Research Article

The effect of post-weld heat-treatment (PWHT) and vibratory assisted welding (VAW) on hardness of 304L stainless steels material

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Abstract
Welding is the most common and frequently used method to join the components. The fusion welding process is the one that is a commonly used method to join 304L stainless steel materials. The fusion welding process generates much residual stresses within the materials. Residual stresses can be modified by a few techniques like preheating post-weld heat treatment but it takes more time and requires specific tools. Vibratory assisted welding is introduced to reduce welding defects. In this, a comparative study has been carried between post-weld heat treatment and vibratory assisted welding for the hardness of 304L stainless steel. From the test results, Post-Weld Heat-Treatment (PWHT) and vibratory assisted welding are two effective methods to increase the hardness of the weldments. 13% and 18% improvement in the hardness of 304L stainless is observed in the case of PWHT and vibratory assisted welding, respectively, to the conventional welding. Even though both PWHT and Vibratory Assisted Welding (VAW) as exhibiting almost similar results PWHT processes are more time-consuming, costly, and Laborious. From the current research, it is identified Vibratory assisted welding is the best suitable technique for reducing weld defects and enhancing properties.

Keywords
Heat treatment, Vibration welding, Hardness, Stainless steel, Frequency.

1.Introduction

Welding is widely used in most fabrication domains, and it is especially important in engineering fields like shipbuilding, structural structures, automotive, and aerospace [1]. Compared to bolted or riveted joints, welding allows for a less-weight joint. Welding provides a permanent joint but it affects the metallurgy of the components. During the joining process through welding, due to the extreme input of heat, the regions near the weld experience severe thermal cycles, thus producing plastic deformation homogeneously at the weld region. This, in turn, induces residual stresses. Due to the residual stresses, the service life of the weld joint is reduced. Grain size and microstructure have a significant impact on the mechanical properties of weldments. Fine-grained materials have superior ductility and strength compared to coarse-grained ones [2, 3].

To overcome this , different methods are used i.e., weld sequence, preheating, design considerations, natural aging, heat-treatment after welding, vibratory stress relief Weld pool oscillation, welding torch vibrations, and work piece vibrations are some mechanisms used to generate fine-grained structure[4–6].

One of the age old methods is Post Weld Heat Treatment (PWHT) process. It is used on a regular basis to ensure that the material strength of a part is retained after welding. PWHT can be used to minimize residual stresses, hardness control, and even improve material strength. PWHT includes a wide range of potential treatments, the most common of which are post-heating and stress relief. This PWHT process mainly encompasses heating the welded material to a definite temperature and cools the material gradually.

If PWHT is done incorrectly or not done at all, residual stresses can combine with load stresses to

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exceed a material's design limitations. This can result in weld failures, increased cracking potential, and increased brittle fracture susceptibility. And another disadvantage is that, process is laborious, time consuming and skilled technician observation is very much needed.

To replace these PWHT processes a novel technique is introduced that is Vibratory Assisted Welding (VAW). It is the process of imparting vibrations to the workpiece in regular intervals of time with force. During the process of welding, to enhance the welded joints mechanical properties and to replace the PWHT process, vibratory assisted welding is the best suitable technique. Studies reveal that the effect of vibrations reduces the welding residual stresses. Few researchers focused on the effect of vibrations on the mechanical properties of welded joints [7]. Effect of harmonic vibrations on the distribution and size of intermetallic compounds during MIG welding of AA-5083-H321 aluminum joints were studied. Authors observed that Intermetallic compounds were increased to 7%, 13%, and 26% for the specimen welded with a vibratory force of 400 N, 2200 N, and 3150N, when compared with the specimens, welded without any vibrating force of welded joint [8]. Finally the weld defects can minimize with PWHT process and these PWHT processes are completely replaced with VAW. But the comparison of weld joints hardness property between the conventional welding, PWHT process and vibratory assisted welding is not done. In this paper the comparison is made in between the above process and results were discussed.

2.Literature review
2.1The effect of Vibratory assisted welding (VAW)
Welding residual stresses are the key factors for reducing service or fatigue life. The vibratory stress relief method is the one that can reduce the welding residual stresses predominantly. The vibratory stress relief method can be simulated using the finite element method to find the welding residual stresses. The results obtained by FEM compared with the Hole drilling method using strain gauges to measure the welding residual stresses. There is a significant reduction in the welding residual stresses using vibratory stress relief [9]. Similarly Thermo-mechanical examination is carried to evaluate the distribution of thermal and residual stresses through numerical simulation [10, 11].

Two different vibration setups i.e., Local Vibration Effect (LVE) and Global Vibration Effect (GVE),

and the effect of these vibration setups on the mechanical properties and microstructural behaviour was investigated. Authors found that GVE has a significant effect on the microstructure and mechanical properties compared to LVE [12].

Vibratory welding has a positive effect on the mechanical properties of aluminium welded connections. The authors studied the effect of time of vibration and vibration voltage on the ultimate tensile strength of the aluminum welded connections. The authors observed that vibratory welding voltage has a significant effect on the ultimate tensile strength and hardness [13, 14]. Mechanical excitations to the vibrating table and electrode also have a significant effect on the mechanical properties of 1018 mild steel. The authors observed that stirring of weld pool with the mechanical excitations influences the hardness and ultimate tensile strength of the 1018 mild steel properties along with the grain structure [15–17].

A novel vibratory welding setup was capable of inducing vibrations at the natural frequency. The authors analysed the influence of vibration frequency, welding speed and welding current on the mechanical properties of mild steel-welded specimens. The optimization technique like surface roughness method has been used to understand the most influential factor for the weld joint strength [18].

2.2Effect of post weld heat treatment (PWHT)
Effect of vibrations and thermal stress relief on the reduction of residual stresses was investigated. Using the finite element method, a simulation has been conducted on steel stiffeners. Different amplitudes and frequencies (sub-resonant) of vibrations have been applied on steel stiffener and residual stresses were monitored [19].

PWHT is a type of heat treatment that is done to welded joints after the welding process is completed to progress mechanical qualities and prevents brittle fracture by altering the metal-metallurgical structure. On the other hand, necessitates the use of specialized instruments and takes longer to finish. To improve the characteristics of welded joints, some researchers have used the PWHT method, which included solution behavior for 30 min at 5350C, trailed by water-quenching and artificial aging for 12hrs at 1750C. PWHT is used on flexible polarity gas weldedAA2219 aluminum alloy joints in this study [20]. Ahmed et al explored PWHT was used at very high temperatures for 0.5 to 50hrs with 0.5-time

interval to progress the tensile & impact-strength of weld-zone [21]. PWHT was applied to Cr-Mo Steel with Shielded Metal Arc Welding (SMAW) in this study, the shaking in engine oil reports less strength compared with PWHT neem-oil quenching is reports improved tensile & hardness of weld-joints. Compared to quenching in neem oil, PWHT with quenching in engine oil improved impact strength. In GMAW, joint strength is enhanced for duplex stainless steel [22]. PWHT is used to improve the tensile & hardness of an AA6661 welded-junction when it is related to weld-joint. The hardness & tensile of the PWHT-joint is increased by 25.6%. Improvement in the mechanical properties of the weld-zone was due to fine-grain structure and a minor gap among grains, which SEM photos captured [23].

The hardness & tensile properties of SM steel was studied with aging at 4600C and superior results were attained [24]. PWHT considerably enhanced the tensile property of aluminum AA2219 alloy. PWHT was conceded at 5350C for half an hour, trailed by water-quenching and artificial aging at 1750C for 12 h. At the weld junction, a more homogeneous microstructure was formed [25]. Impact toughness of an SMA weld-joint of a pressure-vessel is processed with PWHT after 40 h of welding at 6200C. Hardness and transverse weld strength, on the other hand, are reduced. The softening of the weld joint in PWHT is responsible for the increased impact toughness [26].

Aging temperatures below 11500C, significantly improves the micro-level hardness of the TIG-weld duplex steel. PWHT was administered to the joints for 60 min at temperatures ranging from 800-11500C. The weld-joints tensile, impact & hardness of high-strengthened steel with PWHT at 6000C for 1 to 3 h with an interval of 1hr were all enhanced [27, 28].

From the literature, welding residual stresses were measured by the hole drilling method using strain gauges. Local and global vibration has a significant influence on the microstructure and mechanical properties of welded joints. Welding simulations have been conducted on steel stiffeners and applied sub-resonant frequencies and observed that there is a significant reduction in the residual stresses.

Most of the researchers focused on the reduction of residual stresses. Residual stresses in the welded joints arise due to uneven heat input and cooling

cycles. The main objective of this paper is to understand the behavior of the heat treatment after welding and welding with vibrations on the hardness of 304L stainless steel. Here in the case of vibrations during welding, along with the above-mentioned objectives, an attempt is made to analyze the heat input and vibrations on the hardness. In the case of heat treatment after welding, the effect of various heat input ranges on the hardness of 304L stainless steel specimens.

3. Experimental methodology
3.1 PWHT process
In this study, arc welding was performed for SS 304L steels to know the hardness. The material compositions are represented in *Table 1*. A plate of 20mm width, 200mm length, and 5mm thickness is considered and joined using SMAW process. To analyze the hardness of SS 304L weldments, Post-Weld Heat-Treatment was implemented at 650^0C to 1050^0C at an interval of 200^0C which is shown in *Figure 1*. The range of temperatures maintained is 1hr to 4hr, with an interval of 1hr. In every stage, the prepared specimens are quenched in cold water for analysing the hardness of the material at temperatures and at different time intervals.
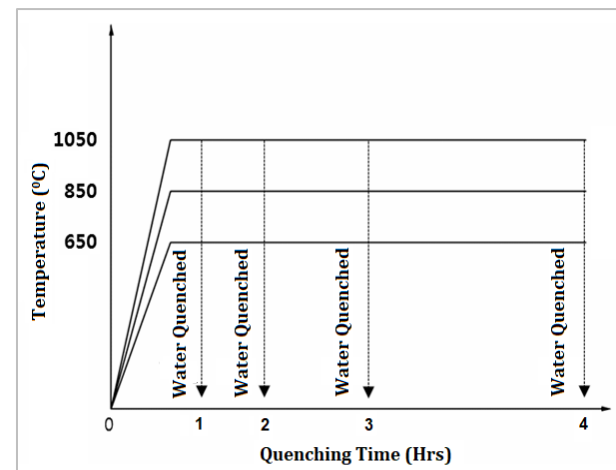

Figure 1 Heat treatment at different temperatures and quenching time

3.2 Vibratory assisted welding
Four springs along each corner were fitted with a platform for placing the specimen. By adding a vibromotor to the vibratory table setup, the vibration platform was prepared. To produce the vibrations, an ammeter, voltmeter, and a dimmerstat were connected to the vibromotor. The experimental setup is shown in *Figure 2*. A supplementary vibratory setup that is proficient in producing mechanical

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excitations to the weld-pool for "manual metal arc welding" is developed to improve the weldment mechanical properties by imparting constructive alterations in the microstructure of the weld region.

Different frequencies were imparted along the weld-bead length at various amplitudes, only trailing behind the welding arc to mechanically stir the weld pool to induce desirable microstructural results.
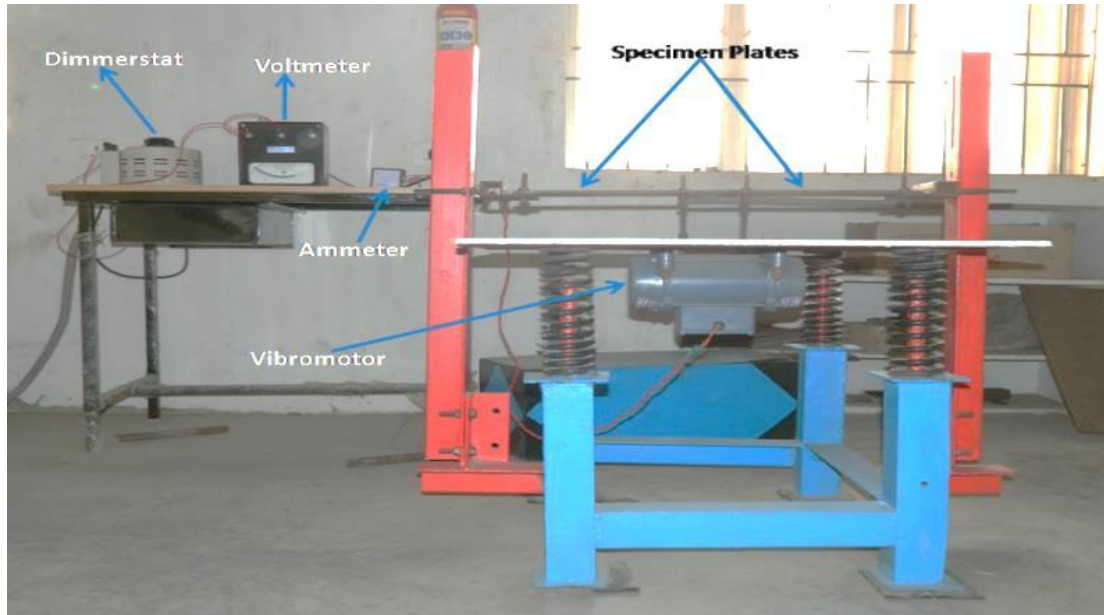

Figure 2 Experimental setup

In terms of voltages, this setup generates the appropriate frequency with amplitude. *Table 1* lists the differences in acceleration and amplitude at 70, 150, and 230 V voltages. *Figures 3* and *4* display the difference in acceleration and amplitude to the input voltage. Beneath the low heat inputs (90–110 A) was the prepared butt-welded joints. To fill the void, there are two passes, the first is the main pass and the second are the root pass. Vibrations transferred to the molten pool up to the solidification state of the weld bead.

3.3 Materials and the weld-joint preparation
In this present examination, 304L stainless steel material of thickness 5mm is selected as the base material. Its material composition is in (% weight) carbon.(C) – 0.3%, Manganese.(Mn) – 2%, Phosphorus.(P) – 0.045% and sulfur.(S) – 0.03%, Silicon.(Si) – 0.75%, Nickel.(Ni) – 8 % and Nitrogen.(N) – 0.1 % which is shown in *Table 1*. As per standard, the weld joints were prepared by inducing mechanical excitations to hardness property to examine the characteristics of vibrations. Excellent formability, high strength and good corrosion resistance makes 304L Stainless steel material is used for several applications in manufacturing. Typical uses of 304L SS material include kitchen

equipment, trim and architectural mouldings. And it is used in the paper, textile, chemical and pharmaceutical industries as processing equipment. For the preparation of the weld joints, specimens were fixed over the flat surface of the vibration table setup and Manual arc welding process is carried. While welding, the required number of vibrations was transferred to the specimens by alternating the dimmer-stat and voltmeter. *Figure 3* shows the line diagram of specimen preparation before welding. The vibrations were transferred to molten pool during welding continuously throughout the process.

The vibrations were measured using a specific device called vibro-meter. Here the velocity, acceleration and displacement are measured for every setoff vibration.
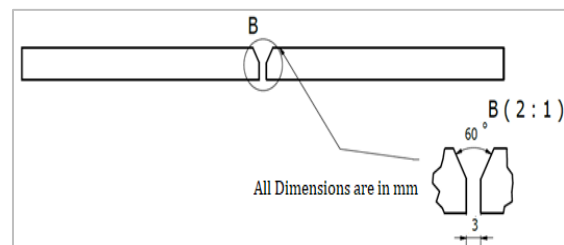

Figure 3 Weld joint dimensions

Table 1 SS 304L chemical composition

Stainless steel material Grade	Chemical composition (Wt%)							
	C	Si	Mn	P	S	Cr	Ni	N
304L	0.03	0.75	2	0.045	0.03	18	8	0.1

3.4 Hardness test of weldments

The "Rockwell Hardness Test" is considered for hardness characterization on weld joints. The weld-joints are indented with the spherical-shaped indenter, at several load conditions. The hardness values vary with the varying load, the amount of load considered during the hardness calculation must therefore be specified. From references, the current protocols and guidelines can be accessed. RHN (Rockwell Hardness Number) values for the weldments within 10kgf of minor-load and 150kgf of major-load, are measured. The general hardness formula for measuring the RHN value is given in Equation 1.

$$RHN = (N - (d/s)) \qquad (1)$$

Where:

N and S – Scale factors;

D – Depth of indentation.

The weld joints maximum RHN values are noted at 150kgf load.

4. Experimental results and discussions

Figure 4 illustrates the hardness test procedure under various load conditions on a "Rockwell hardness testing" unit. Here the hardness values of weld-joints were measured along the weld-bead and Fusion zone for the samples processed with PWHT and VAW. Hardness values are considered at a distance of 10mm gap for each measurement along with the weld bead in the experiment.
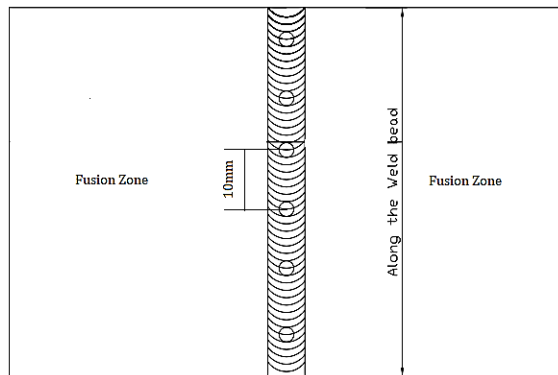
Figure 4 Weld Joint Zones

4.1 Heat treated specimens

Initially, the specimens are prepared without any implication of vibrations and those specimens were transferred to the Post-Weld Heat-Treatment process.

The process is carried at a temperature of 650^0C to 1050^0C at an interval of 200^0C and the time is taken for heat treatment is 1Hr to 4Hrs at an interval of 1Hr. From the hardness results, it is identified that the weld specimen's heat treatment at 1050^0C shows better results when it is compared with the heat-treated at 650^0C and 850^0C. The *Figure 5* shows the hardness values of 304L stainless steel at 1050 degrees centigrade. Hardness has been measured across the weld bead as the centre is considered base.

The graphs shown in *Figure 5* represent that the hardness values are measured for the weld specimens which are undergone heat treatment process. During the experimentation specimens were heat treated at 650^0C and 1Hr to 4Hr at an interval of 1Hr, 850^0C and 1Hr to 4Hr at an interval of 1Hr and 1050^0C and 1Hr to 4Hr at an interval of 1Hr. By observing the results at different temperatures and time, it is concluded that at 1050 ^{0}C the material hardness property is more compared with the other temperatures. In *Figure 5* Hardness values of PWHT at (a) 1050^0C, 1Hr (b) 1050^0C, 2Hr (c) 1050^0C, 3Hr (d) 1050^0C, 4Hr are taken along the Fusion zone and along the heat-affected zone. The peak hardness value is obtained at 1050^0C, 4hrs that is 82 RHN when it is compared with the less time intervals. During the heat treatment process, the heat affected zone of 304L Stainless steel has less thermal-diffusivity than the other metals. Due to the material grade is transformed from austenitic stainless steel to martensitic that allows the HAZ of metal as weaker.

### 4.2 Vibratory assisted welding specimens

During the welding process the specimens were welded with vibrations by varying vibration voltage and welding current. Here, the voltage of the vibromotor is varied from 60 V to 230 V with an interval of 10 V and the welding current is varied from 90amps to 130amps with an interval of 20amps. Initially at 0 V voltage (without any vibrations, conventionally welded), the specimens are welded and gradually the voltage is increased (With vibrations) during the welding process.

The specimens are welded with vibro-motor voltage ranges from 60 V to 230 V with an interval of 20 V at 90amps, 60 V to 230 V with an interval of 20V at
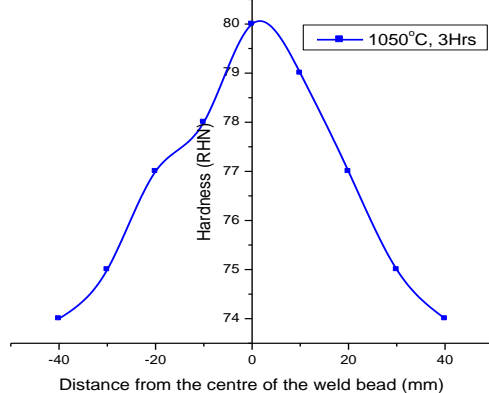
110amps and 60V to 230V with an interval of 20V at 130amps. Initially, the hardness of the specimens is low and gradually increases with the increase of vibrations for 90amps, 110amps, and 130amps from 60 V to 180V and again it is dropped from 180V to 230V.
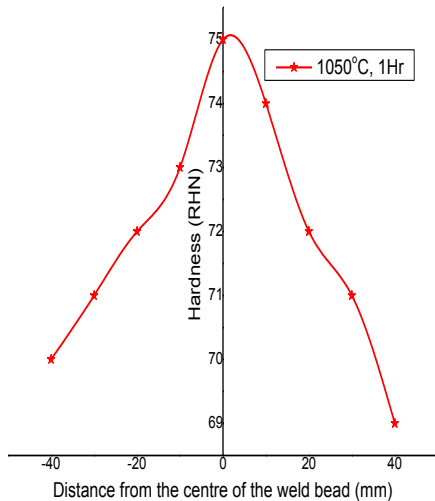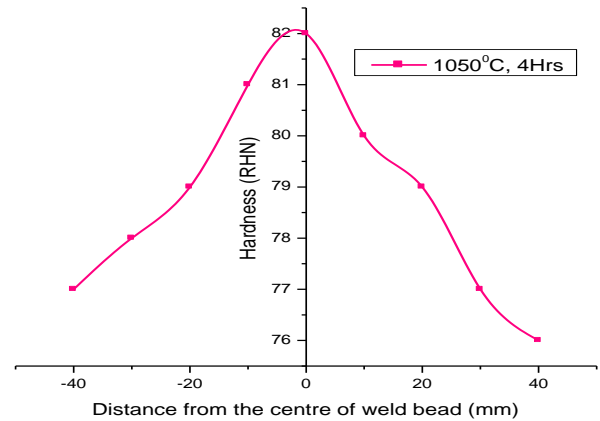

(a)
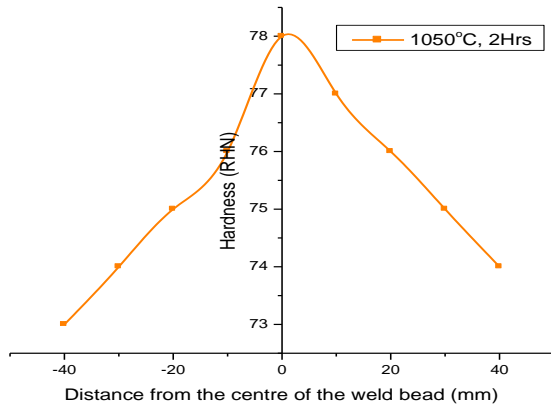
(b)

(c)

(d)

Figure 5 Hardness values of PWHT at (a) 10500C, 1Hr (b) 10500C, 2Hrs (c) 10500C, 3Hrs (d) 10500C, 4Hrs.

The peak value of hardness is identified at 180 V of vibromotor and 110 amps of welding current for 90amps, 110amps and 130amps due to the material grade is transformed from austenitic stainless steel to martensitic that allows the HAZ of metal as weaker those results are shown in *Figure 6*.

The improved hardness with the increased vibrations is due to fine grain refinement of weld-pool during the welding process with excitations. After 180 V of vibromotor voltage, the hardness value is gradually drops because of increased arc gap with high frequency vibrations.

From the above *Figure 6*, it is identified that the peak values of hardness is obtained at 180V with different welding currents that is 90 amps, 110 amps and 130 amps. By considering these input parameters the specimens were tested for the hardness along the weld-bead at a gap of 10mm for each measurement.

The graphs shown in *Figure 7* represent that the hardness values are measured for the weld specimens are prepared with and without vibrations. During the experiments, specimens which are welded at 180 V of vibro-motor and welding currents of 90amp, 110amp, and 130amp showing the peak values of hardness. During this process the specimens are also prepared conventionally of welding those results also shown in *Figure 7* (a). When compared the results of conventional welding with vibrations welding the hardness values are increased due to the refinement of weld-pool during the welding process. And the maximum values of the hardness obtained at the weld bead and gradually reduced at heat-affected zone.

Here also with vibration parameter the welding current also influences the hardness property of weldment. From *Figure 7 (b)* the specimens are prepared at 180V of vibro-motor and 90 amps of welding current the hardness maximum value is obtained as 76 RHN, at 180V of vibro-motor and 110 amps of welding current the hardness maximum value is obtained as 85 RHN and at 180V of vibro-motor and 130 amps of welding current the hardness

maximum value is obtained as 74 RHN. So by observing the results maximum value of hardness is obtained at 180 V and 110amps. Due to molten pool excitation during welding the large dendrites are breaks down in to small dendrites and the grain size also decreasing with vibration. Because of the grain size reduction with vibrations the hardness values are increased for SS 304 L materials.
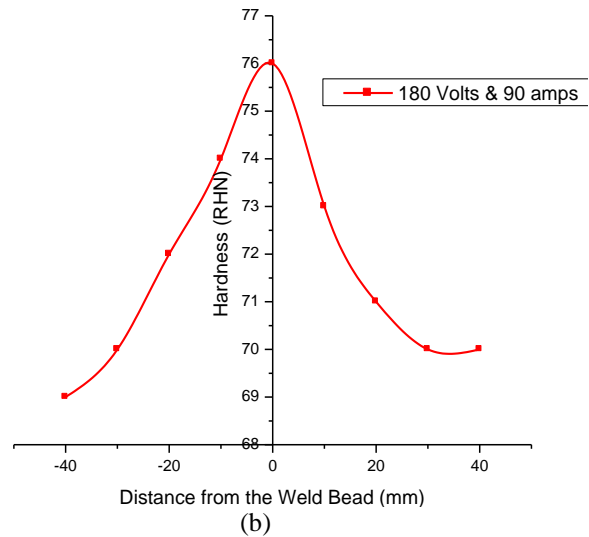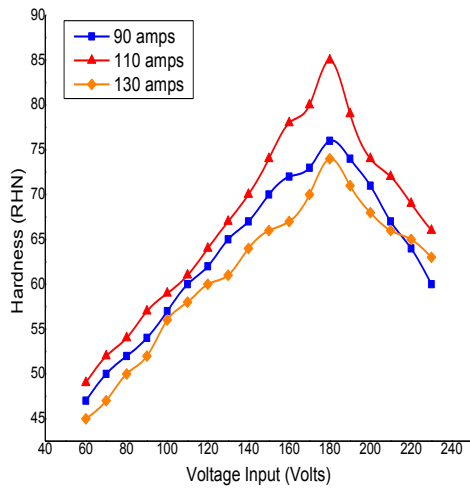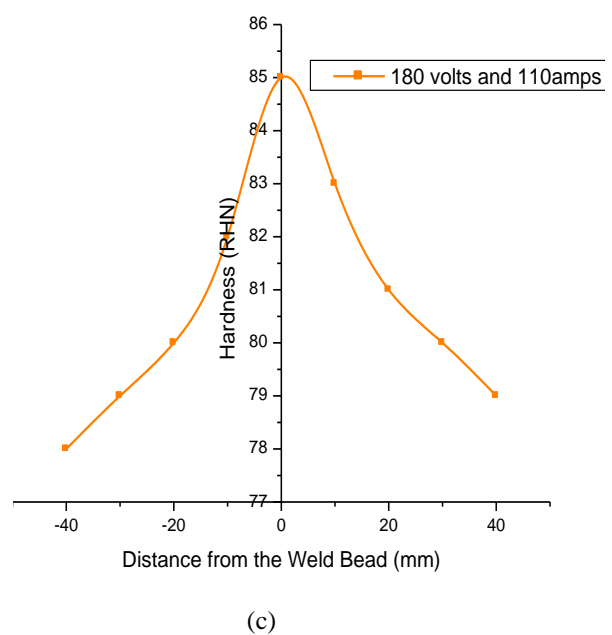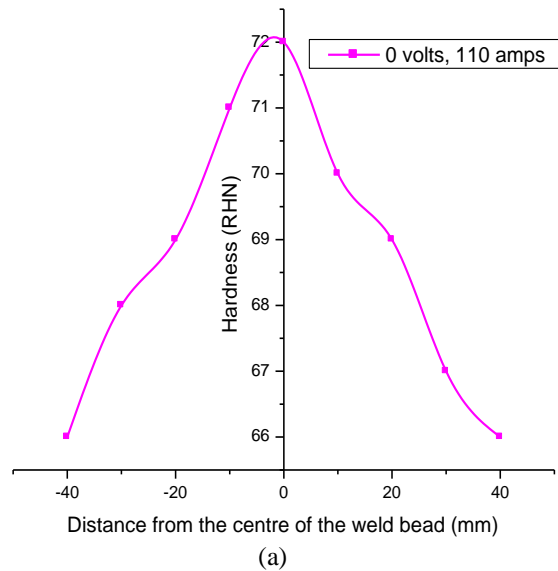

Figure 6 Comparison of Hardness of SS 304L at different vibromotor voltage and welding current
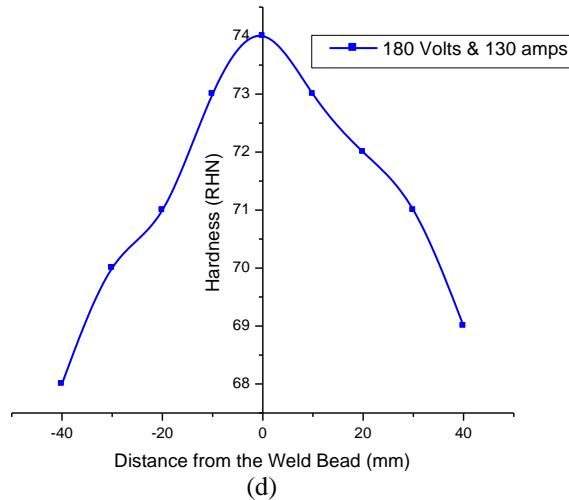

(a)

(b)

(c)

1520

(d)

Figure 7 Hardness values of vibratory assisted weld joints at (a) 0 V & 110amps (b) 180 & 90amps (c) 180 & 110amps (d) 180 & 130amps

4.3 Comparison of heat treated weld joints and vibratory assisted weld joints

The hardness values of the conventional welded specimens, heat-treated specimens and vibratory assisted specimens are compared with each other and identified that the results of vibratory assisted welding are slightly more than the heat-treated specimens, which are as shown in *Figure 8* at optimum working conditions. The maximum hardness obtained for the joints undergone for heat treatment is 82 RHN at 1050^{0}C and 4hrs. And the maximum hardness obtained for the joints prepared with vibrations is 85 RHN at 180 V of vibro-motor and 110amps of welding current. But the hardness value of conventionally prepared weld joints is

72 RHN, which is less than the above two processes. Both PWHT and VAW are much suitable for reducing the residual stresses and other weld defects for improving the weld joint hardness.

In *Figure 8*, the hardness values of the weldments along with the weld bead and HAZ are compared for the weld joints prepared at 110 amps with conventional welding and welded joints with heat treatment that is at 1050^{0} C and 4Hrs heat treatment with welded joints prepared under the influence of vibrations. From the results, it is confirmed that the hardness value for the conventional welding process is less compared with the PWHT and VAW because of weld defects. Due to the refined grain structure with PWHT and VAW, the hardness is increased. And compared with the PWHT and VAW process, Vibratory assisted welding exhibited slightly more hardness. This is because of the continuous refinement of grains with vibrations before attaining the solid-state. A complete list of abbreviations is shown in *Appendix I*.

4.4 Limitations of vibratory assisted welding

- Vibratory assisted welding is suitable for only molten state welding like "SMAW-Shielded metal arc welding, MIG–Gas Metal Arc Welding (GMAW) and TIG–Gas Tungsten Arc Welding (GTAW)."
- During welding process with vibrations if the amplitude is more than 0.5mm leads to arc gap
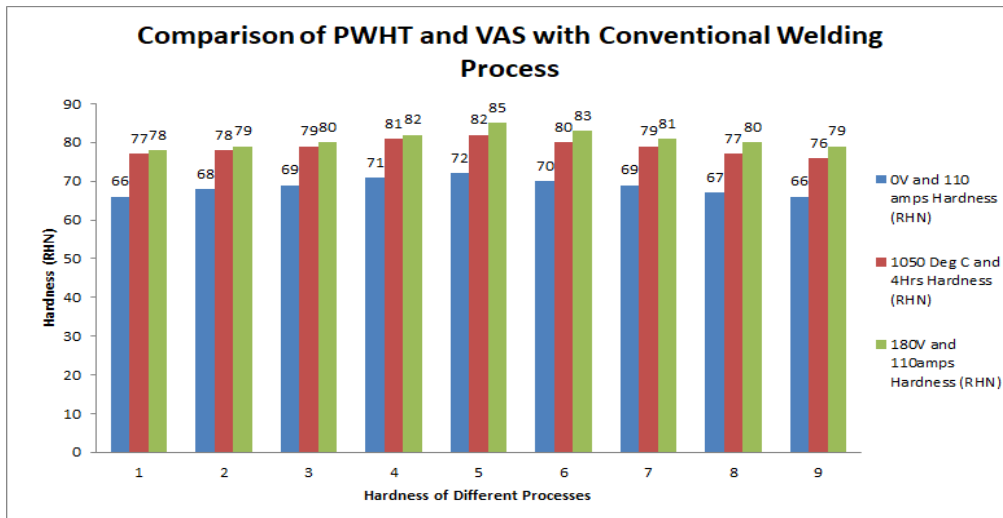- Maintaining constant frequency while welding is a challenge.

Figure 8 Comparison of PWHT and VAW with conventional welding process

5.Conclusion and future work

The hardness of the 304L Stainless Steel is enhanced with PWHT and VAW Process when it is related to the conventional-welding process. The enhanced results are due to reduced weld defects and residual stresses by refining the grain structure with PWHT and VAW processes. Also, the comparison is made between PWHT and VAW and identified that Vibratory assisted welding exhibited slightly more hardness. Even though both PWHT and VAW as exhibiting similar results PWHT processes are more time-consuming, costly, and Laborious. From the current research, it is identified Vibratory assisted welding is the best suitable technique for reducing weld defects and enhancing properties. The following are the major outcomes from the current work

- The hardness of 304L stainless steel enhanced with the vibratory assisted welding and post-weld heat treatment process compared with the conventional welding process.
- With the post-weld heat treatment percentage increase in the hardness of 304L stainless steel is 13% compared to conventional welding
- The percentage increase in the hardness of 304L stainless steel is 18% in the vibratory assisted welding method compared to the conventional welding process.
- Hardness of 304L stainless steel has greatly influenced by the vibratory assisted welding than the post-weld heat treatment process

Mechanical properties like flexural, tensile, fatigue and impact can be investigated further. The microstructure of the weld-zone can also be investigated and analyzed by using this method.

Acknowledgment

None.

Conflicts of interest

The authors have no conflicts of interest to declare.

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Appendix I

S. No.	Abbreviation	Description
1	C	Carbon
2	FEM	Finite Element Method
3	GVE	Global Vibration Effect
4	HAZ	Heat Affected Zone
5	LVE	Local Vibration Effect
6	MIG	Metal Inert Gas Welding
7	Mn	Manganese
8	N	Nitrogen
9	Ni	Nickel
10	P	Phosphorus
11	PWHT	Post Weld Heat Treatment
12	RHN	Rock Well Hardness Number
13	S	Sulphur
14	SEM	Scanning Electron Microscope
15	Si	Silicon
16	SMAW	Shielded Metal Arc Welding
17	SS	Stainless Steel
18	TIG	Tungsten Inert Gas Welding
19	VAW	Vibratory Assisted Welding