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EFFECT OF HIGH-FREQUENCY ELECTRIC RESISTANCE WELDING (HF-ERW) PARAMETERS ON METALLURGICAL TRANSFORMATIONS AND TENSILE PROPERTIES OF API X52 MICROALLOY STEEL WELDING JOINT

This study investigates the effects of frequency, compression force and Vee angle parameters of High-Frequency Electric Resistance Welding (HF-ERW) process on mechanical properties of API X52 microalloy steel welding joint. Therefore, API X52 microalloy steel sheets having thickness of 8 mm was provided to manufacture pipes with the diameter of 16”. with direct weld seams using the HF-ERW method. During the manufacturing process, frequency values of 150, 200 and 250 kHz, compression forces of 2, 4 and 6 mark and Vee angles of 3°, 5°, and 7° were adopted. After changing the welding parameters, from the welded pipes, tensile and Charpy impact test samples prepared to macroscopically evaluate the weld metal flow and examine the effects of these parameters on mechanical properties of the welded joints. According to the results, it was concluded that frequency of 150 kHz, the compression force of 4 mark and Vee angle of 5° yields best mechanical properties in the HF-ERW joint of API X52 microalloy steel.

Keywords: High Frequency Electric Resistance Welding (HF-ERW), Frequency , Compression Force, Vee Angle, Mechanical Behavior, API X52 Microalloyed Steel

1. Introduction

High Strength Low Alloy steels (HSLA) are a group of low-carbon steels in which low amounts of alloying elements have been applied in normalized and rolled conditions to reach yield strengths higher than 257 MPa (40 Ksi) [1,2]. These steels have better mechanical properties and in some cases better corrosion resistance in comparison to rolled carbon steels. In addition, because HSLA steels can have higher strength with low amounts of carbon, their weldability is comparable and in some cases better than that of killed steels [1-3].

High strength low alloy steels are initially formed into raw products by hot rolling process (plate, billet and structural components) and it can be stated that they are often produced in hot rolled condition. However, the production of hot rolled HSLA steels consist special hot roll processes which improve mechanical properties of HSLA steels [2-4]. High strength low alloy steels include many standard grades that are designed to develop combinations of properties like strength, hardness, formability, weldability and corrosion resistance. These steels are not considered in the alloyed steels group although their desirable properties are obtained by low amounts of alloying elements [5,6]. They are categorized as a separate group and are similar to rolled low-carbon steels with improved mechanical properties. These improved properties are obtained by adding low amounts of alloying elements as well as using special techniques like controlled rolling and quenching processes [5-7].

High frequency electric resistance welding (HF-ERW) is one of the most conventional methods used to manufacture long steel pipes in oil & gas transportation lines [8,9]. The process of HF-ERW for steel pipes has been developed in 1940s. It was applied practically in 1950s and became an outstanding method for the production of steel pipes in 1960 and 1970 decades. The appearance of solid state welding apparatus in the early of 1990s became a forerunner for the realization of the frequency based welding process [9-11]. In this process, the produced hot rolled sheets are gradually formed into cylindrical shapes by rolls and the two edges of the sheet are jointed into each other by a combination of mechanical compression and local heating induced by electrical resistance under a high-frequency electric current. The high frequency current is concentrated on the outer edges of the sheet by special probes and creates considerable heat which leads to the melting of sheet edges and eventually by applying mechanical compression using rolls, the two edges of the sheet are welded to each other [8,9]. The advantages of the process includes no need to filling metal and special atmosphere, high speed and small weld width and heat affected zone [10]. The frequency, compression force and Vee angle parameters in

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the process of HF-ERW influence on the welding operation as well as the quality of the final product. The effect of welding frequency relates to the behaviour of heat distribution and the size of the heat affected zone. The more the current frequency, the more will be the current skinned [11].

One the most important parameters in the HF-ERW process is the welding frequency which there is no complete theory yet about the effect of frequency on the weld surface and most of the data have been based on the experimental information. However, the available information hase been experimentally based on getting real and trustful results are not possible by applying simulation as well as doing experimental HF-ERW on small scale. In addition, as doing the test in a real pipe production plant is difficult, time-consuming and costly, so most of the available data are contradicted and imperfect.

In a course which the fore current is located in the vicinity of the back current, the metal shows least electrical resistance and the current normally tends to pass from this course. This property (proximity effect) causes the current to be concentrated on the edges of the sheet and hence better heat concentration will be obtained as well as heat loss will be avoided [12]. Furthermore, because the current movement on the edges of the sheet occurs in two different directions, the gravity will be developed in the edges which help the weld quality to be improved. The combination of skin and proximity effects causes only the opposite edges to be exposed to heat [13].

The other effective factor on the weld quality is the compression force during and after applying heat. By applying compression force, the pasty edges are blended into each other and after cooling substantial joint is provided. The change in the compression force leads to the different grain sizes in the heat region and hence it requires controlled heat treatment to recover the original grain sizes [14]. The removal or reduction of the required heat treatment is significant by detection of the optimized range of compression force. Applying compression force on the melted joint line by the rolls causes the melt inclusions to be removed from the contact surface of the edges and it doesn't remain any inclusion in the weld line. The removed inclusions will be cleared mechanically from the weld seam after finishing the welding process [15]. The plastic deformation induced by compressing force rolls causes the metal flow of the rolled coils to be changed. The metal flow determines the weld quality [16].

The angle and length of the Vee are the other effective parameters in the process of HF-ERW. The suitable Vee angle for the HF-ERW process of steel pipes is between 2 to 7°. The small Vee angles yield higher efficiency but may be accompanied by spark and oxide formation in the weld region. The wide Vee angles yield lower efficiency but don't include detrimental effects of spark and oxide inclusions in the weld region [17]. There will be certainly an optimized range of angle which obtains better mechanical properties.

According to the represented information in this section, frequency, compression force and Vee angle parameters have considerable effects on the obtained weld quality in the HF-ERW process. Therefore, this study aims to evaluate the effect of these parameters on mechanical properties of the weld joint of API X52 steel in an HF-ERW process which has not been the subject the other previous researches.

2. Materials and Experimental Procedure

The steel used in this study was API X52 microalloyed steel. Steel pipes with a diameter of 16”. Were manufactured by HF-ERW process from 8mm thick steel sheets and examined with quantometer. Table 1 shows the composition of the provided steel sheets. In this research, the atomic emission spectroscopy instrument (Spark Emission Spectrometer/Germany) has been used to analyze the chemical composition of the base metal. Table 2 shows the change ranges of the HF-ERW parameters in this study. The pipes were welded using HF-ERW technique by welding machine made of Thermatool Corporation (USA). Figure 1 shows the welding stages in this study.

TABLE 1

Chemical composition of the provided steel sheets

Element	C	Si	Mn	P	S	Cu	Al	Cr	Ni	Ti	V	Nb	Fe
Content	0.08	0.24	1.04	0.018	0.003	0.018	0.04	0.02	0.01	0.0081	0.05	0.04	Balance

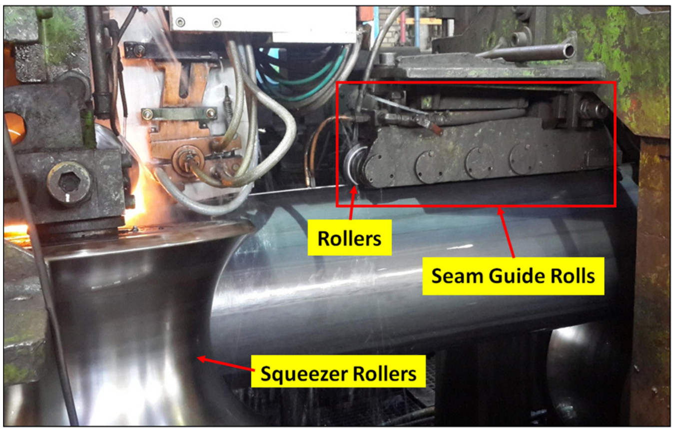


Fig. 1. An overview of the HF-ERW process used in this research

TABLE 2

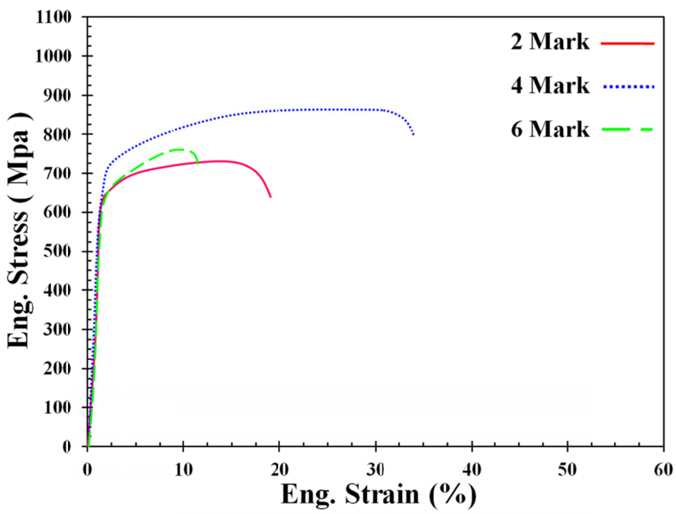
Range of changes in the frequency, compression and Vee angle parameters in the HF-ERW process

Parameter	The range of changes		
Frequency (KHz)	150	200	250
Compression force (Mark)	2	4	6
Vee angle (°)	3	5	7

After welding process, standard samples were prepared from each pipe using CNC milling machine then metallographic observations, Charpy impact and tensile tests were performed on the samples to examine the effect of HF-ERW parameters on mechanical properties of the API X52 steel weld joint. In addition, samples were provided from the section of the weld region in order to metallographic and macroscopic observations of the weld metal flow. Metallographic samples were prepared by different sand papers and wet polishing processes then they were examined by optical microscope. To polish the metallographic samples, a napless cloth with a diamond paste have been used. To etch the metallographic samples, 2% nital solution was used. This has been added to the experimental procedure section. Tensile, Charpy impact and metallographic tests were performed based on ASTM A370, ASTM E23 and ASTM E112 standards respectively. It is worth to note that tensile test was performed using the uniaxial Universal machine (TB1-50t model) at room temperature and strain rate of 10^{-3} s^{-1}. The Charpy impact test was also performed using SANTAM machine with the capacity of 400 j at room temperature.

3. Results and discussion

Tensile test results for the HF-ERW joints of API X52 microalloyed steel prepared by compression forces of 2, 4 and 6 marks are presented in Figure 2a,b. According to the yield strength and ultimate tensile strength values in Figure 2a as well as comparative engineering stress-strain results shown in Figure 2b it is seen that by increasing or decreasing the compression force in HF-ERW in the range of 2-6 mark, there isn't any relationship between yield strength or ultimate tensile strength at different compression forces. In another word, there wasn't any logical change in the yield strength or ultimate tensile strength by increasing or decreasing the compression force rather there is an optimal range for the compression force in HF-ERW. The welding joint of API X52 microalloyed steel prepared with compression force of 4 mark has the highest yield strength and ultimate tensile strength while the least yield strength and ultimate tensile strength corresponds to the weld joint obtained with a compression force of 6 mark. The toughness of the joint prepared by the compression force of 4 marks is considerably higher than that of the other joints while the lowest toughness corresponds to the joint prepared by the compression force of 6 marks. By considering the linear part of the diagram and the elasticity, the stiffness of the HF-ERW joints prepared by the compression force of 2 and 6 mark are almost equal and the stiffness of the joint prepared by the compression force of 4 mark is higher than that of the other joints. The plasticity or the material ability to withstand against permanent deformations without fracture or tearing is significantly higher in the sample prepared with a compression force of 4 mark in compared to other weld joints. While the plasticity of the HF-ERW joints prepared by the compression force of 6 mark is lower than that of the other two joints. The ratios of the yield strength to ultimate tensile strength which are shown by Y.S/U.T.S coefficients are almost equal for all three HF-ERW joints prepared by compression forces of 2, 4 and 6 marks. The range of hardening as well as ductility of the HF-ERW joints prepared by the compression force of 4 mark is higher than that of the other joints which itself indicates the ability of the material to permanent deformation before fracture or breakage. While the ductility of the HF-ERW joint of API X52 microalloyed steel prepared with a compression force of 6 mark is lower than that of the other joints and is more brittle. The elasticity or the material ability to withstand shocks and vibrations which is equivalent to the surface below the stress-strain curve in the linear range of the curve is higher for the joint prepared with compression force of 4 mark in compared to the other two joints and the elasticity values of the joints prepared by compression forces of 2 and 6 mark are almost equal.



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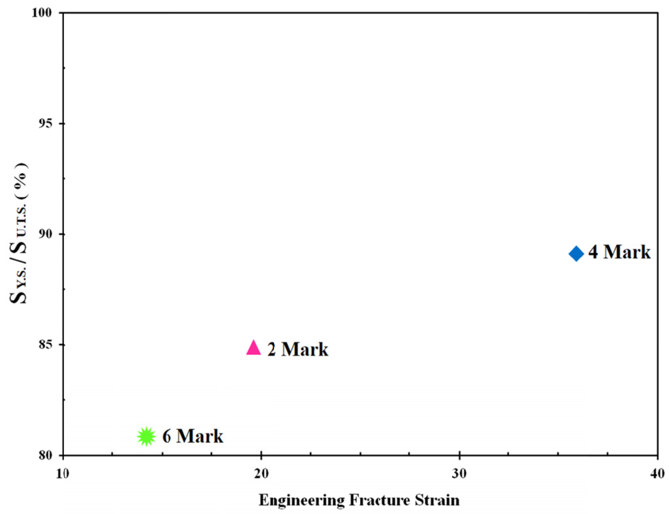


b)

Fig. 2. Tensile test results for the HF-ERW joints of API X52 microalloyed steel prepared by different compression forces

Figure 3 shows the results of Charpy impact test at room temperature for HF-ERW joints of API X52 microalloyed steel prepared by different compression forces. According to the amount of energy absorbed before failure of the joints which are shown in Figure 2, the HF-ERW joints of API X52 microalloyed steel prepared by compression force of 4 mark has the highest value before the fracture which is indicative of higher toughness, more flexibility as well as higher impact load bearings. The higher toughness of the HF-ERW joints of API X52 microalloyed steel prepared by the compression force of 4 mark in comparison to other joints, had been proved previously in the tensile test results (Fig. 2b) corresponding to this compression value. According to the results shown in Figure 3, the amount of absorbed energy before fracture for the HF-ERW joints of API X52 microalloyed steel with compression forces of 2 and 6 marks are almost equal with a little difference. In addition, the absorbed energy in the HF-ERW joints prepared by the compression force of 4 marks is lower which suggests the lower toughness, its brittleness as well as higher sensitivity against impact loads in compared to the two compression forces of 2 and 6 mark. The results of the Charpy impact test had also been proved with corresponding tensile test results with mentioned compression forces. Finally, with considering the results of tensile and Charpy impact tests it is cleared that in the weld region of the HF-ERW joint of API X52 microalloyed steel, according to the obtained results there exists an optimal value equal to 4 mark for the compression force.

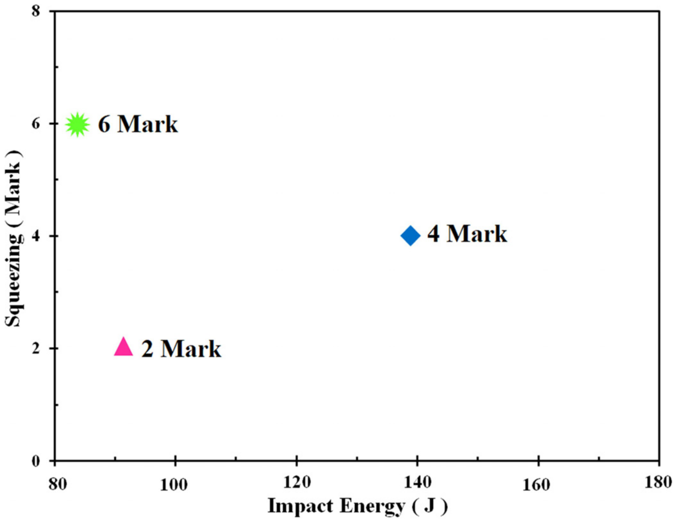


Fig. 3. Charpy impact test results for the HF-ERW joints of API X52 microalloyed steel prepared by different compression forces

After initial forming and preparation of the sheet edges for the HF-ERW process, during passing the pipe from the HF-ERW station, high frequency as well as the required heat, was provided. The presence of the rolls in the intended position caused the required pressure to be provided for the fusion of the heated and pasty sheet edges so that eventually lead to a strong joint similar to forging. Applying the pressure causes the metal components to orient towards the inner and outer surfaces of the pipe and hence metal oxides and other melt inclusions get out from the inner and outer surface of HF-ERW joint and there remain no inclusions or metal oxides in the weld line [18-20]. The homogenous and heterogeneous metal components in different directions, as well as metal flow angles, are effective in the quality of the HF-ERW joint. Macroscopic images of the HF-ERW joints of API X52 microalloyed steel prepared with compression forces of 2, 4 and 6 marks are shown in Figure 4. As seen in Figure 4, metal flow lines are pulled downward and upward which indicates the removal of the inclusions towards the inner and outer surfaces of the pipe. These redundant are removed from inner and outer surfaces by machining and the surface of the weld become levelled to the surface of the pipe body. It is worth noting that the macrographs presented in Fig. 4 have been taken using an optical microscope at 50 X.

It was observed by the evaluation of the metal flow using metallographic images of the joints, that the lines and angles of the metal flow are directly correlated to the applied compres-

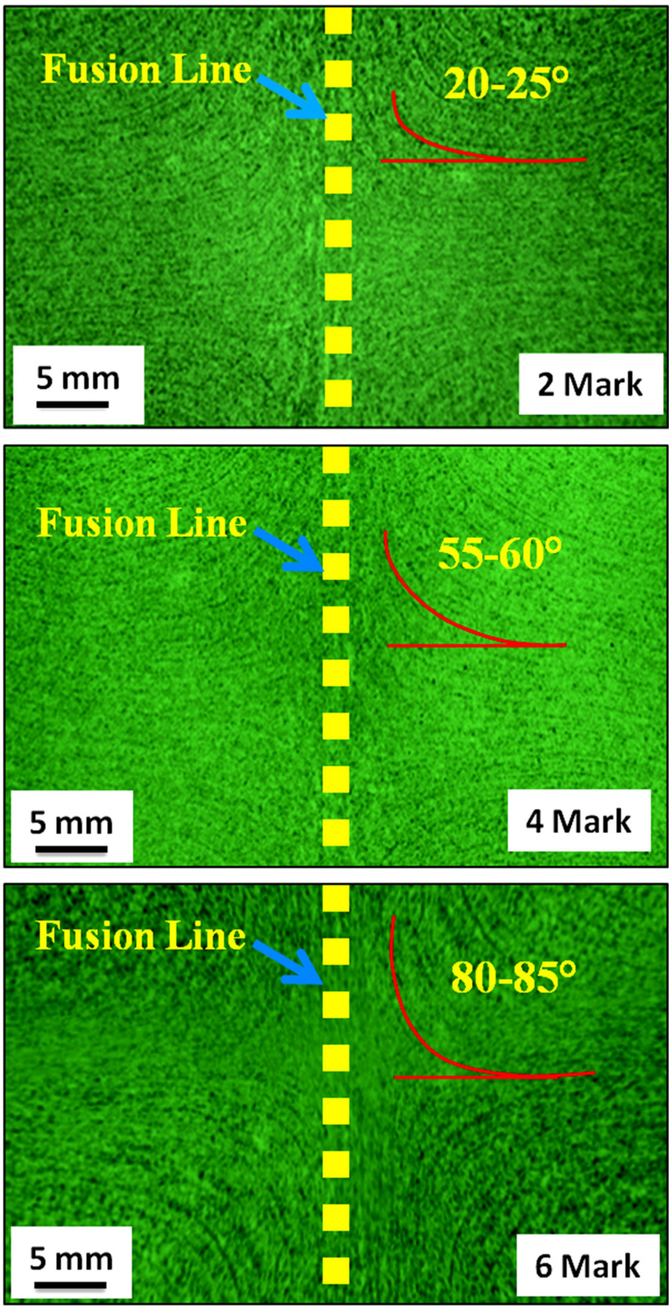
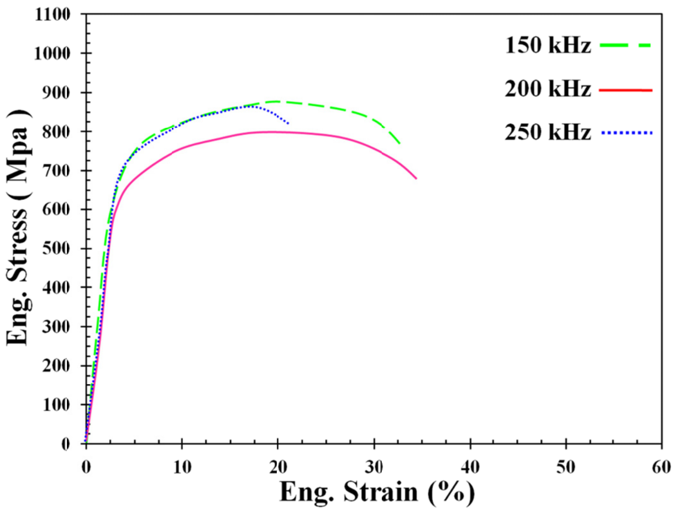


Fig. 4. The angles and metal flow lines in the cross-section of the weld region of HF-ERW prepared by different compression force

sion force in the HF-ERW process. According to the Maksuti et al. [21] studies, a proper weldment occurs when the metal flow angles are in the range of 50-60° which according to Figure 4 the optimum mentioned range correlate with the compression force of 4 marks. The metal angles obtained at 20-25° for the HF-ERW joint of API X52 microalloyed steel prepared with a compression force of 2 marks indicate insufficient applied a compression while metal angles more than 80° with compression force of 6 marks, indicate high and uncommon compression force.

The results of the tensile test for the high-frequency electric resistance welded API X52 steel provided by different frequencies have been represented in Figure 5. According to the yield strength and ultimate strength values in Figure 5a as well as comparative engineering stress-strain results in Figure 5b, it was shown that by increasing or decreasing of the frequency in the range of 150-250 kHz , there wasn't any specific relation between the yield strength/ ultimate tensile strength at different frequencies. In other words, there wasn't any logical change in the yield strength or ultimate tensile strength by increase or reduction of the frequency. The yield strength of all three HF-ERW joint samples was roughly equal while the yield strength of the API X52 microalloyed steel welded by the frequency 200 kHz was more than that of the other two samples. The toughness or material capability to withstand elastic and plastic deformations which are determined by measuring the surface area below the stress-strain curve at 250 kHz is considerably lower than that of the two other used frequencies in the weld joint obtained by the HF-ERW process. While the highest HF-ERW joint toughness in the API X52 microalloyed steel is obtained at 150 kHz. Given the gradient of the linear part of the diagram and the corresponding elastic modulus, the stiffness of the three joints is almost equal. However, the stiffness of the sample welded with a frequency of 150 kHz is slightly higher than that of the other joints. The plasticity or material ability to withstand permanent deformations without breaking or tearing in the HF-ERW joint prepared with the frequency of 150 kHz is more than that of the other joints. While the plasticity of the HF-ERW joint with the frequency of 250 kHz is lower than that of the others. According to the engineering stress-strain curve as well as the ratio of yield strength to ultimate tensile strength in table 4 which is shown with Y.S/U.T.S coefficient, the corresponding value for HF-ERW joint with frequency of 200 kHz is higher than that of the two other frequencies followed by more ductility which itself indicates the material ability for plastic deformation before rupture or failure [22-27]. In the following, considering the surface which is below the curve in the linear part of stress-strain curve (elastic region) that follows Hooke's law, elasticity or the ability of the material to withstand shocks is almost equal, however the elasticity of the HF-ERW joint with 150 kHz frequency is slightly more than that of the other joints.

The results of Charpy impact test which have been performed at room temperature for the HF-ERW joint with different frequencies are shown in Figure 6. According to the absorbed energy before joint fracture which is shown in figure 6, the HF-ERW joint with the frequency of 250 kHz has the lowest absorbed energy before fracture that indicates lower toughness, brittleness and hence its higher sensitivity to impact loads in the welded sample with a frequency of 250 kHz in compared to other samples. However, the low toughness of the weld joint with 250



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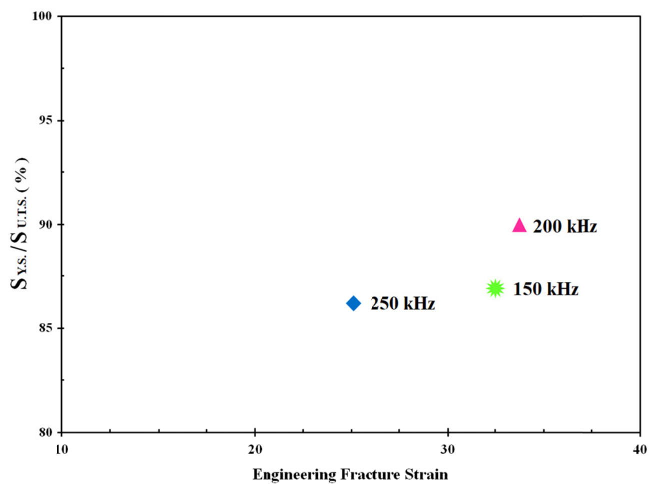

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Fig. 5. Results of tensile test for HF-ERW joints of API X52 microalloyed steel prepared with different frequencies

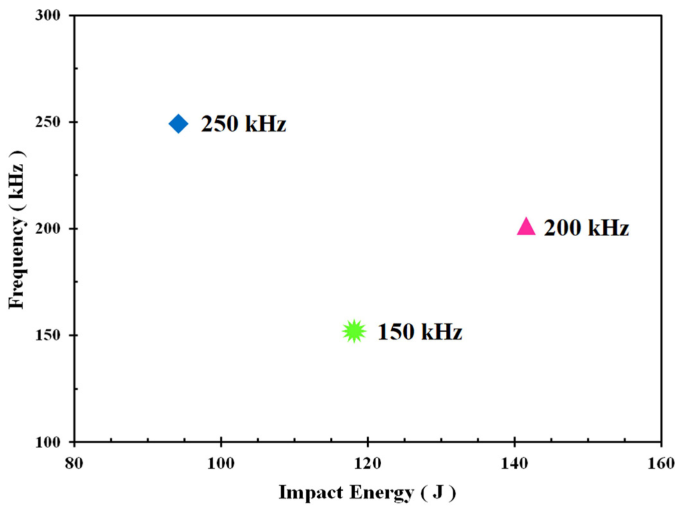
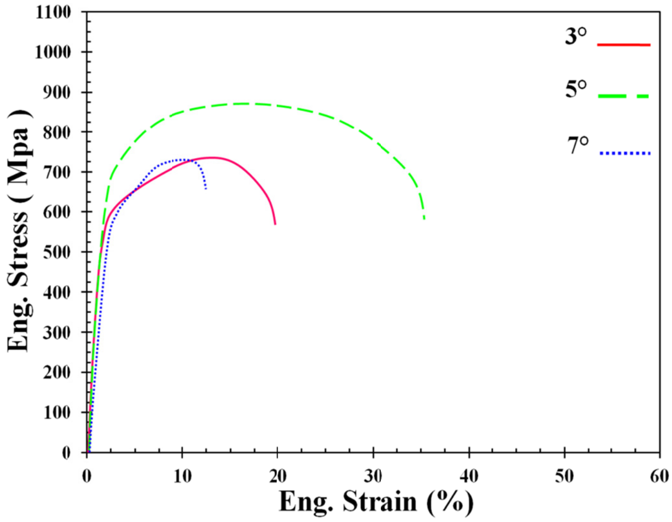


Fig. 6. Charpy impact test results for HF-ERW joints of API X52 microalloyed steel provided by different frequencies

kHz frequency had been proved in the corresponding tensile test results (Fig. 5b) of this frequency. Given the results are shown in figure 6, the amount of absorbed energy before the fracture of the HF-ERW joint prepared by 150 and 200 kHz are higher and are almost equal which this is indicative of higher toughness, flexibility followed by higher impact load bearings. The results obtained in Charpy impact test with corresponding stress-strain diagram with these frequencies have also been proved.

The results of the tensile test for HF-ERW joints of API X52 microalloyed steel prepared with Vee angles of 3, 5 and 7° are shown in Figure 7. According to the yield and ultimate tensile strengths represented in Figure 7a as well as comparative tensile test results shown in Figure7b, it is observed that by the increase or decrease of the Vee angle in the range of 3-7°, there is no clear correlation between yield and ultimate tensile strengths at different angles. The highest yield strength corresponds to the HF-ERW joint prepared by Vee angle of 5° and the lowest value corresponds to the HF-ERW joint prepared by Vee angle of 3°. The ultimate tensile strength of the HF-ERW joint of API X52 microalloyed steel prepared by Vee angle of 5° is also more than that of the other joints. The lowest ultimate tensile strength also corresponds to the joint prepared by Vee angle of 7°. The toughness which is determined by measuring the surface area of below the stress-strain curve is highest for the weld joint prepared by Vee angle of 5° and decreases for the joints prepared by Vee angles of 3° and 7° respectively. Given the slope of the linear part of the diagram and hence the elastic modulus, the stiffness of the HF-ERW joint of API X52 microalloyed steel prepared by the Vee angle of 5° is more than that of the other joints and the stiffness of the joints prepared by the Vee angles of 3 and 7° with a little difference are almost equal and lower than that of the 5° angle. The plasticity or the material ability to withstand permanent deformations without tearing in the Vee angle of 5° is more than the other joints while the plasticity of the HF-ERW joint prepared by Vee angle of 7° is lower than the other joints. The ratio of yield strength to ultimate tensile strength for the HF-ERW joint prepared by Vee angle of 5° is more than that of the other joints and this value is the lowest for the HF-ERW joint prepared by Vee angle of 7°. The ductility of the HF-ERW joint prepared by Vee angle of 5° is more than that of the other joints which itself indicative of the ability of the material to plastic deformation before fracture. While the ductility of the HF-ERW joint prepared by Vee angle of 7° is lower than that of the other joints and is more brittle. According to the surface area below the stress-strain curve in elastic region of the curve based on Hooke's law, the elasticity or the material ability to withstand against shocks for the 5° angle is slightly more than that of the other two joints and the corresponding values for the Vee angles of 3 and 7° are almost equal.

The results of Charpy impact test which have been performed for the HF-ERW joints at room temperature with Vee angles of 3, 5 and 7° are shown in Figure 8. According to the amount of absorbed energy before joint fractures which have been shown in Figure 8, the HF-ERW joint of API X52 microalloyed with Vee angles of 5° has the highest absorbed energy



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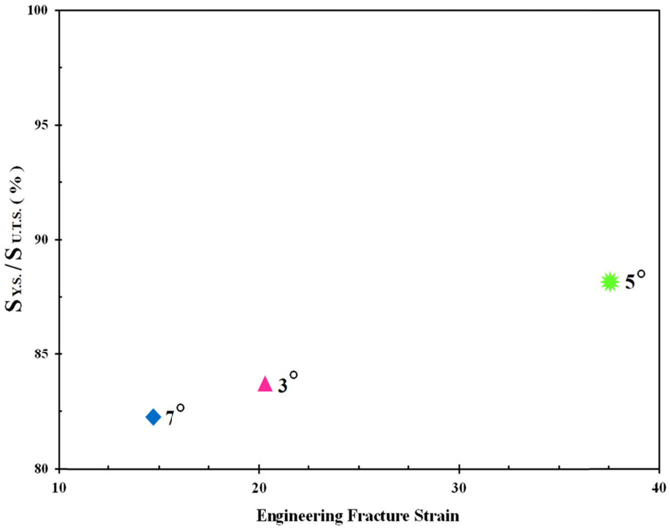

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Fig. 7. Tensile test results for HF-ERW joints of API X52 microalloyed steel prepared by different Vee angles

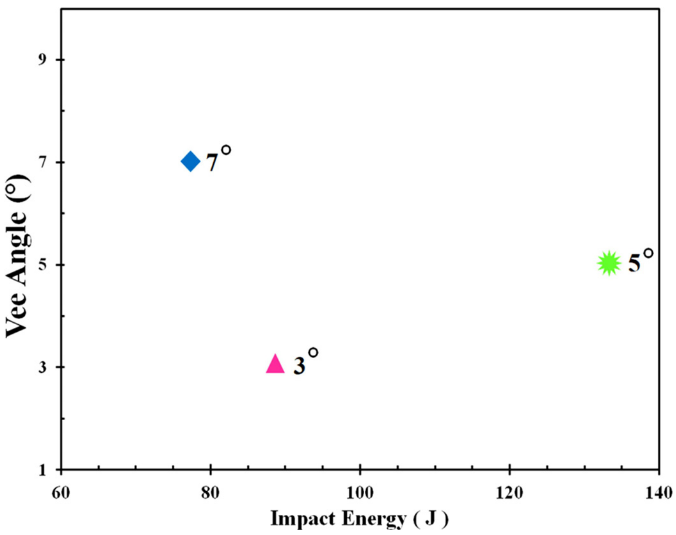

Fig. 8. Charpy impact test results for HF-ERW joints of API X52 microalloyed steel prepared with different Vee angles

before fracture that is indicative of its higher toughness and flexibility. However, the greater toughness of the HF-ERW joint prepared with Vee angle of 5° in comparison to other joints, had been proved in comparative engineering stress-strain curve of HF-ERW joint with Vee angle of 5°. According to the results shown in Figure 8, the absorbed energy before the fracture of the joints with Vee angles of 3 and 7° stay on lower positions respectively which this indicates its lower toughness, greater brittleness and higher sensitivity to impact loads. The results of Charpy impact test consists of considering the comparative tensile test results in Figure 7.

4. Conclusion

The purpose of this study was to investigate the effects of frequency, compression force and Vee angle parameters of HF-ERW process on mechanical properties of API X52 microalloyed steel weld joint. According to the obtained results it can be stated that:

a) The change of each frequency, compression force and Vee angle parameters of HF-ERW process has a significant effect on mechanical properties of HF-ERW joints of API X52 microalloyed steel.
b) There is an optimum value for each of frequency, compression force and Vee angle parameters in the HF-ERW process which by applying that value, better mechanical properties and stronger joints of API X52 microalloyed steel will be obtained.
c) Evaluation of the effect of the frequency used in the HF-ERW process of API X52 microalloyed steel showed that among 150, 200 and 250 kHz values, welding with a frequency of 150 kHz usually yields better mechanical properties while welding with frequency of 250 kHz yields the weakest properties in the HF-ERW joints of API X52 microalloyed steel.
d) According to the results of the effect of compression force it was cleared that among the compression forces of 2, 4 and 6 mark, the compression force of 4 mark yields better mechanical properties like yield strength, ultimate tensile strength, stiffness, plasticity, toughness and ductility while the compression force of 6 mark shows brittle behavior and weakest mechanical properties in comparison to other two compression forces of 2 and 4 mark.
e) Evaluation of the effect of Vee angle in HF-ERW process of API X52 microalloyed steel showed that among 3, 5 and 7° angles, the Vee angle of 5° creates better mechanical properties while the Vee angle of 7° yields brittle and weakest mechanical properties in the joints obtained from HF-ERW of API X52 microalloyed steel.
f) Macroscopic images obtained from metallography of the samples showed that the lines and angles of the metal flow directly correlate with compression of the rolls in HF-ERW station. According to the results, the optimum metal flow for the HF-ERW joint of API X52 microalloyed steel is obtained at Vee angle of 5°.

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