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RESEARCH ARTICLE OPEN ACCESS

MICROSTRUCTURAL INVESTIGATIONS ON THE FRACTURAL BEHAVIOR OF SS304 BUTT JOINTS DEVELOPED THROUGH VIBRATORY WELDING

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ABSTRACT

Determination of weld strength through the fractural behaviour at different loads plays dominant role for selection of weld process in real-time applications. Assistance of vibratory treatment to the conventional welding process can bring major changes in the microstructure of weldment at greater extent. The intervention of increment and decrement in the mechanical properties at different vibratory welding parameters dependent on the grain refinement. The study focuses on analyzing microstructural transformations' influence in the weldments on different mechanical properties at various amplitudes and voltages of 2, 4, 6V. The tests such as tensile, Rockwell hardness and Charpy impact are conducted and fracture modes are identified. SEM analysis is performed to characterize the microstructure of different fractures between the developed butt joint on SS304 and susceptibility to crack is investigated. The fracture is exhibited as more ductile for samples developed with the assistance of vibratory treatment to the gas metal arc welding process. The decrease of columnar dendrites at weld zone and paradigmatic shift to equiaxed shapes under vibratory treatment prompted to achieve maximum enhancement in the mechanical properties and reduction of delta ferrite is responsible for decrement for further ranges.

I. INTRODUCTION

Substantial increment in the demands to produce superior standard products at low-cost driven advancements in the traditional manufacturing methods. Vibratory treatment is most notable advancement to the traditional welding process to minimize the defects of weldment and significant improvement in the weld strength [1],[2]. Studies are proven that the vibratory treatment can enhance the heat transfer at the weld pool which reduce the defects caused by porous regions, blow holes, spilling of weld material etc. [3]. But the analysis over influence of applied vibration parameters such as amplitude, frequency and time is essential to achieve maximum enhancement in the mechanical properties of the weldment [4].

According to [5] performed extensive analysis over influence of vibratory treatment parameters on the tensile strength of the joint in the pulsed ultrasonic tungsten arc welding process and heat evacuation is responsible for achieving maximum enhancement. Singh et al. investigated the influence of work piece frequency on the hardness of the butt joint made under vibratory treatment assistance to shielded metal arc welding process and achieved maximum enhancement at 250 Hz with fine grain structure [6]. Mostafapour and Gholizadeh studied the dependence of vibratory treatment parameters over the impact resistance of the weldments made on SS304 through TIG welding process and noted that the workpiece frequency, electrode voltage are the most dominant parameters among the amplitude, time, current, and welding speed [7]. Given high range frequencies of 15kHz for the welding of AZ31 sheet through TIG welding process and attained the greater reduction in grain size at interstitial sites is responsible for obtaining maximum enhancement in the microhardness [8]. Attempted to study the influence of various types of vibratory treatment in the gas metal arc welding (GMAW) process and observed that the reduction of temperature of molten droplet with the oscillation given to weld pool is essential to attain maximum heat transfer [9]. Weglowska and Pietras studied the grain refinement in the welding of thermoplastics through SEM analysis and stated that the orientation of finer grains is a responsible factor to attain the maximum enhancement in the tensile strength at highest electrode voltage of 20V [10].

Studied the influence of vibratory treatment over the microstructure and mechanical properties over the 316L stainless steel joints developed by using gas-tungsten arc welding and observed the columnar type dendrites exhibited lower length than the equiaxed dendrites which contributed to exhibit higher mechanical properties than the non-vibratory assistance [11]. Applied Taguchi analysis for optimizing process parameters in the vibratory welding to achieve maximum enhancement in the hardness of the butt joint and performed microstructural analysis to study the grain refinement in weldments. It is observed that the auxiliary vibrations supplied to weld zone prompted to significant refinement in the grain structure and leads to improvement in the studied mechanical property [12]. According to [13] applied flux cored arc welding supported with vibratory treatment and studied the influence over microstructure of the weldments. It is observed that proeutectoid ferrite occupied more than the ferrite side, acicular ferrite in the weld zone and observed the effective integrated balance achieved between the yield strength, toughness of the metal. Studied the mechanical properties of CO2 arc welding under the assistance of vibratory treatment and observed that the fatigue life, microhardness are significantly improved with the minimum deformation and residual stress formation [14]. For [15] investigated the microstructure of the weld zone formed through arc welding of AA-5083-H321 of similar metals and observed that the grain size is reduced from 200 to 50 μm under the influence of harmonic vibrations at the time interval of 30 mins.

The research is focused to investigate the microstructural behavior of the weldments developed through GMAW on SS304 under the assistance of vibratory treatment at different electrode voltages and analyze the response on tensile, impact strength [16]. Section-2 presents the materials used in this research along with the methods employed to produce the butt joint and conduct the experimentation. Section-3 presents the results obtained about the studying mechanical properties and SEM analysis to characterize the weldment in terms of enhancement or decrements in the studying properties at different electrode voltages and discusses the grain refinement with the introduction of vibratory treatment in the weld joint. Section-4 concludes the article by stating overall theme of conducted research and major identifications in the performed experimental investigations on vibratory treatment assisted GMAW process.

II. MATERIALS AND METHODS

Gas metal arc welding is preferred to develop the but joint with the assistance of vibratory treatment and SS304 of 5mm gauge is preferred as the base material for the similar welding. ER309 L is selected as the filler material and the chemical composition of the base and filler materials are listed in Table 1.

Table 1 Chemical composition of weld materials

Material	C	Mn	P	S	Ni	Si	Cr	Balance
SS304	0.09	<2.5	<0.048	<0.06	10.4	<1.02	18	Fe
ER309L	0.034	1.28	0.027	0.63	12	0.68	26	Fe

Source: Authors, (2024).

The single V-type butt joint is developed at the angle of 700 in the region of joint and opening of root is maintained as 3 and base is kept at 2mm by considering the thickness of the procured SS304 sheets. The line of welding is considered during the preparation of the samples and it is taken as the perpendicular to the direction of rolling [17]. A novel vibratory welding equipment is designed and fabricated in order to create butt joint through the dissimilar GMAW process from mild steel and stainless-steel plates. The butt joints are made at various frequencies from 600 to 1000 Hz while keeping the time period as constant at each frequency. For every cycle, the time period of each vibration is kept constant for 100 sec at each vibration frequency based on the crystallization temperature of the selected metals for welding. It is known that the SS304 and mild steel start crystallization at the temperature of 420 to 4600C [18]. Although the temperature for recrystallization is very low compared to actual weld pool temperature which is 26000C, still the experimentation is carried out up to maximum range and certain time is allowed for temperature drop to recrystallization state. The experimentation is carried out by manipulating at different ranges of frequences, amplitudes and the observations are made out to investigate the mechanical properties of butt joint at each parameter setting [19]. The highest frequency of workpiece is fixed at 1000 Hz based on the condition of making amplitude less than 0.5mm. Because after crossing the 1000 Hz, there is a possibility of crossing the spark gap greater than 3.0 mm which hinders the welding process [20].

The samples required to conduct the uniaxial tensile, Charpy impact and Brinell hardness tests are prepared according to ASTM D368, E10 and 23 standards. The weldability and susceptibility to crack of weldment is evaluated by conducting the Varestraint hot-ductility test. The microstructure at the welded zone for tensile, impact strength, hardness tested samples are characterized through SEM analysis [21]. The etching process is performed by using 5% Nital reagent {HNO3 (5ml) + ethyl alcohol (100ml)} over these samples in order to remove the blackspots and smoky layer created over the weld zone during the GMAW process.

III. RESULTS AND DISCUSSION

III.1 MICROSTRUCTURES AT DIFFERENT WELD ZONES

The microstructure of the developed butt joint through GMAW process under the assistance of vibratory treatment is characterized through scanning electron microscopy (SEM) technique. The weldments created between the two similar metals of SS304 are tested immediate to the welding process after their solidification. It is observed that the degree of dilution has major influence over the microstructure of the weldments and the increase in electrode voltage reduced the dilution process by rapid decrement in the temperature at the weld zone [22]. Similar effect is observed over the mechanical properties at which the increment in them is found with the decrease of dilution degree. The improvement in heat transfer through convection mode with the effective reduction of conduction to the non-involving (welding process) portions of base metal through the turbulence created by the vibratory treatment. As the convection mode heat transfer is higher, the lower melting of base metal is observed with the increase of electrode voltage.

Figure 1(a) represents the SEM analysis carried over the weld edges at where the interface between weld metal and base metal. It can be observed that the existence of fine side grains at the taken zone which are formed with the effect of higher cooling rates. The temperature gradient is significantly higher in this zone as there is no specific preheat treatment is employed before the GMAW process and it leads to generation of fine surface nuclei on SS304. In later stages, those nuclei are prompted for the effective conversion of fine side grains at the identified zone and those are incapable to exhibit greater resistance over the fracture due stretching of grains at the weld interface. The existence of equiaxed grains is very low in this zone due to the susceptibility of generating columnar dendrites towards the centre of the weldment instead the boundary zone [23].

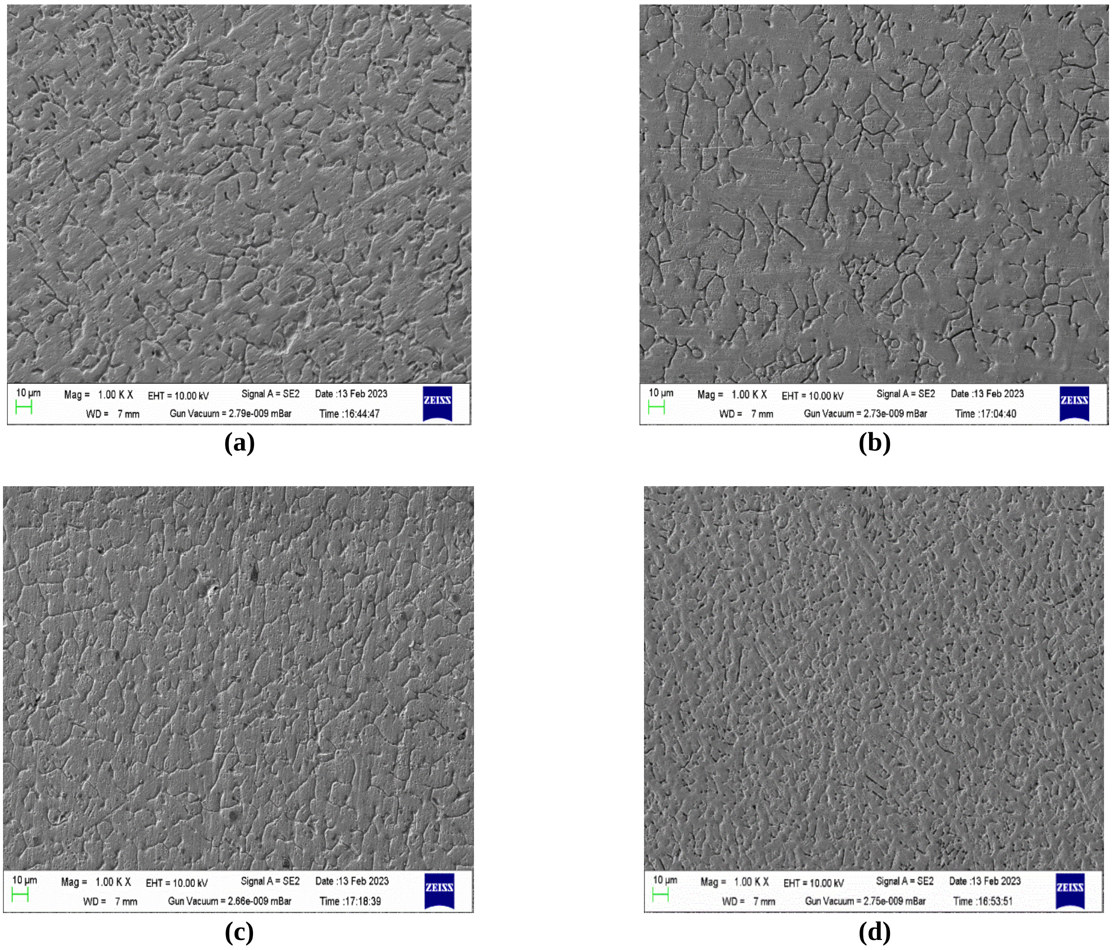

Figure 1 Microstructures at various vibratory weld conditions (a) at weld and base metal interface (b) at intermediate zone with electrode voltage of 2V (c) at intermediate zone with electrode voltage of V (d) at intermediate zone with electrode voltage of 6V.
Source: Authors, (2024).

Figure 1(b) represents the SEM analysis performed at the intermediate zone at where the complete dilution of base metal and filler material occurred at lower electrode voltage such as 2V. The appearance of smaller sized grains in the microstructure shown the existence of austenite with the combination of delta ferrite at the boundaries. The presence of ferrite stabilizing elements in the filler material have shown significant influence at this zone but the accumulation of such elements at the sub grain boundaries due to occurrence of eutectic reactions. The tendency to form of strength improvement barrier such as austenitic-ferritic at this zone is observed after the solidification [24]. The competitive growth into large number of bundles at grain boundaries are strong hinderance for the strength improvement.

Figure 1 (c) represents the SEM analysis performed at the intermediate zone at where the lower dilution of base metal and approximate dilution of filler material at 4V. It can be observed clearly that the growth of grain boundaries into different directions and great misorientations in the sub-grain boundaries. This phenomenon is mostly occurred in the ductile type materials such as SS304 which referred as “high-angle grain boundaries” and formation of such can lead to occurrence of cracks after solidification.

Figure 1 (d) represents the SEM analysis performed at the intermediate zone at where the lower dilution of base metal and complete dilution of filler material at 6V. It can be observed clearly that the growth of grain boundaries followed uniform orientation at the sub-grain boundary and clearly drawn a division between the dendrites, adjacent sub-grains. Although the misorientation is existed, still the degree of such is acceptable due to the growth of sub-grains along the crystallographic directions. It can be drawn a significant reduction in the size of dendrites in the weldment of SS304 from 648.02 to 93.67 µm. No cracks or discontinuities are appeared in the microstructure of butt joint and the areas are broadly stretched towards the centre of the weldment.

It is observed from the performed SEM analysis that the complete elimination of the unmixed weldments and greater heat gradients due to the applied vibratory treatment. The increase in the electrode voltage from 2 to 6V created a path for greater turbulence of weld pool and promote the heat evacuation. The movement of filler material towards to diluted base metal is improved and complete immersion become possible with the electromagnetic vibrations during GMAW process [25].

III.2 MECHANICAL PROPERTIES

The growth of lower sized grains is essential to provide sufficient strength over the penetration of load over the surface of the specimen. The degree of reduction in grain size is higher at higher electrode voltages due to the effective heat transfer with the supplied vibrations. However, the central zones are possessing higher hardness due to their closeness to fusion line whereas the side zones cannot be treated as completed weak because the availability of equiaxed grains at that region is significantly lower. The confirmation is made by applying the same loads at the side zones of the specimens developed from lower voltage of 2V and observed that the hardness at central zone not much varied [26]. It can be observed from the Figure 2 that the specimens developed at lower voltages exhibited lower hardness than the higher voltage supplied butt joint weldments. It is expected that the variation of hardness at the different regions don't show greater difference over the mechanical properties such as tensile, impact strength of weldment.

The stress-strain curves obtained by conducting the tensile strength test on the uniaxial testing machine for the developed butt joint on SS304 through GMAW under vibratory treatment are represented in Figure 3. It can be observed that the tensile strength of the butt joint is increased with the increase of electrode voltage. The intense increase of vibration with the increase of electrode voltage facilitated a direction to the density of mobile dislocations and gradual decrease in dendrite sizes in the butt joint. Consequent increase in the energy of grain boundaries due to significant disorders and existence of high energy at the dislocations which is exhibited by them to cross the grain boundaries prompted as the increment in the tensile strength. The density of dislocations is increased by the stoppage of mobile dislocations at grain boundaries also promoted as the increment in the tensile strength of the butt joint under the assistance of vibratory welding. The findings are agreed with the existing studies that the decrease in grain size at the austenite phase of SS304 is essential to attain maximum improvement in the mechanical properties such as tensile, yield strength [27].

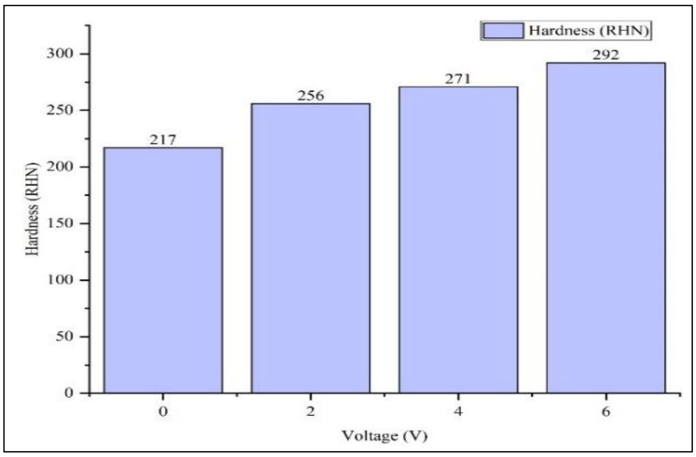

Figure 2: Hardness of the butt joint SS304 at different electrode voltages.
Source: Authors, (2024).

It can be observed from the Figure 4 that the enhancement in the impact strength with the increase of electrode voltage during the GMAW of SS304. The increase of frequency of workpiece brought significant increase the impact strength of weld specimen and the improvement in impact strength is 23.58%. The expose of high frequency vibrations to the weld pool provided a path to increase the heat evacuation rate and improved the fracture energy of butt joint. The highest improvement in the impact strength is noted at 4.24J at maximum frequency of 5.3 Hz at 6V. The gradual increase of frequency from 0 to 6V given maximum enhancement in the impact strength from 3.2 to 4.24 which is about 32.5%. The appearance of finely distributed finer sized dendrites at the weldment provided maximum energy to withstand to the fracture and the existence of equiaxed grains in larger portions with the increase of electrode voltage prompted to attain greater reduction in the arms of dendrites.

It is confirmed from the performed investigations over the mechanical properties through microstructural evidences that the decrease in the dendritic size and increment of grain boundaries at large portions essential to attain maximum enhancement in the strength of weldment. The strongest force to oppose the propagation of crack is obtained by the energy existed at the grain boundaries and the availability of larger number of grain boundaries made to demand greater force to create crack [28]. As the time consumed to create small cracks is higher at initial stages due to effective grain refinement and similar effect is carried for propagation of fracture which can directly contributed to increase the toughness of the weldment.

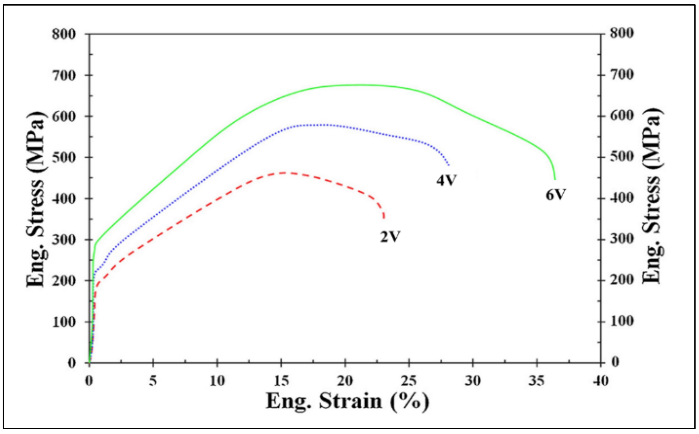

Figure 3: Stress-strain curves for the butt joint SS304 at different electrode voltages.
Source: Authors, (2024).

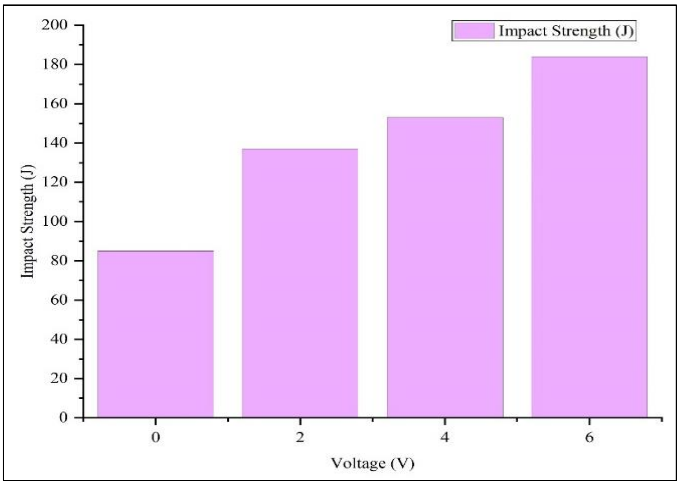

Figure 4: Impact strength of the butt joint SS304 at different electrode voltages.
Source: Authors, (2024).

III.3 CRACK SENSITIVITY ANALYSIS

Varestraint test is conducted in this study to investigate the influence of vibratory treatment during GMAW process on the susceptibility to crack at hotter temperatures in the butt joint of SS304. It is proved that the most frequent problem of developing crack at hotter regions in the weldments developed in SS304 can be avoided through the vibratory treatment to the welding process. At 0V, the weld metal is solidified at the temperature range closer to brittle in nature and gradual shrinkage of base metal with respect to time prompted to inclusion of tensile stress in the weldment. As the developed tensile strength is not sufficient to repel the crack initiation process, it is obvious to effect with hot cracks in the weldment after completion of solidification process. However, the increase of heat evacuation with the vibratory treatment promoted the growth of equiaxed fine grains than coarse type and these possess greater resistance for hot cracks formation till the solidification. It is observed that the existence of two-phase mixture formed by the combination of ferrite and austenite at grain boundaries at larger extent and these acted as strong resistant force for nucleation of cracks in the molten films [29]. The increase of electrode voltage supported for rapid solubility of impurities in the base and filler metals which usually supports for crack nucleation at hotter temperatures. Although the solubility of such impurities in the δ-ferrite phase than the austenite, still it possesses more susceptibility to crack at hot temperatures. The existence of δ-ferrite is less at the higher voltage such as 6V due to effective heat evacuation and rapid solidification of the weld metal is responsible factor behind the decrement in the crack susceptibility even at higher temperatures (Figure 5).

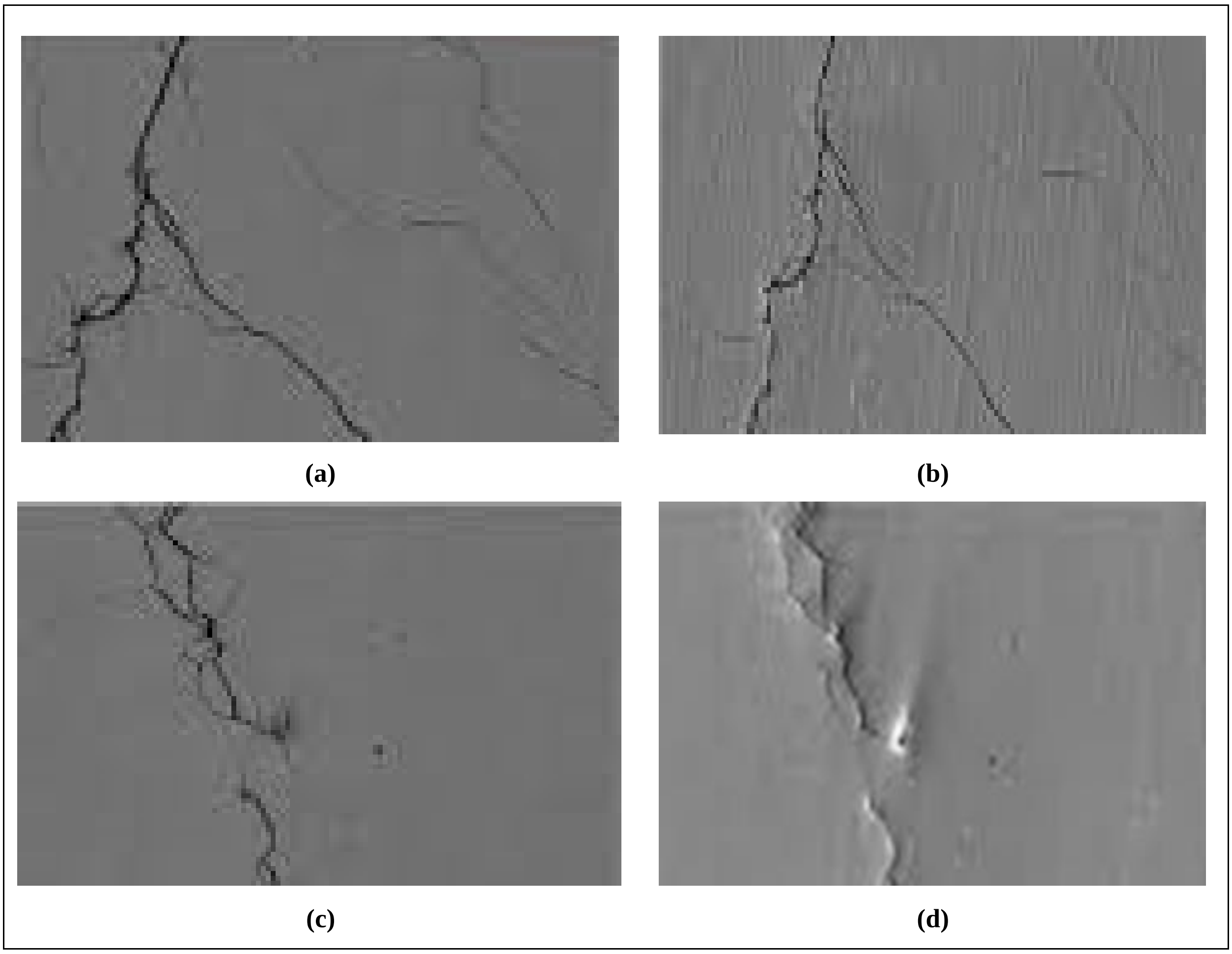

Figure 5: Crack sensitivity of butt joint at (a) 0V (b) 2V (c) 4V (d) 6V.
Source: Authors, (2024).

It is evident from the previous observations that the reduction in dendrite size and distribution of equiaxed grains at larger regions can provide more resistance to fracture. Similar phenomena are observed in the Varestraint test that the equiaxed-grain structure exhibit lower susceptibility to crack compared to columnar type structure which is found at 0V. The flexibility against the shrinkage of weld metal is provided by the vibratory treatment at hotter temperatures and it supported for accumulation of impurities at grain boundaries. These impurities are acted as barriers for nucleation of cracks and initiation at later stages of solidification. It is confirmed from the performed investigations that the reduction of crack length from 14.78 to 6.43mm due to vibratory treatment during the GMAW process for development of butt joint in SS304.

III.4 FRACTURE MODE

The characterization over the specimens after the tensile tests are represented in the Figure 6. It can be observed from the Figure 6 that the butt joints developed at three different voltages such as 2, 4, 6V from no vibratory treatment such as 0V strongly indicating the fracture is ductile in nature. The appearance of primary dimples at lower heat effected zones of the weldment and the secondary dimples (significantly lower diameter) is at higher heat effected zones also confirmed the ductile fracture in the developed weldments. The general tendency of undergoing ductile type fracture in the FCC lattice structured materials such SS304 at atmospheric temperature is followed by the materials even at the higher temperatures also. The larger portion of plastic deformation and increase of the strain energy can be observed from the tensile tests and such tension is exhibited by less diameter sized pores at the necking region. The fracture mechanism is completed in three stages from the initiation to completion such as pore nucleation, growth and joining. The large joining stage of pores is strongly indicating that the strain energy is higher and supported to achieve increase tensile strength with the increase of electrode voltage.

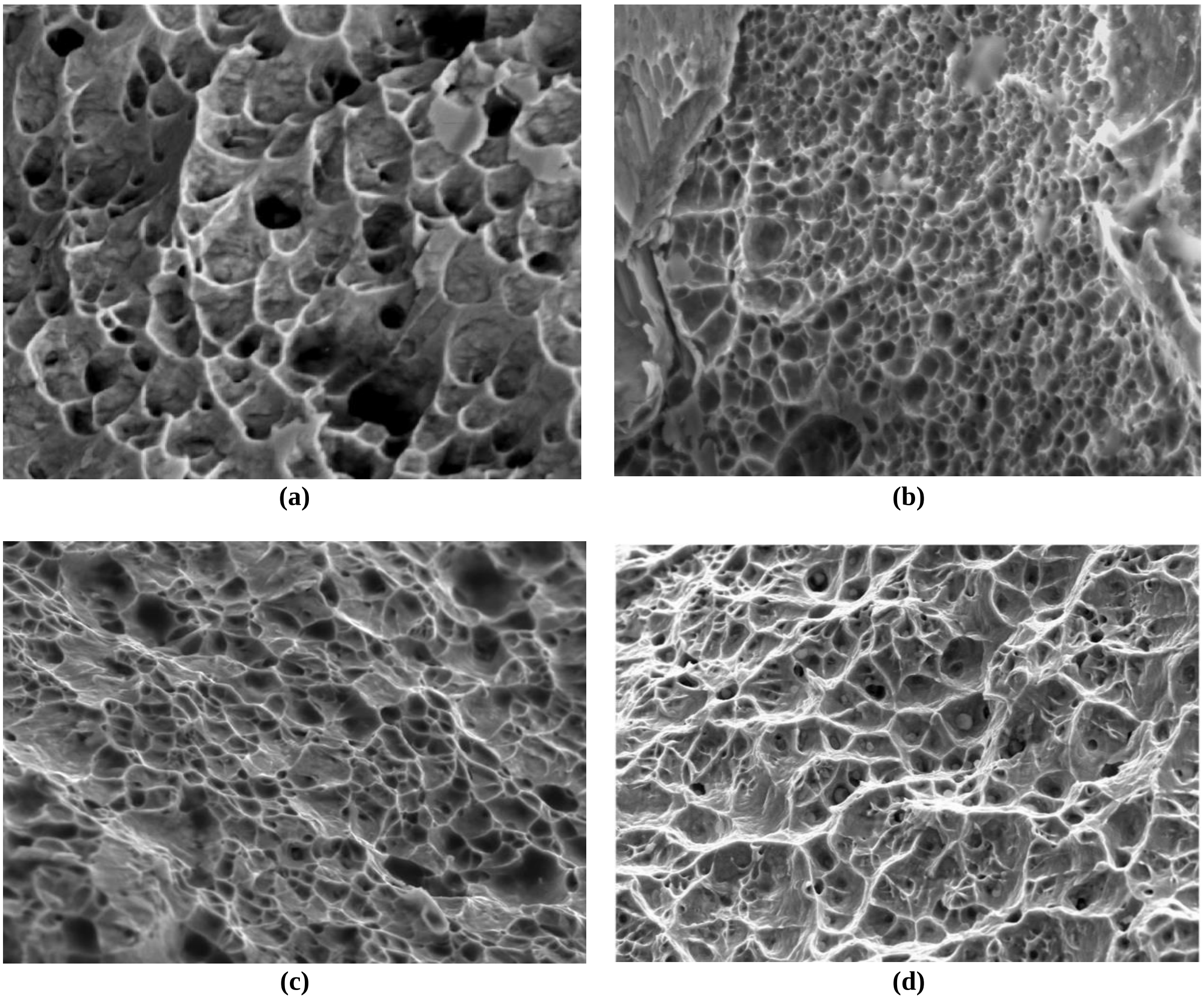

Figure 6: Fracture mode of butt joint at (a) 0V (b) 2V (c) 4V (d) 6V.
Source: Authors, (2024).

It can be confirmed with the characterization tests that the increase of voltage of electrode is most responsible factor behind the greater amount of reduction delta ferrite and rapid increase of austenite at the grain boundaries in the developed butt joint on SS304. The degree of increment in the austenite growth is prompted as the increase in the tensile strength and promoting to the fracture in ductile mode. The reduction in grain size at the austenite phase with the further increase of voltage from 4 to 6V prompted to increase the plastic deformability and increment in strain energy further.

V. CONCLUSIONS

In this research, the influence of vibratory treatment during the arc welding of SS304 is studied by analysing the mechanical properties, mode of fracture, transformation within the microstructure and tendency to crack at hotter regions is studied. The vibratory treatment is given during the welding process at different amplitudes by varying the voltage from 0 to 4V and the tests such as tensile, Charpy impact, Rockwell microhardness are conducted. The major observations made from the performed investigations are:

- The improvement in tensile strength of the weldment is observed with the increase of voltage at different ranges and greatest is found as 537 Mpa at the vibration frequency of 1835 Hz.
- The highest increment in the hardness is observed at the 6V followed by 4, 2 V whereas the lowest is recorded as 0V (no vibratory treatment) during the GMAW of SS304. The rapid growth of austenite in the absence of vibratory treatment is found as the major reason behind the lower hardness.
- The Charpy test results strongly indicated the greatest enhancement in the impact strength of the developed weldment through GMAW for every possible increment in the voltage and highest is shown as 4.29J at frequency of 765 Hz in 6V.
- The intense decrease in the tendency to crack in the weld samples with the assistance of vibratory treatment during the

welding process and effect of vibration over the heat evacuation is found as major behind the desirable decrement. The average length of crack is found as 14.78mm in the weldments at 0V whereas it is limited to 6.43 mm at 6V.

- The fracture is majorly found as ductile in nature with the increase of voltage from 0 to 6V and dimples with significant decrement in their width is observed in the weld samples of SS304.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: K. Ch Sekhar, Dr Rashmi Dwivedi, Dr. V.V. Rama Reddy.
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Discussion of results: K. Ch Sekhar, Dr Rashmi Dwivedi, Dr. V.V. Rama Reddy.
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Resources: K. Ch Sekhar, Dr Rashmi Dwivedi, Dr. V.V. Rama Reddy.
Supervision: K. Ch Sekhar, Dr Rashmi Dwivedi, Dr. V.V. Rama Reddy.
Approval of the final text: K. Ch Sekhar, Dr Rashmi Dwivedi, Dr. V.V. Rama Reddy.

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