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Investigation on the effect of auxiliary vibrations on microstructure and mechanical properties of SMAW butt welded joints

Pravin Kumar Singh*, D Patel & Shashi B Prasad

Department of Manufacturing, National Institute of Technology, Jamshedpur 831 014, India

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In this study, an attempt has been made to investigate the effect of inducing auxiliary vibration into the weld pool during welding and aimed to understand the fundamental role of vibration in controlling the weld pool microstructure and mechanical properties. A vibratory set-up has been used to transfer the mechanical vibration in the molten weld pool during shielded metal arc welding (SMAW) process. Vibratory welding is performed on 6 mm thick mild steel plate with various material combinations using bead on plate technique. A comparative investigation between conventional welding and vibratory welding technique is conducted. The mechanical strength is evaluated using micro-hardness and transverse tensile tests. The result shows the enhancement in yield strength by 28%, 25% and 48% for the combination of $WB_{MS/MS}$, $WB_{SS/MS}$ and $WB_{ST/MS}$, respectively. The metallographical studies show that induced vibration during welding increased the nucleation rate and steeper thermal gradients across the heat affected zone (HAZ) is found. Comparatively finer grain microstructures are observed in the vibratory welding condition.

Keywords Vibratory welding, Weld pool solidification, Microstructure, Microhardness, Shielded metal arc welding

Welding has been applied in various industries like automotive industries, aerospace, manufacturing industries, electronic sectors etc. In every sector the joint efficiency and weld quality is the most necessary requirement. To improve the weld quality generally heat treatment process is widely used. In heat treatment process generally, the materials are heated to a suitable temperature and cooled as per the weld properties requirements. Heat treatment is efficient method for improvement of weld quality, but needs of large sized samples. Further the heat treatment methods are costly and require large space for the operations. Hence, to overcome all these problems vibratory welding techniques have been developed. The Vibratory welding techniques have less investment, more convenient operation, less pollution and shorter manufacturing period. In vibratory welding techniques external auxiliary vibration induced into the molten weld pool through various modes of vibratory setups[1-3].

The vibration technique during welding process controls the distortion and reduces the residual stress[3-8]. Shalvandi *et al.*[9] worked on the ultrasonic stress relief technique, vibration was applied on small and thin parts during the welding operations. Result concluded that the thermal stress was relieved by 40%. Davis and Garland[10] designed a vibrating torch for the tungsten inert gas (TIG) welding operation and found that the solidification cracks have been reduced due to application of vibration during the welding of Al-2.5% Mg alloy. The imposed vibration accelerates the movement of atoms and phase fluctuation tends to affect on the super cooling temperature, which is extremely important during the establishment of new nucleation. Balasubramanian *et al.*[11] reported that the vibration reduced the hot cracks during the welding of the aluminum alloys. Yuan *et al*.[25] introduced the ultrasonic vibrations in the molten weld pool and studied the effect of vibration on the grain structures. A new approach in which an ultrasonic probe is dipped directly in the weld pool of Mg alloy and determined how the following factors affect grain refining: (i) the ultrasound amplitude, (ii) the distance between the probe and the arc, and (iii) the alloy composition. Research concluded that by the application of ultrasonic vibration dendrite fragmentation took place and fine grain structures were observed. Mechanical vibrations were successfully introduced into the molten pool by the various researchers[24].

The unmixed zone, which forms at the fusion boundaries of base metal and filler metal interface, is

*Corresponding author (E-mail: pravinsingh.phd@gmail.com)

the major cause of corrosion along the weld bead interface. The external energy in form of vibration helps to reduce these unmixed zones during the welding process even the unmixed zone is totally done away by the application of ultrasonic vibration. Cui *et al.*[12] discussed the issue of vibration on unmixed zone formation.

In arc welding, vibration can be applied either during or after the process. The post weld vibration technique is referred as vibratory stress relief (VSR) technique. VSR is a stress relieving method. Continuing the search for higher productivity, researchers are now putting their effort to develop the process of arc welding during vibration, i.e., vibration assisted welding (VAW), which can cut most of the expenses related to post-weld vibrations or heat treatments. Production lead time can be considerably reduced due to the parallel processing of vibration and welding. Moreover, VAW leads to improved microstructure and better mechanical properties. There are various vibratory welding techniques have been introduced by researchers. A brief comparative discussion between the various vibratory welding techniques is presented in Table 1.

Vibratory welding technique is a mechanism which improves the microstructures of the welds, leads to enhancement in the mechanical properties of the welded structures. Two velocity components generates in vibratory welding conditions[3], one in the welding direction and the other perpendicular to the welding direction with the help of vibration. The resultant velocity is greater than the velocity of the non-vibratory weld pool (conventional welding). The higher weld pool velocity in vibratory welding apparently produced a higher cooling rate during solidification, resulting in a finer grain structures. According to the principles of solidification, higher cooling rates allow less time for the coarsening of grain to occur during solidification[1,2].

Therefore, the mechanism of grain refinement in vibratory welding technique is considered to be due to the increase in nucleation rate and decrease in growth rate[22-25]. In the case of vibration welding, there are both stirring and vibration within the metal melt takes place. The initial solidified grains are easily broken off due to vibrating forces and dispersed within the entire liquid metal[15-18]. Thus, the number of nuclei in the melt is increased. The oscillation of liquid metal can contribute to increasing the rate of heat transfer and the removal of liquid superheat, which decreases the likelihood of re-melting of initial solid grains[19-21].

Table 1 — Vibratory welding techniques used by various researchers

S. No	Material Used	Vibratory technique	Frequency produced	Process
1	AISI 310	Electromagnetic[13]	0-40 Hz	GTAW
2	MS	Vibratory table[2]	80-400 Hz	SMAW
3	Al alloy (1085,2214)	Electromagnetic[14]	50 Hz	Casting process
4	Nickel alloy(690)	Vibratory table[15]	58 Hz	GTAW
5	MS	Vibratory table[5]	25 Hz	MIG
6	D6AC,D406A	Vibratory table[7]	2.5 Hz	MIG
7	Niomol 490K	Vibratory table[16]	-	SAW
8	AL-6XN	Ultrasonic[12]	20 kHz	SMAW
9	A-105	Vibratory table[17]	54-59 rps	SAW
10	Super alloy 800	Electromagnetic[18]	-	GTAW
11	Al alloy	Vibratory table[11]	100-3000 Hz	GTAW
12	MS	Vibratory table[19]	-	SMAW
13	Al alloy	Wave guide[20]	20 kHz	MIG &TIG
14	304-SS	Vibratory table[21]	375 Hz	GTAW
15	304-SS	Vibratory table[22]	150-350 Hz	TIG
16	AISI 304	Horn plus tool[23]	429 Hz	FSW
17	AZ31 Mg alloy	Vibratory table[8]	15 kHz	TIG
18	MS (PW)	Vibration transfers into the molten weld pool during welding operation.	0-300Hz	SMAW

Note: - SMAW: - Shielded metal arc welding; MIG: - Metal inert gas; GTAW: - Gas tungsten arc welding; SAW: - Submerged arc welding; TIG: - Tungsten inert gas; PAW: - Plasma arc welding; PW*: - Present work.

Based on the existing literature review it was quite reasonable to establish the fact that stirring the molten pool of the weld pool by introducing mechanical vibrations into the weld zone during welding could lead to significant alterations in the microstructure and mechanical properties. With this motivation, it was purposed to take up the present research work with the following objectives: (i) Conception and development of a vibratory setup for inducing auxiliary mechanical vibrations into the molten weld pool during shielded metal arc (SMAW) welding and (ii) To examine the force of vibrations at a frequency of 150 Hz and 300 Hz on the weld pool zones using bead on plate technique involving similar and dissimilar material combinations.

Experimental Procedure

Present investigations were carried out by bead-on-plate experimentation technique using different filler and base material combinations. Mild steel is used as the base material and three different filler coated electrodes were used that included mild steel (E 3106), austenitic stainless steel (SS-316L) and stellite (Co-6). The reason for selecting these material combinations is to include different aspects into the study, e.g., mild steel on mild steel is an example of conventional similar metals welding, austenitic stainless steel on mild steel is a typical application of cladding/overlaying operation used for providing corrosion resistance properties to inferior mild steel, and stellite on mild steel is a typical example of hard-facing that is used to improve the high temperature wear resistance properties of mild steel. The specimen codes and its specification are given in Table 2.

The welding was performed under two different conditions: (i) specimen was prepared under the conventional condition process and (ii) specimen were welded under vibratory condition with an aim to provides a qualitative as well as quantitative comparisons that could form the basis for further work.

The test run was conducted over the mild steel plate using mild steel electrode. This trial run was helpful to determine the position for vibratory setup against electrode like the approximate angle between vibratory setup and electrode holder, angle between base metal and vibratory setup etc. Further the experiment includes laying down weld bead of stainless steel 316 over the mild steel plate and stellite over the mild steel plate using SMAW process. Every combination of weld bead prepared under the three welding conditions; the first weld bead was prepared by conventional SMAW process (no vibration during welding), another two weld beads were prepared under the vibratory SMAW condition at 150 Hz and 300 Hz respectively. Further its hardness, tensile strength and micro-structural properties were investigated. The detailed experimental flow chart is shown in Fig. 1.

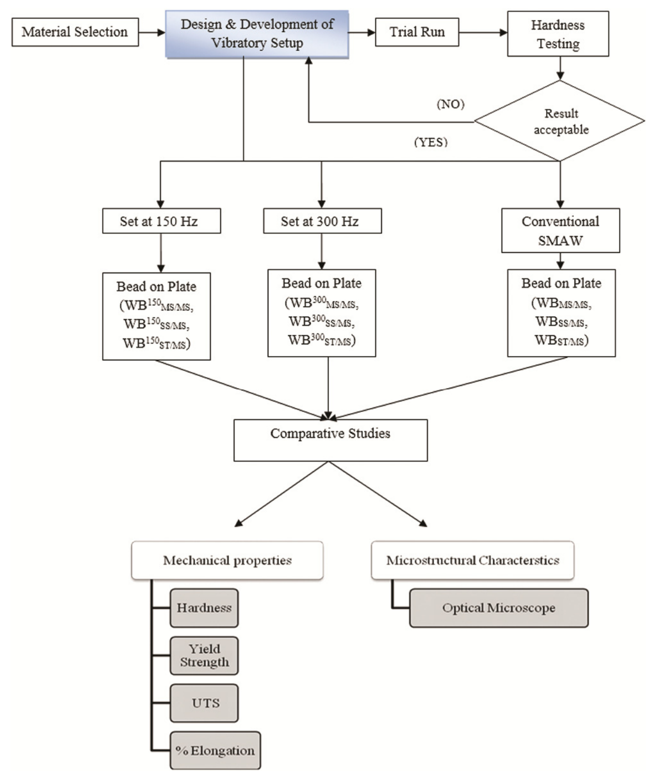


Fig. 1 — Schematic block diagram of vibration set-up

Table 2 — Specimen codes and its specification

Specimen code	Filler metal and base metal combination		Applied frequency to the weld zone	Current (A)
	Filler metal	Base metal (6 mm)		
$WB_{MS/MS}$	E-3106	Mild steel	No vibration	110
$WB^{300}_{MS/MS}$	E-3106	Mild steel	300 Hz	110
$WB^{150}_{MS/MS}$	E-3106	Mild steel	150 Hz	110
$WB_{SS/MS}$	Stainless steel (SS-316 L)	Mild steel	No vibration	120
$WB^{300}_{SS/MS}$	Stainless steel (SS-316 L)	Mild steel	300 Hz	120
$WB^{150}_{SS/MS}$	Stainless steel (SS-316 L)	Mild steel	150 Hz	120
$WB_{ST/MS}$	Stellite (CO-6)	Mild steel	No Vibration	120
$WB^{300}_{ST/MS}$	Stellite (CO-6)	Mild steel	300 Hz	120
$WB^{150}_{ST/MS}$	Stellite (CO-6)	Mild steel	150 Hz	120

WB: Conventional shielded metal arc weld bead for each material combination

Design of vibratory setup

With the aim to improve the mechanical properties of the butt welded joint vibratory setup has been designed and developed. Figures 2 and 3 show the schematic diagram[26-28] of vibratory welding setup used in the present investigation. Vibratory setup is capable to stir the molten weld puddle before it solidifies. As shown in Figs 1 and 2 the tip of the rod is submerged into the molten weld zone. Vibration transfers through the rod into the molten weld zone and stir the molten metal before it solidifies. It has been done in the manner that the vibratory tip is inserted into the molten weld pool and is made to keep contact with it, while maintaining a constant speed along with the welding arc while welding process takes place. So this case resembles the quasi-stationary state where the observer finds that at any instant of time across the entire weld length the vibratory tip is submerged in the weld pool[27,28].

The vibrating rod is made up of thorium-zirconium-tungsten (T-Z-W rod) alloy, which make it to sustain at very high temperature. The melting point of T Z W rod is around 3500°C. The diameter of the rod is 3 mm and having a conical shape at one end side of the rod. The other end of the rod is attached with a non-conducting holder, used to grip the vibratory setup during welding operation.

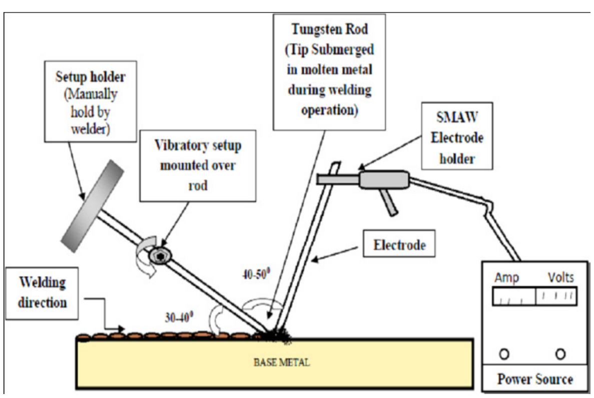


Fig. 2 — Top view of vibratory set-up

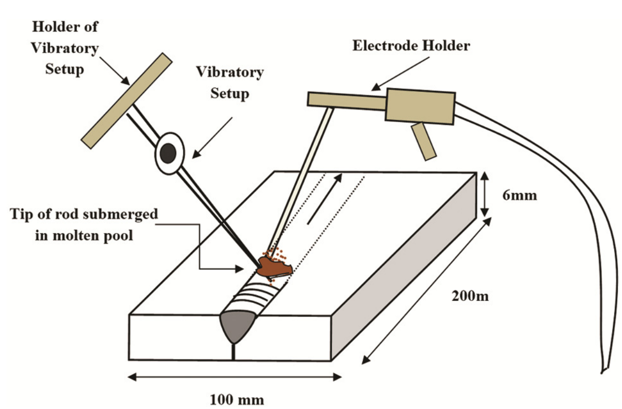


Fig. 3 — Experimental flow chart

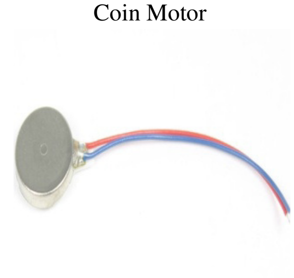
The eccentric rotation mass motor (ERM) is used to generate the vibration during the welding process. ERM motor is attached to the middle of the thorium-zirconium-tungsten rod. It is the most important device of the vibratory setup and works on the principal of rotation of unbalanced mass. The rotating unbalanced mass around the central shaft introduces energy into the system and creates vibrations.

The amount of vibration generated depends upon the speed of motor rotation (RPM), power supplied, weight of the rotating mass and the weight of the system to which it is attached. In present investigation, two ERM motors were used. The specifications of the motors are presented in Table 3. To prevent the ERM motor from high heat during welding operation, ceramic pipes and piece of glasses were covered around ERM motor.

Mechanical testing and microstructure characterization

The specimens were prepared using standard procedures like belt grinding, polishing using fine grades of emery paper up to 1500 grit size. This helped in removing the coarse and fine oxide layers as well as scratches on the surfaces that were to be analyzed. The hardness value was measured along the center line, and the mid-thickness of the weld joints.

Table 3 — Specification of the ERM motor

Specification	Micro Motor	Coin Motor
Image of ERM motor		
Rated operating voltage	6 V	9 V
Operating environment	-20°C to 60°C	-20°C to 60°C
Starting voltage	2.3 V DC Max	3 V DC Max
Direction of rotation	Arbitrary rotation	Arbitrary rotation
Rotor speed	9000± 1000 RPM	17,500± 2500 RPM
Rated frequency	150 Hz	300 Hz

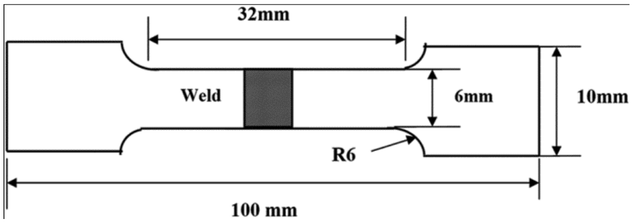


Fig. 4 — Dimensions of tensile specimen

The distance between the two measuring points was 1 mm, each point was measured three times to inquire about its average value.

The tensile specimens were prepared in accordance with ASTM E-08 standards. Schematic diagram of tensile specimen is shown in Fig. 4. Tensile specimens were tested on a universal testing machine, (Make: FIE, Capacity: 600kN). Observations that were recorded from this test include yield strength (YS), ultimate tensile strength (UTS) and percentage elongation. The displacement rate was 0.5 mm/min. The elongation was measured with the extensometer (FIE makes) GL-50 mm.

In order to study the effect of auxiliary vibrations induced in the weld zone and its consequentially effect on the corresponding HAZ, microstructrual studies were conducted on different weld samples.

Results and Discussion

Effect of vibration on microstructure

The microstructure properties are showing a dramatically changes after the implementation of vibrations into the weld pool. Figure 5 shows the microstructure of heat affected zone (HAZ) for $WB_{SS/MS}$. Figure 5a depicts the heat affected zone (HAZ) of the weld specimen prepared under the conventional welding condition and Figs 5b and 5c show the HAZ of the specimen welded under the vibratory condition at 150 Hz and 300 Hz, respectively. Result shows that small size of grains was observed in the HAZ for the vibratory welding conditions.

During the conventional solidification process, an epitaxial growth occurs from the unmelted zone and dendrite grows in uniform pattern as shown in microstructure figure of $WB_{MS/MS}$ (Fig. 6a). In other case, the vibratory welded microstructure showing fragmented dendrites. The external applied force in the form of vibration fragmentize of growing dendrite and uniform smaller fine grain structure were formed as shown in Fig. 6b $WB^{150}_{MS/MS}$.

Figure 7a shows the metallographic structure of $WB_{ST/MS.}$ The conventional microstructure has coarse

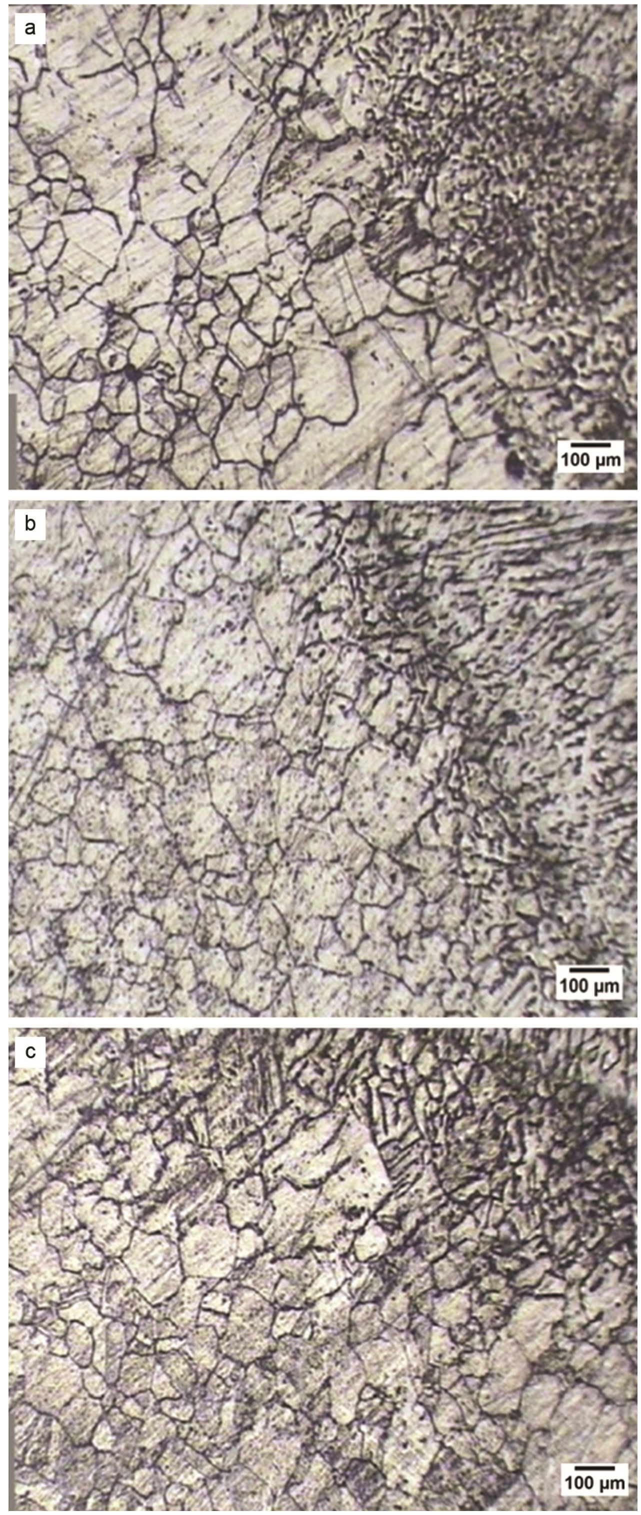


Fig. 5 — Photomicrographs showing the fusion boundary zone and HAZ of the weld bead specimen ($WB_{SS/MS}$)

grain structure as compare to the $WB^{150}_{ST/MS}$ (Fig. 7b) $WB^{300}_{ST/MS}$ (Fig. 7c). It is interesting to note that as proposed frequency increases from 150 to 300 Hz,

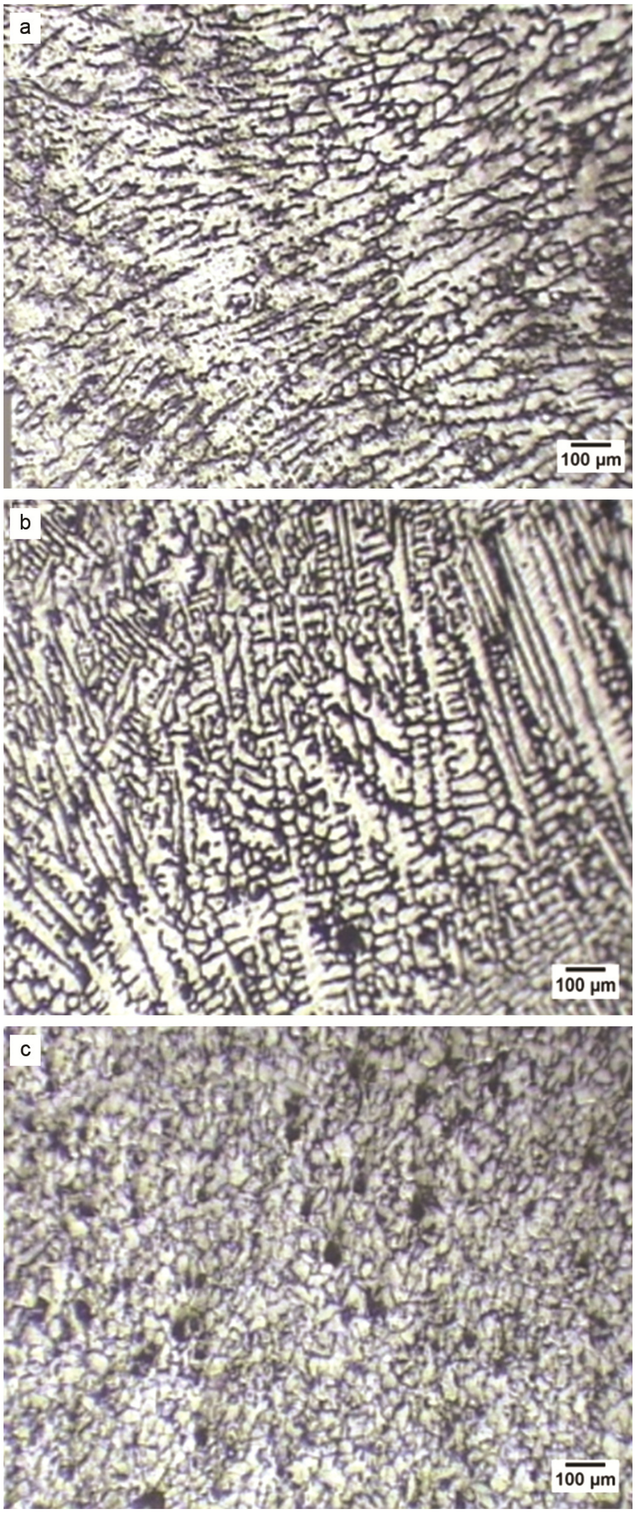


Fig. 6 — Photomicrographs showing the Weld zone of the weld bead specimen ($WB_{ST/MS}$)

more fine grains were observed in the microstructure image, it is clear that, the $WB^{300}_{ST/MS}$ has finest grain structure as compared to $WB^{150}_{ST/MS}$ and $WB_{ST/MS.}$

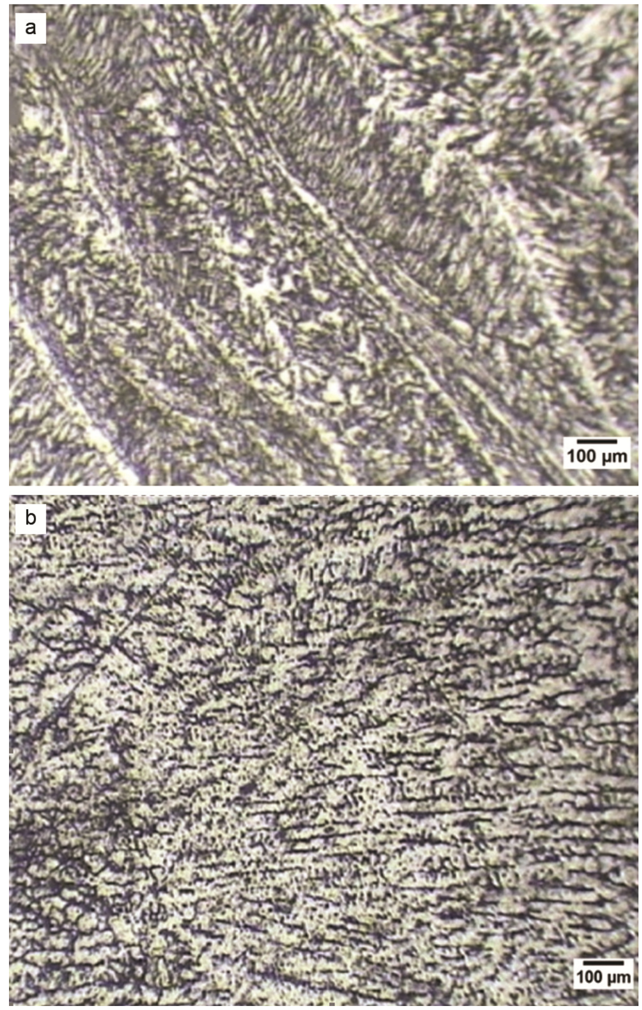


Fig.7 — Comparative study of photomicrographs showing the weld zone of the weld bead specimen ($WB_{MS/MS}$)

In present investigation the microstructure studies attributed following points: (i) the dendrites are not able to grow to their fullest extent during vibratory conditions as this dendrite would have grown up during conventional SMAW condition; and (ii) applied vibration fragmentize the growing dendrites and these dendrites acts as a new nucleus site for further solidification process; (iii) vibration techniques during welding stir the molten metal before its solidification; this type of interruption increases the cooling rate of the molten weld zone and helps to reach the super-cooling temperature; (iv) Above discussion concluded that the applied vibration breaks the growing dendrites, increases the cooling rate, helps to prevent the new born nucleus from re-melting, increase the number of grains and finally produces the fine grain structure.

Effect of vibration on micro-hardness

Micro-hardness across different weld samples ($WB_{MS/MS}$, $WB_{SS/MS}$ $WB_{ST/MS}$) were measured in the transverse direction and presented in graphical form (Figs 8-10). Blue line represents the hardness value of weld zone when it is welded at 300 Hz, red line shows the hardness property for 150 Hz of welding condition and black line is for conventional condition. Figure 8 is hardness plot for $WB_{MS/MS}$ specimen, Fig. 9 is hardness plot for $WB_{SS/MS}$ and Fig. 10 is presenting the hardness plot for $WB_{ST/MS}$ specimen.

From the result analysis it was observed that micro-hardness of the weld zone was found to increase in vibratory conditions and also found that when the frequency increases the hardness value improved. The enhancement in micro-hardness attributed to the fact that when auxiliary mechanical vibration introduced into the weld pool during welding process more fine grain structures were formed. This smaller and finer dendrite size of the weld pool tends to the relatively higher micro-hardness during V- SMAW (vibratory SMAW) process.

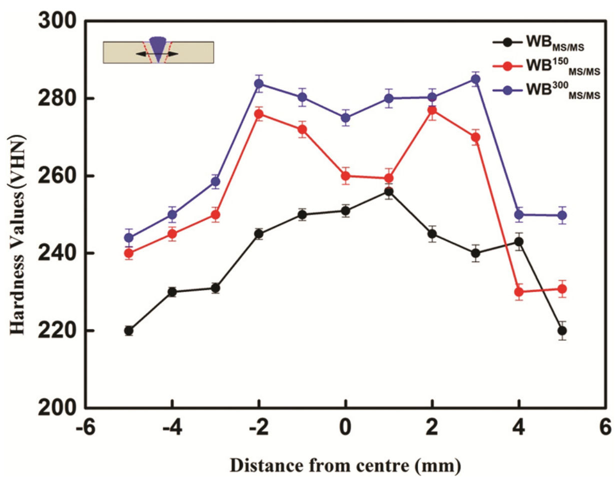


Fig. 8 — Microhardness Plot of $WB_{MS/MS}$ specimen

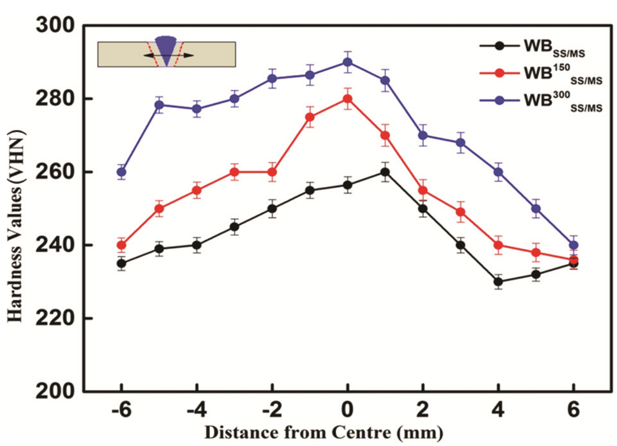


Fig. 9 — Microhardness plot of $WB_{SS/MS}$ specimen

However, from these plots it is also observed that in certain directions micro-hardness did not fluctuate much, the reason for which is that these areas were not stirred very well by the vibratory disturbance as the vibrations set-up was inclined towards the welding direction.

Effect of vibration on tensile properties

The results of tensile tests are shown in Figs 11-13. The tensile strength value reported are on average of at least three tested specimens for each condition.

For the condition of $WB_{MS/MS}$ the yield strength shows an increase of 15% when the 150 Hz of frequency transferred into the weld pool (Fig. 11). Increasing the frequency of vibration from 150 Hz to 300 Hz the yield strength shows an improvement of 20%. Also the % elongation is increased by about twice of its value.

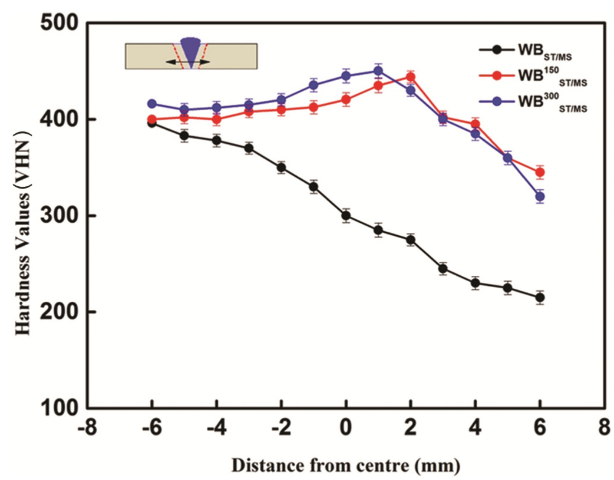


Fig. 10 — Microhardness Plot of $WB_{ST/MS}$ Specimen

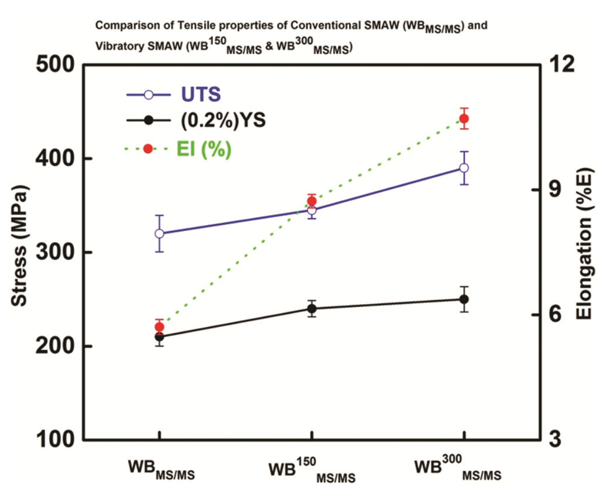


Fig. 11 — Tensile properties for $WB_{MS/MS}$

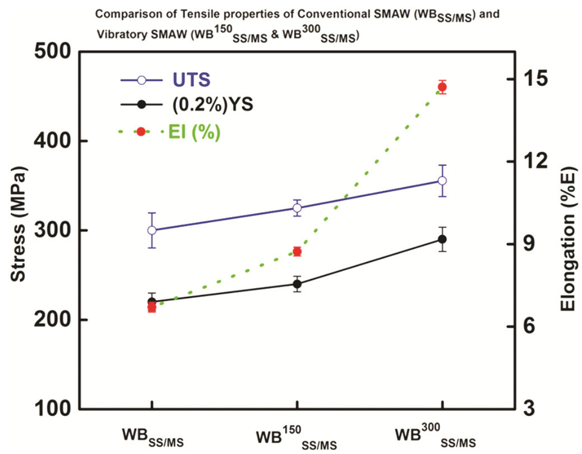


Fig. 12 — Tensile properties for $WB_{SS/MS}$

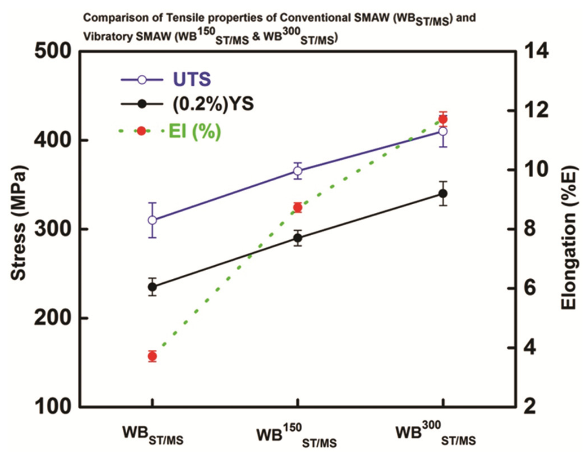


Fig. 13 — Tensile properties for $WB_{ST/MS}$

From Fig. 13, it can be seen that the UTS value increased by 30% in case of $WB^{300}_{ST/MS}$ with respect to $WB_{ST/MS}$. The tensile properties are increasing gradually with increasing the frequency of the vibration. It is noted from Fig. 12 that there is an improvement in UTS and yield strength without any loss in ductility. The UTS and yield strength value for $WB^{300}_{SS/MS}$ with respect to $WB^{150}_{SS/MS}$ is increased by 30 MPa and 50 MPa, respectively.

Conclusions

The present work shows that applied vibration by vibratory set-up in the bead on plate technique of various material combinations enhanced the mechanical properties of welded joints and improved the microstructure characteristics.

Bead on plate weld investigation shows that increasing in the frequency the hardness values increases and more fine grain structures were obtained. With the significance of the microstructure, the tensile strength and yield strength have been improved without any loss of ductility.

A maximum ultimate tensile strength of 402 MPa was achieved for $WB^{300}_{ST/MS}$ which is 30% higher than $WB_{ST/MS}$ and 13% higher than $WB^{150}_{ST/MS}$. Highest percentage elongation has been found for the condition of $WB^{300}_{SS/MS}$ more than double of the $WB_{SS/MS}$.

Microstructure studies of the welded joints revealed that due to auxiliary stirring of the weld pool during vibratory welding condition, steeper thermal gradients are established and more fine grain structures were obtained.

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