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Research Article

Mechanical vibration-assisted enhancement of weldment mechanical properties

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ABSTRACT

The paper explores ways to increase the mechanical properties of weldments such as tensile strength, hardness and impact toughness by using mechanical vibrations when performing the actual welding operation. As interest in using vibration for improving welded joints continues to rise, the authors of this study sought to gain insight on the mechanism by which mechanical vibrations create enhancement and also for optimizing the setting of parameters that can create better mechanical performance within welded joints. In order to carry out this investigation, a proper welding procedure was developed along with an experimental apparatus that included a mechanical vibration assisted welding system to apply mechanical vibrations to the welded area during the welding operation. Following the completion of a proper welding procedure, a number of standardized mechanical tests were conducted to determine the mechanical characteristics of the resulting welded joint. Results indicate that the presence of a mechanical vibration applied during the welding operation has a direct impact on the microstructure of the welded joint, resulting in reduced porosity, improved bonding at the joint face, and higher mechanical performance. Thus, compared to conventional welding methods, vibration-assisted welding allows for significantly higher tensile strength, hardness, and toughness. The relationship between Process Parameters and Weld Quality was examined along with Insights for Optimizing Process Parameters. The results from this study provide Evidence that Vibration Assisted Welding is a Feasible Process to Improve Weldment Properties when Implemented in Industry today. Future studies should be conducted using different Methods of Welding and focused on clarifying the Vibration Parameters used; additionally, the Long Term Performance of Vibration Enhanced Weldments needs to be evaluated.

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INTRODUCTION

Welding processes are an important part of the manufacturing process for a variety of products such as; automobiles and aerospace vehicles, along with buildings. Welding processes are utilised to create strong joints between metal parts. However, conventional welding processes often produce welds that do not exhibit adequate mechanical properties due to inappropriate microstructure of the welds and the potential for weld defects such as porosity and cracking.

Developing other methods for increasing the mechanical properties of welds has been a topic of interest to researchers and engineers for many years. One method of improving the mechanical properties of welds is through the application of mechanical vibrations while performing welding procedures.

The application of mechanical vibration during the welding process creates dynamic forces that are introduced into the molten metal during the welding process and results in creating the desired microstructure; Increasing the bond strength at the interface of the weld. Research has demonstrated that the introduction of mechanical vibration during weld formation reduces the amount of porosity in the weld and improves the mechanical properties of the weld (i.e. Tensile strength, hardness and impact toughness) by producing a finer grain structure as compared to a conventional weld without vibration.

Although the utilisation of vibration to improve weld properties is a concept that has existed for years, advancements in technology and materials sciences have facilitated additional research on the benefits of utilising this technology and its application in improving the properties of welds.

Researchers have demonstrated that the mechanisms involved with controlling vibration during a welding operation can improve the mechanical properties of a welded joint. Specifically, Rao et al. created a vibratory welding system that provided mechanical vibrations to the weld pool. This system allowed for greater refinement of the microstructure and improved mechanical properties. Examples of improvements to the mechanical properties of welded components include [1]. Flexural strength, ultimate tensile strength (UTS), impact strength, and hardness; all exhibited improvements when utilized in conjunction with the vibratory welding process. The mechanical vibrations produced by the vibratory welding system were able to increase flexural strength and strengthen the mechanical properties of regions located within the heat-affected-zone (HAZ) of the welded component. In addition, the application of mechanical vibrations prevented excessive dendrite growth during the solidification of the molten metal and facilitated the refining of the microstructure [2]. In addition to researching how to improve the mechanical properties of welded components using mechanical vibrations, researchers have also explored the relationship between UTS and creating uniformity and fine-grained structures during the welding process using dynamic solidification effects as a means of developing a predictive capability based on two input parameters (vibration voltage and vibration time) [3]. Rao et al. [4] demonstrated that the introduction of mechanical vibrations to the weld pool can significantly increase the tensile strength of the welded component. The gains achieved in tensile strength were attributed to a greater refinement of the microstructure and reduced dendrite size within the HAZ of the welded component.

As Ramakrishna and his colleagues pointed out, welding can impact the metallurgical properties of the parts involved. They proposed many procedures to improve mechanical characteristics, one of which was Post-Weld Heat Treatment or PWHT. Ding and his colleagues performed PWHT studies on aluminium alloy AA2219 and Ahmed and his colleagues researched PWHT on Cr-Mo Boiler Steel, both showing that PWHT could enhance the mechanical characteristics of welded assemblies at particular temperatures [5]. A more recent invention called Ultrasonic Complex Vibration Welding has superior output performance when compared to more common Linear Vibration Systems, since Ultrasonic Complex Vibration Welding employs a dual-axis vibration stress to join metals. The application of Ultrasonic Complex Vibration Welding has created a new opportunity to weld diverse component types like wedged foil electrodes of aluminium and Copper widely used throughout battery technology and electronic markets [6]. The advancement of ultrasonic complex vibration welding has provided a means to weld electronic assembly parts in narrow spaces without requiring electric resistance welding, thus avoiding the creation of welding defects due to the presence of metal particulate contamination [7]. Using an ultrasonic apparatus at either 20 kHz or 27 kHz and a custom-designed welding tip, one can achieve equivalent weld strength to that of the base metal when joining Copper, Nickel-Clad Copper and Steel or Nickel-Coated Steel. Ultrasonic complex vibration welding uses two-dimensional vibration energy to produce the highest-quality joining properties for dissimilar metals and foils than conventional linear ultrasonic welding when joining dissimilar materials. Important examples of this technology include the joining of aluminum and copper in electrode foils for use in most electronic devices, lithium-ion batteries (Li-Ion), electric double-layer capacitors (EDLC), and many industrially manufactured components. A number of different welding tip designs have been developed and investigated for their vibration and effect on welding characteristics in order to join a wide variety of materials [8].

Prior to the development of ultrasonic complex vibrations, ultrasonic welding did not have the capabilities to weld deep and remote locations. Therefore, the two most commonly used methods of welding were electric resistance welding and laser welding, both of which were susceptible to critical defects due to the melting and ejection of metal particles. The introduction of elongated, circular to elliptical-shaped vibrating tips and improvements such as the implementation of high-tech vibration-velocity detectors and static-pressure control systems have increased the effectiveness of ultrasonic complex vibration welding systems [9]. Emerging evidence demonstrates the advantages of applying two-dimensional (2-D) stress at the weld point when performing Ultrasonic Metal Welding (UMW). To accomplish this, a new type of complex vibration source has been created that connects a longitudinal transducer and a torsional transducer on opposite ends of the welding horn. This design permits for individual adjustment of longitudinal and torsional vibrations creating a 2-D vibration path for the purposes of welding [10]. Liu and others have utilized a more sophisticated method using Empirical Mode Decomposition (EMD) as a method for measuring residual stresses in metal components based upon the vibration signal generated from elastic waves propagating through the component being tested. The results indicated by experimental testing on complicated welded assemblies such as automotive frames, rail vehicle structures, and aerospace components provide ample evidence of the methods ability to aid in developing an economical, non-destructive means of estimating residual stresses on welded components [11]. The influence of electromagnetic (EM) vibration on the gas tungsten arc welding (GTAW) process was studied by Sabzi and colleagues who found that increasing the intensity of the EM vibration had a positive impact on many areas including reducing columnar dendrites, converting microstructure from columnar to equiaxed dendrites, decreasing delta ferrite content, improving overall mechanical properties and reducing hot cracking susceptibility. All these changes resulted in more ductile fracture modes occurring in welded joints [12].

Ultrasonic vibration introduced to local dry underwater welding (U-LDUW) was presented by Liao et al. as a new method, enabling improvements in several areas such as reducing grain size, increasing ferrite, breaking up dendritic crystals, and improving the mechanical properties when compared to other forms of LDUW. U-LDUW holds promise for solving problems involved with welding large underwater structures [13]. Ultrasonic welding of Aluminium-Titanium alloys was carried out by Feng et al., producing satisfactory metallurgical bonding with a shear load of 3650N. Electron backscatter diffraction analysis confirmed that dynamic recrystallization took place at the interface of the Aluminium-Titanium alloys, due to the combined effects of heat and plastic deformation [14]. Dey et al. [15] emphasized the importance of vibration welding (VW) for bonding thermoplastics and composites and demonstrated its advantages compared to other techniques. The investigation focused on determining the relationship between VW joint design, processing parameters, and material properties in relation to joint strength, with a goal of determining the influence of optimal processing, material choices and design approaches on increased weld strength. Shi and Lin [16] conducted a study using an optical crack measurement method to evaluate the Environmental Stress Cracking Resistance (ESCR) of nano-silica reinforced Polycarbonate (PC) nanocomposite made with 1 Vol.-% nano-silica. They concluded that the degree of improvement in ESCR for the two Stress Cracking Agents (SCAs) varied. Increasing ESCR was significantly improved in water (DI Water) and slightly improved in isopropanol. The difference in the degree of improvement was theorized to be caused by the plastic deformation response of nano-sized silica.

Khmelev et al. [17] provided a detailed account of their development of a stand specifically designed for the quality control of welds produced using ultrasonic welding. The objective of this stand is to provide the inspector with a visual view of the welding process while at the same time providing the inspector with the ability to adjust the welding parameters to obtain the best possible weld quality. Weld cladding is a surface modification method to protect components used in corrosive environments and it uses gas tungsten arc welding (GTAW) to optimally adjust the parameters of welding. Gill et al. [18] focused on the preheated filler wire in conjunction with the GTAW process to enhance the quantity of clad deposited while also reducing the dilution of the base metal and narrowing the width of the Heat Affected Zone. They investigated the obstacles to using this process and the opportunities presented. Gill et al. [18] also looked into ways of optimally using preheated filler wire during GTAW. They looked for ways to optimize clad deposition while reducing the dilution of the base metal and reducing the width of the heat affected zone (HAZ). They discussed the challenges and potential improvements using preheated filler wire in GTAW. UVFSW has been found to have a positive impact on both microstructure and mechanical properties of aluminium and titanium alloys, through Improvements in the formation of intermetallic compounds; improving the appearance of the welds; and reducing the amount of flash and size of the waves, which suggests enhanced material flow. The use of UVFSW resulted in a fragmented Titanium base, resulting in titanium particles located at the interface between the two materials. In comparison to FSW, UVFSW produced an ultimate load of 4.40kN @ 1000 RPM while FSW yielded only 2.52kN @ 1200 RPM with a more ductile failure mode [19]. A different study evaluated how mechanical vibration during the gas metal arc welding process influences the properties of AA6061-T6 aluminium alloy. The results indicate that mechanical vibration increases tensile strength by a maximum of 83.3% when performed at 300 Hz, primarily due to an improved grain structure. The authors concluded that the lack of intermetallic compound formation results in improved corrosion resistance of vibration-assisted welds [20].

Novelty and Objective of Research Work

- The goals of this research were to identify the mechanism(s) responsible for the improvement of welding properties due to mechanical vibration and develop optimal process parameters for maximum performance in the welded product. The experimental investigations conducted for this research provided the following novel findings:

- Optimal settings of mechanical vibration parameters (frequency, amplitude) that maximized the mechanical properties of the welded products were identified.
- A unique experimental design to conduct vibratory treated arc welding processes with MS1018 was developed and mechanical properties of the completed weldments were characterised based on ASTM Testing procedures.
- Statistical analyses were used to verify that the mechanical properties achieved represent the maximum achievable based on the mechanical vibration parameters applied.

Material Composition

The research aims to determine how mechanical vibration influences the strength of mild steel welds. To carry this out, research utilized 5 millimetre thick 1018 mild steel (MS) Plates as the primary material to be studied. Prior to testing, each sample was thoroughly created to ensure all samples were the same preparation and have no environmental factors affecting results. The chemical makeup of the 1018 MS Plate is located in Table 1; it includes predominantly iron (Fe) (98.81%-99.26%). The Carbon (C) content is very low, 0.18%, providing excellent Weldability and Formability. Manganese (Mn) content is between 0.6%-0.9% providing high strength and hardness. The Maximum allowable concentrations of Phosphorus (P) and Sulphur (S) in the chemical composition of 1018 MS is 0.04% and 0.05%, respectively; anything over these amounts will adversely affect the mechanical characteristics of the MS Plate. The 1018 Mild Steel exhibits desirable characteristics of excellent Weldability, Machinability and Cost Effectiveness; therefore, it is the preferred choice for a variety of applications in the manufacturing and construction industries.

The chemical make-up and element content of the E 6010 filler electrode can be seen in the above table (Table 2). Carbon, which accounts for 0.08%, affects both the strength and hardness of the electrode and will also influence the properties of the weld joint. Manganese, on the other hand, makes up 0.5% of the composition, enhancing the strength and ductility of the metal. Silicon, present at a level of 0.4%, aids in the deoxidation of the weld metal while also providing good fluidity during the welding operation. The composition of the E 6010 filler electrode has been developed to provide the user with an electrode that will provide stable arc characteristics, good weld bead appearance and compatibility for all types of welding applications.

Researching 1018 mild steel was important for this investigation since it is frequently used in many industries due to the material›s exceptional mechanical and weldable properties. Testing with 1018 mild steel plates was also advantageous because 1018 mild steel offers the greatest mechanical properties, including very high ductility and weldability. Additionally, the 5 mm thickness of the 1018 mild steel plate was selected because it represents an average thickness in many industries and provides practical relevance while remaining feasible for experiment purposes.

The E6013 filler metal electrode was chosen because of its compatibility with 1018 mild steel, its ease of use, its ability to produce smooth weld beads with minimal defects, and its significant importance to the overall results of the study. The electrode is also the most popular filler electrode used in several of these same applications. Therefore, this research should have practical application to other real-world situations as similar results have been presented in other published literature.

By focusing on 1018 mild steel, this research should provide a good foundation to be used in a wide variety of practical applications. The sample preparation process included cutting 11 018 mild steel plates down to precise dimensions using advanced machining techniques. Additionally, the surfaces were thoroughly cleaned and ground to remove contaminants and other imperfections that could interfere with the welding process, ensuring that the surfaces were free of any defects prior to welding.

A study was conducted to examine how mechanical vibration affects the mechanical properties of mild steel weldments. The study was conducted by welding samples using the chosen welding method while applying the mechanical vibration that was introduced into the welds. The experimental parameters were carefully controlled to ensure that a true evaluation could be made of the influence of mechanical vibration on the welded samples. After completing the welding, different mechanical testing of the welded samples was performed to determine their physical properties. Mechanical tests include tensile strength test

Table 2. Composition of E6013 filler electrode

Elements	Carbon (C)	Manganese (Mn)	Silicon (Si)
%	0.08	0.5	0.4

Table 1. Composition of 1018 mildsteel

Elements	Iron	Carbon	Manganese	Phosphorous	Sulphur
%	98.81-99.26%	0.18%	0.6 - 0.9%	0.04% max	0.05% max

for evaluation of welded joint›s strength; hardness tests for determination of welded material›s relative resistance to deformation; and impact tests for evaluation of the toughness of the welded specimens. Identification of how the application of mechanical vibration had a positive effect on the physical properties of the welds of mild steel was made by analysing the results from the mechanical tests.

MATERIALS AND METHODS

A vibratory welding system was created to include mechanical vibration in the welding procedure. The purpose of the vibratory welding system is to add mechanical vibrations, in a controlled manner, to the welding setup for the benefit of both the weld process and the properties of the final weld. The vibratory welding system consisted of a vibration generator, e.g., a vibrometer, coupled to the welding equipment for the purpose of generating the mechanical vibrations for this study. The methodology employed in this study is represented as a flowchart in Figure 1.

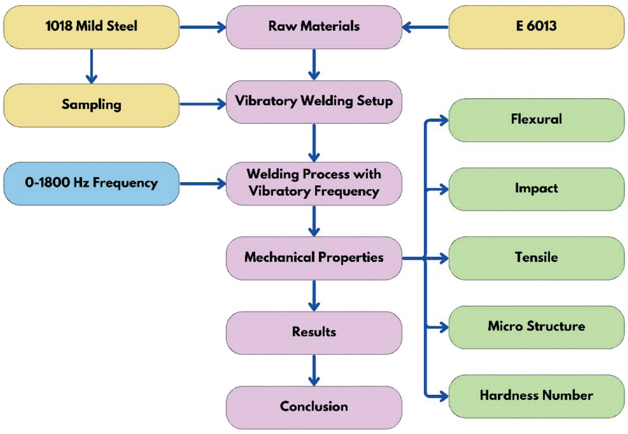

Figure 1. Experimental procedure.

Numerous different calibrated instruments have been used to measure the parameters connected to vibration, including a dimmer to control the voltage to the vibromotor, an ammeter to follow the electric current to the system and a voltmeter to record the voltage supplied to the system, which provided the investigators with precise control of the frequencies and amplitudes of the vibrations they created during their experimental investigation of vibration effects. Depending on how much voltage is supplied to the vibratory welding machine, vibrations can consist of frequencies from 0 Hz to 1800 Hz. The investigators used these frequency ranges to research the effects that frequency variations have on the mechanical character and properties of the weld produced during their experimental investigation. By manipulating the frequency and amplitude of the vibrations, the investigators determined the optimal conditions required to obtain the best mechanical characteristics of the welded component.

The project used Metal Arc Welding and an E6013 electrode for welding. The interface allowed for a level of flexibility and control over the welding process which allowed for the investigation of the effects of mechanical vibrations on the welding process as well as the resulting properties of the weld.

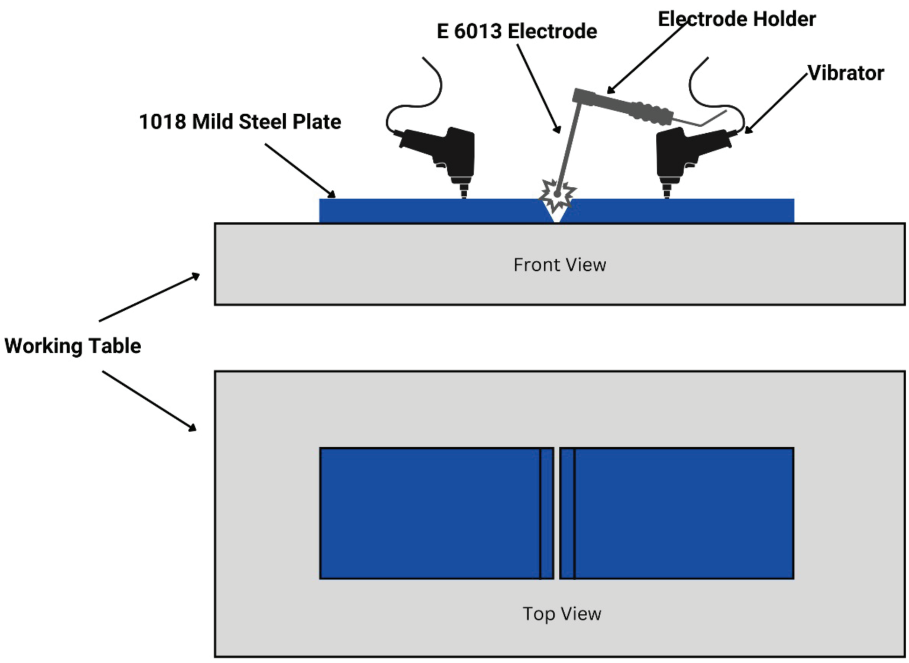

Figure 2. Schematic of vibratory welding experimental setup .

The ability of the system to regulate and record vibration parameters provided dependable, reproducible results that further advanced our knowledge of how mechanical vibration improves weld quality and performance. The principal mechanical properties used to define material performance (primarily metals and alloys) under a variety of loading conditions are: flexural strength, ultimate tensile strength (UTS), and impact strength. These mechanical properties reveal whether or not a weld has been successfully created, as these are three of the most important characteristics to determine how strong a material is.

The flexural strength of a material, or how well it withstands bending forces, is an important mechanical property of structural materials such as beams, columns, and bridges, which must support bending forces. Flexural strength is evaluated in a flexural test in which a sample is supported at both ends and bent until it fails; this evaluation provides a direct measure of the material's flexural strength. Material composition, microstructure, and processing conditions influence the flexural strength of a material. The higher the flexural strength of a material, the better it is able to resist bending forces and less likely to fail under bending loads. Thus, high flexural strength is critical for ensuring structural integrity and safety in engineering design.

In testing for Flexural Strength using the 3-Point Bend Test, a specimen is loaded in the middle until the specimen fractures. Because of the data it generates regarding the specimen's Bending Modulus of Elasticity (E B), Bending Failure Stress (σ f), Bending Failure Strain (ε f) and the specimen's performance under Bending Stress (B S) or (F C), it closely simulates real life conditions. If the specimen has the correct geometry and load directionality, there should be only minor variations in the resulting values; therefore control of the specimen geometry and load directionality, during testing, is critical for producing the most accurate test results. The 3-Point Bend test was performed in accordance with the standards outlined in ASTM D790 using a Universal Testing Machine (UTM) with an appropriate Fixture to ensure accurate positioning of the specimen and loading of the load cell. The fixture was designed and built to enable measurement of Flexural Stress based on the equation (1).

$$\sigma_f = \frac{(3PL)}{(2bd^2)} \tag{1}$$

Where, σ_f represents the flexural stress, P is the maximum load applied to the specimen, L is the span length between the supports, b is the width of the specimen, d is the thickness of the specimen

The experimental analyses yielded substantial data pertaining to the behaviour of welded connective elements subjected to bending loads. An observed trend that as weld power increases during welding via raising the vibromotor amplitude and voltage input, this increase results in an increase in flexural strength (the resistance of a material to outward bending) of each of the welds made. Therefore, it can be inferred that mechanical vibration enhances the quality/performance of welds in terms of improving their flexural strength and as such should be included within the manufacturer's design methodology for welded joint design and manufacturing to create more reliable and resilient structures. The analysis of a stress/strain curve will enable identification of the following critical material mechanical properties, Ultimate Tensile Strength, Yield Strength, Modulus of Elasticity, Percent Elongation at Fracture and material mechanical behaviour. These material mechanical properties are utilised by engineers when determining which material is most appropriate based upon the required engineering design specifications.

Analysis of the stress-strain curve allows determination of crucial mechanical properties like UTS, yield strength, modulus of elasticity, and elongation at fracture. These properties offer insights into material mechanical behavior, aiding material selection and engineering design. UTS, a critical parameter in material selection and engineering design, signifies the maximum stress a material can withstand without breaking. Materials with higher UTS values are deemed stronger and more suitable for applications where tensile strength is paramount, such as structural components, aerospace, and load-bearing elements. UTS is commonly determined via a uniaxial tensile test, where a material specimen is progressively subjected to increasing tensile force until fracture occurs. The Eqn. (2) is used to computeUTS.

$$\sigma_{UTS} = \frac{F_{max}}{A_0} \tag{2}$$

Where, σ_{UTS} is the ultimate tensile strength, F_{max} is the maximum load applied to the specimen, A_0 is the actual cross-sectional area of the specimen To ascertain the ultimate tensile strength (UTS) of materials, tensile tests performed on Universal Testing Machines (UTM) of standardized test specimens, such as those outlined in ASTM D638, are conducted to achieve a uniform testing and opportunity for precise end-user comparison across multiple laboratories/studies where the same material has been tested as described within this standard. The specimens will be standard in dimension and/or shape, thus enabling meaningful comparisons between laboratory and/or field testing end results involving UTM testing of materials. Once the specimen is attached to the testing apparatus, it is subjected to a progressively increasing tensile load until the specimen breaks due to the application of progressively increasing force to the specimen. During testing, extensometers and/or similar measurement devices will continuously monitor the elongation of a defined portion of the specimen. After testing has been completed, elongation data will be used in conjunction with data regarding load applied to the specimen to develop a stress-strain curve that defines the behaviour of the material under tension. Engineering strain (ε) will be calculated using elongation data as defined in the following formula; Eqn (3).

$$\varepsilon = \frac{\Delta l}{l_0} = \frac{l - l_0}{l_0} \tag{3}$$

Where, ε is the engineering strain, ΔL is the change in gauge length, L_0 is the initial gauge length, L is the final length of the gauge section, The engineering stress $\sigma = \frac{F_n}{A}$, F_n is the force applied to the specimen, A is the cross-sectional area of the gauge section. The ultimate tensile strength (UTS) of a material typically reveals two very important mechanical properties of the material: strength and ductility. Therefore, materials with a high UTS can undergo significant deformations prior to rupture (fracture). This is an important property for materials subjected to dynamic or high-speed loads, which are often associated with failures caused by excessive deformation. UTS is, therefore, an extremely important property to consider when selecting materials or when designing engineered structures or components and for evaluating the structural integrity of materials. In addition, determining a material's UTS will assist in ensuring that a structure is designed and constructed to be safe, reliable, and functional in various engineering discipline applications.

Impact strength or toughness is another mechanical property of materials and refers to a material's ability to absorb energy and undergo plastic deformation prior to brittle fracture under impact. Toughness is critical when selecting materials for numerous applications subject to sudden, high-speed impacts, such as automotive and aerospace components and structures. Impacts may be quite severe and therefore it is necessary to possess the ability to quantify a material's impact strength through the use of one of the many standardized test methods such as Charpy and Izod. These tests induce an impact on a notched sample with a pendulum and then the amount of energy absorbed in breaking the sample is measured to provide an indication of that sample's ability to withstand impact-induced fracturing.

Effectiveness of welding processes is determined through the measurement of fracture toughness of welded specimens using Izod impact testing. The mechanical vibration generated during the welding process allowed controlled application of mechanical vibration on the specimen to assess impact toughness through the Izod test. The results of this study indicate a positive relationship between energy absorbed at fracture and the amplitude and acceleration of mechanical vibrations applied to the specimen controlled by voltage to the vibromotor. Mechanical vibration applied during welding also has significant positive effects on bonding quality, microstructure refinement, reduction of porosity, and improvement of impact toughness. The positive correlation discussed above indicates the potential for the use of mechanical vibration to improve the impact toughness of welded joints. The factors affecting impact strength include material composition, microstructure, and processing methods. High impact strength results in greater toughness and resistance to fracture when subjected to impact loads, therefore, it is of utmost importance for the safety and reliability of equipment and structures. Improving impact strength can be accomplished by alloying, heat treating, and the use of reinforcement fillers and/or fibers to increase the ability to absorb energy and resist plastic deformation. The impact strength must also be understood to ensure that equipment and structural components will safely and reliably perform as required when exposed to high-velocity impacts.

RESULTS AND DISCUSSION

The study's findings section includes data and evaluations derived from experiments testing the effect of mechanical vibration on welded joint mechanical properties. It contains an overview of all equipment and procedures used in the experiments and the results of performed tests such as three-point bend and Izod impact tests. This section also demonstrates how changing mechanical vibration parameters (amplitude and voltage input) affects flexural strength and impact toughness of welded joints. Results allow direct comparison between welds produced using mechanical vibration and those made without this technique, providing an assessment of the effectiveness of mechanical vibration

Table 3. Experimental results

Frequency (Hz)	Flexural stress (MPa)	Tensile strength (MPa)	Impact strength (J)
0	496.30	313.00	104.00
200	530.80	339.40	117.30
400	540.20	360.80	133.30
600	575.70	390.20	145.90
800	587.20	423.60	157.10
1000	630.60	452.10	163.50
1200	645.10	464.50	175.80
1400	661.80	497.90	184.10
1600	643.30	482.60	158.50
1800	635.80	459.20	144.60

as a method of improving welded joint quality. This section includes suggestions for optimising welding parameters to achieve improved mechanical properties. The experimental results presented in Table 3 include the results of tests conducted to investigate the effects of mechanical vibration frequency on welded joint properties, including flexural stress, ultimate tensile strength, and impact strength, over vibration frequencies ranging from 0 to 1800 Hz.

Flexural Strength

A recent study demonstrated that increases in the frequency of vibrational waves corresponded with an increase in the flexural stress of welded joints. The average flexural stress of welded joints measured at 0 Hz (i.e., there were no vibrations) was 496.3 MPa while flexural stress increased as frequency increased from 496.3 MPa to 661.8 MPa between 0 Hz and 1400 Hz with an equal percentage increase of between 6.9%-33.5%, therefore the vibration provided additional strength to the bond and structural integrity of the joint giving it increased resistance to bending loads exerted on it, particularly for components that will endure bending loads. Table 4 provides further details about these results shown in table 4.

This table shows how much flexural properties of welded joints change based on mechanical vibration frequency.

a) Frequency (Hz)

The mechanical vibration frequency (measured in Hertz) refers to how many times the material was vibrated while it was being welded and how quickly it vibrated. This property controls how quickly the material is vibrated and how quickly the material appears

b) Maximum Load (N)

In a flexure test, the maximum load is the maximum amount of force the sample can take before it breaks. The max load of flexure tests was found to rise from 727.97 N (0 Hz) to 876.12 N (1600 Hz). The rise in max load shows that the higher mechanical vibration frequencies give welded connections more load tolerance before failure occurs.

c) Flexural stress (MPa)

The flexural stress (i.e. the stress calculated by dividing the Maximum Load by the cross-sectional area) shows the amount of stress applied to the sample when it reaches its Maximum load (based on its geometry) and increases as the mechanical vibration frequency increases. At 0 Hz, the flexural stress is 496.34 MPa and at 1600 Hz is 653.34 MPa. This patent trend indicates a rising ability of mechanical vibration frequency to contribute to increased flexural stress at failure (Fig. 3).

d) Flexural strain at the maximum flexural stress (mm/mm)

It is a dimensionless measure of how much the specimen deforms under the maximum load that is determined from how much it has changed in length divided by its original length. An increase in the flexural strain occurs as the frequency of mechanical vibration increases from 0 Hz with a number of 0.02 mm/mm to 1600 Hz with a number of 0.19 mm/mm will also provide evidence that mechanical vibration at an increased frequency will permit welded joints to experience an increase in deformation prior to rupture.

e) Flexural load at the maximum flexural stress (kN)

Itrepresents the applied flexural load at which the specimen experiences its maximum amount of stress, thus providing additional data regarding the load capacity at that critical point. An increase in the flexural load during mechanical vibration from 0 Hz of 0.73 kN to 1600 Hz of 0.88 kN indicates that welded joints can withstand more mechanical vibration with an increased load applied at their maximum flexural stress. Flexural strain and flexural load at maximum flexural stress were compared against frequency as shown in Figure 4.

g) Maximum flexural load, as expressed in megapascals (MPa)

It refers to the amount of elongation experienced by a specimen when it is subjected to a maximum applied load. It also indicates how much a material will stretch before reaching its maximum applied load when it is subject to bending forces. An increase in maximum

Table 4. Testresults of flexural strength

S. No	Frequency (Hz)	Max. load (N)	Flexural stress (MPa)	Flexural extension at maximum flexural load (MPa)
1	0	727.97	496.34	38.33
2	200	758.73	530.81	39.70
3	400	777.49	540.28	41.07
4	600	803.75	575.75	42.44
5	800	833.01	587.22	43.80
6	1000	843.77	630.69	45.18
7	1200	873.53	645.16	46.55
8	1400	880.38	660.37	45.97
9	1600	876.12	653.34	43.44

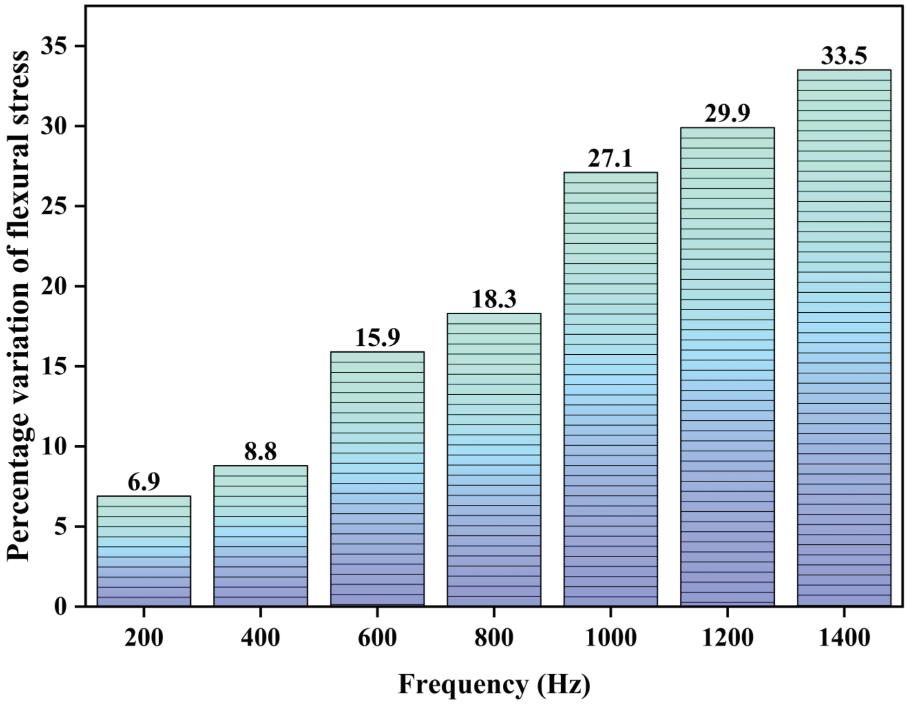

Figure 3. Comparison of % of the rise in flexuralstress.

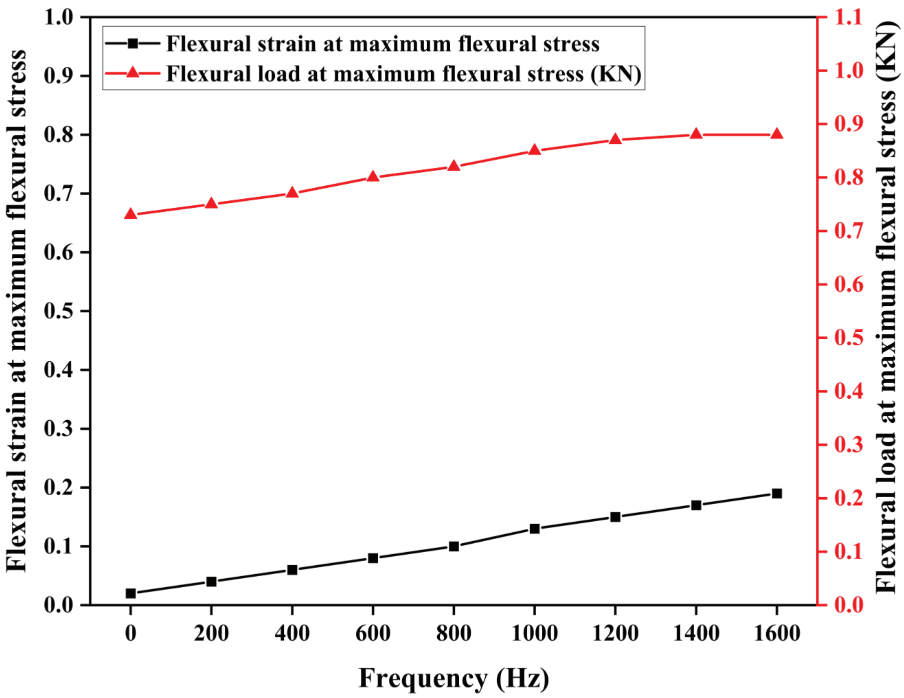

Figure 4. Comparison of flexural strain and flexural load at maximum flexural stress.

flexural load from 38.33 mm at 0 Hz to 43.43 mm at 1600 Hz indicates that with increased mechanical vibration frequency, the welded joints of the material can sustain greater elongation before reaching their maximum applied load.

h) Modulus (Automatic) (GPa)

The modulus (automatic) is a measure of the elastic properties of a material. The modulus of elasticity reflects a material's ability to resist deformation when subjected to stress. A greater modulus of elasticity indicates greater stiffness (less elongation) of a material, which can resist higher loads before elastic deformation occurs. An increase in modulus of elasticity from 191.18 GPa at 0 Hz to 210.57 GPa at 1600 Hz indicates that with increased mechanical vibration frequency, the welded joints become stiffer and experience less deformation when subjected to bending loads. The relationship between the modulus of elasticity and frequency is shown graphically in Fig. 5.

Tensile Strength

The welded joint tensile strength increased with increasing vibration frequency, as did the flexural strength increase noted above. The tensile strength ranged from a minimum of 313.0 MPa (0 Hz) to a maximum of 497.9 MPa (1400 Hz). The percentage increase in tensile strength compared to the 0 Hz value ranged from 8.4% to 59.1%. The tensile strength presented in relation to vibration frequency is shown in Fig. 6.

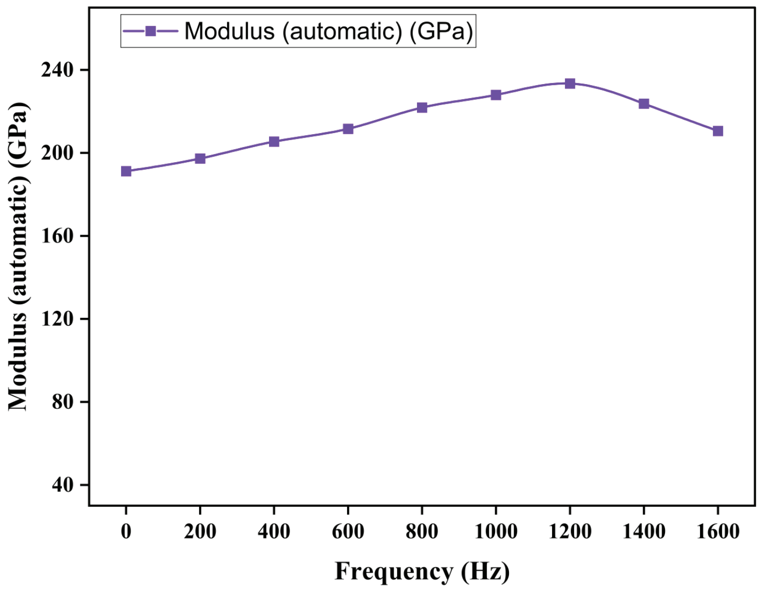

Figure 5. Comparison of modulus of elasticity with frequency.

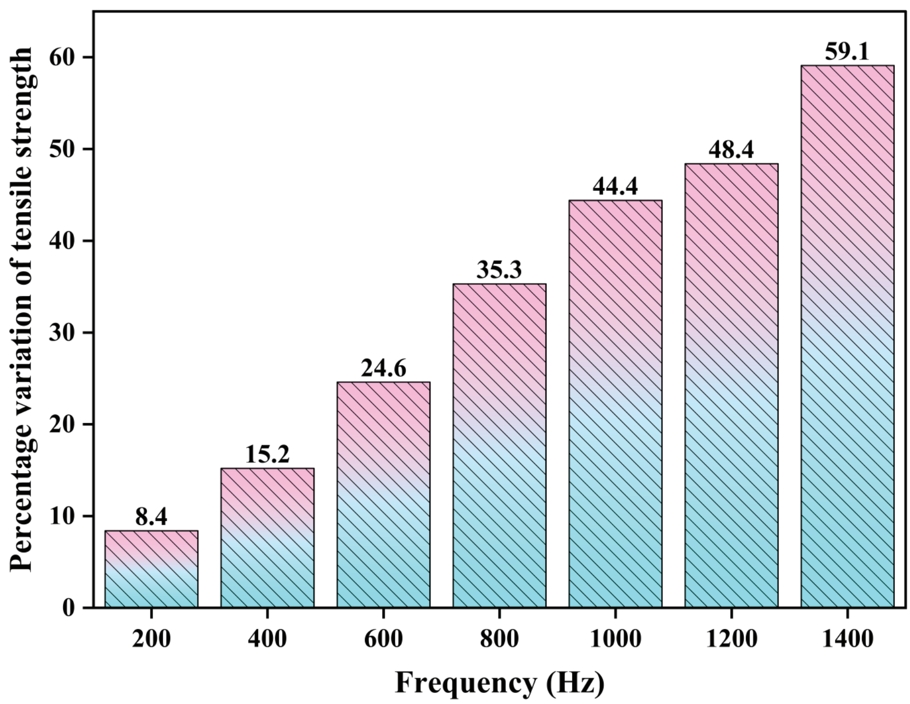

Figure 6. Comparison of % of the rise in tensile stress.

The increase in tensile strength with an increase in vibratory frequency suggests that the use of mechanical vibration enhances the bond and their cohesion within the welded joints through enhanced bonding of the base metals of the welded joint. It is apparent that the tensile strength of welded joints has improved and it will be possible for welded joints to withstand tension or stretching forces that occur where the component are subjected to these tensile or dynamic forces from a mechanical loading stand point. The complete tensile strength test results can be found in Table 5, along with the graphical representation of the test results shown in Fig. (7) to (9) inclusive.

In the detailed analysis of the tensile properties of welded joints that were exposed to differing Mechanical Vibration frequencies, the following information can be gleaned;

a) Frequency (Hz)

This column is an indication of the Mechanical Vibration frequency applied to the welded joint specimens during testing. Mechanical vibration frequency is one of the significant parameters being evaluated in order to better understand how it affects the mechanical characteristics of welded joints.

b) Maximum load (N), and break load (Std) (N)

Maximum and break load comparisons with reference to frequency are shown in Fig. 7 for both loading tests and indicate the maximum amount of force that a specimen can withstand prior to failure. The break load additionally gives an indication of how much load a specimen can carry while

Table 5. Test results of UTS

S. No	Frequency (Hz)	Tensile strain at break (std) mm/mm	Tensile strain at Max. load mm/mm
1	0	0.15604	0.12
2	200	0.16513	0.12
3	400	0.1752	0.13
4	600	0.19033	0.13
5	800	0.20344	0.13
6	1000	0.20954	0.13
7	1200	0.22264	0.13
8	1400	0.23375	0.13
9	1600	0.19375	0.12

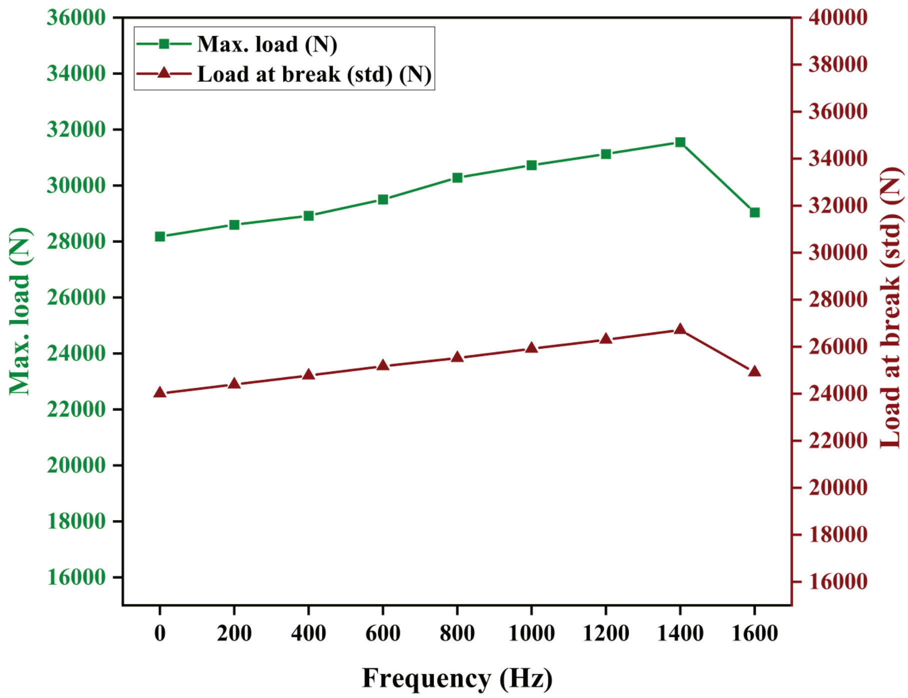

Figure 7. Comparison of maximum load and load at break.

under tension. Maximum and break loads for specimens were observed to increase as the mechanical vibration frequency increased, e.g., a specimen at 0 Hz has maximum load of 28176.61 N, while at 1400 Hz the maximum load is 31550.34 N.

a) Ultimate tensile strength (MPa)

The UTS and tensile strength at break with respect to frequency is shown in Fig. 8. The maximum stress it can withstand before failure called as UTS. UTS increases with increasing vibration frequency, indicating that higher frequencies result in stronger welded joints. The UTS ranged from 313.07 MPa at 0 Hz to 497.92 MPa at 1400 Hz.

b) Tension strength at break (Standard Deviation) (MPa)

This column shows the specimen's tension strength at break. As tension strength increases as Vibrational Frequency Increases, so does the resistance to fracture. Breaking tension strengths were measured ranging from 266.79 MPa (0 Hz) to 427.52 MPa (1400 Hz).

c) Tension strain at break (Standard Deviation) (mm/mm)

This column denotes the tension strain that the specimen experienced at break. Tension strain is a measure of how much longer a material has become from its original length; therefore, tension strain is calculated by taking the change in length and dividing it by the length of the original specimen. As frequency increases, both tensile strains at break increase, indicating an increase in the capability to deform before breaking. Measuring ranges for tensile strains at breaking point ranged from 0.16 mm/mm (0 Hz) to 0.24 mm/mm (1400 Hz).

d) Tension strain at maximum load (mm/mm)

This column shows the tension strain that was placed on the specimen when it reached the maximum load. The tension strain is calculated as the change in length divided by the length of the original specimen.

e) Tensile stress at yield (2 percent off set) (MPa)

Tensile stress at yield is defined as a value of tensile stress where a defined amount of plastic deformation occurs in a given sample (often 2 percent off set from the linear portion of the stress-strain curve). Vibration Frequency has an effect on tensile yield stress whereby increasing the frequency of the oscillations will result in a higher tensile yield stress for that material, which indicates that the material has a greater resistance to plastic deformation. The tensile yield stress of the material at 0 Hz was measured as 243.95 MPa and increased to 417.13 MPa as the vibration frequency was increased to 1400 Hz.

f) Tensile stress at preset point (MPa)

The tensile stress at a preset point represents where a material will behave in a tension loading situation, and is typically used to compare tensile yield stress with preset point. A visual comparison of the tensile yield and preset point tensile stress values can be found in Figure 9.

These findings highlight how the frequency of mechanical vibration can greatly affect the tensile properties of welded joints. The welded joints produced from mechanical vibrations at higher frequencies exhibit greater ultimate tensile mount, greater fracture toughness, and

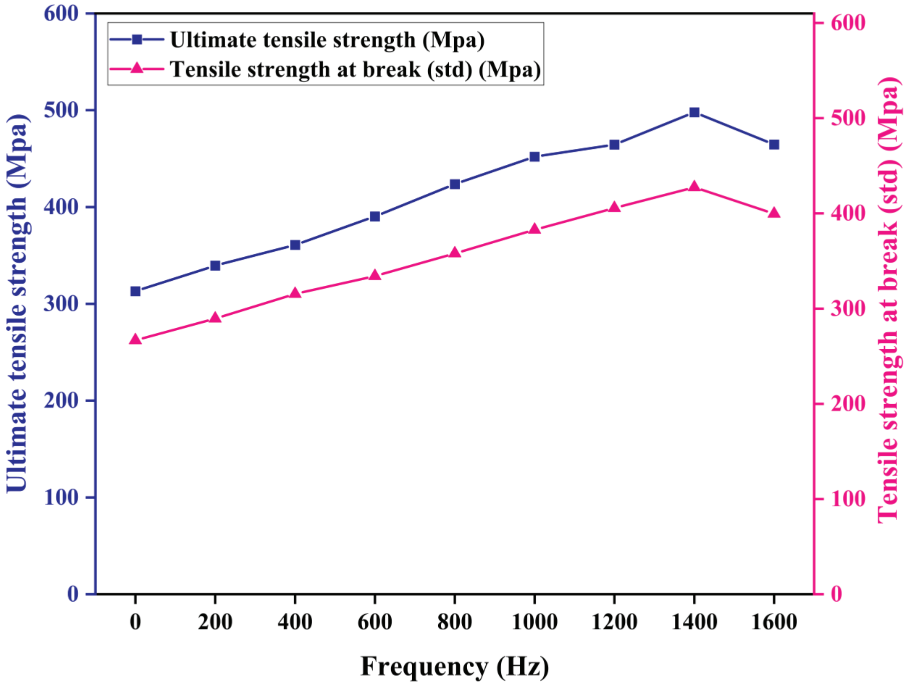

Figure 8. Comparison of UTS and tensile strength at break.

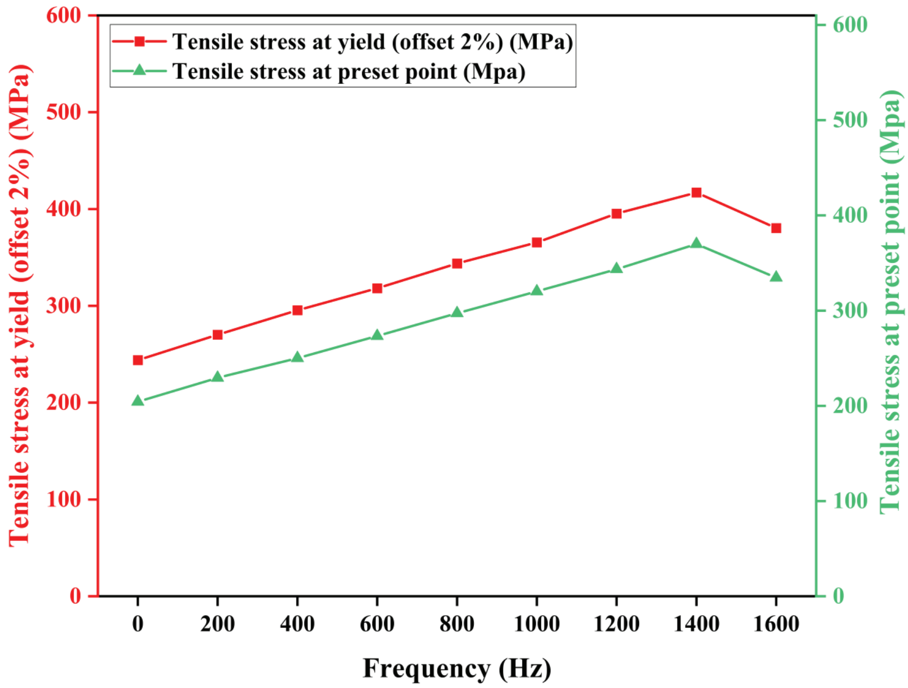

Figure 9. Comparison of tensile stress at yield and preset point.

greater ductility than those produced at lower frequencies. Therefore, by using both ultimate tensile strength (UTS) and fracture toughness as a measure of the mechanical performance of the welded joint when subjected to various frequencies of mechanical vibration, one can gain insight into the effect of mechanical vibration on the tensile properties of welded joints.

Impact Strength

With the increase in frequency of vibration comes an increase in impact strength (Capacities). With respect to the impact strength measured (at 0 Hz), there were increases of 12.8% and 77.1% for 0 Hz and 1400 Hz, respectively, indicating that the frequency of vibrating welds directly affected the impact strength. Vibrations provide assistance for absorbing energy and continuing plastic deformation until failure, therefore increasing the durability, and resilience to high-speed/low-F/V impact loading conditions. The tests conducted to quantify the impact strength provide an indication of the material, over time, of its ability to sustain impact loading and absorb energy, therefore, supporting greater robustness in high-speed/low-F/V loading applications. The data on the impact strength in relation to frequency is presented in Fig. 10. The results of the Impact strength tests and their relationship to frequency are explained in this report.

a) Impact strength: Impact strength represents how much energy the material is absorbs when it breaks! Impact strength is measured in joules (J). Based on the data provided, the tested impact strengths were between 104 J at 0 Hz and 184.1 J at 1400 Hz. High Impact Strength indicates that the material has greater energy absorption properties of the material and therefore has more resistance to breaking when hit or loaded from above.

b) Trend analysis: The data indicates there is a consistent upward trend in the measured impact strength of the welded joints as the level of mechanical vibration increases with increasing mechanical vibration frequency. This analysis shows that increasing mechanical vibration frequency increases the impact resistance of the welded joint. Therefore, indicating that as mechanical vibration frequency is increased, they will also have more impact resistance and greater energy absorption properties.

c) Importance of the results: The impact strength values provide insight into the ability of the welded joint to withstand large forces/impacts when it is subjected to sudden forces caused by external forces. Therefore, this is an important characteristic of welded joints due to their utilization in high-impact or shock-loading applications; thus providing greater toughness and resilience when compared to other forms of support. Additionally, the increased impact strength will provide greater reliability and durability of the welded joints to withstand real-world operating conditions.

d) Comparison and interpretation: The impact strength values obtained from the various frequency ranges are compared to demonstrate the advantage of mechanical vibration as a method of improving the impact resistance of welded joints. The results obtained from testing can also be compared against known quantity of requirements or

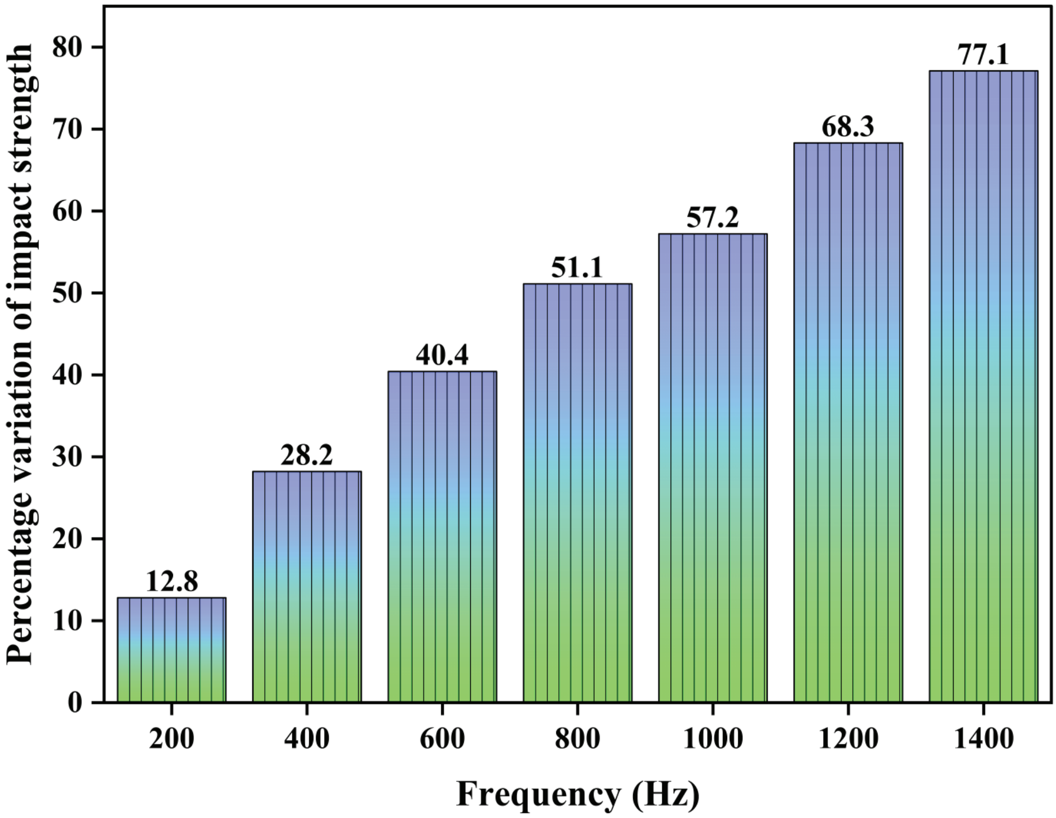

Figure 10. Comparison of % of the rise in impact stress.

standards applicable to industry or government to determine if the welded joints are acceptable or non-compliant with established performance standards.

e) Practical implications: The information gathered through the testing of welded joints provides important information to design engineers, material scientists and manufacturers working on material development and selection for applications where impact resistance is critical. The data provided from this research helps with determining material selection, process optimizations, as well as product design so that welded joints meet their intended performance requirements and safety regulations.

By testing the impact strength of welded joints, it was found that the mechanical response of welded joints to impact loading can be improved through the use of mechanical vibration to improve impact resistance and performance. Additionally, these results show that the use of mechanical vibration in welding processes may improve the mechanical properties of welded joints. In general, the results suggest that by increasing the frequency of mechanical vibration during welding, the mechanical bond of welded joints will be improved; in turn, this will directly improve the mechanical properties of welded joints, including flexural stress, tensile strength, and impact strength. Additionally, the findings illustrate the significance of optimising vibration parameters such as frequency to improve the mechanical properties of welded joints. Because of this, the findings indicate that the optimisation of mechanical vibration parameters in welding may enable the production of welded joints that are stronger, tougher, and more reliable in various engineering applications.

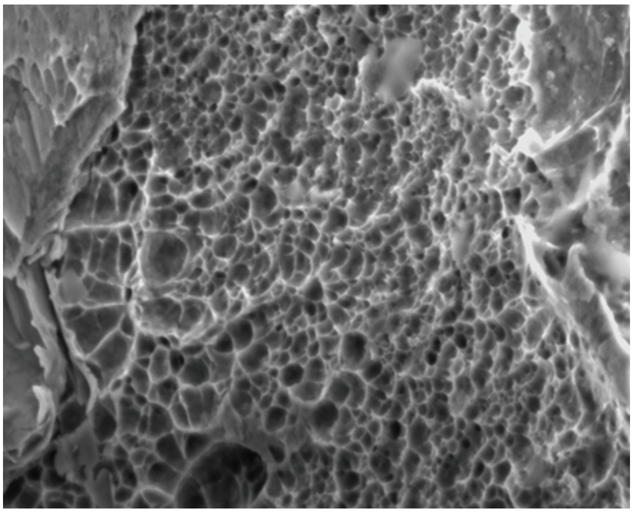

Figure 11. Microstructural characterization of weld sample.

Figure 11 shows that the distribution of filler metal throughout the weldment is important for increasing the mechanical properties being tested. It is shown that vibration treatment allows for an efficient initiation of the solidification process with increasing frequency, as the weld pool fills the voids in the porous areas. The vibration treatment will cause additional changes in the weldment due to the solidification process taking place over a longer period than with conventional welding processes. For example, higher frequencies in some areas may result in creating very minor bulges due to increased amounts of filler material being deposited. The ability to effectively adjust vibration settings and ensure the frequency ranges used for both workpieces and electrodes are appropriate will have an important positive effect on the mechanical properties of weldments produced using vibration. These benefits are a result of the increase in the amount of liquid superheat produced by the welding heat.

CONCLUSION

An effort is made in this study to develop a deeper understanding of vibratory treatment as well as the ability to optimise the mechanism that enhances the joint constructed by welding mild steel 1018, arc welding, via maintaining an experimental rig that allows controlled mechanical vibratory motion to be introduced during the welding process. The relationship between frequency and amplitude of the vibrational motion and the resultant welded joint attributes and welding parameters will provide the means for determining the optimal conditions for enhancing the mechanical performance of the welded joint. Notably, from the conducted experiments:

- ✓ The mechanical properties of welds created using vibration assisted welding showed an improvement compared to those created without vibrational treatment. Welds that were created at higher frequencies produced the greatest flexural stress, greatest tensile strength, and greatest elastic moduli of any of the welds tested.
- ✓ When mechanical vibration frequency increases, there is greater enhancement of mechanical characteristics, therefore concluding that vibratory treatment has potential for improving the characteristics associated with welded joint strength and performance.
- ✓ With increased frequency of vibrational force applied to welded joints, the welded joints performed better with regard to energy absorbance and resistance to fracture upon application of impact on both sides. This indicates that increasing vibrational frequency will improve welded joint toughness/resilience.
- ✓ Statistical analyses confirm that proper welding parameter determination optimizes the welding parameters in order for welded joints to exhibit the improved mechanical characteristics described previously and in Table IV.

The findings of this study illustrate that there are potential advantages to be had by utilizing mechanical vibrations to improve the mechanical characteristics of welded joints. Manufacturers can improve the performance of welded structures and open up more applications through proper optimization of the welding parameters.

Future Scope

Certainly! It is exciting to see what future projects will be accomplished using what has already been established in terms of the impact of different parameters on the welding process (i.e., vibration amplitude and frequency duration). Manufacturers wanting to further investigate the mechanical properties of welded joints as they relate to vibration amplitude and frequency duration should continue to conduct research to ascertain how the mechanical vibrations created during the welding operation affect the microstructure of the welded joint. As more is learned through research, this information can be used to develop better welding practices and optimise equipment used to achieve these higher performing mechanical properties.

REFERENCES

[1] Rao PG, Rao PS. Mechanical properties improvement of weldments using vibratory welding system. Proc Inst Mech Eng C J Mech Eng Sci 2015;229:776-784. [CrossRef]

[2] Rao PG, Rao PS, Krishna AG. Flexural strength improvement of welded joints prepared by vibratory welding process. Int J Manuf Mater Mech Eng 2015;5:1–16. [CrossRef]

[3] Rao PG, Rao PS. Development of a prediction tool for tensile strength of the welded joints prepared by vibratory welding process. Mater Focus 2017;6:319–324. [CrossRef]

[4] Rao PG, Rao PS, Krishna AG, Sriram CV. Improvement of tensile strength of butt welded joints prepared by vibratory welding process. Int J Mech Eng Technol 2013;4:53–61.

[5] Ramakrishna G, Rao PS, Rao PG. Methods to improve mechanical properties of welded joints: View point. Int J Mech Eng Technol 2016;7:309–314.

[6] Tsujino J. 27 kHz ultrasonic complex vibration welding system using various exchangeable welding tips for different welding specimens. In: Proc IEEE Int Ultrason Symp (IUS); 2018. p. 1–9. [CrossRef]

[7] Tsujino J, Sugimoto E. Ultrasonic welding of electronic parts and devices using a long and thin complex vibration welding tip. In: Proc IEEE Int Ultrason Symp (IUS); 2014. p. 947–950. [CrossRef]

[8] Tsujino J, Sugimoto E. Ultrasonic complex vibration welding of many metal foils and terminals of Li-ion battery and capacitor. In: Proc IEEE Int Ultrason Symp (IUS); 2016. [CrossRef]

[9] Tsujino J, Sugimoto E. Ultrasonic welding using a long and thin complex transverse vibration welding tip with vibration detector and static pressure controller. In: Proc IEEE Int Ultrason Symp (IUS); 2015. [CrossRef]

[10] Asami T, Tamada Y, Higuchi Y, Miura H. Development of dumbbell-shape vibration source with longitudinal and torsional transducers for ultrasonic metal welding. In: Proc IEEE Int Ultrason Symp (IUS); 2017. p. 1–4. [CrossRef]

[11] Liu X, Shi G, Liu W. A novel residual stress detection method for complex large welded structures based on excitation vibration response. In: Proc International Conference on Artificial Intelligence and Electromechanical Automation (AIEA); 2020. p. 342–345. [CrossRef]

[12] Sabzi M, Dezfuli SM. Drastic improvement in mechanical properties and weldability of 316L stainless steel weld joints by using electromagnetic vibration during GTAW process. J Manuf Process 2018;33:74–85. [CrossRef]

[13] Liao H, Wang Z, Zhang B, Chi P, Wang Y, Tian J, et al. Microstructure and mechanical properties of SUS304 weldments manufactured by ultrasonic vibration assisted local dry underwater welding. J Mater Process Technol 2023;322:118183. [CrossRef]

[14] Feng W, Zhang J, Gao J, Xiao Y, Luo G, Shen Q. Microstructure and texture evolution of aluminum and titanium ultrasonic welded joints. Mater Charact 2023;195:112542. [CrossRef]

[15] Dey K, Gobetti A, Ramorino G. Advances in understanding of multiple factors affecting vibration weld strength of thermoplastic polymers. J Adv Join Process 2023:100164. [CrossRef]

[16] Shi S, Lin L. On the environmental stress cracking of a vibration-welded polycarbonate (PC)-based nanocomposite. Polymer (Guildf) 2023;285:126338. [CrossRef]

[17] Khmelev VN, Slivin AN, Abramov AD. Stand for controlling of quality of weld producing at ultrasonic welding of thermoplastic materials. In: Khmelev VN, Slivin AN, Abramov AD. Stand for controlling of quality of weld producing at ultrasonic welding of thermoplastic materials. In: Proc Int Conf Young Spec Micro Nanotechnol Electron Devices (EDM); 2017. p. 246–249. [CrossRef]

[18] Gill JS, Majid M. Hot filler wire addition in computer assisted arc welding and cladding processes: A review. In: 023 10th International Conference on Computing for Sustainable Global Development. (INDIACom). Mar. 15-17, 2023New Delhi, India, 2023. p.328–332.

[19] Yu M, Zhao H, Xu F, Chen T, Zhou L, Song X, et al. Effect of rotational speed on microstructure and mechanical properties of Al-Ti friction stir welds with ultrasonic vibrations. J Mater Process Technol 2023;320:118119. [CrossRef]

[20] Ilman MN, Widodo A, Triwibowo NA. Metallurgical, mechanical and corrosion characteristics of vibration assisted gas metal arc AA6061-T6 welded joints. J Adv Join Process 2022;6:100129. [CrossRef]