Journal of Engineering and Technology for Industrial Applications

ISSN ONLINE: 2447-0228

ITEGAM-JETIA

Manaus, v.11 n.55, p. 183-191. September/October 2025.
DOI: https://doi.org/10.5935/jetia. v.11 n.55.2200

RESEARCH ARTICLE OPEN ACCESS

ENHANCEMENT OF MECHANICAL AND MICROSTRUCTURAL PROPERTIES OF SIMILAR MILD STEEL WELDS UNDER VIBRATORY PROCESSING

Japhia Sudarsan Nalla[1], Basanta Kumar Palai[2], P. Govinda Rao[3]

[1*]Research Scholar, Dept of Mechanical Engineering, GIET University, Gunupur, Odisha, India
[2]Associate Professor, Dept of Mechanical Engineering, GIET University, Gunupur, Odisha, India
[3]Professor, Dept of Mechanical Engineering, Avanthi's Research and Technology, Bhogapuram, India.

[1]https://orcid.org/0009-0003-7345-0547, [2]https://orcid.org/0000-0002-7551-3340, [3]https://orcid.org/0000-0002-3350-8782

Email: japhiasudarsan.nalla@giet.edu, basantapalai01@gmail.com, govind09.p@gmail.com

ARTICLE INFO

Article History
Received: June 9, 2025
Revised: June 30, 2025
Accepted: October 3, 2025
Published: October 31, 2025

Keywords:
Vibrational welding,
Hardness,
Micro structural Properties,
Mild Steel.

ABSTRACT

This study investigates the influence of vibratory conditions on the mechanical and microstructural properties of MS-1018 samples. A comprehensive experimental approach was employed, which included Vickers hardness tests and metallographic analysis, to evaluate the effects of varying frequencies ranging from 0 Hz to 1800 Hz. The results of the Vickers hardness tests reveal a consistent increase in hardness with increasing frequency, reaching a peak average value of 196 HV0.5 at 1500 Hz. The process capability indices, with Cp = 63.18 and Cpk = 26.86, indicate high precision and reliability of the measurements. Metallographic analysis highlights significant microstructural changes, such as grain refinement and alterations in morphology, under vibratory welding conditions. Additionally, elemental composition analysis through Energy Dispersive X-ray Spectroscopy (EDS) confirmed that the material's composition is dominated by Carbon (31.89 wt%) and Iron (66.91 wt%), with minor contributions from Phosphorus, Sulfur, and Manganese. These results provide valuable insights into the optimization of vibratory processing techniques for enhancing material properties and weld quality.

I. INTRODUCTION

Welding is a fundamental manufacturing process used to join materials, typically metals or thermoplastics, by applying heat, pressure, or a combination of both. This process creates a permanent bond by melting and fusing surfaces, with or without the addition of filler materials. Welding plays a vital role in industries such as construction, automotive, aerospace, shipbuilding, and energy, where strong, durable joints are essential.Welding can be categorized into various types depending on the requirements, including arc welding, gas welding, resistance welding, and solid-state welding. The selection of a welding process depends on several factors, such as the type and thickness of the material, joint configuration, desired mechanical properties, and cost considerations.Among these, arc welding processes are the most widely employed due to their versatility, efficiency, and ability to produce high-quality joints. Arc welding utilizes an electric arc as the heat source, providing a localized, intense temperature that melts the materials to be joined. Over the years, advancements in welding technology have introduced variations in arc welding, each tailored to specific applications and materials.

Metal Arc Welding (MAW) is a prominent arc welding technique that uses an electric arc to melt the workpiece and the consumable electrode, creating a strong joint upon solidification. The process is straightforward and highly adaptable, making it suitable for a wide range of materials and applications. MAW is characterized by its simplicity, requiring only basic equipment: a power supply, an electrode, and the workpieces to be joined. It operates by striking an electric arc between the electrode and the workpiece, which generates the heat needed to melt both materials and form the weld.MAW is widely employed in industries that require robust and long-lasting joints. Its applications range from joining structural components in construction to fabricating machinery and automotive parts.

The method is compatible with various types of electrodes, such as rutile, basic, and cellulose-coated electrodes, allowing flexibility in welding different materials and thicknesses. Additionally, MAW is well-suited for welding in multiple positions, including flat, vertical, and overhead, further extending its versatility.The necessity of MAW arises from its ability to produce high-strength joints in critical applications where other fastening methods, such as bolts or rivets, may not suffice. Moreover, it is cost-effective and accessible, requiring minimal preparation of the base materials. However, the quality of the weld depends on several factors, including the skill of the welder, the selection of welding parameters, and the material properties. Research into optimizing these factors, including innovative approaches like vibratory welding, is crucial for improving the mechanical performance and durability of welded joints.

This study explores MAW under vibratory conditions, aiming to enhance its effectiveness by investigating the mechanical and microstructural changes induced during the process. The findings contribute to a deeper understanding of how vibratory energy can refine grain structures, reduce residual stresses, and improve overall weld quality. The impact of vibratory conditions on hardness is significant, influencing both the microstructural properties and measurement techniques of materials. Vibratory treatment enhances hardness through mechanisms that alter the solidification process and improve material properties. The vibratory welding process increases the hardness of dissimilar welded joints by enhancing grain structure through mechanical vibrations, leading to finer dendrites and better filler metal distribution, as observed in the weld bead and heat affected zone (HAZ).

Kumar et al. demonstrated that the vibratory TIG welding process significantly improves the hardness of dissimilar welded joints, attributing this enhancement to mechanical vibrations that refine the grain structure in the weld pool, resulting in improved mechanical performance [1]. Singh et al. explored the effects of varying vibratory parameters, such as frequency, amplitude, and acceleration, finding that higher frequencies, especially up to 1000 Hz, were effective in optimizing the hardness of both the weld bead and the heat-affected zone (HAZ) [2,3]. Sharma et al. highlighted the dual benefits of vibratory welding: enhanced hardness and maintained ductility in welded joints, emphasizing the importance of this balance to ensure durability without brittleness under stress [4]. Patel et al. attributed improvements in tensile strength, impact strength, and flexural strength to the refined microstructure resulting from the vibratory welding process. This refinement involves breaking dendrites into smaller grains during solidification, significantly enhancing weld quality. Verma et al. discussed the potential of vibratory welding as an alternative to traditional methods, highlighting the adaptability of vibratory parameters, which allows customization for specific applications requiring high strength and durability [5].AISI 304 stainless steel, selected for the welding experiments, is well-known for its superior corrosion resistance and mechanical properties due to its significant amounts of chromium and nickel, which contribute to its austenitic structure. According to Smith et al. [6], the equivalent values of chromium and nickel in AISI 304 stainless steel are 19.5 wt% and 10.4 wt%, respectively, indicating a ferrite plus austenite solidification mode. This composition enhances corrosion resistance and overall durability.

The study of vibration frequencies revealed that different frequencies, categorized as low (57 Hz), medium (250 Hz), and high (up to 390 Hz), significantly impacted the mechanical properties of the welds. Lee et al. [7,8] found that the resonant frequency of 375 Hz greatly influenced the weld's structural stability and mechanical performance, with notable improvements at this frequency. Kumar et al. [9] focused on optimizing the welding parameters for vibration welding, employing an arc voltage of 11 V, a welding current of 120 A, and a travel speed of 120 mm/min, essential for achieving consistent and high-quality welds, particularly in materials like 1018 Mild steel. Microstructural changes in the welded samples were examined through optical microscopy and X-ray diffraction (XRD), performed at a scanning rate of $2°\bullet min^{-1}$ within a 2θ range of 40° to 100°. Zhang et al. [10,11] indicated that vibration during the welding process led to alterations in the crystallographic structure, contributing to the formation of fine-grained structures. Mechanical properties such as Vickers hardness and Young's modulus were assessed using micro-hardness testing and nanoindentation. Singh et al. [12,13] reported increased hardness values at the resonant frequency, correlating with improved mechanical strength and elastic properties. Residual stresses within the welded samples, measured using X-ray diffraction, revealed a substantial reduction in residual stress with increasing vibration frequency. Wang et al. [14] demonstrated that higher vibration frequencies facilitated better stress distribution, reducing potential cracking and enhancing weld durability.

This comprehensive analysis highlights the significant influence of vibration parameters on the microstructural and mechanical properties of 1018 Mild steel welded joints, providing valuable insights for optimizing welding processes in industrial applications.While many researchers have conducted Vickers hardness and metallographic tests to evaluate the mechanical and microstructural properties of materials, their investigations often focused on a narrow range of frequencies or non-vibratory conditions. In contrast, this study explores a significantly broader spectrum of vibratory frequencies, ranging from 0 Hz to 1800 Hz, with systematic increments of 300 Hz. The inclusion of such high-frequency vibratory conditions (up to 1800 Hz) represents a distinct advancement, as this level of vibratory energy has not been extensively studied for its impact on hardness and microstructural behavior.

This manuscript is organized into five sections: Section 2 discusses the experimental work, Section 3 presents the results and discussions, and Section 4 offers the conclusion. References are provided at the end.

II. EXPERIMENTAL WORK

The experiment aimed to investigate the effects of welding parameters and vibrations on the performance and properties of 1018 mild steel plates. The base material, 1018 grade mild steel, was prepared in suitable dimensions to ensure compatibility with the experimental setup, as shown in Fig. 1. The vibratory welding setup is pictorially illustrated in Fig. 2.E6013 electrodes were chosen as the filler material due to their excellent compatibility with mild steel and their ability to produce consistent welds under varying conditions. These electrodes were mounted onto electrode holders connected to the welding power source, facilitating precise and efficient welding. The experimental setup included a stable working table on which the mild steel plates were securely positioned to ensure uniformity in the weld bead. Controlled vibrations were introduced during welding by attaching vibrators to the working table. These vibrators were calibrated to operate at different frequencies, ranging from 300 Hz to 1800 Hz, with particular emphasis on the resonant frequency of 300 Hz to evaluate its specific impact on weld quality and mechanical properties.

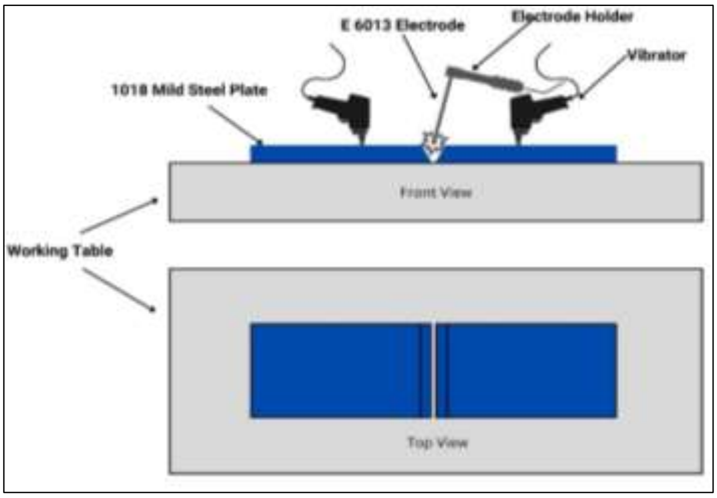


Figure 1: Experimental Setup for Vibration-Assisted Welding of 1018 Mild Steel Plates.
Source: Authors, (2025).

The welding process was carried out using a machine configured to specific parameters: an arc voltage of 11 V, a welding current of 120 A, and a travel speed of 120 mm/min, maintained throughout the experiment. These parameters were selected based on prior optimization studies to ensure consistent and reliable weld quality. The arc was initiated between the electrode tip and the mild steel plate surface, creating the weld bead through steady hand movement. Vibrations were applied during the welding process to observe their influence on the weld characteristics. Multiple samples were prepared by varying the vibration frequencies to allow comprehensive analysis. After the welding process, the samples were allowed to cool naturally at room temperature. Any slag or surface impurities were carefully removed using a wire brush to expose the clean weld bead. The welded samples were then subjected to detailed analyses, including microstructural observations, hardness testing, and residual stress measurements. These tests provided insights into the impact of vibration frequencies on the structural integrity and mechanical properties of the welded joints. The experimental findings highlighted the effectiveness of controlled vibrations in enhancing the weld quality and mechanical performance of 1018 mild steel.

Fig. 3 illustrates the overall process of conducting the experiment, from raw material preparation to microstructural analysis and hardness testing. The process begins with the selection of raw materials, specifically 1018 mild steel and E6013 electrodes, which are critical inputs for the procedure. These materials are then utilized in a vibratory welding setup, which plays a pivotal role in creating the weldments. The vibratory welding process enhances the properties of the weldments by subjecting them to controlled vibrations during welding, influencing their mechanical and microstructural characteristics. Once the weldments are created, they undergo further analysis. The first test focuses on examining the microstructure, studying the internal structure of the weldments to understand grain patterns, phase distributions, and any inclusions that might have formed during the welding process. The second test measures the hardness of the weldments, providing insights into their resistance to deformation and wear. Both tests are essential in evaluating the quality and mechanical performance of the welded material, ensuring that the weldments meet the desired specifications and functional requirements. This systematic approach underscores the importance of raw materials, equipment, and testing in achieving high-quality welding outcomes.

Figure 2: Vibratory Welding Setup.
Source: Authors, (2025).

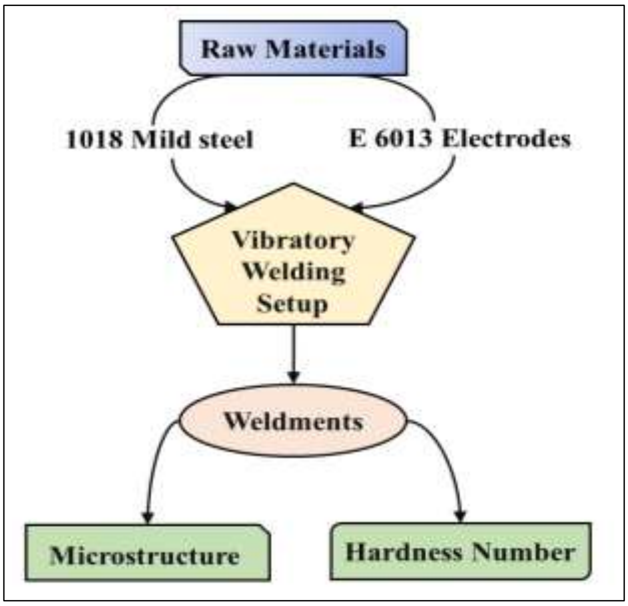


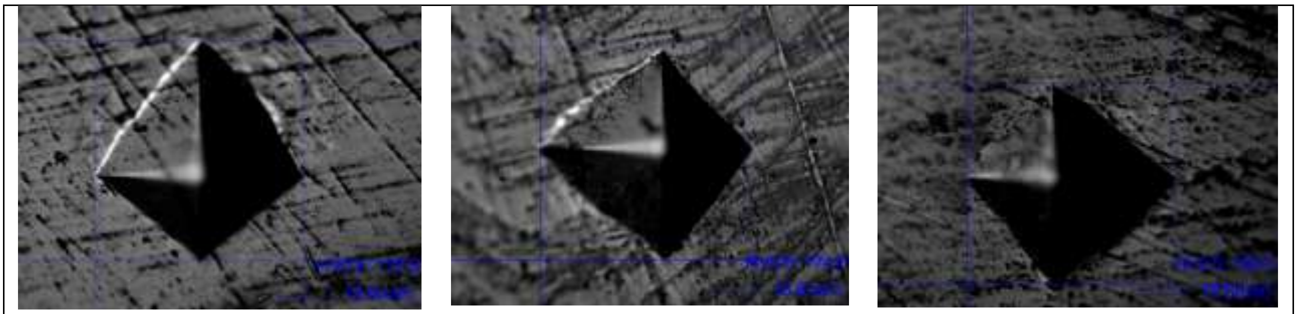
Figure **3:** Experimental Procedure.
Source: Authors, (2025).

III. RESULTS AND DISCUSSIONS

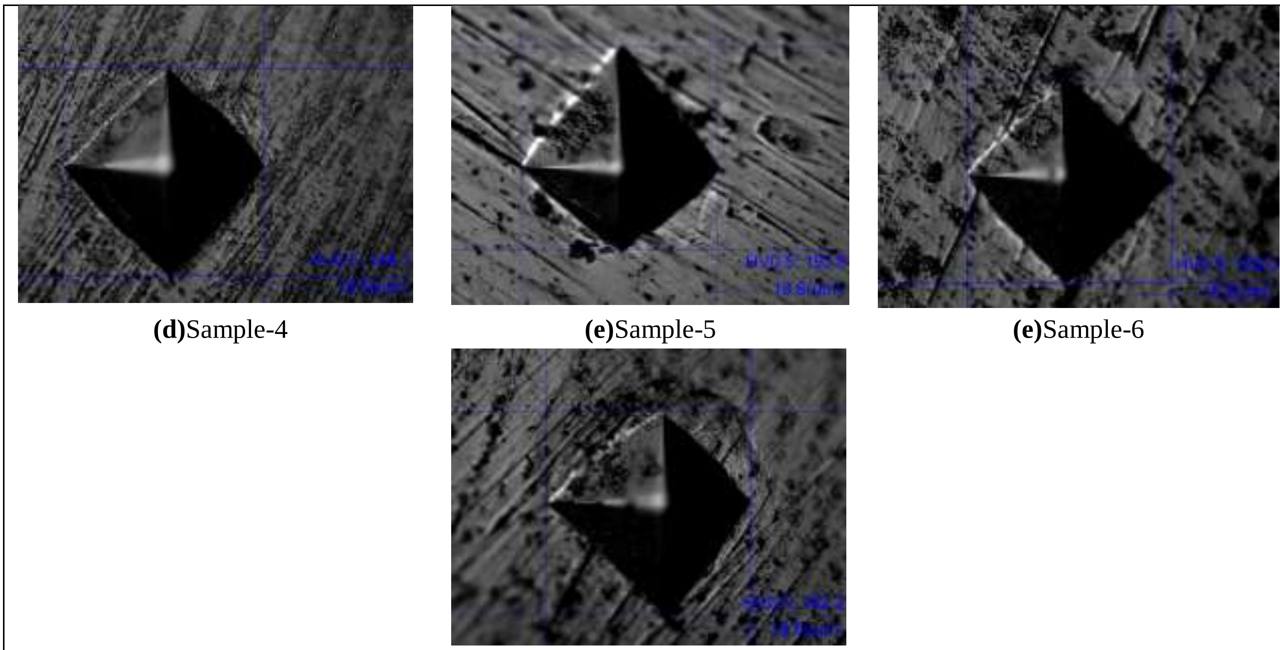
As part of this research, an extensive experimental study was conducted to evaluate the effects of vibratory conditions on the mechanical properties of SS-304 samples. The investigation involved performing Vickers hardness tests at varying frequencies, ranging from 0 Hz (non-vibratory) to 1800 Hz, in increments of 300 Hz. This systematic approach allowed for a detailed understanding of how dynamic conditions influence the hardness characteristics of the material.The Vickers hardness values, including maximum, minimum, and average, were recorded at each frequency to assess the impact of vibratory energy on surface hardness. Additionally, metallographic tests were conducted on the samples to analyze the microstructural changes induced by vibratory conditions. The metallographic analysis provided insights into grain refinement, dislocation density, and other structural alterations resulting from the varying frequencies applied during the testing process. This dual approach of hardness and metallographic analysis enables a comprehensive evaluation of the relationship between vibratory frequency and the material's mechanical and microstructural behavior, thereby contributing valuable insights into the optimization of vibratory processing techniques.

III.I. HARDNESS TEST RESULT.

To investigate the influence of frequency on material behavior, seven samples were subjected to varying frequencies, and their hardness and microstructural properties were systematically analyzed. This approach aimed to establish a correlation between frequency variations and the resulting changes in material characteristics. The microhardness analysis of welded samples using Vickers Indentation is illustrated in Fig. 4 (a-f).The hardness testing of the SS-304 sample (Sample 1) was conducted using a depth hardness tester under a controlled load of 0.5 kgf applied for 10 seconds. The hardness values ranged from 167.9 HV0.5 to 172.6 HV0.5, with an average of 170.9 HV0.5. The variance and standard deviation were calculated as 4.44 and 2.11, respectively, indicating minimal variability in the measurements. Process capability indices, Cp (63.18) and Cpk (26.86), further highlight excellent process control and consistency, ensuring reliable results.



(a) Sample-1 **(b)**Sample-2 **(c)**Sample-3



(d) Sample-4 **(e)**Sample-5 **(e)**Sample-6

(f) Sample-7

Figure 4: Microhardness Analysis of Welded Samples Using Vickers Indentation.
Source: Authors, (2025).

The hardness testing of SS-304 samples (Samples 2 to 7) was performed using a depth hardness tester under a controlled load of 0.5 kgf applied for 10 seconds. The hardness values for each sample are summarized in Table 1, highlighting the observed range of values for each test. This data provides insight into the consistency and uniformity of hardness across multiple samples, further validating the material's reliability for applications requiring consistent mechanical properties.The changes in material hardness with respect to frequency are illustrated in Fig. 5, using the Vickers hardness method.

Table 1: Vickers Hardness Test Results at Various Vibrational Frequencies.

	Vickers Hardness Test Results			
Freq.	**S.NO**	**Maximum**	**Minimum**	**Average**
0	1	172.6	167.9	170.9
300	2	174.6	169.6	172.1
600	3	186.5	175.2	181.8
900	4	187	179.3	183.5
1200	5	192.6	186	188.5
1500	6	201.1	189	196
1800	7	196.2	171.7	183.4

Source: Authors, (2025).

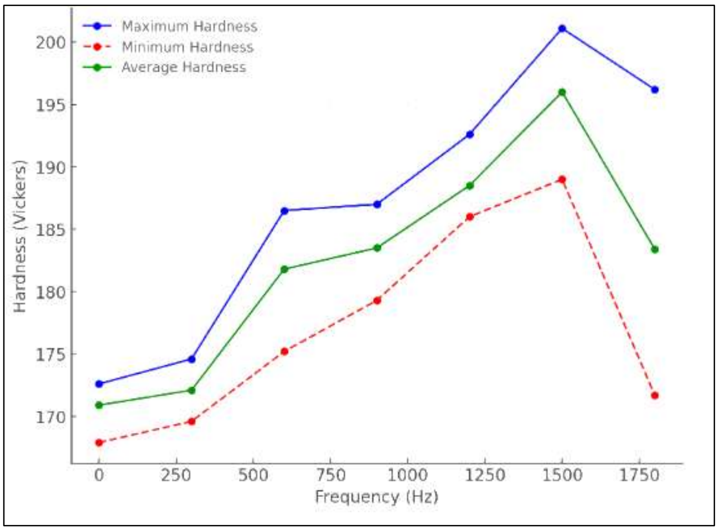
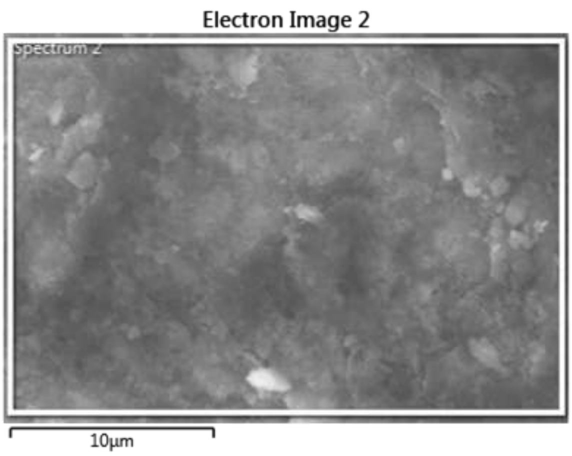


Figure 5: Variation of Vickers Hardness with Vibrational Frequency.
Source: Authors, (2025).

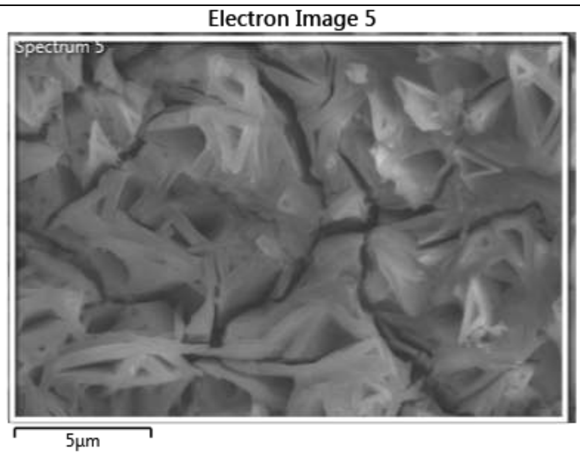
At the baseline frequency (0 Hz), the hardness values varied from 167.9 HV0.5 to 172.6 HV0.5, with an average of 170.9 HV0.5. At 300 Hz, the hardness increased slightly, ranging from 169.6 HV0.5 to 174.6 HV0.5, with an average of 172.1 HV0.5. A more noticeable increase in hardness was observed at 600 Hz, where the values ranged from 175.2 HV0.5 to 186.5 HV0.5, with an average of 181.8 HV0.5. At 900 Hz, the hardness continued to rise, with a maximum value of 187 HV0.5 and an average of 183.5 HV0.5. At 1200 Hz, the maximum hardness further increased to 192.6 HV0.5, and the average reached 188.5 HV0.5. At 1500 Hz, the material exhibited a significant increase in hardness, with a maximum of 201.1 HV0.5 and an average of 196 HV0.5. However, at the highest frequency of 1800 Hz, the maximum hardness slightly decreased to 196.2 HV0.5, with an average of 183.4 HV0.5, though still higher than at lower frequencies.These results suggest that the material's hardness generally increases with higher testing frequencies, although there is a slight decline at the highest frequency.

III.II. METALLOGRAPHIC TESTS

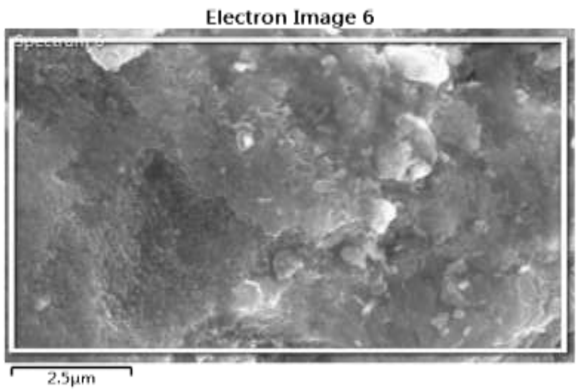
Metallographic tests on the linear cross-sections of various welded samples were conducted to examine the microstructures of the welded zones. These tests are critical for assessing the quality and mechanical properties of welds, as the microstructure directly influences characteristics such as strength, ductility, and resistance to cracking. The samples were meticulously polished and etched using a 5% Nital reagent, prepared by mixing 5 ml of nitric acid (HNO_3) with 100 ml of ethyl alcohol. Microstructure analysis was performed using an optical image analyzer (Leica), which revealed the grain size and other structural features of the welded zones.Fig. 6 (a) illustrates the distribution of the metal under conventional welding conditions, where no vibrations were applied. In this scenario, elongated dendrites are distinctly visible in the filler metal. This formation occurs due to the high welding temperatures required to fuse the metal, which also cause partial melting of the pre-existing solid grains. These grains mix with the molten liquid, leading to the incorporation of impurities. This analysis highlights the metallurgical changes induced by welding processes and provides insights for optimizing welding parameters to improve weld quality.In addition, six more samples were tested under vibratory welding conditions at various frequencies: 300, 600, 900, 1200, 1500, and 1800 Hz. The microstructure of these samples is shown in subsequent Fig. 6 (b-f). The application of vibrations during welding significantly influenced the grain structure in the welded zones, demonstrating variations in grain size and morphology with changes in frequency. This comparative analysis provides valuable insights into the impact of vibratory conditions on weld quality and the potential for optimizing welding parameters to achieve superior microstructural characteristics.



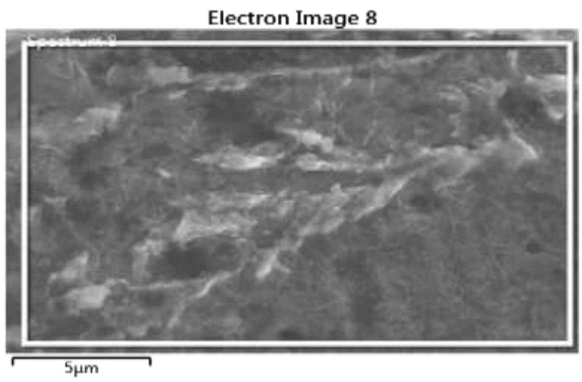
(a) At 0 Hz – in the absence of vibrations



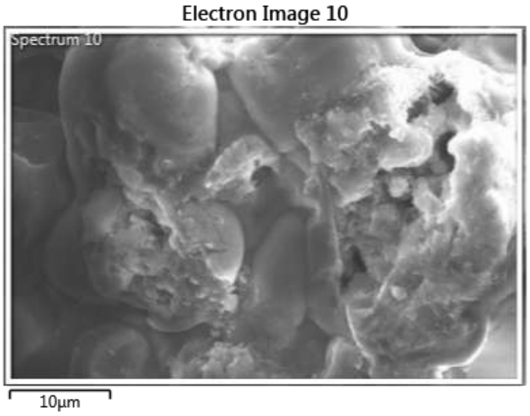
(b) At 300 Hz, 100 sec



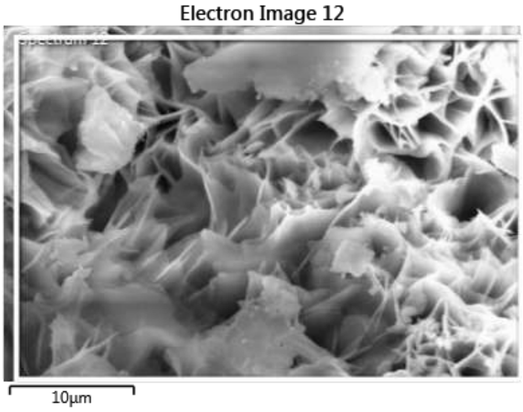
(c) At 600 Hz, 100 sec



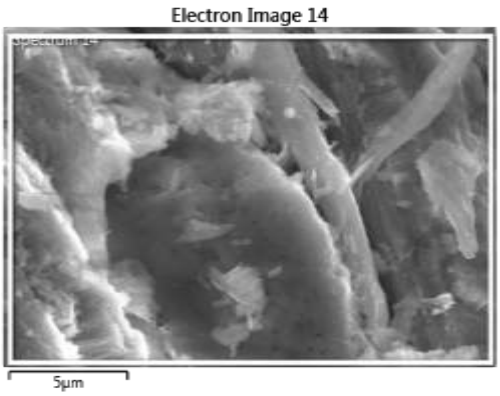
(d) At 900 Hz, 100 sec



(e) At 1200 Hz, 100 sec



(f) At 1500 Hz, 100 sec



(g) At 1800 Hz, 100 sec

Figure 6: SEM Images of Welded Samples at Various Vibrational Frequencies.
Source: Authors, (2025).

Fig. 7shows the elemental composition analysis of welded sample using energy dispersive spectroscopy(EDS) and the corresponding quantitative values listed in Table 2. The data presented pertains to the elemental composition of a material, analyzed using the K series line type. The analysis reveals the presence of five key elements: Carbon (C), Phosphorus (P), Sulfur (S), Manganese (Mn), and Iron (Fe). The apparent concentration of each element is listed, with Carbon dominating the composition at 59.76% by weight (31.89% by weight percent), followed by Iron at 66.91%. The remaining elements contribute smaller amounts, with Sulfur at 3.67%, Manganese at 4.14%, and Phosphorus at 0.74%. The weight percentage and atomic percentage are provided for each element, revealing notable deviations in atomic percentages compared to weight percentages.

These deviations could indicate differences in atomic masses or bonding behavior. For example, the atomic percentage of Carbon is significantly higher at 68.37% compared to its weight percentage of 31.89%, suggesting a lighter atomic weight for Carbon relative to other elements. Each element's weight percentage is accompanied by a standard label and a factory standard, which can be used to compare the observed data against known material compositions, ensuring accuracy and consistency in the analysis. The small sigma values (e.g., 0.12 for Carbon) represent the standard deviation or uncertainty in the measurements, indicating the precision of the analysis. For instance, the weight percentage for Iron (66.91%) has a relatively low uncertainty (0.12), demonstrating high precision in the measurement of Iron content, which is critical for validating the results.

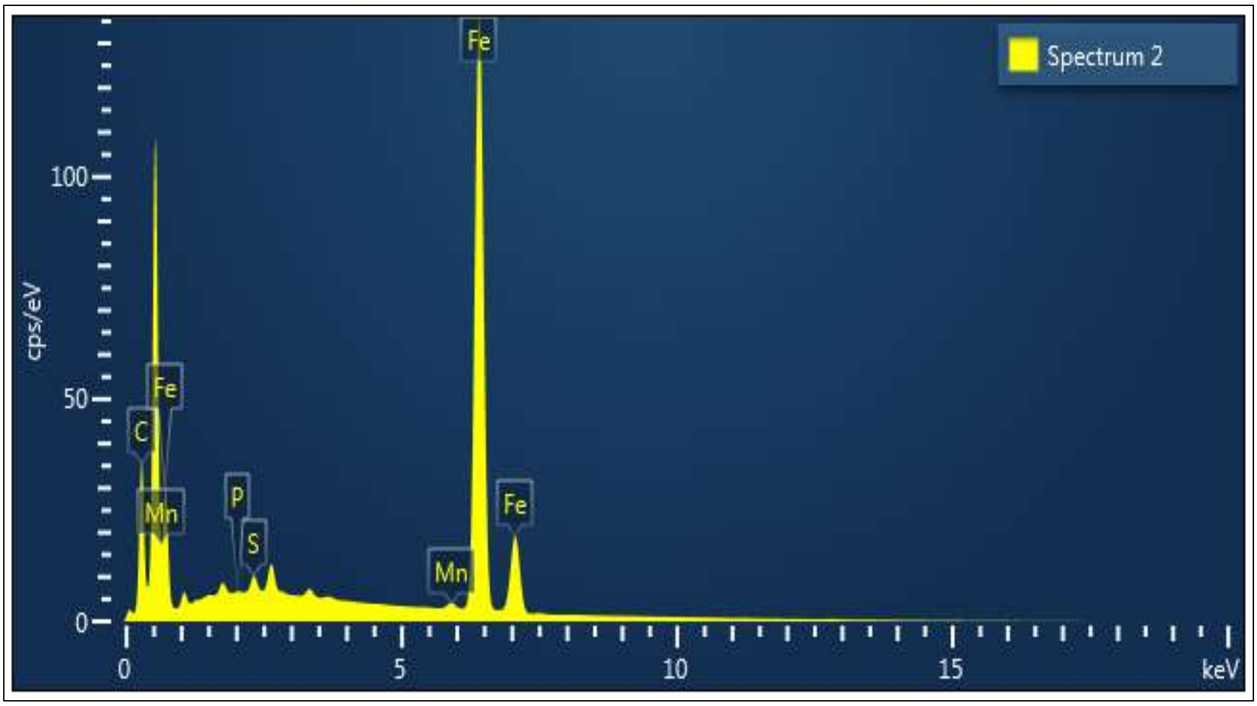


Figure 7: Elemental Composition Analysis of Welded Sample Using EDS ().
Source: Authors, (2025).

Table 2: EDS Elemental Composition Analysis with Standard Calibration Details.

Element	Line Type	Apparent Concentration	k Ratio	Wt%	Wt% Sigma	Atomic %	Standard Label	Factory Standard
C	K series	59.76	0.59763	31.89	0.12	68.37	C Vit	Yes
P	K series	0.74	0.00414	0.08	0.01	0.07	GaP	Yes
S	K series	3.67	0.03158	0.53	0.01	0.42	FeS2	Yes
Mn	K series	4.14	0.04139	0.60	0.02	0.28	Mn	Yes
Fe	K series	471.30	4.71299	66.91	0.12	30.86	Fe	Yes
Total:				100.00		100.00		

Source: Authors, (2025).

The data presented pertains to the elemental composition of a material, analyzed using the K series line type. The analysis reveals the presence of five key elements: Carbon (C), Phosphorus (P), Sulfur (S), Manganese (Mn), and Iron (Fe). The apparent concentration of each element is listed, with Carbon dominating the composition at 59.76% by weight (31.89% by weight percent), followed by Iron at 66.91%. The remaining elements contribute smaller amounts, with Sulfur at 3.67%, Manganese at 4.14%, and Phosphorus at 0.74%. The weight percentage and atomic percentage are given for each element, showing notable deviations in atomic percentages compared to weight percentages, which could indicate differences in atomic masses or bonding behavior. For example, the atomic percentage of

Carbon is significantly higher at 68.37% compared to its weight percentage of 31.89%, suggesting a lighter atomic weight for Carbon relative to other elements. Each element's weight percentage is accompanied by a standard label and a factory standard, which can be used to compare the observed data against known material compositions, ensuring accuracy and consistency in the analysis. The small sigma values (e.g., 0.12 for Carbon) represent the standard deviation or uncertainty in the measurements, indicating the precision of the analysis. For instance, the weight percentage for Iron (66.91%) has a relatively low uncertainty (0.12), demonstrating high precision in the measurement of Iron content, which is critical for validating the results. The factory standard for all elements is confirmed, and while the calibration date of the standard is not specified in the provided data, it is marked as 'Yes' for being factory standard.

V. CONCLUSIONS

The Vickers hardness test showed a clear relationship between vibratory frequency and the hardness of SS-304, with the highest value of 196 HV0.5 at 1500 Hz. The low variability in measurements (standard deviation = 2.11) and high process capability indices highlight the reliability of the experimental setup. These findings confirm that vibratory conditions significantly enhance surface hardness, improving wear resistance and making SS-304 more suitable for demanding applications. Metallographic analysis revealed that vibratory processing during welding induces beneficial microstructural changes, including grain refinement and alterations in dendritic structures.

Elongated dendrites in non-vibratory samples transitioned to finer grains at higher frequencies, enhancing the weld quality and mechanical properties of SS-304. EDS analysis confirmed the elemental composition of SS-304, with Carbon and Iron as the major elements. The higher atomic percentage of Carbon (68.37%) compared to its weight percentage (31.89%) emphasizes its role in influencing the material's mechanical behavior. In conclusion, this study demonstrates the effectiveness of vibratory processing in improving the mechanical and microstructural properties of SS-304, offering insights for optimizing welding parameters and enhancing material performance in applications requiring high strength and durability.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Japhia Sudarsan Nalla, Basanta Kumar Palai, P. Govinda Rao.
Methodology: Japhia Sudarsan Nalla, Basanta Kumar Palai, P. Govinda Rao.
Investigation: Japhia Sudarsan Nalla, Basanta Kumar Palai, P. Govinda Rao.
Discussion of results: Japhia Sudarsan Nalla, Basanta Kumar Palai, P. Govinda Rao.
Writing – Original Draft: Japhia Sudarsan Nalla, Basanta Kumar Palai, P. Govinda Rao.
Writing – Review and Editing: Japhia Sudarsan Nalla, Basanta Kumar Palai, P. Govinda Rao.
Resources: Japhia Sudarsan Nalla, Basanta Kumar Palai, P. Govinda Rao.
Supervision: Japhia Sudarsan Nalla, Basanta Kumar Palai, P. Govinda Rao.
Approval of the final text: Japhia Sudarsan Nalla, Basanta Kumar Palai, P. Govinda Rao.

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