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Research Effect of Vibration Parameters on Assisted Orbital TIG Welding for Stainless-Steel Tube

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Abstract : The Vibration Assisted Welding shown the effective solution to increase penetration, microstructure, and mechanical properties of the weld metal of Stainless-Steel 304 (SS304). Thus, the experiment was made a vibration on the surface of the SS304 tube by a piezo actuator during the Orbital TIG Welding using metal filler. The TIG welding parameters were set for purpose of creating a full penetration and different ultrasonic vibration parameters (Amplitude of voltage at 2V, 4V, 5V, Frequency at 400Hz, 500Hz, 600Hz). The bead geometry, mechanical properties, and the microstructure of tube welds was discussed in this paper. The result illustrates that microstructures of the weld zone are the finer and uniform, which observed in samples assisted by the vibration. The vibration process has significantly affected the mechanical properties of butt welds using Orbital Welding process. The highest tensile strength is 534 MPa at 2V for voltage amplitude and 600Hz for frequency, which is higher than specimen without vibration is 408MPa. It is also found that the hardness slightly increases with the various frequency from 200Hz to 600Hz at 2V for voltage amplitude.

Keywords: Orbital Welding; Vibration Assisted Welding; Stainless Steel; Mechanical Properties; Metallurgical welding.

1. Introduction

Stainless steel finds extensive application in the semiconductor industry owing to its remarkable qualities such as corrosion resistance, exceptional strength, and long-lasting durability. Primarily employed in the manufacturing of equipment and components like vacuum chambers, heat exchangers, valves, and fittings, stainless steel plays a pivotal role in ensuring the efficiency and reliability of semiconductor operations. Stainless-steel 304 grade (SS304) is an austenite stainless steel that offers good resistance to oxidation, good weldability and is commonly used in high-pressure applications. Therefore, joining pipes in this industry requires high standards of weld quality and purity.

In recent years, Orbital TIG Welding (OTW) process a precision welding technique, operates on the fundamental principle of automated circumferential motion around the workpiece (Figure 1). A specialized welding head, guided by computerized control systems, orbits the welding arc consistently, maintaining optimal parameters such as arc length, travel speed, and electrode angle. This automated process ensures a uniform weld bead, minimizes defects, and enhances the overall quality of the weld. The precision inherent in orbital welding makes it particularly suitable for applications where accuracy and repeatability are paramount, such as in aerospace, semiconductor manufacturing, and critical infrastructure construction [1].

Although there are various techniques used in different industries, this welding method still faces some significant issues. One common issue in arc welding is the presence of residual stresses inside the weld [2, 3, 4, 5, 6]. The reason behind this issue is the concentration of a large amount of heat in a small area, leading to overheating. As a result, the mechanical properties of the weld tend to decrease due to the influence of the microstructure consisting of coarse-sized phases. To address this problem, welds need to undergo post-weld heat treatment to relieve stresses and improve the weld's mechanical properties [7, 8].

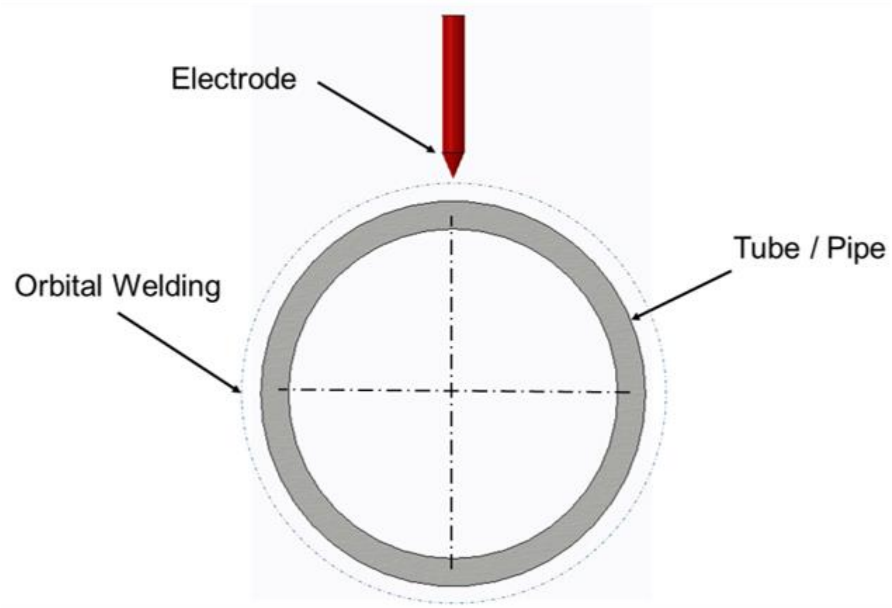


Figure 1. The principle of Orbital Welding.

Another approach to improve the microstructure of the weld and its surrounding areas is by introducing mechanical vibrations to the weld pool, welding electrode, and workpiece [9, 10, 11]. Among these, workpiece vibration is widely used in various arc welding processes due to its benefits in enhancing the structure and mechanical properties of welds. Integrating mechanical vibrations into arc welding procedures is an essential aspect of this advancement. Several techniques can be applied to transfer mechanical vibrations to the weld domain, including electric arc fluctuation, coupled laser beam thermal effects, direct wave-induced vibration of the material, electromagnetic stirring, and ultrasonic vibration.

In the research of Jose et al. [12] explores the emerging field of Vibration Assisted Welding (VAW), a technique that utilizes vibrations during the welding process to significantly improve the quality of welds. VAW offers a promising alternative to traditional heat treatments and post-weld vibration treatments, effectively reducing residual stresses and distortions, thereby enhancing mechanical properties. This review comprehensively examines various techniques and their impact on microstructure, mechanical properties, and residual stress, providing valuable insights for future research directions. Clearly, Singh et al. [13] investigates the effect of mechanical vibration on the weld pool during the Shielded Metal Arc Welding (SMAW) process using mild steel plates. The research proposes a new concept of a vibratory welding setup that can transfer mechanical vibrations to the weld zone and generate a resonance frequency of 300 Hz.

The study compares the microstructure and mechanical properties of welded joints created using conventional and vibratory welding techniques. The results show that vibratory welding significantly improves the mechanical properties of the weld joint, including hardness, tensile strength, and impact strength. The study utilizes Taguchi and ANOVA techniques to optimize the process parameters of vibratory welding, identifying the optimal settings for achieving desired weld quality. The research emphasizes the importance of grain refinement in improving the mechanical properties of welded joints.

The study reviews previous research on vibratory welding techniques and highlights the advantages of vibration-assisted welding (VAW) over post-weld vibration techniques. Moreover, this research paper investigates the impact of vibration-assisted arc welding (VAW) on the quality of welded joints. The study focuses on analyzing the effects of vibration amplitude, frequency, welding speed, and electrode angle on the hardness and deposition rate of the welds. The results indicate that VAW significantly improves the mechanical properties of welded joints by reducing porosity and promoting better metal penetration, leading to increased hardness and deposition rate in specific parameter ranges.

The impact of vibration-assisted arc welding (VAW) on the quality of welded joints is investigated by Habib et al [14]. The study focuses on analyzing the effects of vibration amplitude, frequency, welding speed, and electrode angle on the hardness and deposition rate of the welds. The results indicate that VAW significantly improves the mechanical properties of welded joints by reducing porosity and promoting better metal penetration, leading to increased hardness and deposition rate in specific parameter ranges.

Additionally, the research paper of Singh et al [15] investigates the influence of vibrations applied during arc welding on the microstructure and mechanical properties of stainless-steel butt welds. The study found that applying vibrations during welding significantly increases the microhardness and mechanical strength of the weld joints while maintaining acceptable ductility. This improvement is attributed to the fragmentation of dendrites in the weld microstructure, leading to the formation of new nucleation sites and a finer grain structure.

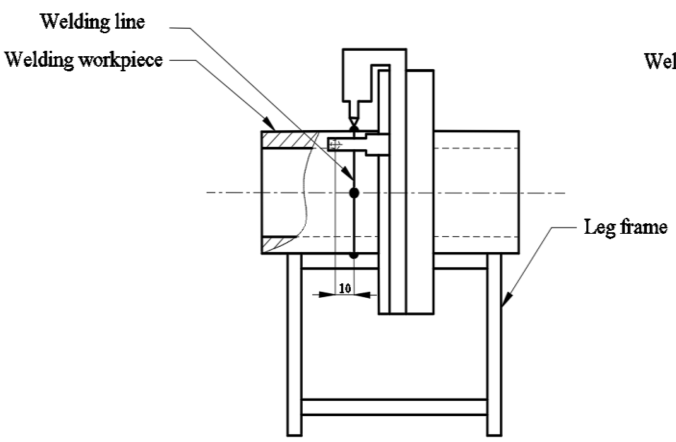
Nowadays, stainless-steel tubes are widely used in various industries due to their excellent corrosion resistance and mechanical properties. However, the welding of stainless-steel tubes can be challenging, as it requires precise control of parameters to ensure high-quality welds. In some recent studies, vibration-assisted welding has the potential to improve the productivity and quality of stainless-steel tube welding by reducing distortion, improving weld bead appearance, and enhancing mechanical properties. By applying controlled vibrations to the welding process, it can improve welding quality, increase productivity, and reduce the risk of defects.

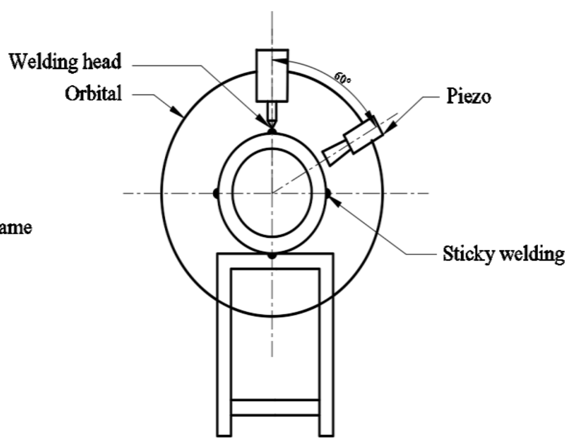
The vibrations can help to break up the weld pool, improve material flow, and reduce the formation of pores and other defects. Thus, vibration-assisted TIG orbital welding is a promising technique that can address some of these challenges by improving welding quality and productivity. The primary objectives of this research are to investigate the influence of vibration-assisted orbital welding parameters on the weld quality, mechanical properties of stainless-steel tubes. The study will focus on evaluating the effects of various vibration parameters, such as frequency, amplitude on the weld characteristics, including weld bead geometry, microstructure, and mechanical properties.

2. Material and Process

2.1 Design of experiment

In this study, an oscillator setup on the surface of the pipe is established as shown in Figure 2. The piezoelectric (PZT) is designed to rotate along with the electrode throughout the Orbital TIG welding process. The fixture carrying the PZT is positioned at an angle of 60 degrees relative to the electrode (Figure 2b), and the distance between the center of the PZT and the gap is 10mm (Figure 2a). The purpose of this setup is to protect the PZT from thermal effects caused by the welding process. Figure 3 shows the experimental model before starting a weld.





a) Side view of experimental model **b) Front view of experimental model**

Figure 2. The position of PZT in the Orbital TIG welding.

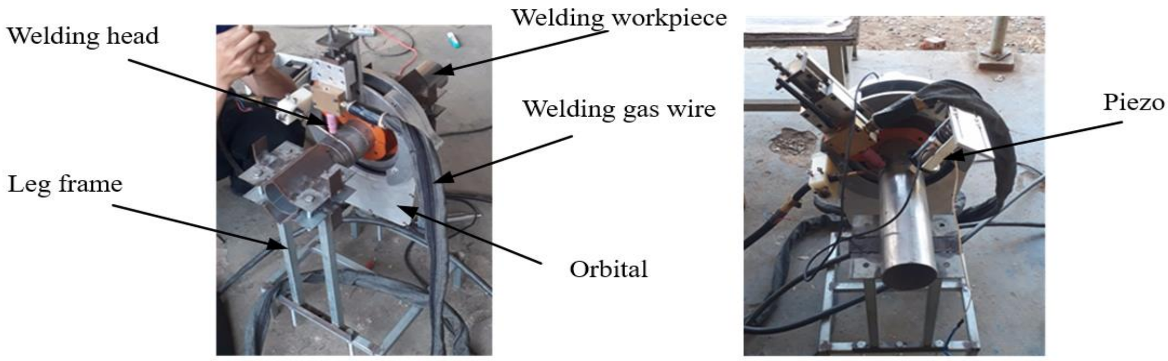


Figure 3. Experimental model in the reality before starting a weld.

2.2 Preparation of specimens

Samples used in this experiment are stainless steel 304 (SS304) with an outer diameter of 76 mm, a thickness of 2 mm, and a length of 50 mm. During this welding process, a filler wire GM-308 with a diameter of Ø0.8 mm is added, which is suitable for welding austenitic stainless steel and has the chemical composition illustrated in Table 2. Moreover, Chemical composition of SS 304 is showed in Table 1.

Table 1. Chemical composition of stainless steel 304 (% wt) [16]

C	Si	Mn	P	S	Ni	Cr
0,08%	1%	2%	0,045%	0,03%	8%-10.5%	18% – 20%

Table 2. Chemical composition of wire filler GM-308 (% wt)

C	Mn	Si	Cr	Ni	P	S
0.06 max	1.0 ~2.5	0.65 max	19.5 ~ 21	9 ~11	0.03 max	0.03 max

In this study, 6 welds were performed, including 1 weld without vibration and 5 vibration-assisted welds with varying amplitude and frequency to investigate their influence on the quality of the welds. The welding parameters are presented in Table 3.

Table 3. Welding parameters

Sample code	Welding parameters	PZT parameters	
		Voltage Amplitude (V)	Frequency (Hz)
S0	Amperage (I): 70A Speed (V_s): 3.36mm/s Filler speed (V_f): 4mm/s Gas flow: 8 LPM	Non-Vibration	
S1		2	400
S2		2	500
S3		2	600
S4		4	400
S5		5	400

2.3 Study of metallurgical specimens

A standard sample preparation procedure to observe and compare the weld profile, penetration, and microstructure of the welds has been carried out in 6 steps as shown in Figure 4a. First, samples will be cut at the specified position according to ASME IX standards (Figure 5a), with sampling for tensile strength testing

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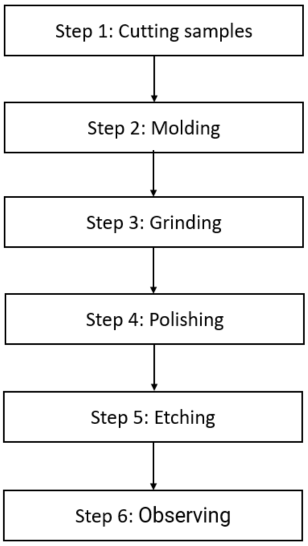
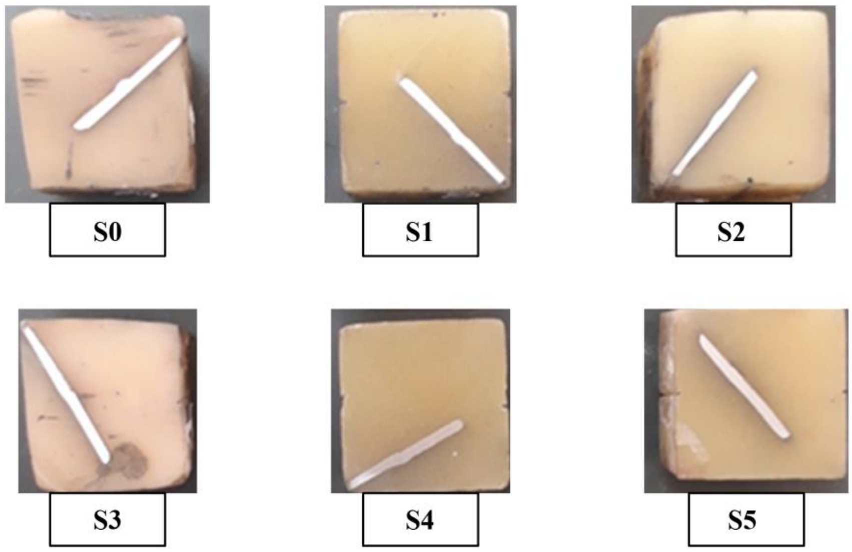
and for this preparation process. Subsequently, the samples were cold molding (Figure 4b) to facilitate perform in the Grinding, Polishing, and Etching steps using a solution consisting of HCl and HNO_3 in a 1:1 ratio, following ASTM E407 standards. Finally, the samples will be observed by the OX.2653-PLM metallurgical microscope from Euromex – Netherlands.



a) Process of metallurgical preparation

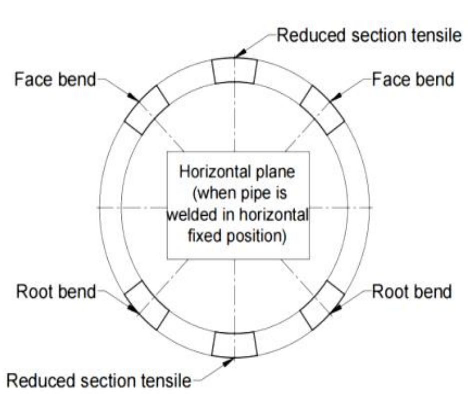


b) Samples are cold mouted

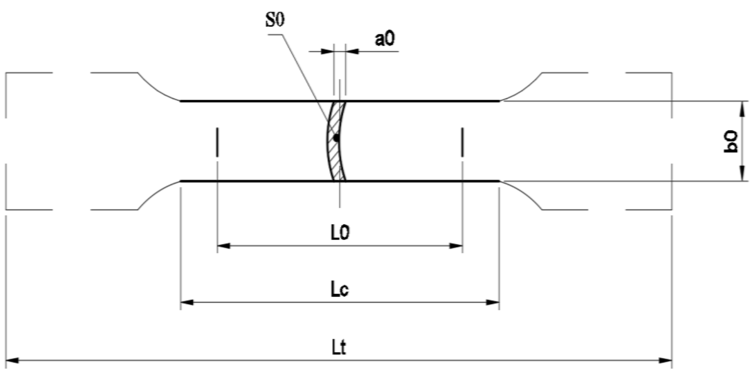
Figure 4. Metallurgical preparation.

2.4 Tensile testing

In this paper, butt welds were performed, and sampling for tensile strength testing was conducted according to ASME IX standards (Figure 5a) [17], which clearly specifies the locations for mechanical property testing of pipe welds. This includes the 0° and 180° positions, which are designated for tensile strength testing. However, the profile of the tensile samples was taken according to ISO 6892-1 standards to optimize the length of each pipe sample. The values of samples are fully presented in Figure 5b and Table 4. According to the guidelines of ISO 6892-1, the minimum length of a sample after butt welding is 87.5 mm; therefore, the length of each pipe prepared for this experiment is 50 mm, making the total length of the sample after welding 100 mm. Additionally, this study also conducted hardness testing using the HR150A hardness tester according to the Rockwell scale B.



a) Position of tensile testing based on ASME IX standard.



b) Reduced section tensile based on ISO 6892-1 standard.

Figure 5. Position and section of tensile testing.

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Table 4. Value of reduced section tensile (mm)

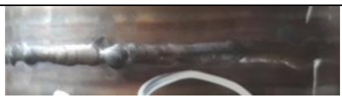
Factor	S_0	a_0	b_0	L_0	L_c	L_t
Dimension	25	2	12.5	50	60	87.5

3. Result and Dicussion

3.1 Welding bead geometry

Observing the appearance of the welds in Table 5, the bead geometry of the weld can be clearly seen. With the S0 sample, a good surface and smooth weld was achieved by using OTW without vibration. However, welding weaves appeared when vibration was introduced during the welding process. In this case, as the frequency of the PZT increased, the weave became more bigger and uniform; however, when the Voltage Amplitude was increased, the continuity and stability of the weld were severely affected. Additionally, the group of weld samples with varying vibration frequencies (S1, S2, S3) showed a wider weld width than the S0 sample, but the height of the weld was reduced. This is attributed to the high-frequency vibration, which facilitated the molten metal to drop more easily into the weld pool, resulting in a weld with better bonding capabilities. Conversely, the group of weld samples with high Voltage Amplitude (S4, S5) exhibited a smaller weld width compared to the S0 sample. From these results, it can be concluded that increasing the vibration frequency of the PZT is more beneficial than increasing the Voltage Amplitude to create a good surface, continuous weld with good bonding.

Table 5. Result of visual testing.

Sample code	PZT parameters		Bead geometry		
	Voltage Amplitude (V)	**Frequency (Hz)**	**Visual image**	**Width (mm)**	**Height (mm)**
S0	Non-Vibration			3.7	0.3
S1	2	400		3.9	0.25
S2	2	500		3.9	0.25
S3	2	600		4	0.25
S4	4	400		3.5	0.3
S5	5	400		3.5	0.3

3.2 Mechanical properties

Effect of PZT parameters on Tensile testing

The tensile strength results of 6 samples are presented in Table 6. In fact, the Ultimate Tensile Strength (UTS) of the S0 sample (non-vibration) is 408 MPa, which is lower than the UTS of basic metal at 550 MPa [18] due to the welding not achieving full penetration. From Table 5, it can be observed that the UTS of the 5 welded samples with vibration-assisted shows that there is significant difference as changing the vibration parameter.

As a result, the S2 sample has the highest UTS at 543 MPa, which is close to the UTS value of basic metal, while the S5 sample has the lowest UTS at only 278 MPa.

Table 6. Result of Ultimate Tensile Strength

Sample Code	**PZT parameters**		**Ultimate Tensile Strength (MPa)**
	Voltage Amplitude (V)	**Frequency (Hz)**	
S0	Non-Vibration		408
S1	2	400	491
S2	2	500	494
S3	2	600	**534**
S4	4	400	390
S5	5	400	**278**

To begin with, the survey of the effect of oscillation frequency on the UTS of samples in Figure 6 shows that the UTS of samples S1, S2, and S3 increases to 491MPa, 494MPa, and534 MPa respectively as the frequency of the PZT increases from 400 Hz to 600 Hz, while maintaining a Voltage Amplitude of 2V. Figures 7b, c, d indicate that the penetration of samples S1, S2, and S3 is greater than that of sample S0 (Figure 7a). This result shows that when the frequency of the PZT is increased, the oscillation frequency increases, leading to higher UTS for welded joints S1, S2, and S3 compared to the sample without oscillation S0. This result is also found in the study by Pavel and colleagues [19] due to having less porosity and more penetration, molten metal can dilute more area of the basic metal and create a strong bond.

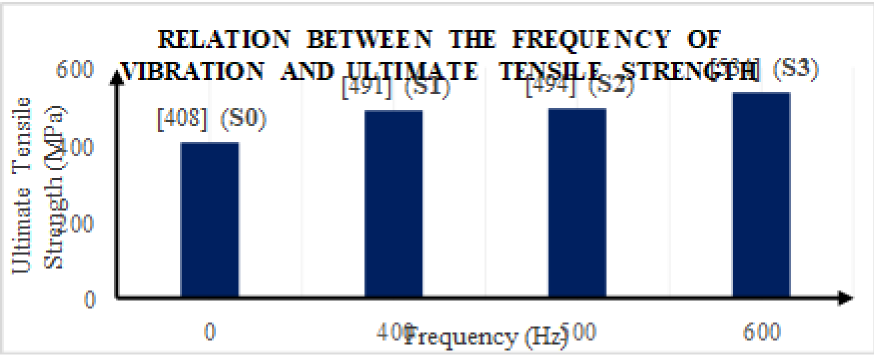
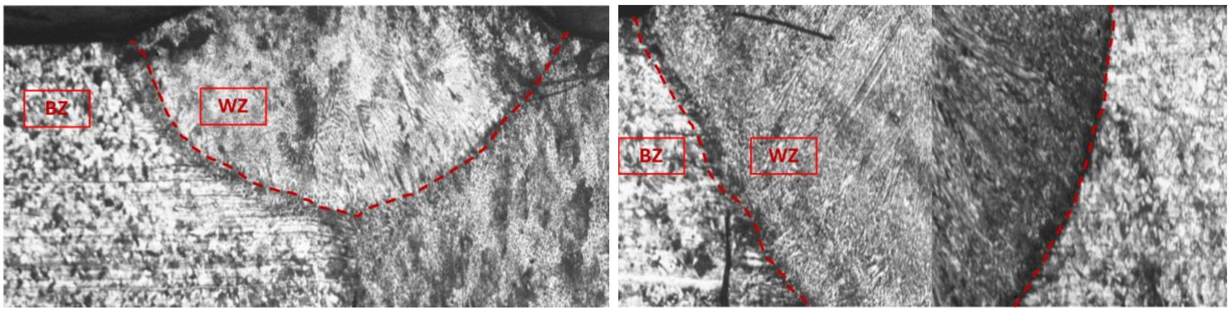
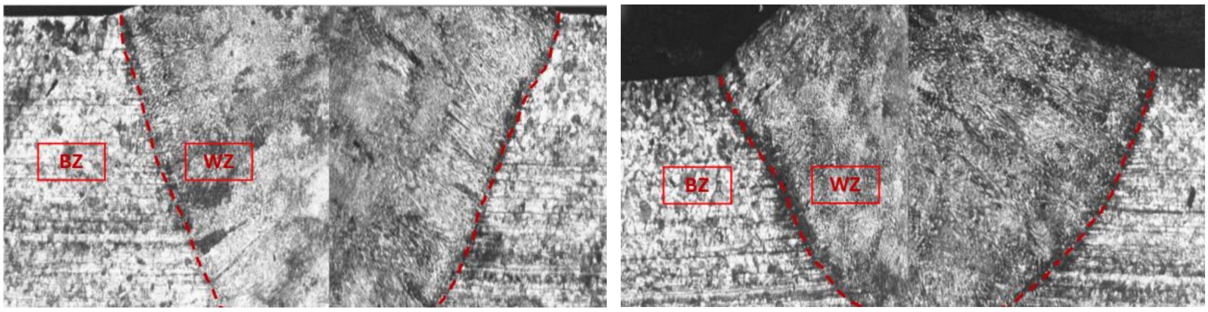


Figure 6. The chart of relation between the Frequency of Vibration and Ultimate Tensile Strength.



a) S0 *b) S1*



c) S2

Figure 7. The microstructure and weld profile of S0, S1, S2, S3.

BZ-Basic metal zone, WZ-Welding Zone

In contrast, observing Figure 8 shows that when the Voltage Amplitude of the PZT is increased to 2, 4, and 5 Volts for the S1, S4, and S5, the results show significant changes. Specifically, the UTS decrease progressively from 491MPa (S1), 390MPa (S4), and 278MPa (S5). Notably, the UTS results for samples S4 and S5 are considerably lower than the 408 MPa recorded for sample S0. From Figures 9c and d, it can be observed that the profile of the weld zone is narrowed in the lower area, indicating a weak bonding capability in the butt joint. In particular, the smallest UTS value (178 MPa) occurs when the Voltage Amplitude is at its highest (5V), indicating that increasing the Voltage Amplitude of the PZT does not enhance tensile strength in this experiment.

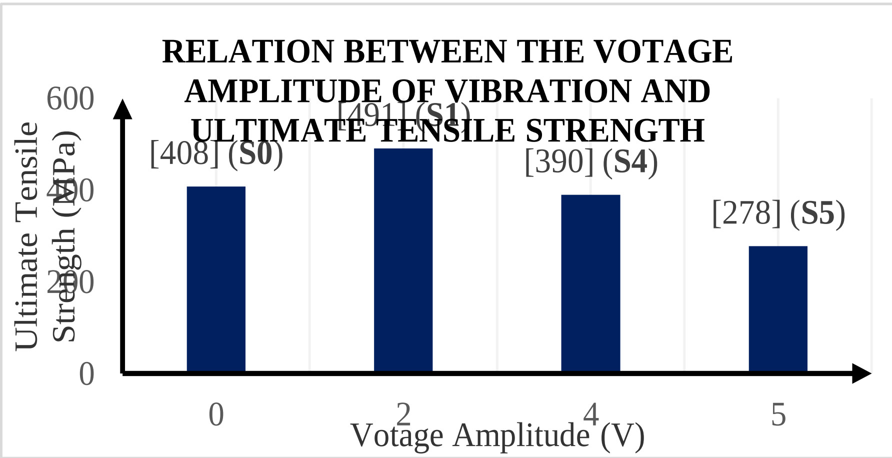
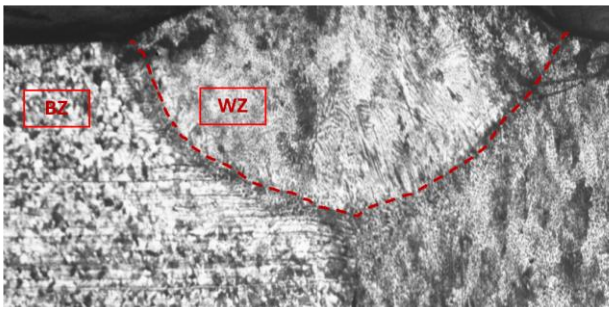
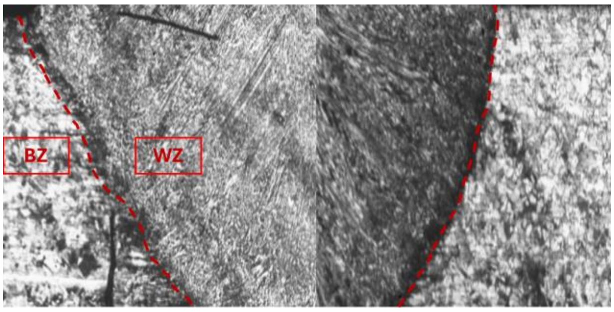


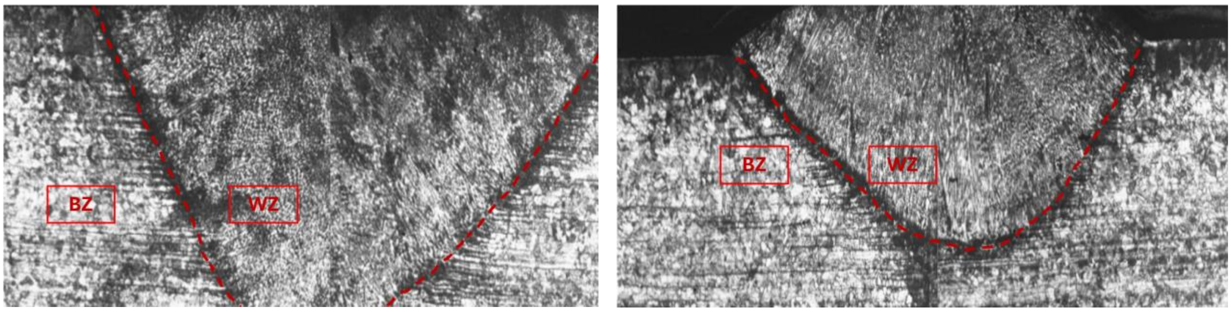
Figure 8. The chart of relation between the Voltage Amplitude of Vibration and Ultimate Tensile Strength.



a) S0



a) S1



c) S4 *d) S5*

Figure 9. The microstructure and weld profile of S0, S1, S4, S5.

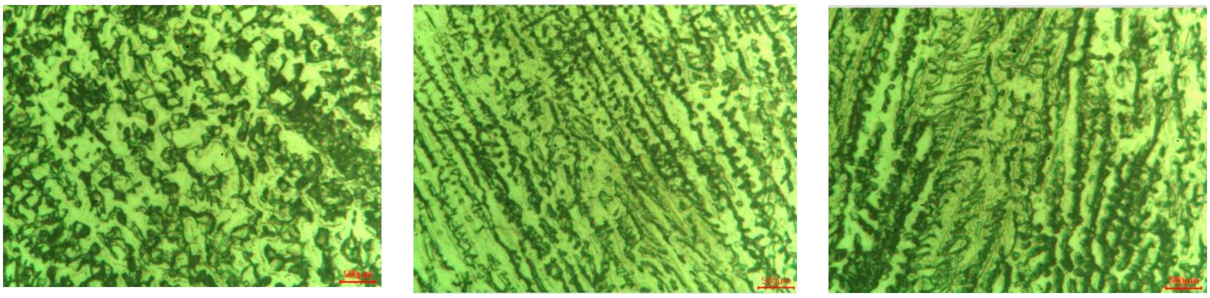
BZ-Basic metal zone, WZ-Welding Zone

Effect of PZT parameters on Hardness testing

Observing the hardness results of the samples in Table 7 indicates a slight difference between the sample without vibration assistance and the samples with applied vibration. Specifically, the hardness in the weld zone of the S0 sample is 79 HRB, while the highest hardness of 84 HRB is found in the S3 sample, which has the highest UTS value in the vibration with a voltage amplitude of 2V and a frequency of 600 Hz. Although this difference is not significant, it still shows that applying vibration in the OTW process helps improve the hardness of the weld zone, as the dendritic crystals formed during solidification will fracture into finer and more orderly phases (Figure 10).

Table 7. Result of hardness testing

Sample code	**Votage Amplitude (V)**	**Frequency (Hz)**	**Hardness in weld zone (HRB)**	**Hardness in basic metal zone (HRB)**
S0	Non - Vibration		79	83
S1	2	400	82	82
S2	2	500	83	81
S3	2	600	84	84
S4	4	400	82	82
S5	5	400	80	83



a) S0 - Coarse-sized phases *b) S3 – Finer dendrites* *c) S5 – Coarse dendrites*

Figure 10. The microstructure X500 in weld zone.

Conclusion

The results of this study have investigated that altering the parameters generating vibrations of PZT significantly affects the weld profile, mechanical properties, and microstructure of the weld zone.

- When the vibration frequency increases, the width of the weld bead also increases, which contributes to enhancing the bonding of the butt weld using the automatic pipe welding technology. However, increasing the voltage amplitude leads to instability in the weld seam, and it can occasionally deviate from the gap.

- The vibration frequency positively affects the Ultimate Tensile Strength (UTS) of the weld, while the voltage amplitude has an opposite effect. Specifically, UTS reaches its highest value of 534 MPa when the voltage amplitude is at its lowest value of 2V and the frequency is at its highest value of 600Hz.

- Changing the parameters that create vibrations from PZT shows a pronounced change in the microstructure of the weld zone. As the vibration frequency increases, the dendrite crystals become finer and develop in an orderly manner towards the center of the weld. Consequently, the hardness of the weld zone is also enhanced when both vibration parameters from PZT are increased.

- Furthermore, this study also demonstrates that the penetration depth and the metal deposition rate in the weld pool with assisted vibration are higher than those in the weld without vibration.

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