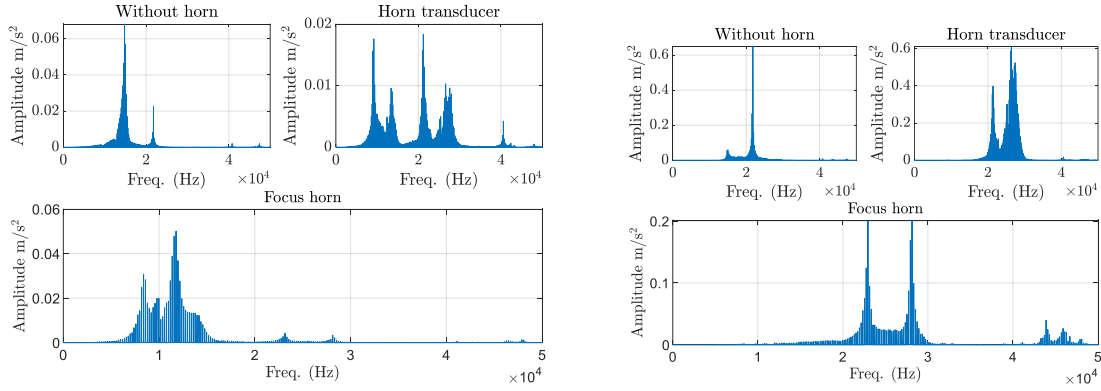


Figure A1. 2: The spectrum of 20 kHz transducer with respect to the transducer configuration for the frequency range of 0-15 kHz, 15 kHz-30 kHz.

For the transducer without the horn, the amplitude becomes 100 times higher at approximately 20 kHz compared to the lower frequency of 15 kHz. Similarly, for the transducer with the conical and the focused horn, the amplitude increased approximately 33 and 4 times, respectively, compared to the peaks that appeared at lower frequencies (0 – 15 kHz). As shown in **Figure A1.3**, at higher frequencies the vibration amplitude becomes half for the transducer without the horn and the focused transducer. The transducer with the conical horn produced is approximately half as the one for 25 kHz (**Figure A1.2(b)**).

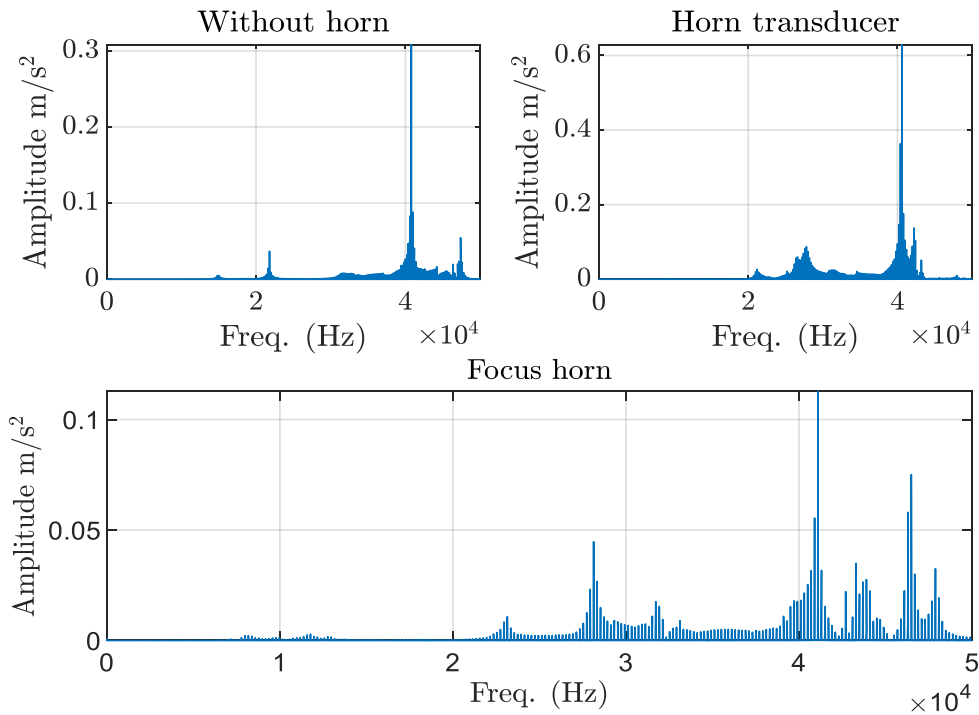
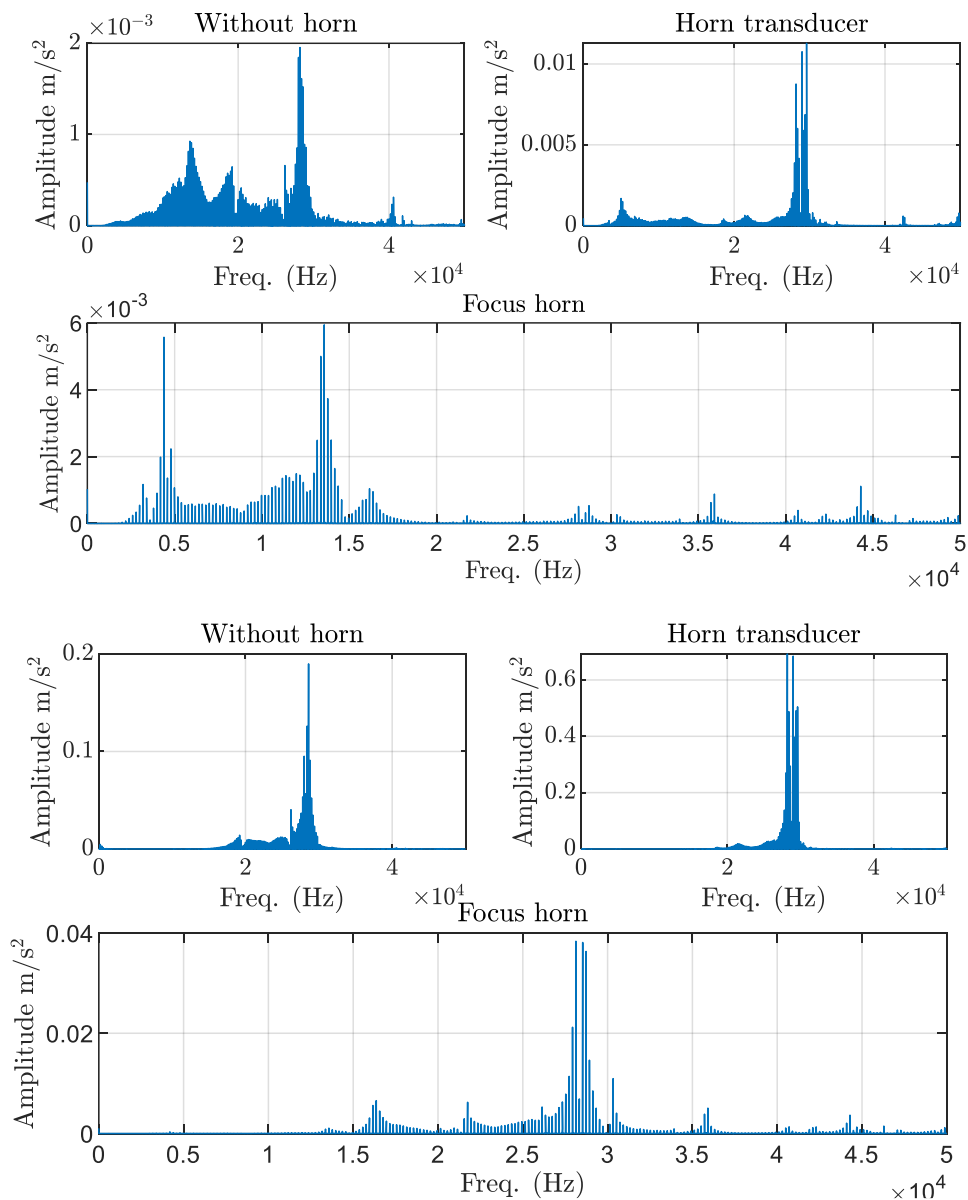


Figure A1. 3: The spectrum of 20 kHz transducer with respect to the transducer configuration for the frequency range 30 kHz to 45 kHz

28 kHz transducers

The same procedure employed for the 20 kHz transducer is replicated for this transducer. Spectral analysis of the transducer was conducted to pinpoint the frequency range that generated the highest vibration output. As depicted in **Figure A1.4**, the focused horn exhibited a maximum displacement amplitude of 5.8 mm/s^2 at 4 kHz, within the 0 – 15 kHz range. Additionally, the vibration amplitude reaches its zenith at approximately 28 kHz when subjected to excitation between 15-30 kHz. When excitation is applied outside the transducer's resonance frequency, some maxima are observed; however, these peaks do not compare to the levels achieved when the correct frequency sweep is selected for the transducers.



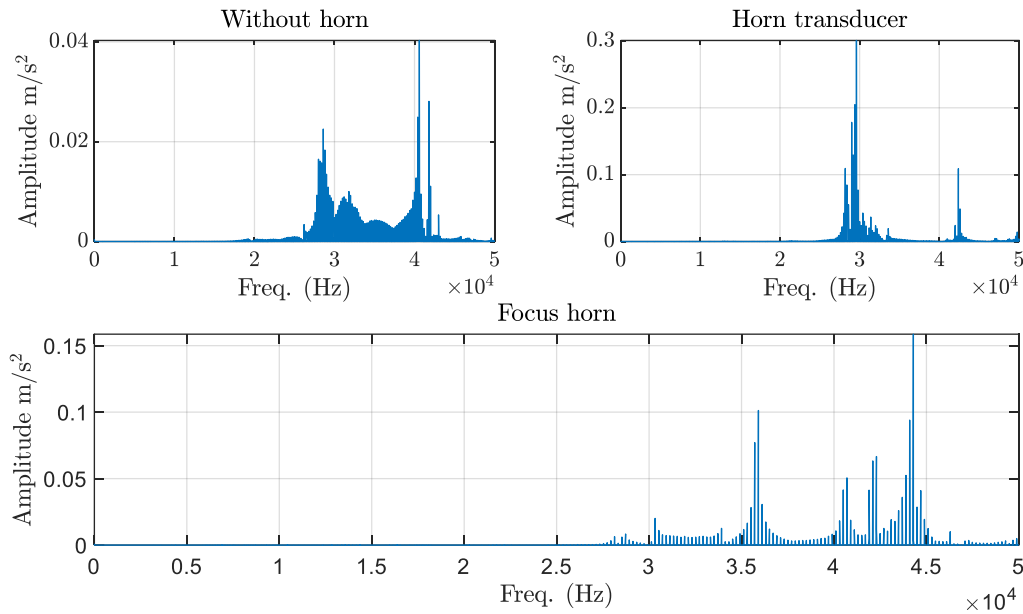
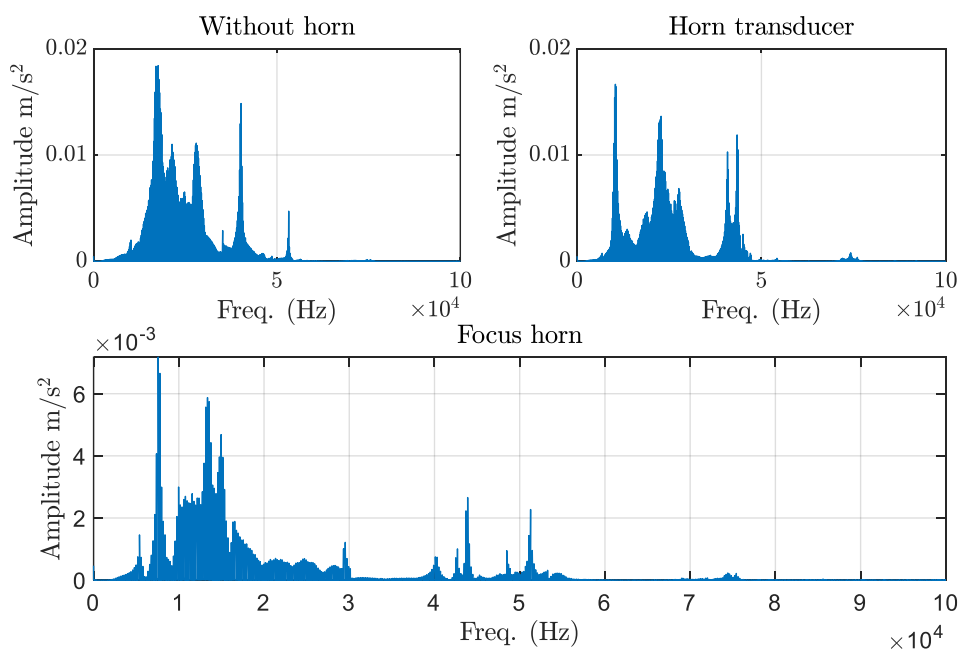


Figure A1. 4: The spectrum of 28 kHz transducer with respect to the transducer configuration for the frequency range of 0-15 kHz, 15 kHz-30 kHz and 30- 45 kHz.

40 kHz transducers

The spectrum tests carried out for the other two transducers are replicated for the 40 kHz transducer. As illustrated in **Figure A1.5**, the higher frequency range showed higher than the lower frequency range. employing the conical horn results in an approximately 300-fold increase in the peak value. The amplitude also rises for the focused transducer. This higher vibration output with the conical transducer can be attributed to more efficient reflection occurring at the tip of the transducer.



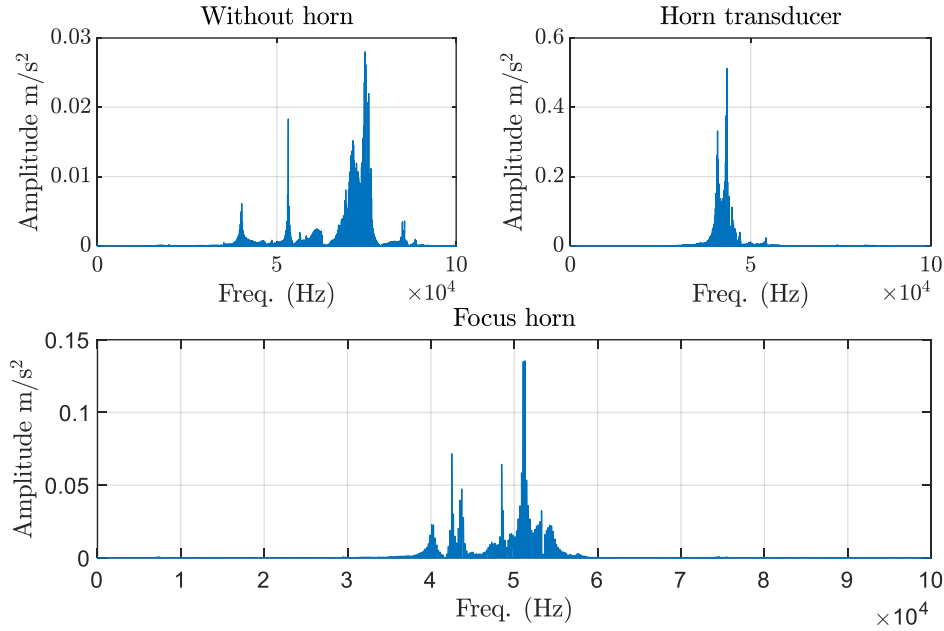


Figure A1. 5: The spectrum of 40 kHz transducer with respect to the transducer configuration for the frequency range of 0 – 30 kHz, and 30 – 60 kHz

Evaluation of transducer response for use in butt joints: Tightening Torque on Front-end Surface Amplitude at varying Operation Frequencies

In preparation of the ultrasonic assisted welding trials, we identified 3 types of configurations that can be used and showcased:

- Langevin transducers: used without horns for the butt joints, or with horns (conical or focused) to be used in spot welding of battery connectors.
- Probe horns to be used in spot welding of battery connector in contact and contactless modes (purchased with the Qsonica 55 control Unit)

Excessive tightening torque increases the clamping of the piezoelectric ceramic within the transducer, resulting in a damping effect on vibrational energy produced by the transducer, thus limiting the electromechanical coupling coefficient. On the other hand, if the tightening torque is too loose, stretching stress of the piezoelectric ceramic becomes greater than the tightening torque and results in loss of mechanical energy in the contact surfaces of the transducer. Therefore, it is essential to determine an optimal tightening torque that produces the minimum energy loss.

The intensity of vibration propagated from the transducer to the plates is measured by the amplitude, which is the vertical displacement experienced at the front-end surface of the transducer.

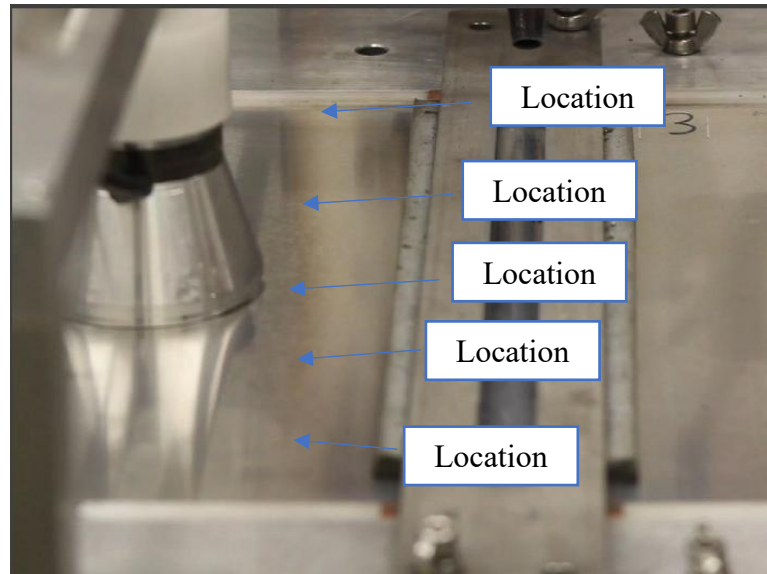


Figure A1. 6: Locations of the vibration measurement along the plates.

This is the vibration level that excites the plates to be welded during ultrasonic vibration-assisted laser welding. **Figures A1.6 – A1.17** represent measurements of vibration amplitudes at 5 different locations on the plate with varying tightening torques of 0.4, 0.8, 1.6, and 3.2 Nm. The measurements are classified based on the three operation frequencies, namely: 20, 28, and 40 kHz. Each plot is characterized by major signal peaks that are produced either by the operation frequency or total distortions based on harmonics. The total harmonic distortion is a measurement that indicates the quantity of distortion output of a voltage or current. A higher harmonics signal indicates that the sinusoidal wave produced by the power ultrasonic generator is not purely sinusoidal but contains higher frequency components that are contributing to the harmonic distortion of the signal.

Considering the following plots (**Figures A1.6 – A1.17**), higher amplitudes signify increased vibrational energy transmission from the piezoelectric ceramic to the front-end surface of the transducer and, a reduced loss in vibration energy. The plots give qualitative and qualitative insights into the interactions between the operation frequency, tightening torque of the transducer, and the specific location on the plates to achieve the maximum amplitude, sufficient to produce cavitation bubbles within the fusion/melt zone of a welded joint during ultrasonic vibration-assisted laser welding process.

20 kHz transducer

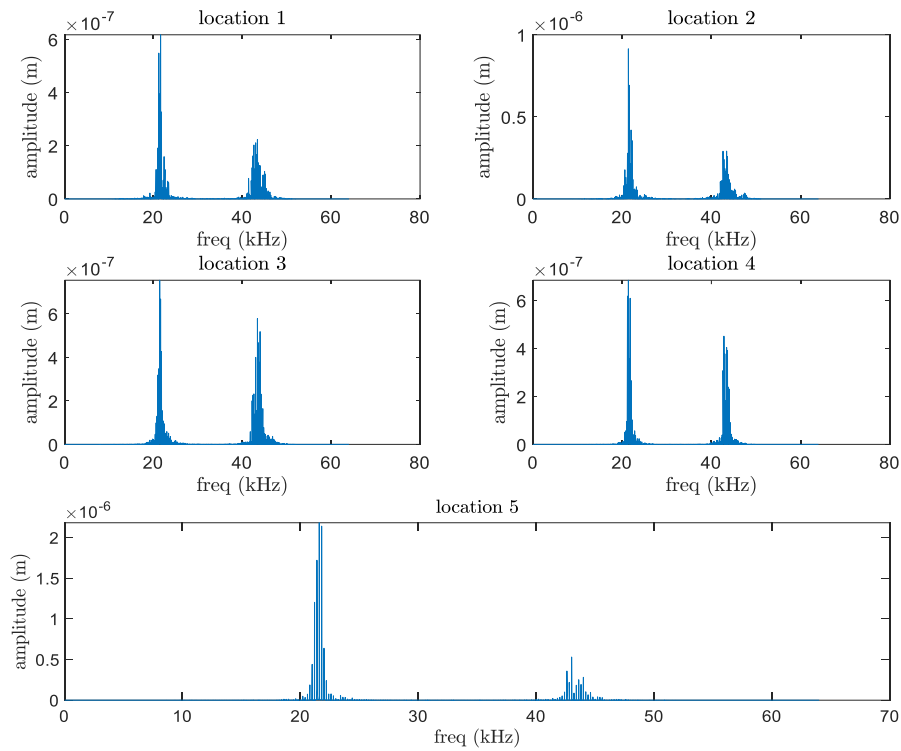


Figure A1. 7: Vibration amplitude of transducer under pressure of 0.4 Nm

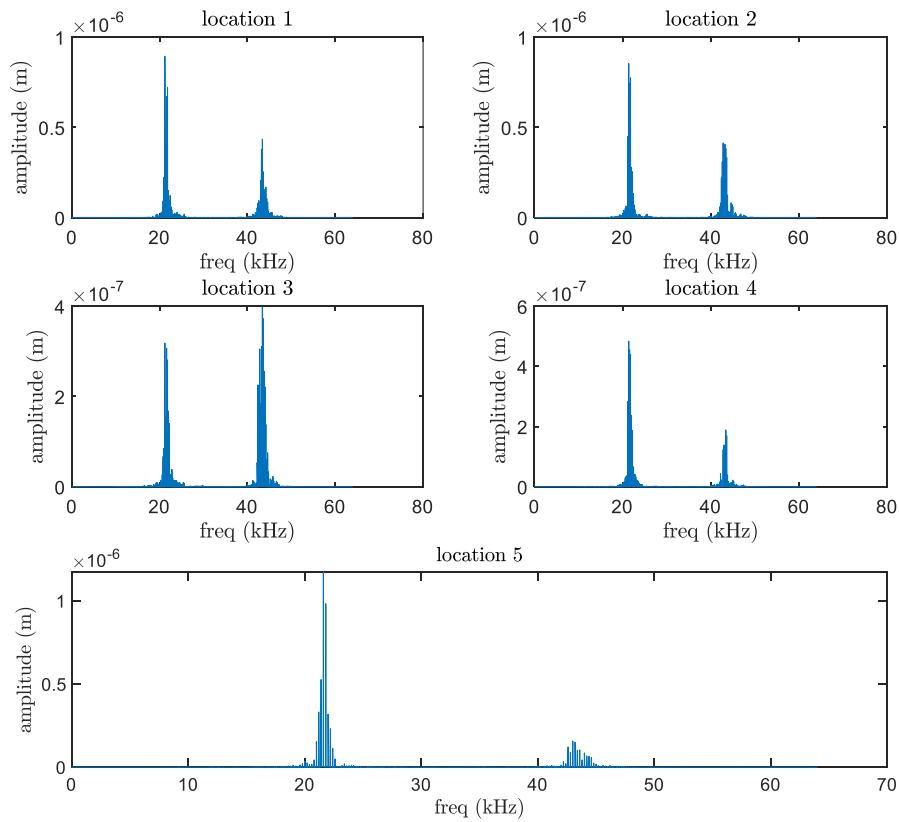


Figure A1. 8: Vibration amplitude of transducer under pressure of 0.8 Nm.

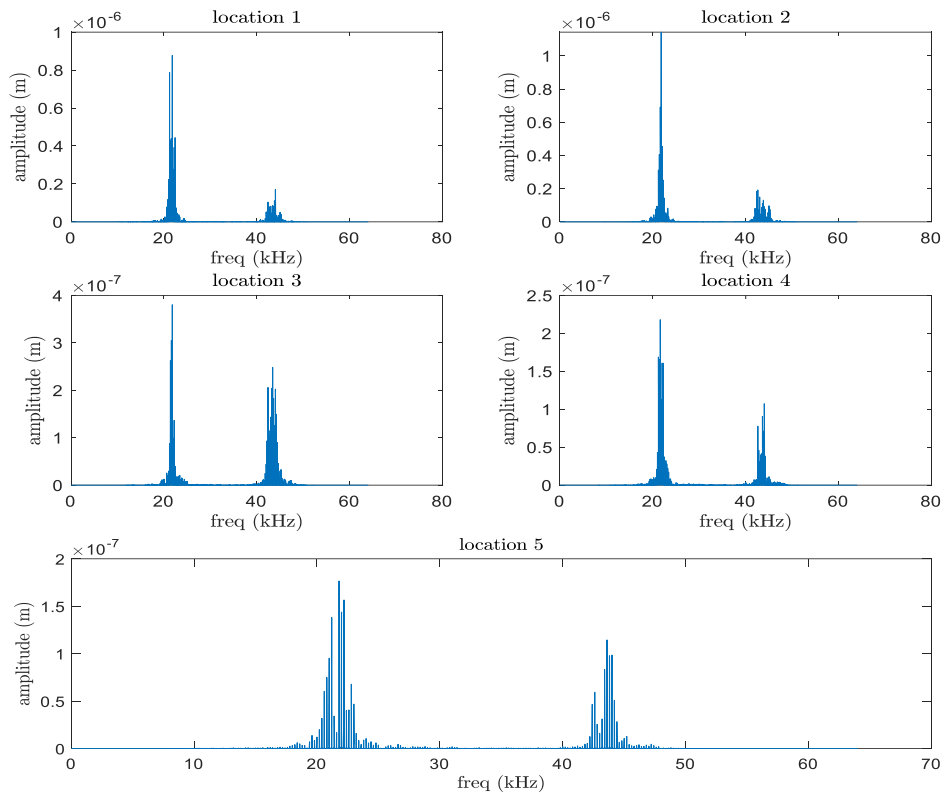


Figure A1. 9: Vibration amplitude of transducer under pressure of 1.6 Nm.

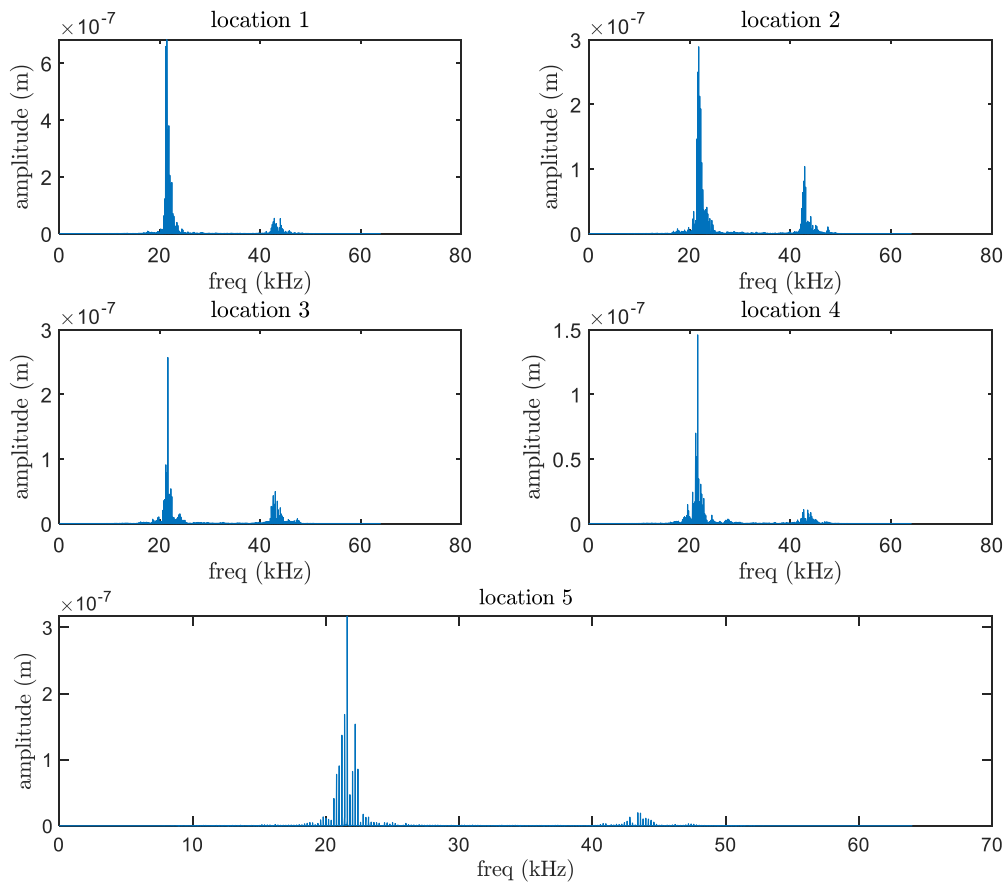


Figure A1. 10: Vibration amplitude of transducer under torque of 3.2 Nm.

28 kHz transducer

At an operating frequency of 28 kHz, the maximum vibration displacement was observed at location 2, measuring 1.8 μm , followed by location 1 with 1.0 μm . Locations 4 and 5 experienced the least vibration, both registering a common amplitude of 0.2 μm when subjected to a tightening torque of 0.4 Nm. When the tightening torque was increased to 0.8 Nm, location 1 exhibited the highest amplitude at 1.0 μm , while locations 4 and 5 displayed the lowest displacement at 0.23 μm .

Under a tightening torque of 1.6 Nm, location 1 recorded the highest amplitude, which was ten times greater than the displacement at location 4. Finally, at a tightening torque of 3.2 Nm, location 1 again displayed the largest displacement. These findings suggest that location 1 is the optimal placement for the transducer to achieve maximum vibration energy for laser welding excitation.

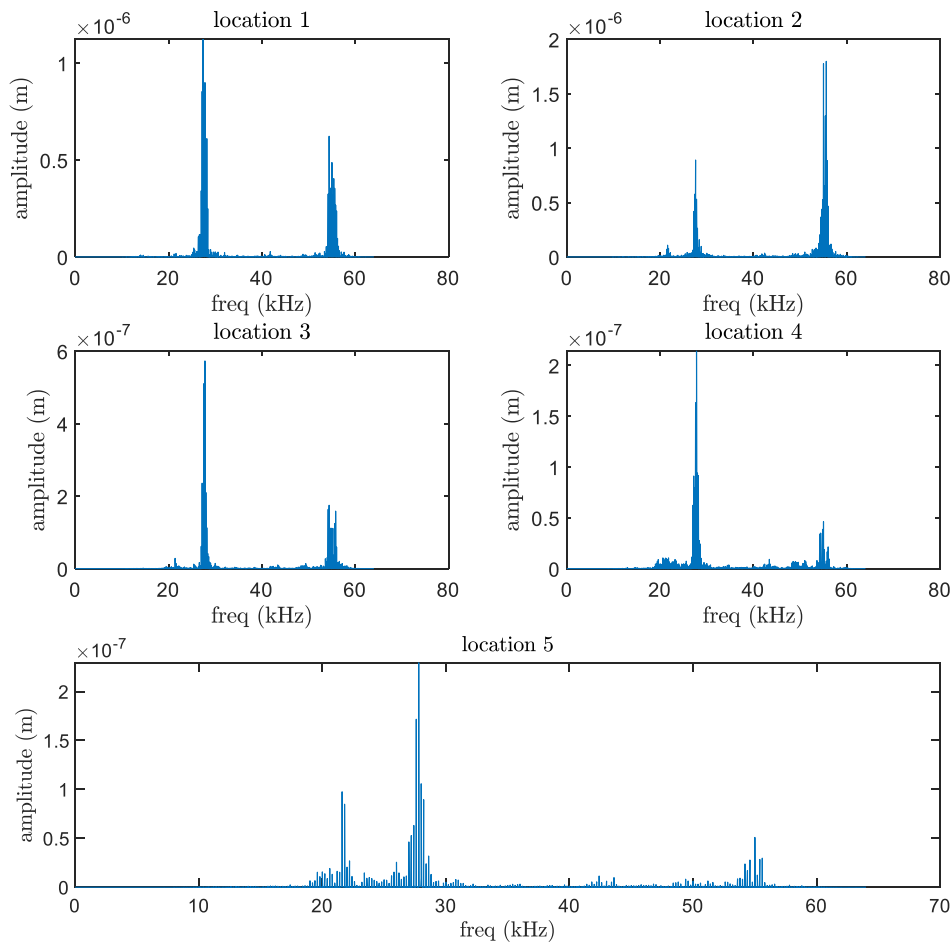


Figure A1. 11: Vibration amplitude of transducer under torque of 0.4 Nm.

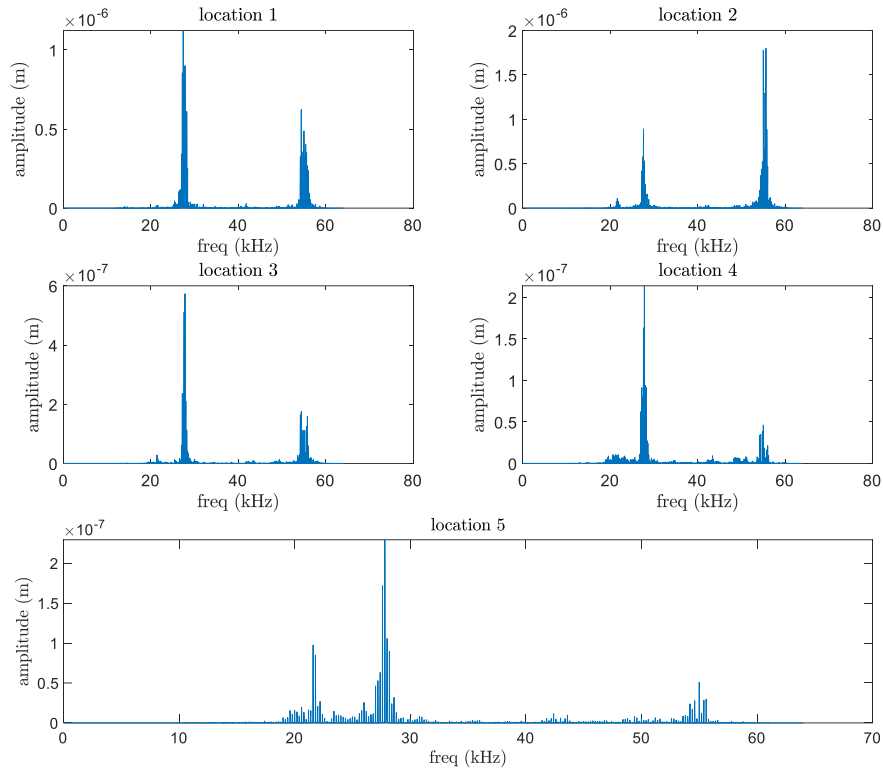


Figure A1. 12: Vibration amplitude of transducer under pressure of 0.8 Nm.

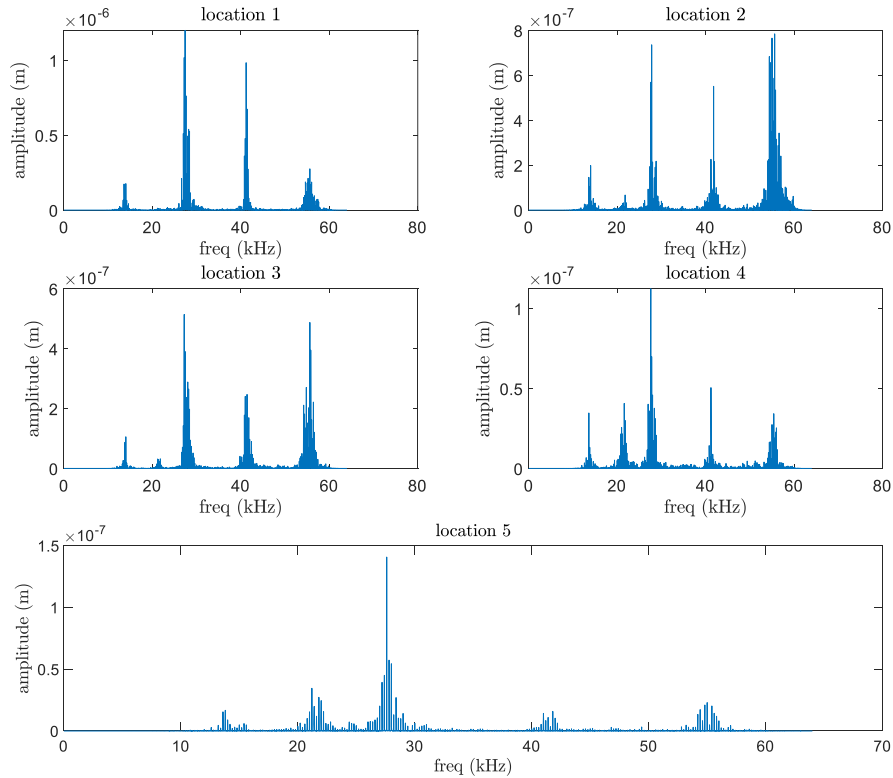


Figure A1. 13: Vibration amplitude of transducer under pressure of 1.6 Nm.

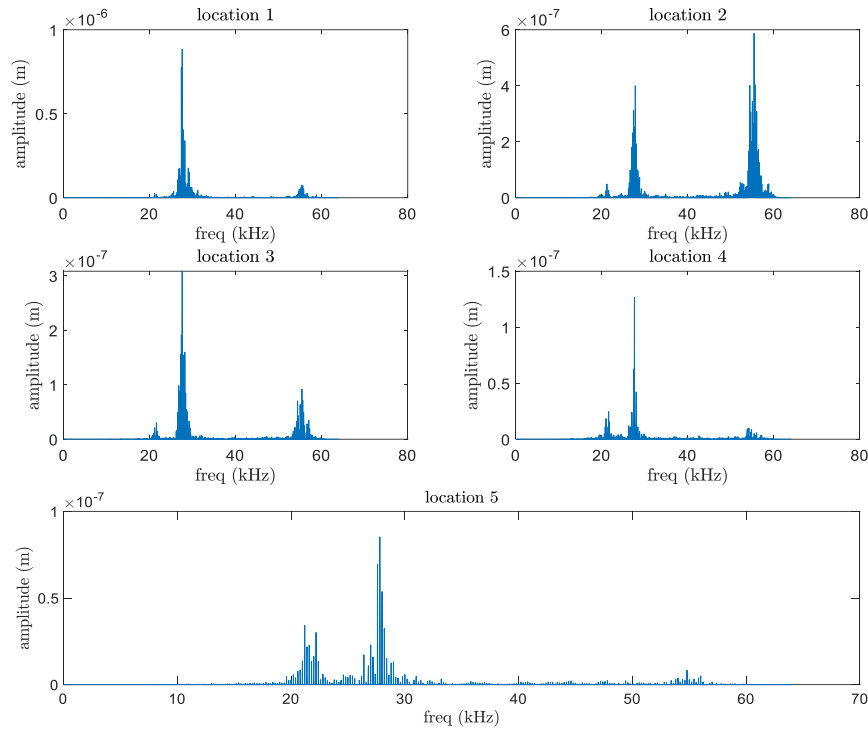


Figure A1. 14: Vibration amplitude of transducer under pressure of 3.2 Nm.

40 kHz transducer

Increasing the tightening torque from 0.4 Nm to 1.6 Nm, location 1 vibrated with the highest amplitude of approximately 3.8 μm . However, at a tightening torque of 3.2 Nm, location 2 experienced the largest displacement at an amplitude of 1 μm . It can be inferred that the harmonic distortion increased from location 1 to location 5 for each tightening torque.

With respect to specific locations at varying frequencies, the amplitude at different tightening torques can be compared, in order to determine the optimal tightening torque range for the transducer. For instance, considering location 1 across the three frequencies, little or no significant change occurred as the tightening torque increased from 0.4 Nm to 1.6 Nm. There was a sudden decrease in amplitude as the tightening torque increased to 3.2 Nm. This indicates that the optimal tightening torque ranged between 0.4 Nm and 1.6 Nm for the specific transducer. The author conducted research to determine the ideal pre-tightening force for the sandwich transducer. The results of the study revealed that when the pre-tightening force reached its optimum level, the amplitude on the front surface of the sandwich transducer reached its peak, and the resonance resistance tended to be minimized.

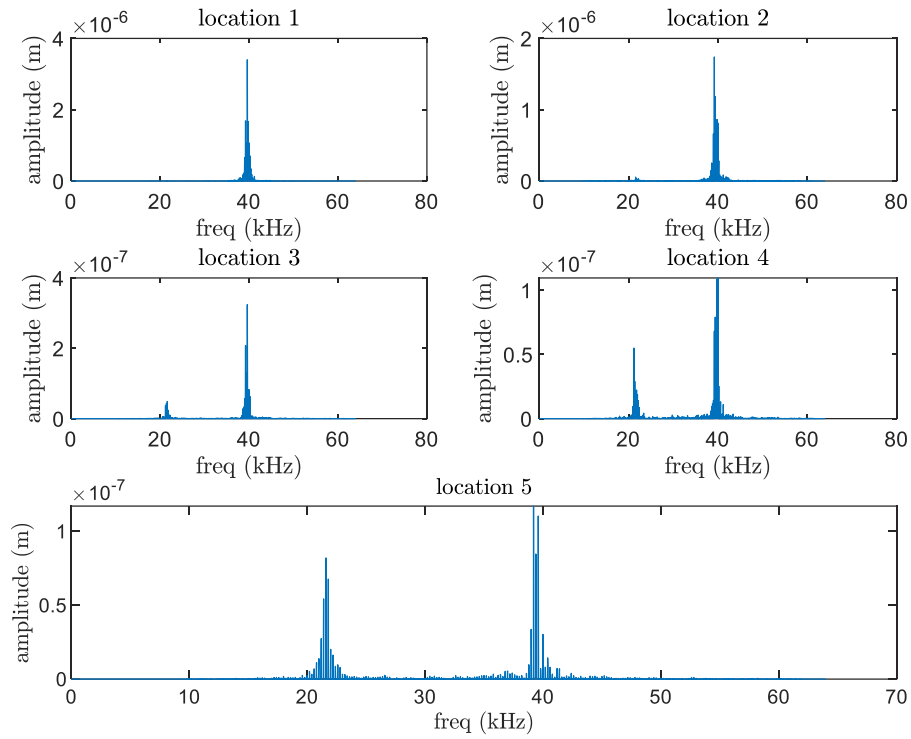


Figure A1. 15: Vibration amplitude of transducer under pressure of 0.4 Nm.

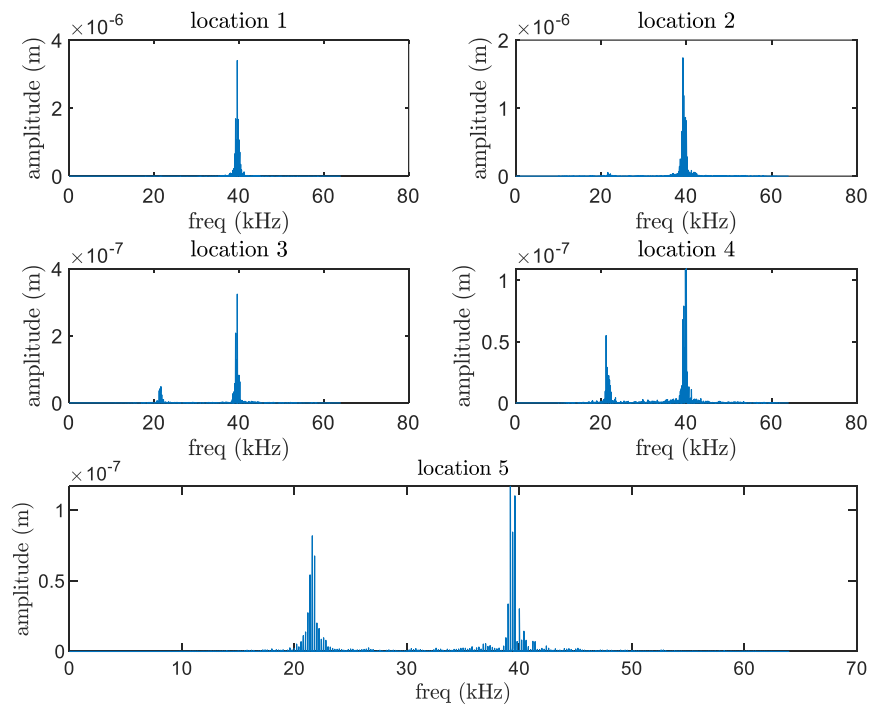


Figure A1. 16: Vibration amplitude of transducer under pressure of 0.8Nm.

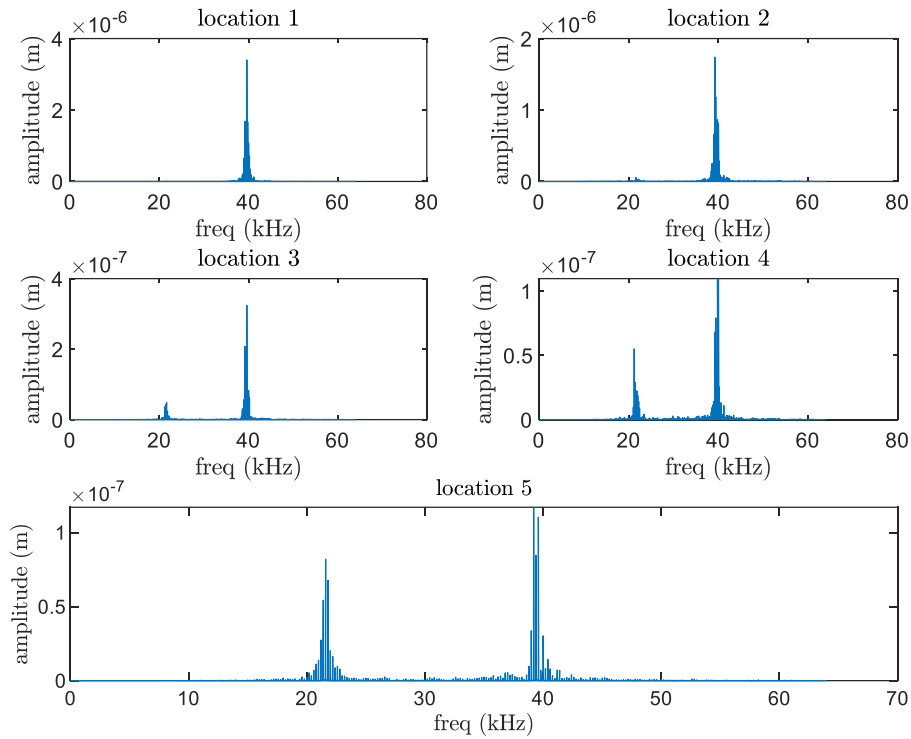


Figure A1. 17: Vibration amplitude of transducer under pressure of 1.6 Nm.

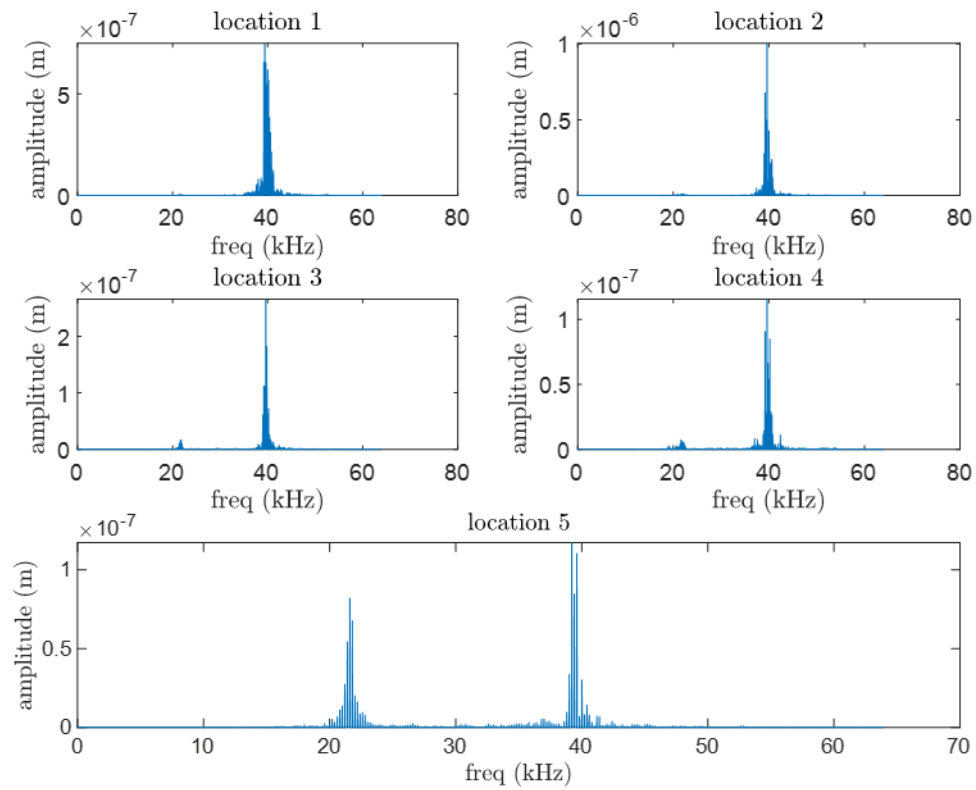


Figure A1. 18: Vibration amplitude of transducer under pressure of 3.2 Nm.

In summary, the experimental study on the effect of tightening torque on vibration amplitude at varying operation frequencies 20, 28, and 40 kHz. Tightening torque values of 0.4, 0.8, 1.6, and 3.2 Nm were considered to determine the maximum vibration at 5 different locations on the plate. Generally, location 1 experienced the highest displacement amongst the locations. As shown by the study the transducers performed better when the torque force is between 0.8 to 1.6 Nm.

Appendix II

Vibration Level Test for Lap and Butt Joints during Welding Process

In this study, an investigation is carried out on the impact of the welding process on vibration amplitude. Specifically, we examine two distinct types of welding: lap joints and butt joints.

Lap joints

In this section, the impact of the welding progress on lap joints using both 28 kHz and 40 kHz transducers was recorded. The experimental setup for the vibration analysis of lap and butt joints is displayed in **Figure A2.1**.



Figure A2. 1: . Experimental setup for vibration analysis during ultrasonic vibration assisted laser welding process

As the welding process progresses from 0% to 100% along the plate, the wave amplitude increases. In this measurement, the power sent to the transducer is set to 70 W, and the tightening pressure is 1 Nm.

Holder for the plate welding

Prior to welding, the plates need to attach to each other. For this purpose, a holder is made from plastic as shown in **Figure A2.2**. The upper side of the plastic holder is covered with foil to make the holder more reflective.

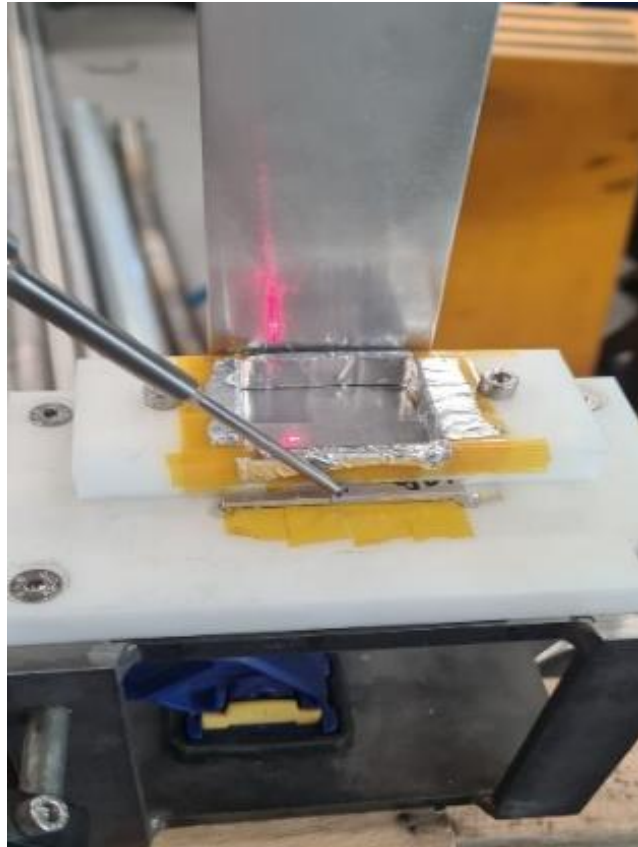


Figure A2. 2: Plastic holder for welding the ‘L’ shape plates.

It is noteworthy that the wavelength of the shear and the compressional wave is longer than the foil thickness attached to the plastic material. However, the aluminium foil is more reflective than the plastic material and hence the wave amplitude increases at the centre of the plastic holder. **Figure A2.3** shows an analysis of the lap joints vibration level for 0-100 % welding progress with a 28 kHz transducer.

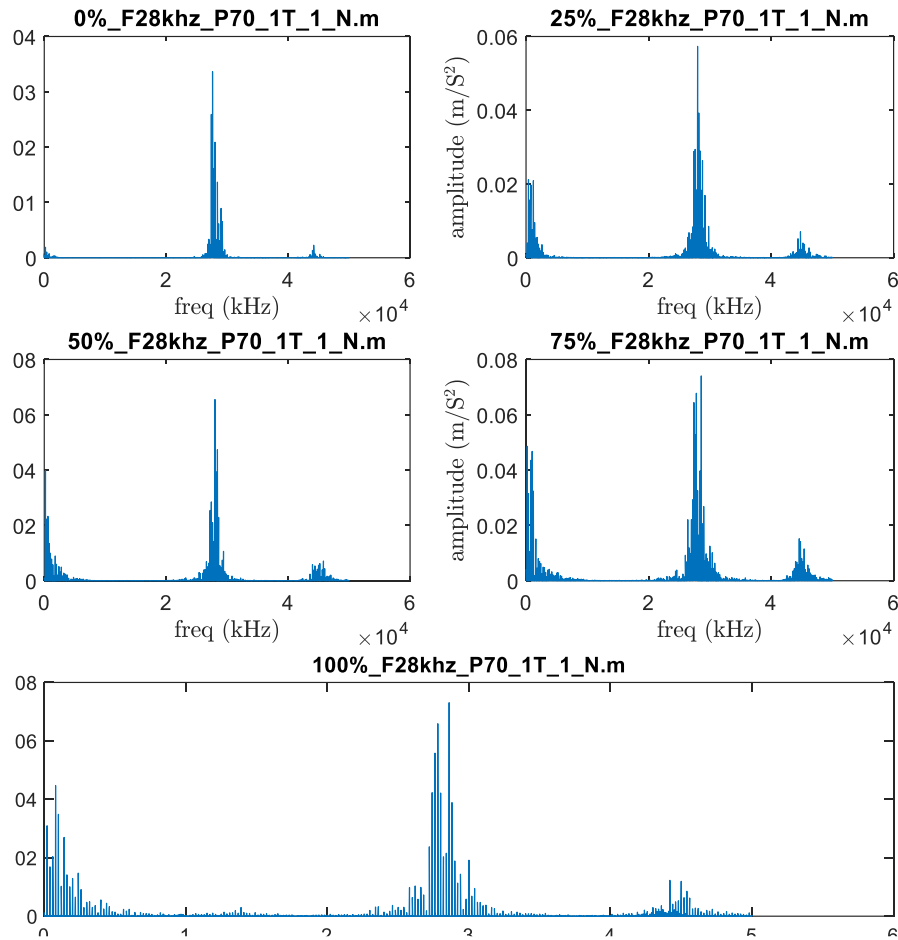


Figure A2. 3: Analysis of the lap joints vibration level for 0-100 % welding progress with a 28 kHz transducer.

The measurement was repeated with the 40 kHz transducer and the results are plotted in **Figure A2.4**. As shown in the figure, as the weld progress along the plate the vibration amplitude increases. The maximum vibration amplitude for the 40 kHz transducer, increases by 20 % compared to the one shown in **Figure A2.3**.

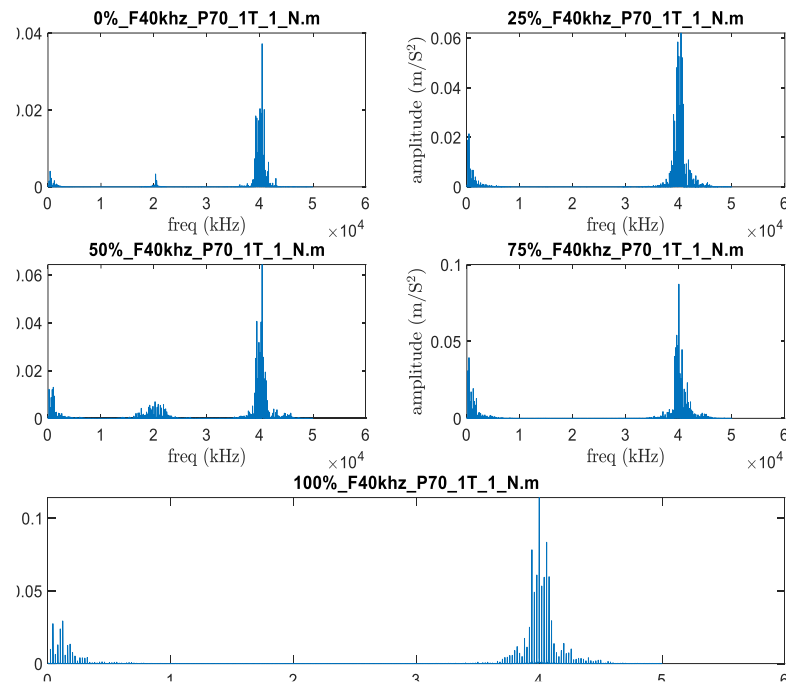


Figure A2. 4: Analysis of the lap joints vibration level for 0-100 % welding progress with a 40 kHz transducer.

Butt joints

The same procedure is followed to identify the effect of butt weld progress on the vibration amplitude. As shown in **Figure A2.5**, the vibration amplitude of the plate increases as the welding progress along the plate from 0% to 100 %.

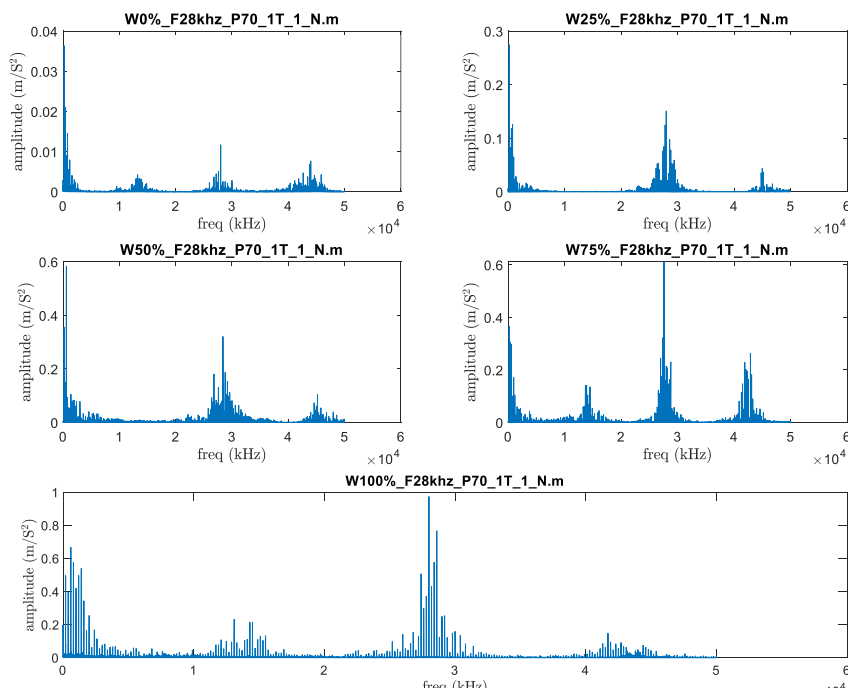


Figure A2. 5: Analysis of the butt joints vibration level for 0-100 % welding progress with a 28 kHz transducer.

The test was repeated with the 40 kHz transducer and the results are plotted in **Figure A2.6**. The vibration amplitude increases as the welding progress along the plate. Compared to the results presented in **Figure A2.5**, the maximum vibration amplitude increased with an approximate percentage of 84% at an operation frequency of 40 kHz.

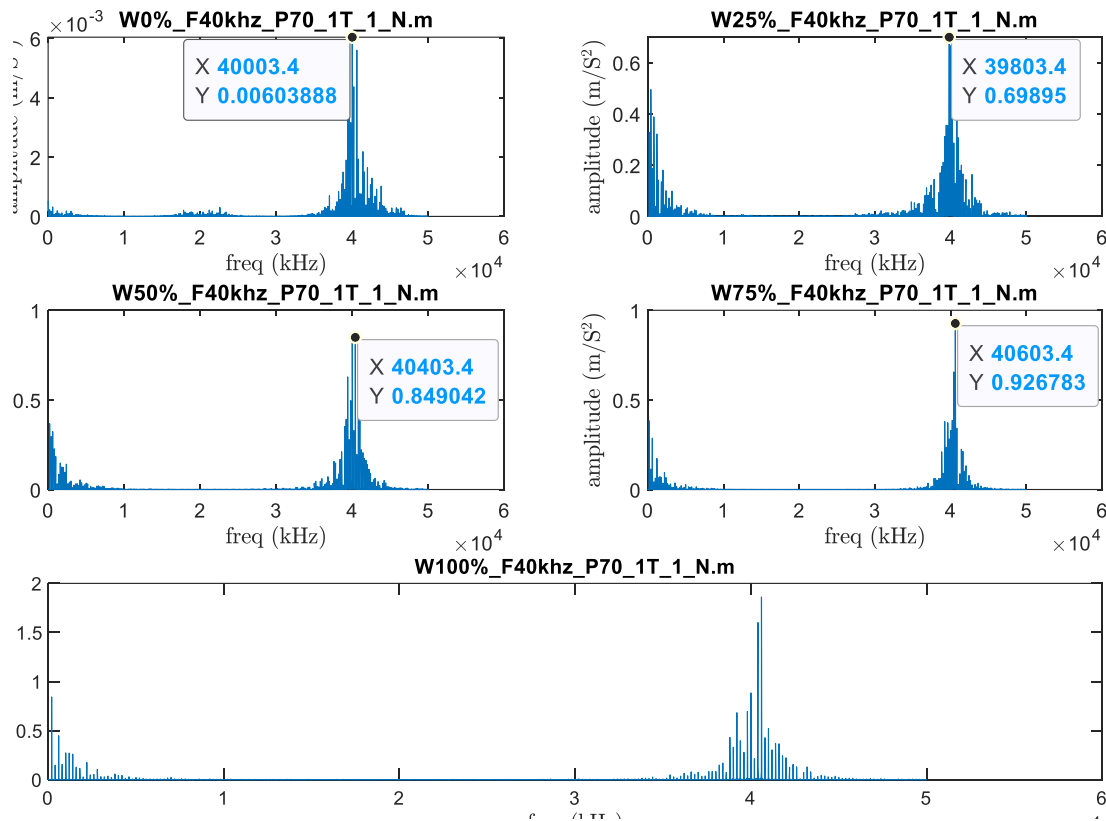


Figure A2. 6: Analysis of the butt joints vibration level for 0-100 % welding progress with a 40 kHz transducer.

It can be inferred that during the ultrasonic vibration-assisted laser welding of lap and butt joints, there is increased penetration depth to the joints to promote the creation of molten pool towards the most intricate zones within the joints. Consequently, as the welding process progresses, the increased penetration requires higher input to generate sufficient vibration displacements, resulting in higher vibration displacements.

Appendix III

Trials using In-house designed Horns for Battery Connectors Welding

Laser beam welding generates more initial heat due to its high-power fusion process when compared to other conventional joining methods. However, the rapid laser pulses result in relatively low overall heat transfer to the battery cell, which dissipates rapidly and mainly heats up the cell terminal. While higher heat levels could potentially harm the cell core, this is generally not a concern when the method is applied correctly. Laser welding of battery terminals is a vital step in the production of lithium-ion batteries, guaranteeing dependable connections between battery components. The application of ultrasonic vibration assistance to the laser welding of the battery connectors is investigated in this section. Although contactless excitation is the aim of the chapter, it is worth checking the effect of other remote vibrations that can generate mainly shear and compressional waves on the welding impedance value. The current battery head that is used for connecting the battery is illustrated in **Figure A3.1**. Several locations can be used to remotely vibrate the plate to have either shear, or compressional waves dominated. For the laser welding process, the battery is placed in the plastic cover, shown in **Figure A3.1(a)**, and the top plate illustrated in **Figure A3.1(b)** is welded to one of the battery terminals.

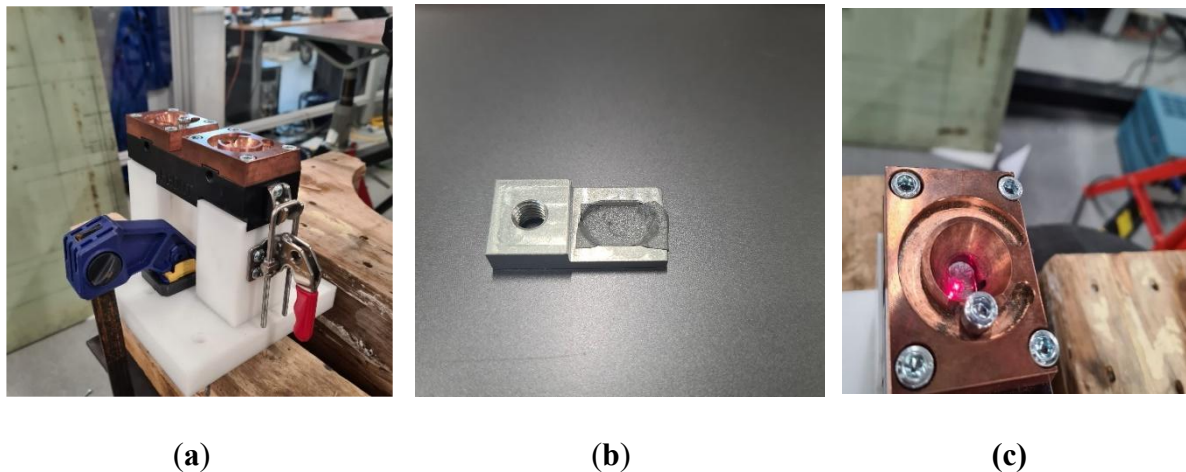


Figure A3. 1: The (a) battery plate holder used for connecting the plate to the battery head (b) the plate inside the battery head connector that will be welded to the battery head, (c) the top view from the battery head connector.

While the vibration level is expected to drop when using contactless vibration compared with contact one [198], it is necessary to find the effect of contact vibration on the welding improvement, in terms of the impedance value. For this purpose, an L shape plate was placed on a holder and the vibration level from a 20 kHz HPUT was measured using contact vibration. The needle transducer was unsuitable for contact excitation as it can slip when it is fixed to generate contact vibration on the plate. As a result, the molten pool area during the welding and solidification phase will not experience the anticipated vibration levels due to reduced coupling. Additionally, attaching the transducer for contact vibration increases its temperature to around 120°C, which can potentially distort vibration efficiency and harm the equipment [199]. Therefore, another transducer with a focused horn is used (see **Figure A3.2 (b)**). The horn end tip used in this measurement is slightly bigger than the needle transducer and hence does not slip from the plate. The industrial transducer with the needle horn is more user-friendly, however, the transducer with the focused horn used in this section is compatible with the amplifier that is developed within Brunel Innovation Centre (BIC). Before using the HPUT with the focused horn, it was characterised to find the transducer resonance frequencies.

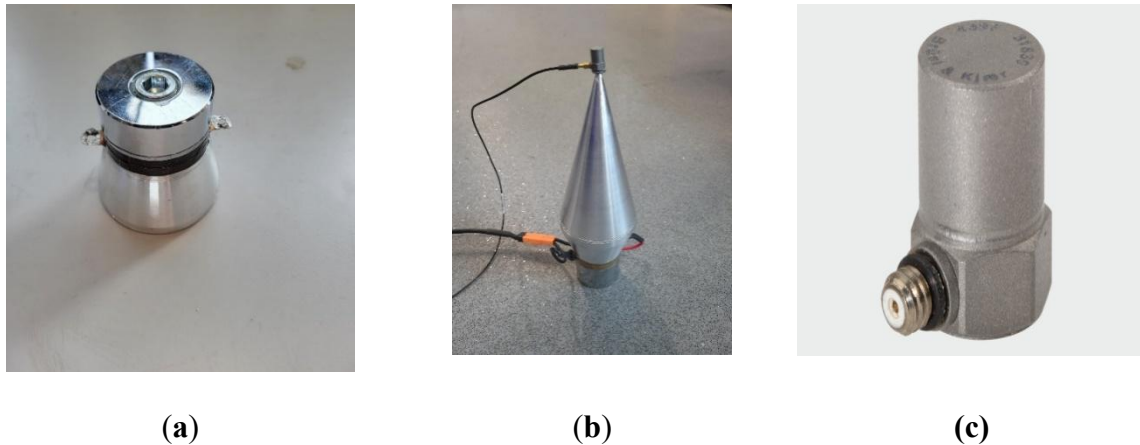


Figure A3. 2: The 20 kHz transducer used for further investigation. (a) A Plain transducer, (b) transducer with an accelerometer attached to its end tip and (c) a high-frequency accelerometer, type 4397.

A sweep sine signal, starting from 15 kHz to 30 kHz was sent from the amplifier to the transducer followed by measuring the transducer response by the accelerometer. As seen in **Figure A3.3**, the transducer without the focused horn has a single narrow band resonance frequency, at 21.8 kHz region. The power in the focused horn, however, is equally split between two narrow-band frequency regions, at 22.9 kHz and 28.1 kHz.

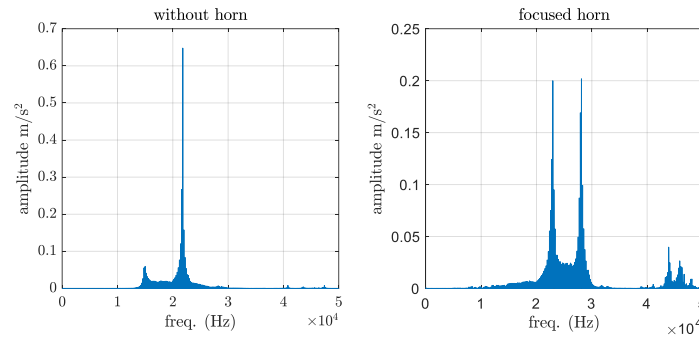


Figure A3. 3: The spectrum of the transducer (a) without and (b) with a focused horn.

The contact and contactless vibration output from the focused transducer were measured as shown in **Figure A3.4**. To find the vibration level associated with each measurement, the high-frequency accelerometer type 4397 is used (see **Figure A3.2 (c)**) to evaluate plate response. The accelerometer is operating on a single axis, hence, to record the plate vibration for the in-plane and out-of-plane excitation, the accelerometer should be oriented in the desired direction. It is expected that the vibration at a zero-degree angle generates an in-plane motion to the plate in the contact and the contactless excitation mode. From the previous assessments made on this transducer, it was found that the transducer produces the highest vibration at a 45-degree angle in contact mode. For the contactless excitation, it was found that the maximum vibration is associated with the case where there is a 15 mm distance from the end tip of the horn and the plate.

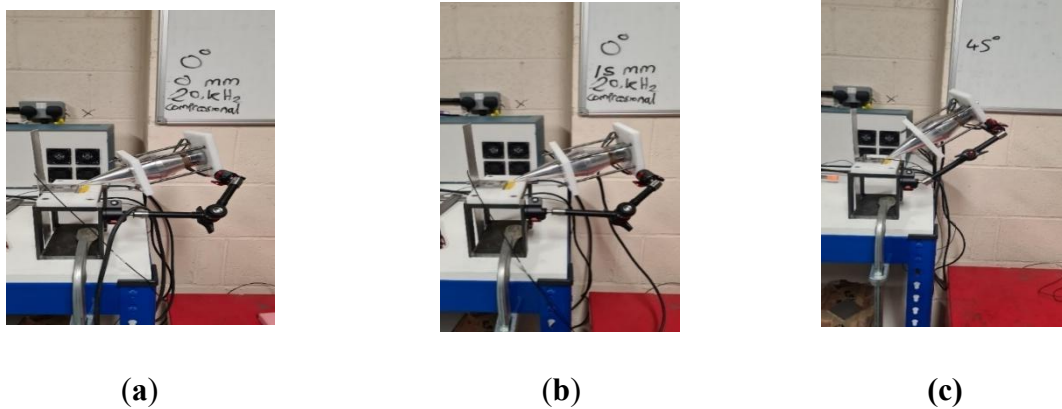


Figure A3. 4: The experimental configuration generates (a) contact, (b) contactless vibration at approximately 0 degrees and (c) contactless vibration at 45 degrees.

As illustrated in **Figure A3.5** the vibration level from the contact excitation is approximately 50 times higher in amplitude compared with the contactless one. Therefore, it is expected to have a higher intensity cavitation initiation in the molten pool area [199144 – 203148]. Intensity is defined as the power carried by ultrasound waves through a unit area normal to the

direction of propagation [204]. Low-intensity ultrasound leads to stable cavitation of microbubbles, while high intensity ultrasound leads to inertial cavitation with microbubble collapse [205].

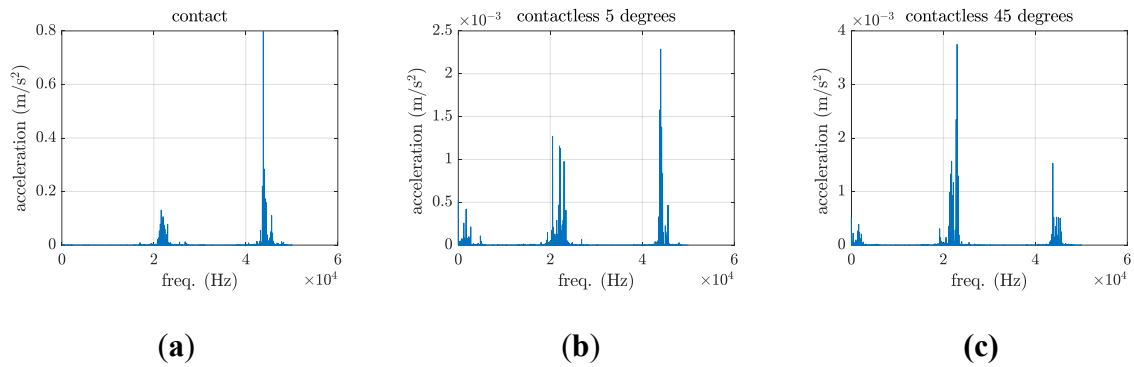


Figure A3. 5: The vibration output from the contact, contactless excitation, and contactless excitation at a 45-degree angle.

The transducer with 45 degrees generates shear and compressional waves with approximately the same amplitude. In contrast, the transducer with the 0-degree angle is expected to produce the in-plane or mainly compressional waves. The produced vibration for the contactless excitation was performed at 45 degrees with a 15 mm distance from the molten pool area. **Figure A3.6** shows the different HPUT positions for producing shear, compressional and contactless vibration at the welding molten pool area during the laser operation.

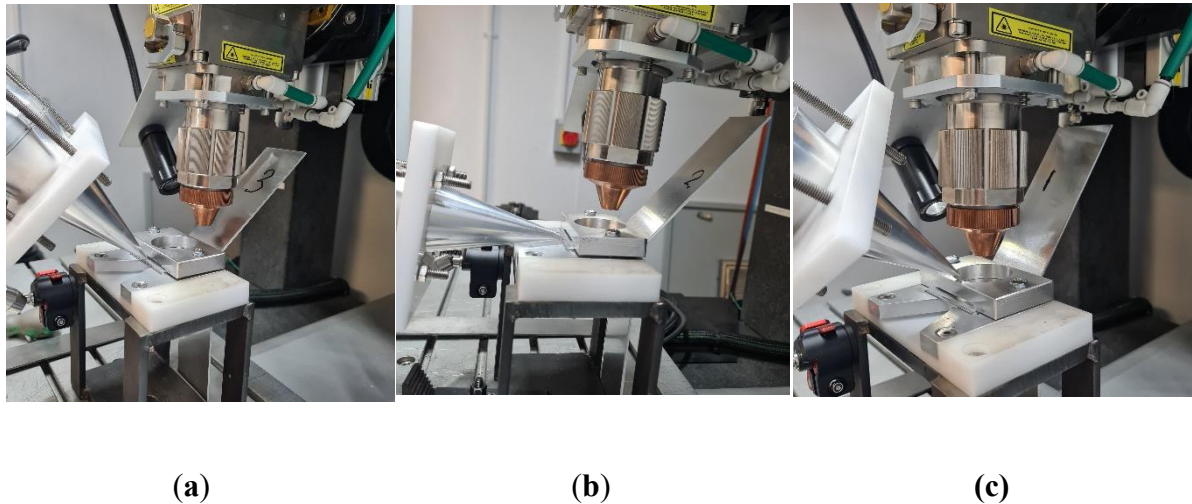


Figure A3. 6: Ultrasound vibration-assisted welding using (a) shear, (b) compressional and (c) contactless vibration.

The same procedure was followed, as explained in Chapter 4 to compare the effect of different wave types, shear and compressional waves, and contactless excitation on the welding quality regarding the impedance value.

An HPUT that can be integrated into the laser welding system has been characterised to find the optimum distance and angle from the plate to produce the maximum contactless vibration. The optimum distance to excite the plate was found to be 20 mm. The optimum angle for the out-of-plane and in-plane displacement was 60 degrees. The 60 degrees could also be the optimum angle that the piezoelectric inside the transducer to generate a higher vibration output but is not the best angle to drive mainly shear and compressional waves.

The effect of different wave types on laser welding improvement was investigated. It was shown that there is a negligible difference in the welding improvement in the impedance value for the contactless vibration compared with the contact ones. The lowest impedance value was associated with ultrasonic-assisted welding with the compressional wave, as the pure fluid cannot support shear wave propagation.

Contact and Contactless Ultrasonic Vibration

This section explores the application of both contact and contactless vibration on the plates during the welding process. To achieve the desired vibration and optimal vibration amplitude, the transducer holder is constructed using steel material. The steel holder firmly holds the transducer to prevent external interference. The contactless vibration is applied to the plates at an optimised distance and angle, which were comprehensively discussed in the previous chapter. The experimental setup for this study is depicted in **Figure A3.7**.

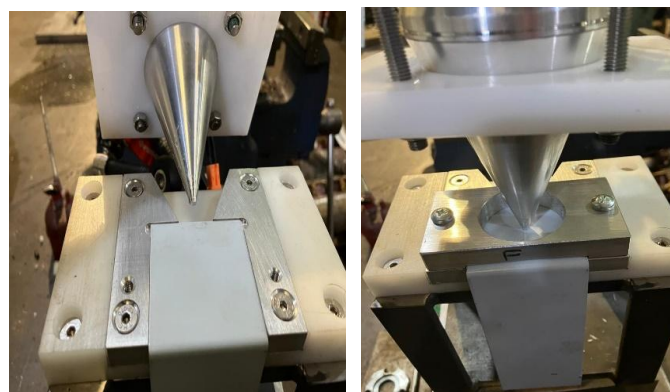


Figure A3. 7: The transducer configuration (a) placing the bottom plate and (b) placing the top holder.

As discussed earlier, it is expected that the vibration will be more noticeable with the contacted mode, leading to an improvement in material distribution and refinement in the molten pool area.

Pull Test Results

In chapter 6, the pull test results for weld samples produced at 20 kHz and 40 kHz with both small and large tip horns were discussed in detail while a summary of the mean values and standard deviations were provided in Tables 6.2 and Tables 6.3. Table A 3.1 shows the comprehensive values of the average load and final extension, as well as the corresponding standard deviations for 5 repetitions.

Table A3. 1: Pull Test Results for 20 kHz with Small and Large Tips comparing Contact and Contactless Modes

Horn Type/Diameter (mm)	Placement/Angle	Load (N)	Final Extension (mm)	Average Load, N	Average Final Extension (mm)
Small Tip/3.3	Contactless /45°	591.3	15.4	561.0	14.0
		530.3	13.7		
		562.2	12.8		
		506.2	12.1		
		615.1	16.0		
Standard Deviation		39.47	1.49		
Large Tip/33.3	Contact / 0°	486.2	8.9	530.7	10.7
		512.4	12.8		
		530.7	10.1		
		553.6	12.1		
		570.6	9.5		
Standard Deviation		29.77	1.51		
Large Tip/33.3	Contactless /45°	476.5	12.1	533.1	13.2
		507.8	11.4		
		533.1	12.8		
		558.6	15.2		
		589.5	14.3		
Standard Deviation		39.18	1.40		
No Ultrasonic Vibration	N/A	465.2	13.1	509.0	11.0
		491.8	9.8		
		507.6	9.8		
		528.1	11.9		
		552.4	10.4		
Standard Deviation		29.88	1.30		

Table A3. 2: Pull Test Results for 20 kHz with Small and Large Tips comparing Contact and Contactless Modes

Horn Type/Diameter (mm)	Placement/Angle	Load (N)	Final Extension (mm)	Average Load, N	Average Final Extension (mm)
Small Tip/3.3	Contactless /45°	504.9	10.8	527.0	12.7
		482.3	12.1		
		573.4	14.2		
		554.9	11.3		
		519.5	15.1		
Standard Deviation		33.09	1.67		
Large Tip/33.3	Contact / 0°	507.3	11.2	516.0	9.7
		538.5	8.5		
		492.8	10.1		
		570.8	7.8		
		470.6	10.9		
Standard Deviation		35.17	1.33		
Large Tip/33.3	Contactless /45°	562.1	15.1	520.4	13.0
		502.8	11.1		
		536.8	17.1		
		477.9	12.3		
		522.4	9.4		
Standard Deviation		39.18	2.77		
No Ultrasonic Vibration	N/A	465.2	13.1	509.0	11.0
		491.8	9.8		
		507.6	9.8		
		528.1	11.9		
		552.4	10.4		
Standard Deviation		29.88	1.30		

Shear Test Results

This section explores the use of contactless vibration to improve welding quality by utilizing different optimized horns. To facilitate comparison, several tests are conducted without ultrasonic assistance. A tensile test was conducted on the welded plates to examine the ductility of the welded joints. The welded plates were subjected to tensile loads at different loads, producing corresponding extensions. The test was conducted with varying ultrasonic frequencies, comparing these ultrasonic vibration-assisted tests with the scenario characterised with no input of ultrasonic waves. In the loading test without ultrasonic, the maximum applied force in the pull test is 11.4 N and the extension value of 4.7 mm is observed.

Shear test results for 20 kHz ultrasonic transducer

A focused ultrasound horn operating at 20 kHz and an industrial horn are used. One of the objectives of the study is to generate ultrasonic vibrations at specific locations that generate optimal vibrational displacements when a shear load is applied. Therefore, contact vibration is employed to primarily transmit compressional waves into the fluid-filled area. The results obtained are compared to observe the effect of transducer type and the transducer placement angle on the ductility of the welded joints. The types of transducers considered were tapered and industrial transducers, while the angles of placement were 45 degrees and 90 degrees. Tests under contactless and contact modes were also considered. The results of these experiments are summarized in **Table A3.1**. It could be inferred that the relationship there between the applied load and extension obtained obeys Hooke's Law. Generally, the trend revealed that the use of industrial transducers produced weld joints with superior ductility than weld joints produced using tapered transducers. With respect to the modes of placement, contact mode produced better results. For instance, the tapered transducer placed under a contactless mode at 45 degrees and load of 142.23 N produced an extension of 4.11 mm, while with the same transducer under the contact mode, and a load of 130.16 N, increased the tensile length of the weld by 4.9 mm. During the experiments, the laser speed was set at 2750 mm/min, and the laser power was set at 200 W. The ultrasonic power compatible with the Brunel amplifier was 70 W, while the industrial transducer had a power output of 20%. It is not recommended to increase the power amplification of the industrial horn as it tends to overheat the horn and produce low amplitude noise instead of the desired signal.

Table A3. 3: Shear test results associated with the 20 kHz with tapered and the industrial transducer

Transducer Type	Placement Angle	Load (N)	Final Extension (mm)	Average Load, N	Average Final Extension (mm)
Tapered	Contactless on the Spot/45Deg	191.99	11.36	195.82	13.96
		301.53	31.18		
		219.23	20.56		
		124.10	2.57		
		142.23	4.11		
Tapered	Contact Compressional/ 90Deg	81.19	2.17	113.01	3.22
		130.16	4.90		
		127.68	2.58		

Industrial	Contactless on the Spot/45Deg	150.0948	8.286093	173.88	12.16
Industrial	Contactless on the Spot/45Deg	211.1743	17.77847		
Industrial	Contactless on the Spot/45Deg	151.0384	7.39504		
Industrial	Contactless on the Spot/45Deg	183.2179	15.19137		

Shear test results for 28 kHz ultrasonic transducer

The same procedure is followed for the 28 kHz and the results are tabulated in **Table A3.2**. Considering the tapered transducer, the experiment showed that under the contact mode, the nature of ductility of the weld joint was superior to the ductility of the weld joint under the contactless mode. From the table, the average load for a 28 kHz tapered transducer under the contact mode, subjected to an average shear load of 119.36 N produced an average final extension of 6.05 mm, while under the contactless mode, a higher average load of 119.7 N produced a smaller extension of 4.95 mm. This may be an indication that the contact mode provided stronger acoustic waves that led to an improved distribution and discontinuity of brittle inter-metallic compounds formed during the laser welding process. This comparison is considered due to the minute difference between the average shear load applied, which is easier to compare their resulting extensions.

Table A3. 4: Shear test results associated with the 28 kHz with tapered and the focused horn

Transducer Type	Placement/Angle	Load (N)	Final Extension (mm)	Average Load, N	Average Final Extension (mm)
Focused	Contactless on the Spot/45Deg	92.1241	4.25	113.47	5.20
		68.58	1.41		
		130.67	7.26		
		157.58	8.16		
		118.38	4.90		
Tapered	Contact Com- pressional/ 90Deg	174.42	14.12	119.36	6.05
	Contact Com- pressional/ 90Deg	90.28	4.28		
		127.60	3.44		
		78.20	1.22		
		129.14	5.40		
		116.51	7.86		

Tapered	Contact Com- pressional/ 90Deg	111.04	4.76	111.04	4.766
Tapered	Contactless on the Spot/45Deg	114.73	2.41	119.70	4.95
		133.81	5.78		
		125.88	7.23		
		77.44	1.94		
		146.62	7.37		

Shear pull results for 40 kHz ultrasonic transducer

Furthermore, the welding process was carried out using the 40 kHz power ultrasonic transducer. The outcomes corresponding to this specific frequency are depicted in **Table A3.3**. To compare the contact mode results with the contactless mode results using tapered transducer, no significant trend could be inferred from individual tests. Variations could be because of metallurgical defects, material discontinuity within the microstructure of the weld joints.

Table A3. 5: Shear Pull test results associated with the 40 kHz with tapered and the focused horn.

Transducer Type	Placement Angle	Load (N)	Final Ex- tension (mm)	Average Load, N	Average Fi- nal Exten- sion (mm)
Conical	Contactless on the Spot/45Deg	170.13	9.27	173.29	12.91
		152.50	11.95		
		191.21	16.01		
		225.76	18.90		
		126.86	8.45		
Tapered	Contact Compres- sional/90Deg/Top	83.81	3.253	125.7393	7.31
		105.19	5.061		
		128.29	7.397		
		167.00	11.23		
		144.39	9.61		
Tapered	Contactless on the Spot/45Deg	93.05	2.37	164.97	11.75
		182.47	10.25		
		235.33	23.39		
		147.20	10.38		
		166.82	12.36		

Contact Ultrasound to assist Laser Welding of Al-Cu Joints

An L-shaped plate was initially used to evaluate the integrity of the ultrasonic vibration. Laser beams possess the capability to concentrate their energy into minute spots, with diameters

measuring less than a millimetre. This concentration results in power densities ranging from 10^3 to 10^7 watts per square millimetre, which can be effectively applied to the welding joint. This intense energy allows the formation of a 'keyhole' weld beneath the point of laser beam impact. The keyhole, efficiently absorbing laser energy, facilitates the creation of low heat-input welds. Notably, high productivity arises from the rapid processing speeds achievable in thinner materials and the ability to accomplish deep penetration welds in thicker materials with a single pass. These productivity benefits, coupled with the automated nature of laser welding, make it a reliable and repeatable method for autonomous welding operations [206]. However, as a result of defects and voids that are commonly found in laser welded joints, the application of ultrasonic waves into the melt pool during the laser process has shown promising results. Here, the acoustic waves were propagated into the melt-pool to enhance the quality of the welds. Similar to the previous section, the vibration was applied at various frequencies, specifically 20 kHz, 28 kHz, and 40 kHz.

Appendix IV

Butt Joint

Following the potential results from the preliminary experimental study where the plates are printed simultaneously with the horn vibration, in this section further study is carried out to optimise the vibration output from the transducer horn.

We used 3 different transducers with the natural frequency of approximately 20 kHz, 28 kHz and 40 kHz. To make the vibration level at its optimum value, the horn length should be proportional to the half of the wavelength associated with the transducer. Table A4.1 proposes the dimensions for the horn length at the varying natural frequencies.

Table A4. 1: Proposed dimensions for the horn length with different natural frequencies

Transducer [kHz]	Length L [mm]	Outer diameter OD [mm]	Tip Diameter TD [mm]
20	127	66	3.3
28	91	66	3.3
40	62	45	2.25

In this study three different transducer configurations were selected for further study: (a) cylindrical (b) conical and (c) step horn. Furthermore, the same horn dimension was selected for all the transducers. To model and simulate the real case, the piezo electric inside the transducer is designed and modelled in this study. Since the scope of this work is to design and propose the optimal horn shape, a single frequency was considered for the optimization process.

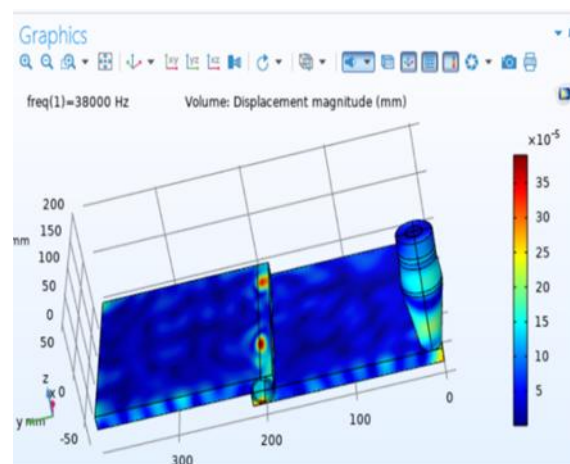


Figure A4. 1: The piezo electric that generates vibration. The back mass of a transducer where the horn

At approximately 22 kHz the transducers generated optimal vibrations, transmitted to the horn. The piezo electric cover served as a back mass for the horn. It was observed that, having a horn with a dimensional length of the half of the natural frequency wavelength yielded a high amplitude vibration at the transducer horn.