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Research Paper

The Improvement of Mechanical Properties of the Incoloy 825 Weld Metal by Applying Electromagnetic Vibration

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ABSTRACT

In this study, the effect of applying electromagnetic vibration simultaneously along with welding to improve the mechanical properties of the Incoloy 825 superalloy weld metal was investigated. The samples were welded by the GTAW method and the simultaneous application of electromagnetic vibration under voltages from zero to 30 volts. The impact toughness and hardness of the weld metals produced by different voltages were measured. The microstructure of base and weld metals was investigated by an optical microscope and SEM. Microstructural studies showed that the weld metal has a fully austenitic matrix with fine precipitates on the grain boundaries and within the grains. It was found that the application of electromagnetic vibration by the fragmentation of the dendrite tips and their entry to the weld metal molten pool contribute to the increasing of heterogeneous nucleation and therefore grain refinement. The result of impact and hardness tests depicted that by applying the electromagnetic vibration the impact toughness and hardness of the weld metal are increased from 27.7 to 35.3 jols and from 205.5 to 257.7 Vickers, respectively. It was found that electromagnetic vibration improves the hardness and impact energy of the weld metal by affecting the parameters, refined equiaxed dendrites, structure within grains and better distribution of precipitates.

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1. Introduction

Superalloys are one group of the important engineering materials that show resistance to heat, corrosion, and oxidation and are divided into three groups, namely Nickel, Iron-Nickel, and Cobalt-based [1-3]. The Incoloy 825 superalloy (alloy 825) is one of the Nickel-Iron-based superalloys, which have excellent mechanical properties and are resistant to corrosion at relatively high temperatures. Alloy 825 is used in different industries such as the aerospace industries, the equipment of oil and gas wells, the nuclear industries, the manufacture of the acidic environments tubes, the lines of injecting chemical materials, and the under-pressure equipment [4]. Good weldability can be expected because of the presence of high Nickel and Chromium in this alloy and the presence of the austenitic structure [5-7].

The solidification microstructure and grain size of the weld metal severely affect the mechanical properties and sensitivity to the hot cracking of the weld metal. To control the grain structure, different methods, including inoculation and external excitation, such as molten pool stirring, arc oscillation, arc pulsation, are utilized [8-9]. The vibration and stirring of weld pool are extremely effective in the weld metal solidification microstructure and solidification modes so that making and applying the optimized vibration can play a key role in the correction of solidification structure, the improvement of mechanical properties, and the decreasing of sensitivity to the hot cracking of weld metal [9]. In general, vibration can be applied to the weld pool by three methods, namely ultrasonic, mechanical, and electromagnetic ones [10-11].

The applying of electromagnetic vibration simultaneously with welding by the alternating current resulted in applying the Lorentz force to the weld pool and molten vibration with the same frequency. The turbulence and agitation of the weld pool lead to increasing the dendrite tips fragmentation, thereby detaching the partial melting grains and decreasing the weld pool temperature. Decreasing the pool temperature causes greater stability of the fragmented dendrite tips, detached grains, and heterogeneous nucleation places in the weld pool [8-9].

Dehmolaei et al. [10] investigated the effect of electromagnetic vibration on the microstructure of dissimilar weld joints of alloy 800 and HP heat resistant steel. They reported that vibration, in addition to refining the weld metal structure, causes the unmixed zone to be eliminated at the interface. The research of Ghadam Dezfuli et al. [12] showed that the use of electromagnetic vibration during welding of 304 stainless steel ameliorates the weld metal structure and changes the solidification structure from columnar mode to the fine equiaxed dendritic. It was found that vibration can reduce the sensitivity to the hot cracking of the weld metal. By studying the effect of ultrasonic vibration on the weld joint properties of 321 stainless steel, Nabahat et al. [13] showed that vibration with variation in the morphology and size of ferrite and austenitic dendrites leads to an increase in grains refinement and improves the impact energy and hardness of the weld metal. The investigations by Parvin Singh et al. [14] revealed that the use of mechanical vibration during the welding of mild steels develops the fine grain structure and improves the yield strength and ultimate tensile strength of the weld metal. The effects of the electromagnetic vibrations of the welding on the weld metal microstructure of the 304 stainless steel in a simultaneous manner were investigated by Anderson et al. [15]. They reported that vibration could cause grains refinement and decrease the space between the primary and secondary dendritic arms. Sakthivel et al. [16] reported that mechanical vibrations during the welding contribute to the grains refinement and improves the mechanical properties of the weld metal of 316 stainless steel. The effect of the arc vibrations on microstructure and mechanical properties of Tantalum weld joints was studied by Sharier et al. [17] found that the greatest effect of arc vibration is on the fusion zone and that the heat-affected zone (HAZ) leads to the formation of fine equiaxed grains in the fusion zone and the reduction of the grain size in the HAZ.

Due to the wide applications of alloy 825 and the desirable effects of vibration on the microstructural and mechanical properties of weld joints, the influence of electromagnetic vibration on the microstructure aspects and mechanical properties in the alloy 825 weld joints was evaluated. The welding was carried out by the GTAW method.

2. Experimental details

In this study, alloy 825 with an 8 mm thickness as a base metal and Inconel 82 (ER NiCr-3) with a 2.4 mm diameter as a filer metal were used. Table 1 shows the chemical combination of base and filler metals.

Table 1. Chemical composition of base and filer metals (Wt%)

	Incoloy825	Inconel82	Chemical composition	Incoloy825	Inconel82
%C	0.03	0.1	%Al	0.09	0
%Fe	31.4	3	%P	0	0.3
%Ni	43.3	67	%Nb	0.06	2-3
%Cr	19.65	18-22	%Ti	0.75	0.75
%Cu	1.51	0.5	%Si	0.13	0.5
%Co	0.74	0	%S	0	0.15
%V	0.03	0	%Mn	0.21	2.5-3.5
%Mo	2.13	0			

or welding, specimens with the dimensions of 100 mm×50 mm×8 mm from the base metal were prepared. All butt joints were provided in 35° V grooves. The welding routes were performed by gas Tungsten arc welding with the direct current electrode negative (GTAW-DCEN). One of the weld joints was produced without vibration, and the others were produced under the concurrent electromagnetic vibration at the voltage levels of 6, 12, 20, 25, and 30 V. Figure 1 shows illustrate the schematic of the electromagnetic vibration welding apparatus.

In order to study the microstructure of the base and weld metals, the specimens of 10×20×8 mm dimensions were cut from the weld joints so that the weld bead could be placed in the middle of them. All the specimens were ground on the Silicon Carbide paper of 60-3000 grit and then were polished on nylon cloth with the 0.25 µm diamond paste. The microstructures were investigated using an optical microscope model MEIJI Techno-IM7200 and a scanning electron microscope (SEM) equipped with EDS point analysis model MIRA3-TESCAN. The specimens were electro-etched by the oxalic acid solution under 20 V for 15 seconds.

To measure the average length and width of the dendrites, the Image J software version 1.52V was used, and about one hundred fifty measurements were made to analyze each image. For this purpose, each image was divided into five zones, and inside each area, three circles with a diameter of ten millimeters were selected, and ten measurements (the length and width of dendrites) were performed inside each circle.

The Vickers hardness test (INNOVATEST Nexus Series) was performed on three specimens of each weld and base metals with a 30 kg load. From each weld metal, three samples (with 5 mm ×5 mm ×55 mm dimensions) based on ASTM E23 standard were prepared, and then the impact test was performed on all of them. At last, the average hardness and impact tests results for the three samples were reported. The fracture surfaces were investigated by SEM.

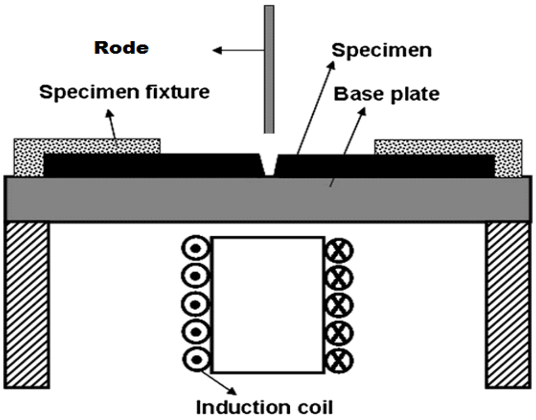


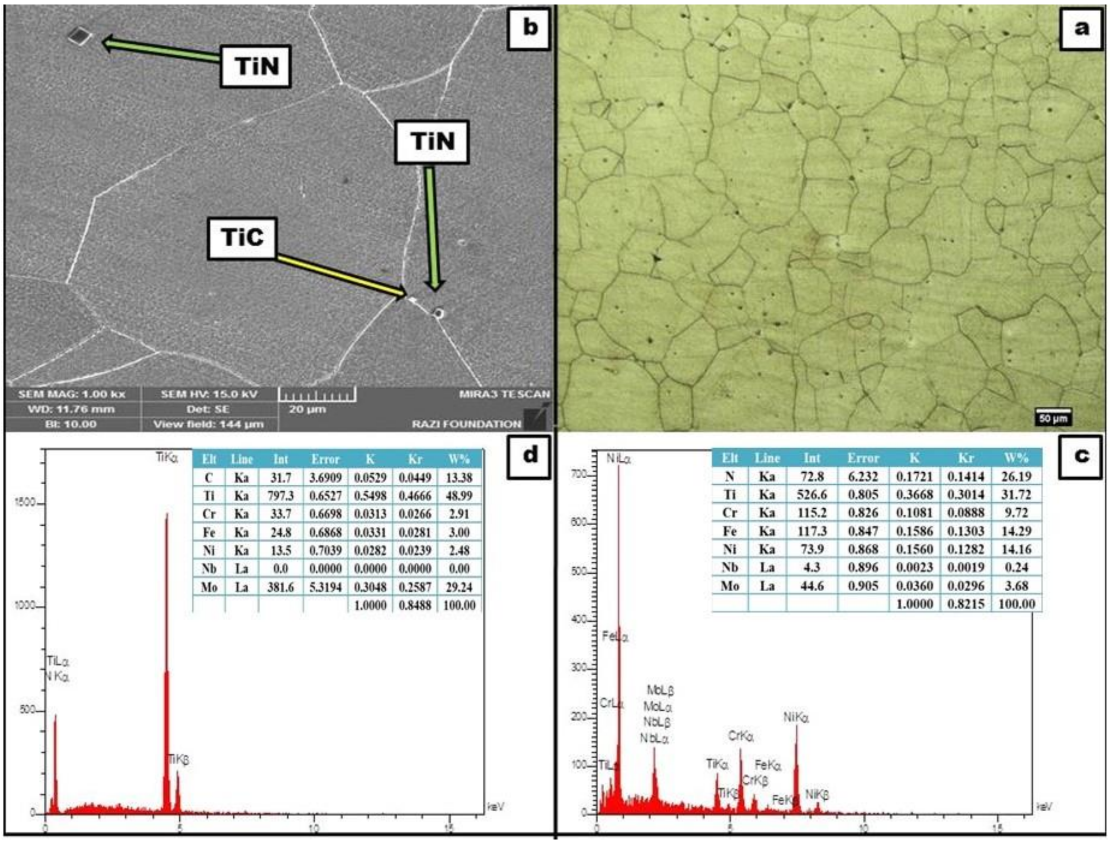
Fig. 1. Schematic of the electromagnetic vibration device

3. Results and discussion

3.1. Microstructure

3.1.1. The microstructure of base metal

The Incoloy 825 microstructure has been illustrated in Figure 2. The optical image (Figure 2a) indicates the microstructure of the as-received alloy 825 containing an austenitic with precipitates in the matrix and along the grain boundaries. The SEM image in Figure 2b reveals two types of precipitate with different sizes and morphologies. The polygonal type (coarser) is in the matrix and on the grain boundaries, while the spherical type (finer) is more in the matrix [18]. Figures 2c and 2d (EDS analysis results) show that the polygonal and spherical types are TiN (or Ti(N,C)) and TiC, respectively [19]. The same results have been reported by other researchers [20-22].



Elt	Line	Int	Error	K	Kr	W%
C	Ka	31.7	3.6909	0.0529	0.0449	13.38
Ti	Ka	797.3	0.6527	0.5498	0.4666	48.99
Cr	Ka	33.7	0.6698	0.0313	0.0266	2.91
Fe	Ka	24.8	0.6868	0.0331	0.0281	3.00
Ni	Ka	13.5	0.7039	0.0282	0.0239	2.48
Nb	La	0.0	0.0000	0.0000	0.0000	0.00
Mo	La	381.6	5.3194	0.3048	0.2587	29.24
				1.0000	0.8488	100.00

Elt	Line	Int	Error	K	Kr	W%
N	Ka	72.8	6.232	0.1721	0.1414	26.19
Ti	Ka	526.6	0.805	0.3668	0.3014	31.72
Cr	Ka	115.2	0.826	0.1081	0.0888	9.72
Fe	Ka	117.3	0.847	0.1586	0.1303	14.29
Ni	Ka	73.9	0.868	0.1560	0.1282	14.16
Nb	La	4.3	0.896	0.0023	0.0019	0.24
Mo	La	44.6	0.905	0.0360	0.0296	3.68
				1.0000	0.8215	100.00

Fig. 2. Microstructure of Incoloy 825 a. optical image b. SEM image c. EDS analysis of TiN precipitate d. EDS analysis of TiC precipitate

3.1.2. Microstructure of weld metal

Figure 3 shows the weld metal microstructure at different vibrational voltages. The figure illustrates that in all images, the structure is austenitic, and by increasing the intensity of vibration, the structure of the weld metal has become finer. It can obviously be seen from the figure that the finest structure is obtained at 30 V. Figure3 reveals that the microstructure of the weld metal is a solidified equiaxed dendritic in which the grains in the weld center are finer, and by increasing the intensity of the applied magnetic fields the finer equiaxed dendritic grains are obtained. The results of the image analysis from the length and width of dendrites in different specimens have been presented in Table 2. As can be observed in Table 2, by applying the electromagnetic vibration, the average length and width of the dendrite in the weld metal from 241.1418 µm and 17.6368 µm (no vibration) are reduced to 28.4161 µm and 7.7081 µm (vibration with 30v), respectively. Electromagnetic vibration causes the agitation and turbulence of the weld pool. The high turbulence of the weld pool leads to increasing the dendrite tips fragmentation, detaching the partial melting grains from base metal, and decreasing the weld pool temperature. The entry of the fragmented dendrite tips and detached grains into the weld pool increases the heterogeneous nucleation places in the weld pool, thereby forming a finer structure after solidification [23-24]. In addition, the turbulence of the molten pool contributes to a further decrease in the pool temperature and an increase in the cooling rate, thereby reducing the distance between the dendrites arms from the fusion line toward the weld center. As a result, it is expected that finer equiaxed dendrites are formed in the weld center [18, 25-27].

Table. 2. The average length and width of dendrites in weld metal for different vibration voltages

	0V	6V	12V	20V	25V	30V
The average length of dendrites (µm)	241.1418	135.6367	73.3534	65.9405	64.8960	28.4161
The average width of dendrites(µm)	17.6368	13.6517	9.6856	8.9592	8.56179	7.7081

By increasing the cooling rate, the solidification rate (R) is increased. The increase of the solidification rate and the constitutional supercoiling (the reduction of G/R ratio) from the pool boundary toward the centerline of weld make an alteration to the solidification mode from the columnar mode (close to the fusion line) to the axial dendrite in the weld center. Increasing the intensity of electromagnetic vibration will make this alteration more evident (Figure 3) [23,25-26]. By increasing the solidification rate and growth speed (G) due to vibration, the distance between the dendrite arms and the columns in the weld metal will be decreased, and the tendency to refinement will be increased in this area [28-29]. It has been found that the weld metal structure, including fine equiaxed dendrites in respect to columnar grains, has more ductility and that the possibility of the segregation and accumulation of alloy elements with low melting temperatures on the grain boundaries will be lower [9].

The SEM image of the weld metal (Figure 4a) shows many precipitates with an irregular shape in the matrix (finer) and on the grain boundaries (coarser). The EDS spectra obtained for these precipitates indicate that both fine and coarse precipitates are rich in Niobium and Nickel, Iron and Chromium (Figure 4b). These precipitates may be identified as Niobium Carbide NbC (Fe, Ni, and Cr may have been obtained from the austenitic matrix). On the one hand, about %3 Niobium is in the chemical composition of the filler metal (Table 1); on the other hand, the coefficient of the Niobium distribution in the Nickel-based alloys is less than one; hence, Niobium has the tendency toward the segregation in the interdendritic zones and forms the precipitates of NbC [9,18]. In addition, Figure 5 shows that vibration has made a more uniform distribution of precipitates in the weld metal microstructure. The existence of precipitates in the microstructure of the weld metal at the end of solidification, especially their uniform distribution (due to vibration), puts an obstacle to the movement of the grain boundaries through pinning, and therefore, the reduction of grain boundaries movement can contribute to the grains refinement and the increasing of hardness and strength [18,20].

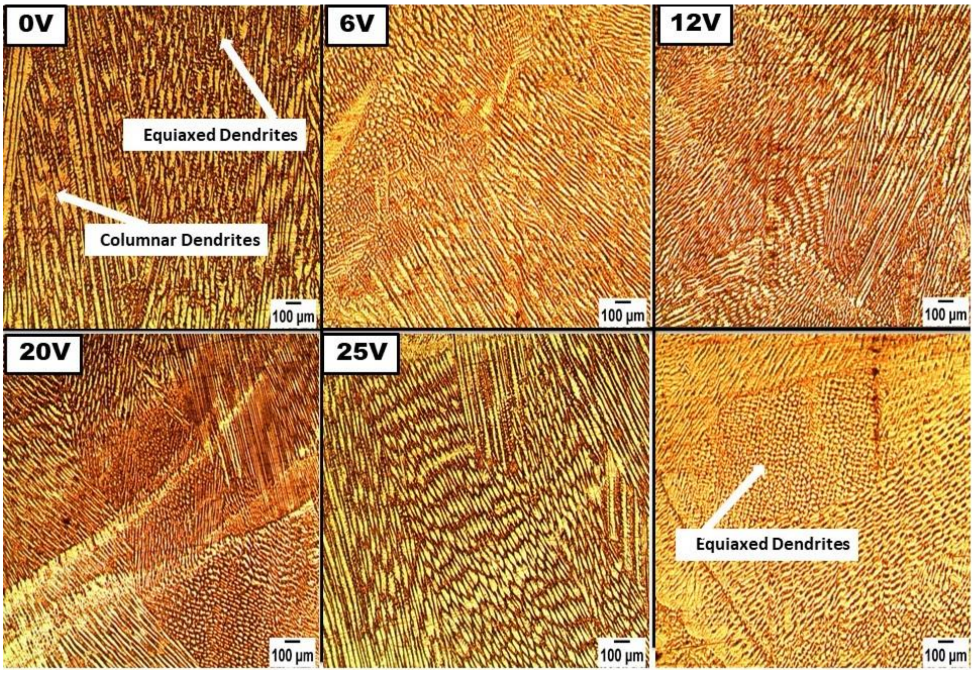
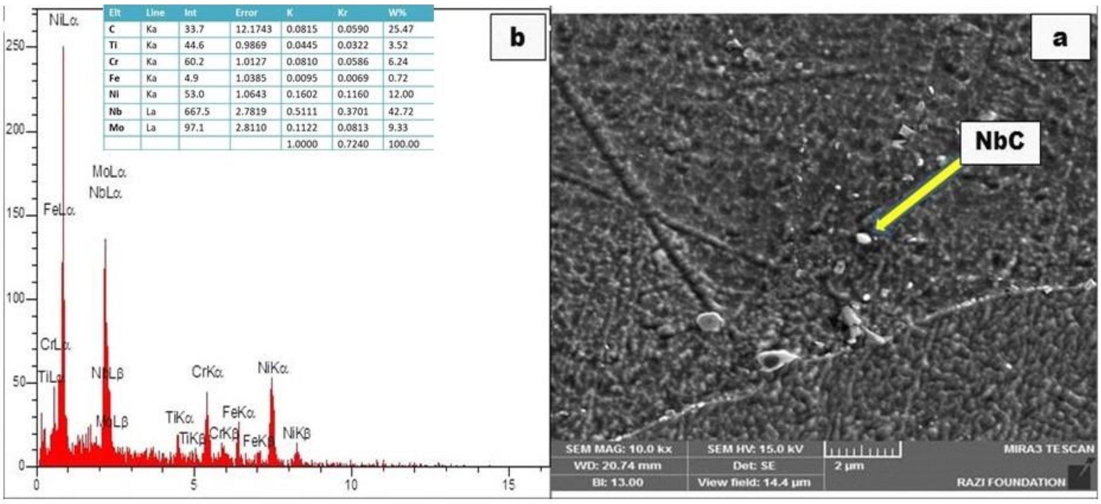


Fig. 3. Optical images of the Inconel 82 weld metal microstructure at different voltages



Elt	Line	Int	Error	K	Kr	W%
C	Ka	33.7	12.1743	0.0815	0.0590	25.47
Ti	Ka	44.6	0.9869	0.0445	0.0322	3.52
Cr	Ka	60.2	1.0127	0.0810	0.0586	6.24
Fe	Ka	4.9	1.0385	0.0095	0.0069	0.72
Ni	Ka	53.0	1.0643	0.1602	0.1160	12.00
Nb	La	667.5	2.7819	0.5111	0.3701	42.72
Mo	La	97.1	2.8110	0.1122	0.0813	9.33
				1.0000	0.7240	100.00

Fig. 4. SEM image and EDS analysis of NbC precipitates in Inconel 82 weld metal

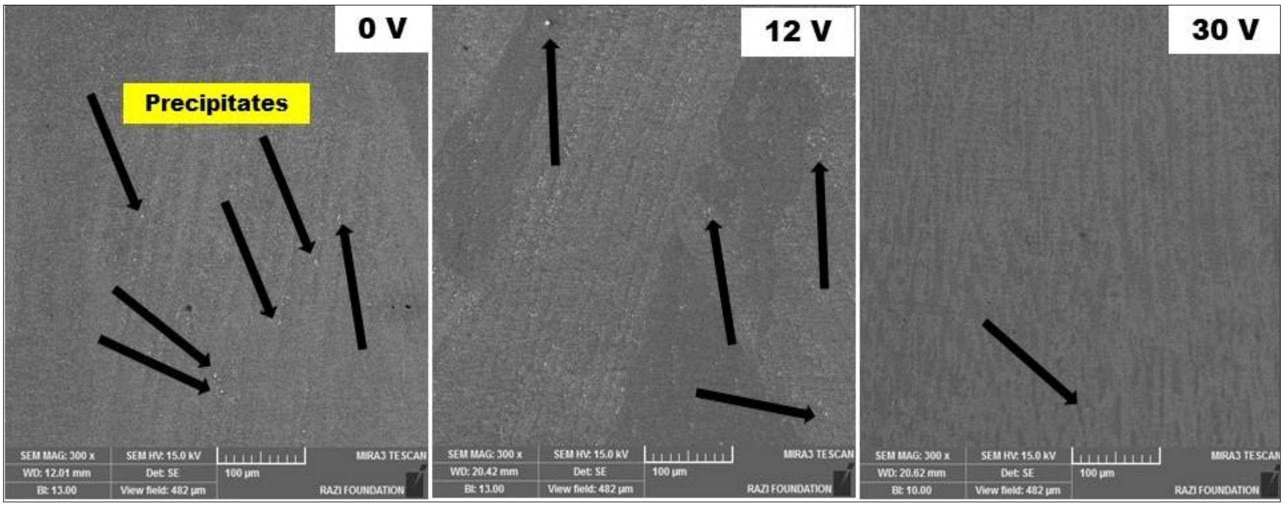


Fig. 5. SEM images of the Inconel 82 weld metal microstructure at different voltages

3.2. Mechanical Properties:

Table 3 shows the results of the hardness and Charpy impact tests of weld metal at different vibration voltages. The results disclosed that the highest hardness amount for the specimen under electromagnetic vibration 30 V and the lowest amount for the specimen without vibration had been obtained. The presence of the delicate dendritic structure and equiaxed fine grains in the specimen under electromagnetic vibration with 30 V and the more uniform distribution of the precipitates in this situation raises the hardness of weld metal considerably. Figure 6 shows the hardness profiles from the weld center toward the base metal for the specimens under different vibration voltages. It has been observed that the greatest hardness in all the weld metals is related to the weld center, resulting from the greater amount of formation of fine equiaxed dendrites in the weld center. The decreasing of hardness in the heat-affected zone (HAZ) is due to the grain growth and dissolution of precipitates in HAZ, whose welding thermal cycles with the increasing of HAZ temperature cause these microstructural changes.

Table 3. The results of the hardness and Charpy impact tests of weld metal at different voltages

	0V	6V	12V	20V	25V	30V
Average Hardness (HV)	205.5	210.6	215.4	226.9	237.4	257.7
Average energy (J)	27.3	30.5	31	31.2	31.6	35.3

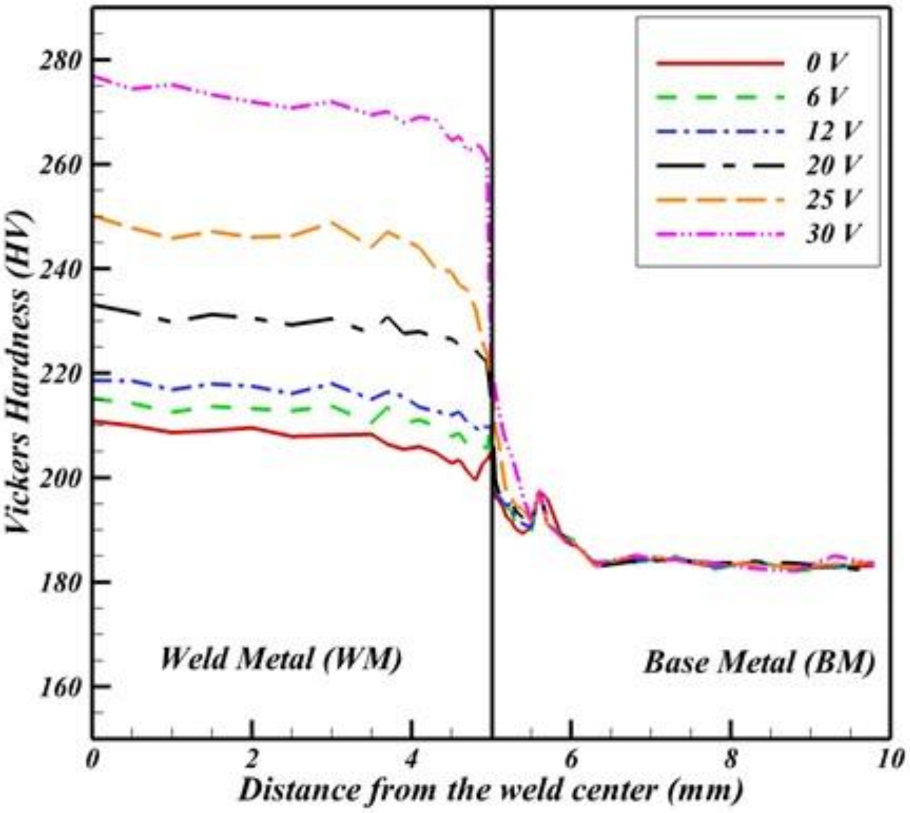


Fig. 6. Micro-hardness profile in weld and base metal for different vibration voltages

An increase in the vibration facilitates the formation of the structure with the equiaxed fine grains in the weld metal center, thereby reducing the distance between the dendrite arms and the columnar grains. The grains refinement can simultaneously improve the hardness and impact toughness. Grain refinement based on the Hall-Petch equation (H: Hardness, H0 and KH are constant, D: Grain Size) increases the hardness [30]. Also, grain refinement can improve the impact toughness by increasing grain boundary density as a barrier to crack propagation [9,13]. Due to the fact that vibration causes grain refinement and increases fine equiaxed dendrites, it can improve hardness and impact toughness at the same time.

$$H = H_0 + K_H D^{-\frac{1}{2}} \qquad (1)$$

Therefore, it is expected that by increasing the vibration, an increase in the hardness amount will be observed. It is noteworthy that the presence of Niobium Carbide in the structure of the weld metal is the factor through which the hardness in this area is elevated and that the vibration of the weld pool distributes these precipitates with a finer size and a greater uniformity [31]. Besides the formation of the Carbide precipitates and the hindering of the movement of grain boundaries, Niobium improves the mechanical properties of the weld metal with dissolution in the austenitic matrix [32].

The results in Table 3 show that the best impact energy amount (27.3 J) for the specimen under electromagnetic vibration 30 V and the lowest amount (35.3 J) for the specimen without vibration have been obtained. It can be seen that by increasing the intensity of the applied vibration, the impact energy is partially improved. By applying the electromagnetic vibration and increasing its intensity, the microstructure of the weld metal is changed from the columnar dendrites to the equiaxed fine dendrites (particularly in the weld center). Increasing the equiaxed fine grains results in a decrease in the distance between the dendrite arms, thereby making a better distribution of intergranular eutectics melt. The grain refinement increases the grain boundaries in the weld metal microstructure (the obstacles on the route of the crack growth) and improves toughness (impact energy). Additionally, increasing the applied vibration by a more uniform distribution of precipitates enhances the impact energy. Figure 7 depicts the SEM images of the surfaces of the weld metal fracture before and after applying the vibration. Figure 7 reveals that the type of fracture in all weld metals is soft, while by increasing the voltage, the effects of plastic deformation, voids, and deep dimples with a high number are frequently observed on the fracture surface in the specimens which have been under vibration. The smaller the diameter of these dimples is and the greater their depth and dispersion are, the greater the ductility of the resulting structure will be, thereby improving the impact energy [25].

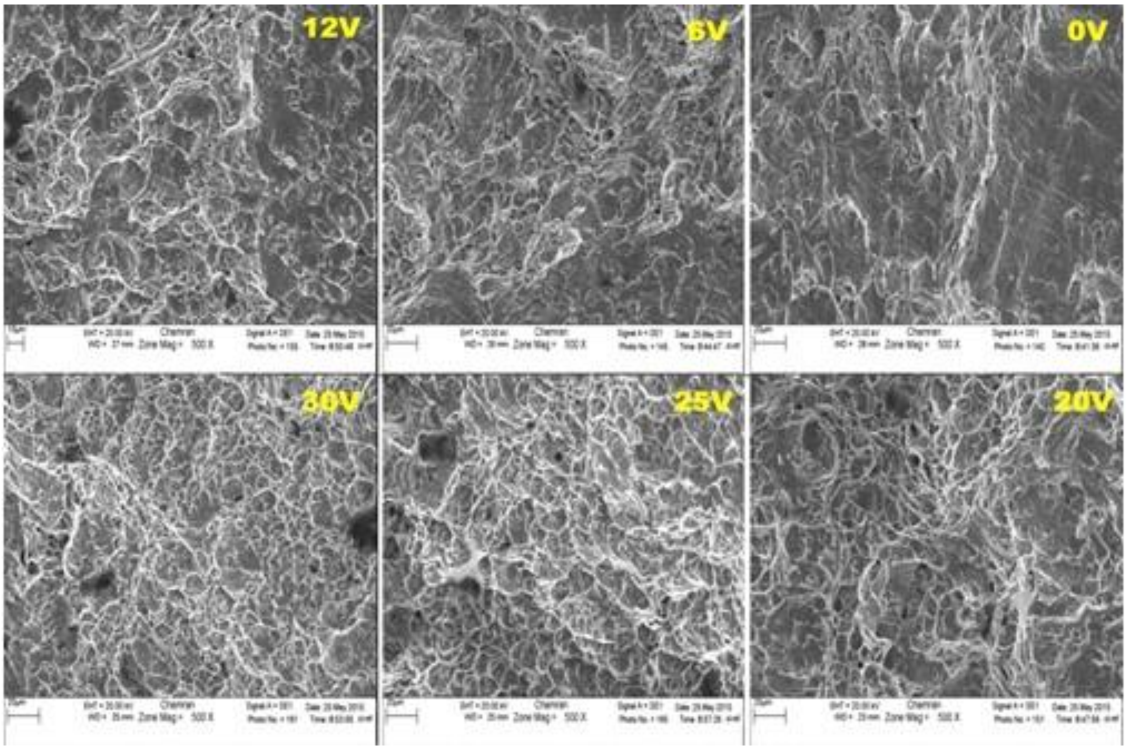


Fig. 7. SEM images of the fracture surface at different vibration voltages

4. Conclusions

1. It was found that the alloy 825 has an austenitic matrix along with the precipitates of TiC and TiN or Ti(N,C), respectively, with different spherical and polygonal morphologies on the grain boundaries and within grains.
2. Results showed that applying the electromagnetic vibration leads to an increase in the fine equiaxed grains and a decrease in the distance between dendrite arms within the weld metal grain structure.
3. Using the electromagnetic vibration led to a better precipitates distribution and prevented the grain boundaries movement in the weld metal.
4. Appling the vibration increased the hardness amount of weld metal. The maximum hardness was obtained at vibration voltages 30V in the weld center (257.7 HV).
5. By using electromagnetic vibration, the impact energy was increased up to more than 29.5%. The minimum and maximum impact energy of the weld metal for weld joints without vibration (27.3 J) and under 30 V vibration (35.3 J) was observed, respectively.

References

[1] E. B. Howard and L. G. Timoty, Desk Edition, Metals Handbook, ASM International, United States of America,1985.

[2] E.F. Bradly, Superalloys A Technical Guide, 2nd Edition, ASM International, Metalspark, OH44073, 1988.

[3] M.J. Donachie, S.J. Donachie, Superalloys: a technical guide, 2nd Edition, ASM International, 2002.

[4] J. R. Davis et al, ASM Specialty Handbook: Nickel, Cobalt, and Their Alloys, Printed in the United States of America, 2000.

[5] R. Coppola, S. R. Fiorentin, Study of γ′-precipitation kinetics in alloy 800 at 575° C by small angle neutron scattering. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 22, 4, 564-572, 1987.

[6] J. C. Lippold, Investigation of Weld Cracking in Alloy 800, Welding Journal, 63, 3, 91-103, 1984.

[7] R. S. Dutta, R. Purandare, A. Lobo and S. K. Kulkarni, "Microstructural Aspects of the Corrosion of Alloy 800", Corrosion Science, 46, 2937–2953, 2004.

[8] K. Balasubramanian, S. Raghavendran1 and V. Balusamy., Studies on the effect of mechanical vibration on the microstructure of the weld metal. International Journal of technology and Engineering Systems, 2, 3,253-256, 2011.

[9] S. Kou, Welding metallurgy, second ed. Hoboken, John Wiley & Sons Inc, 2003.

[10] R. Dehmolaei, M. Shamaniana, A. Kermanpur. Effect of electromagnetic vibration on the unmixed zoneformation in 25Cr–35Ni heat resistant steel/Alloy 800dissimilarwelds, Materials Characterization, 59, 12, 1814-1817, 2008.

[11] A. Abugh, I. K., Kuncy., Microstructure and Mechanical Properties of Vibrated Castings and Weldments: A Review, Journal of Engineering Studies and Research 19(1) ,7, 2013.

[12] M. A. G. Dezfuli, Dehmolaei, R., & Zaree, S. R. A. (2019). Microstructural Aspects of 304 Stainless Steel Weld Joints with the Simultaneous Application of Electromagnetic Vibration., Metallography, Microstructure, and Analysis, 8(2), 226-232.

[13] M. Nabahat, Ahmadpour, K., & Saeid, T. (2018). Effect of ultrasonic vibrations in TIG welded AISI 321 stainless steel: microstructure and mechanical properties. Materials Research Express, 5(9), 096509.

[14] P. Singh, Patel, D., & Prasad, S. B. (2017). Investigation on the effect of vibrations on cooling behavior and mechanical properties of SMAW butt welded joints. Sci. Bull. Ser. D, 79.

[15] A. V. D. Queiroz, Fernandes, M. T., Silva, L., Demarque, R., Xavier, C. R., & Castro, J. A. D. (2020). Effects of an external magnetic field on the microstructural and mechanical properties of the fusion zone in TIG welding. Metals, 10(6), 714.

[16] P. Sakthivel, & Sivakumar, P. (2014). Effect of vibration in Tig and arc welding using AISI 316 stainless steel. International Journal of Engineering, Research and Science & Technology, 3(4), 116-130.

[17] Y. Sharir, Pelleg, J., & Grill, A. (1978). Effect of arc vibration and current pulses on microstructure and mechanical properties of TIG tantalum welds. Metals Technology, 5(1), 190-196

[18] R. Dehmolaei, M. Shamaniana, A. Kermanpur, Microstructural characterization of dissimilar weld between alloy 800 and HP heat resistant steel,59,10, 1447-1454, 2008.

[19] D.Y. Seo, J. Tsang1, R. Kearsey, W.J. Yang2, K.S. Cho, J.H. Lee, and P. Au1, Crack Growth Rate Behaviour and Microstructural Features of Incoloy 800H under Fatigue and Creep-fatigue Conditions, In ICF12, Ottawa 2009.

[20] M. Sireesha, V. Shankar, SK. Albert, S. Sundaresan, Microstructural features of dissimilar welds between 316LNaustenitic stainless steel and Alloy 800, Mater Sci Eng A, 292:74–82, 2000.

[21] L. Sundar and D. R. G. Achar, Review of Weld Cracking in Alloy 800, Indian Welding Journal., 16, 3, 81-86, 1984.

[22] R. Dehmolaei, M. Shamaniana, A. Kermanpur, Microstructural changes, and mechanical properties of Incoloy 800 after 15 years' service, Materials Characterization 60, 3, 246-250, 2009.

[23] C.C. Hsieh, P.S. Wang, J.S. Wang, W. Wu. Evolution of microstructure and residual stress under various vibration modes in 304 stainless steel welds. The Scientific World Journal. 2014 Jan 1;2014.

[24] S. P. Tewari, Influence of Longitudinal Oscillation on Tensile Properties of Medium Carbon Steel Welds of Different Thickness, Science & Technology Asia 14, 4, 17-27, 2009.

[25] Y. G. Zhao, Y. H. Liang, Q. D. Qin, W. Zhou and Q. C. Jiang, Effect of Mechanical Vibration on the Microstructure, Impact Toughness and Thermal Fatigue Behavior of Cast Hot Working Die Steel, ISIJ international 44 (7), 1167-1172, 2004.

[26] J. Prakash, S.P. Tewari, B.K. Srivastava, Nucleation, grain growth, solidification and residual stress relaxation under stationary and vibratory welding condition—A review. Int. J. Engg. Techsci. 1, 1, 2010.

[27] C. Zhang, M. WU, J. DU, Improving Weld Quality by Arc-Excited Ultrasonic Treatment, Tsinghua Science and Technology, 6, 5, 475-478, 2001.

[28] B. Pucko, V. Gliha., Charpy toughness of vibrated microstructures. Metalurgija., 44, 2, 103-106, 2005.

[29] S. Kou, Y. Le., Improving weld quality by low frequency arc oscillation., Welding Journal 64, 3, 51-55, 1985.

[30] D. Facchini, (2012). Biomedical nanocrystalline metals and alloys: Structure, properties and applications. In Nanomedicine (pp. 36-67). Woodhead Publishing.

[31] Y. Mizutani; Y. Ohura, K. Miwa., Effect of the Electromagnetic Vibration Intensity on Microstructural Refinement of Al-7%Si Alloy., Materials Transactions, 45, 6, 2004.

[32] T.Y. Kuo, H.T. Lee, Effects of filler metal composition on joining properties of alloy 690 weldments, Materials Science and Engineering A, 338,202-212, 2002.