EFFECT OF PLASTIC DEFORMATION ON THE MICROSTRUCTURE AND PLASTICITY OF HIGH FREQUENCY ELECTRIC RESISTANCE WELDING

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Abstract: *High frequency electric resistance welding is one of the most extensively used methods for production of longitudinally welded carbon steel pipes suitable for line pipe, casing and tubing. In this pipe production process, the hot rolled steel strip goes into the continuous cold forming process and its edges are continuously joined by a combination of localized high-frequency electric resistance heating and plastic deformation. The heated edges up to the welding temperature squeezed together at the "Vee" apex by the forge pressure rolls, plastically deformed and a forge type weld is formed. The plastic deformation which is realized under the action of the squeezing rolls caused changes of the microstructure constituents in the bond line and in the heat affected zone and plays principal role on the quality of the welded joint. In this paper microstructure and plasticity of the welded joint were investigated by light microscopy and flattening testing. The obtained results shows that plastic deformation plays principal role on the microstructure and plasticity of the welded joint.*

KEYWORDS: MICROSTRUCTURE, PLASTIC DEFORMATION, HIGH FREQUENCY WELDING, PLASTICITY.

1. Introduction

High-frequency electric resistance welding (HFERW) process is one of the most extensively methods for production of high quality longitudinal seam welded carbon steel pipes suitable for line pipe, casing and tubing. In this process, hot rolled strip is gradually formed into round shape through roll-forming stands, and its edges are joined by a combination of localized high-frequency electric resistance heating and forge pressure, as schematically illustrated in Figure 1 [1,2,3]. Most of these pipes are produced according to API Standard [4] plus client supplementary requirements. Under this heat input condition and forge pressure it is possible to improve the weld joint quality and productivity of longitudinal seam welded carbon steel pipes.

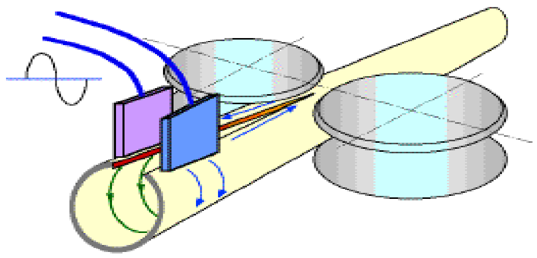


Fig.1 *Schematic illustration of HFERW*

The high-frequency current applied to the strip edges through sliding contacts, concentrated on the surface layer of the strip edges due to the "skin" and "proximity" effects, generate joule heat and the hot " Vee" converge edges are forged together in the weld squeeze rolls and a forge type weld is achieved [5]. The HF weld is a true forge weld in that no filler metal is added and, if done properly, no molten or oxidized metal is left on the bond line.

One of the most important factor in the high frequency electric resistance welding (HFERW) is plastic deformation which is present in the entire manufacturing process, from the beginning to the end of the manufacturing process. Almost in all manufacturing operations, plastic deformation directly or indirectly participates on the development of these operations at room temperatures or at elevated temperatures. Depending on the intensity of cold plastic deformation and the sizes of pipes (diameter and wall thickness), it can happen changes of mechanical properties, i.e. strength increased due to work hardening or decreased due to Bauschinger effect [6].

Figure 2 shows that during HFERW, all of the molten thin layer and metal oxides and other inclusions are squeezed out of the weld toward the outside and inside surfaces as a result of plastic deformation of the squeezing rolls.

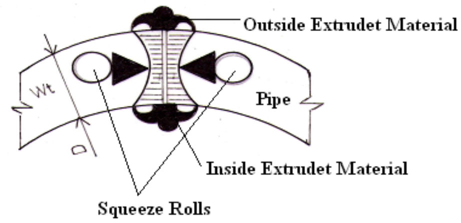


Fig.2 *Effect of plastic deformation on the HFERW*

The material extruded on the inside and outside weld surfaces, usually removed by scarfing while still hot and forms a typical HFERW weld with narrow bond line (BL) or fusion line (FL) and associated local heat affected zone (HAZ) is formed [5]. The high frequency electric resistance welded seam is subjected to post weld heat treatment in-line such as induction heating and gradually air cooling, the purpose of which is to eliminate zones of excessive hardness from the initial welding process as such zones could be susceptible to various forms of environmental cracking.

The plastic deformation which is realized under the action pressure of the squeezing rolls caused metal flows of the hot rolled coils towards the outside and inside surfaces of the bond line. This flow pattern consists of streaks and striations. The orientation of this pattern, with respect to the new surface, indicates the direction of metal flow lines (fibres), respectively flow angles during plastic deformation [6]. The flow lines, respectively flow angles ($\alpha_1, \alpha_2, \alpha_3, \alpha_4$), Figure 3, are a natural consequence of applied plastic deformation of the squeezing rolls. The orientation of the flow lines indicates the direction of the metal flow during plastic deformation. By the measurement of the flow angles ($\alpha_1, \alpha_2, \alpha_3, \alpha_4$) and especially flow angle ($\alpha_1+\alpha_3$), it is possible to determine directly whether the squeezing pressure and relevant welding temperature are correct or not.

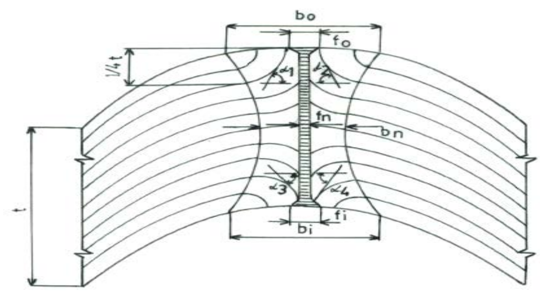


Fig.3 *Flow lines (fibres) and flow angles around bond line during plastic deformation*

Microstructural changes that takes place during the HFERW covers the properties of the welded pipes, defects associated with welding and the performance of welded pipes in service.

Forge weld area of HFERW may be divided into four zones, Figure 4, [7]: 1-bond line (BL) or fusion line (FL); 2-heat affected zone (HAZ); 3-edge of the heat affected zone and 4-base metal or parent metal (BM). These different zones are normally defined by the peak temperature experienced at certain distance from the fusion line during welding. Each zone in the weld area is characterized by a unique microstructure and hence different mechanical properties. The zones of the weld area are quite narrow and it is difficult to investigate the behavior of specific location without interference from the adjacent zones with different properties.

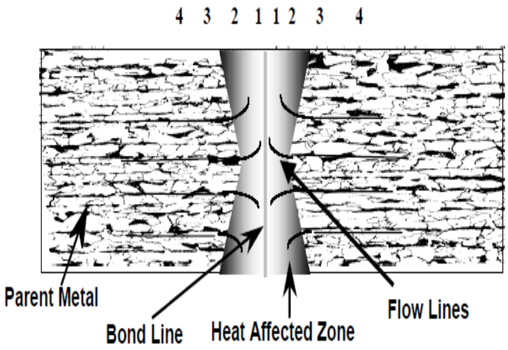


Fig.4 *Schematic illustration of constitutive parts of weld area*

2. Experimental procedure

High-frequency electric resistance welding was conducted using an L-16 in, pipe mill Newco IMK-Ferizaj, Kosova. Newco IMK-Ferizaj-Kosova produces high frequency electric resistance longitudinal seam welded steel pipes with Ø114.3-406.4mm diameter and 3.2-12.7mm wall thickness. Casing pipes Ø114.3x5.21mm are typical case in the mill production schedule, hence in this paper these pipes were investigated. Pipes Ø114.3x5.21mm were fabricated from high strength steel coils J55 according to API [4] standard, using the pipe mill equipped with a contact type high frequency electric resistance welding machine-Thermatool. The frequency of current was 400kHz.

Chemical composition and mechanical properties of the used steel are given in Table 1 and 2.

Table 1: Chemical composition of used steel coils J55

Steel coils	Chemical composition [wt-%]							
	C	Mn	Si	P	S	Al	Nb	N
API grade J55	0.141	1.113	0.229	0.014	0.008	0.047	0.017	0.0072

Table 2: *Mechanical properties of used steel coils J55*

Steel coils	Mechanical properties		
	Re	Rm	$A_{2"}$
	[MPa]		[%]
API grade J55	453	557	32.5

The influence of plastic deformation can be observed by examining the flow lines, respectively flow angles around fusion (bond) line.

The flow lines are visible in all metallographic specimens and the degree of upset is different, depending from the intensity of plastic deformation of squeeze weld rolls.

Under the action of plastic deformation, the squeezing amount (Sa), Figure 5 is defined as the difference between the circumference length measured at "Vee" angle in the front of the squeezing rolls and at pipes in the rear of squeezing rolls, which is usually 1-5mm. In this paper squeezing amount (Sa=Cb-Ca) varies from 1.7-5.9mm.

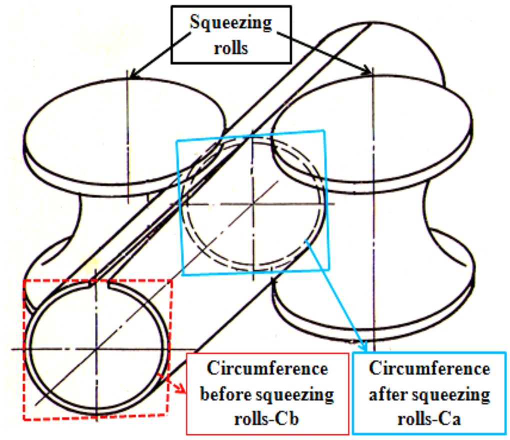


Fig.5 *Squeezing amount during HFERW*

Plasticity of welded joint was confirmed by conducting flattening testing [4].

In order to determine metallographic macro and micro analysis, the metallographic specimens were prepared by standard metallographic techniques that includes grinding, polishing and etching with suitable etchant (nital and Oberhoffer) to reveal the macro and microstructure.

For the experimental procedure, pipe rings (10-15cm long) were extracted from several pipes for use as the specimens, Figure 6.

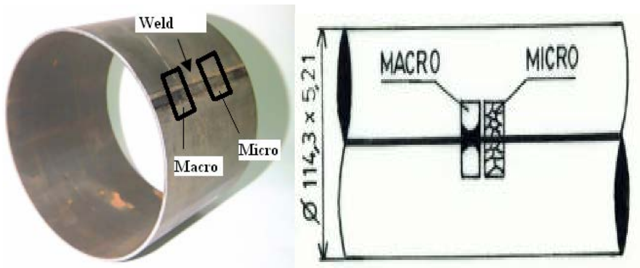


Fig.6 *Sketch illustrating the used specimens*

3. Results and discussion

Figure 7 shows the effect of plastic deformation on the flow lines and flow angles depending on the squeezing amount (Sa=1.7-5.9mm).

The flow lines and flow angles (α_1,α_2,α_3, α_4, $\alpha_1+\alpha_3$ and $\alpha_2+\alpha_4$) were measured separately for each cases of squeezing amount and obtained results were presented in the relevant illustration in Figure 7, together with the values of the squeezing amount at the bottom of the right side of the illustrations. From the presented illustrations in Figure 7 it is clear that increasing of plastic deformation, respectively increasing of the squeezing amount, increased the orientation of flow lines towards the outside and inside of wall thickness. Flow angles also increased with the increasing of plastic deformation and should be noted that for small angles ($\alpha_1+\alpha_3<50^o$), "Y" flow, Figure 8a, in the outside weld joint were occurred cracks. Cracks or breaks were occurred also for larger angles ($\alpha_1+\alpha_3>70^o$), "T" flow, figure 8b. Optimal values for ($\alpha_1+\alpha_3$) were 60 ± 10^o. Plasticity of the welded joint, in this case measured by the flattening testing is good only for optimal values of ($\alpha_1+\alpha_3=60\pm10\,^{o}$).

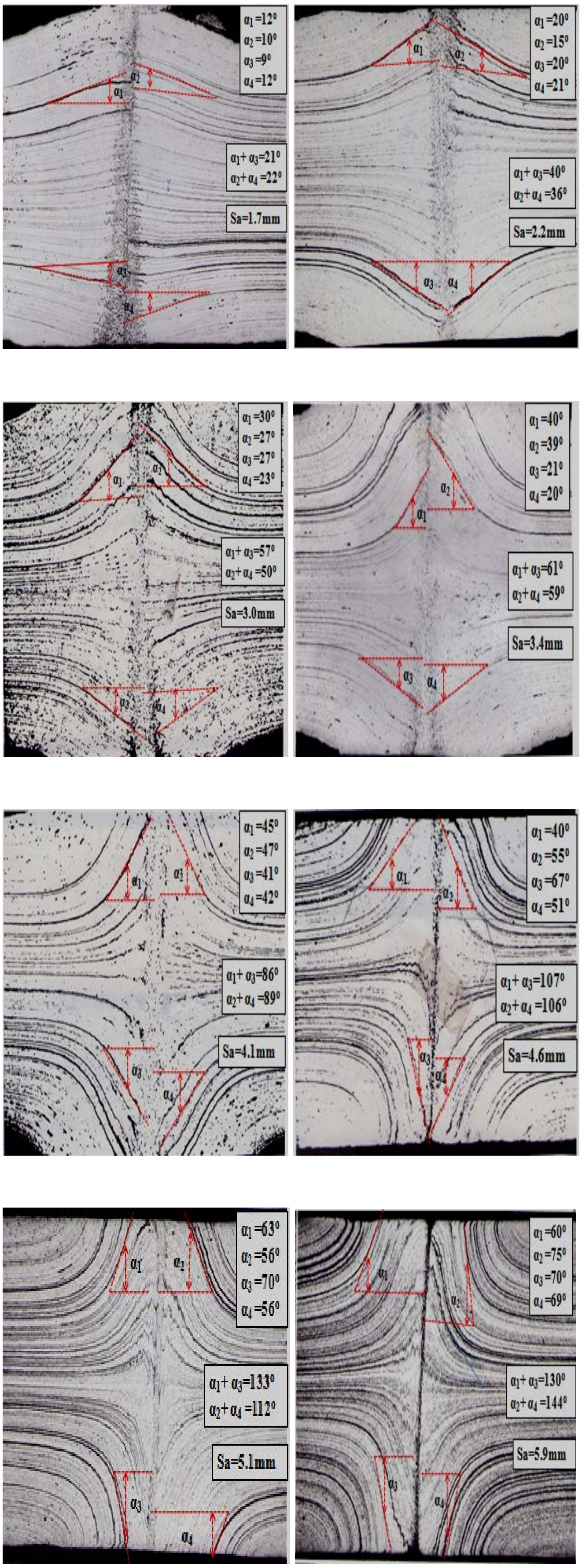


Fig.7 *Flow lines and flow angles depending on the squeezing amount*

(a) (b)

Fig.8 *Metal flow during HFERW :a-"Y" flow, b-"T" flow*

The test specimens for flattening testing were flattened in a hydraulic press, DIHNAFORIN PS 2043, at room temperature between to parallel plates with the weld line located 90^o and 0^o to the applied force. The specimens (rings) were flattened to a specified height (h=2/3D=76.2mm) according to API, Figure 9.

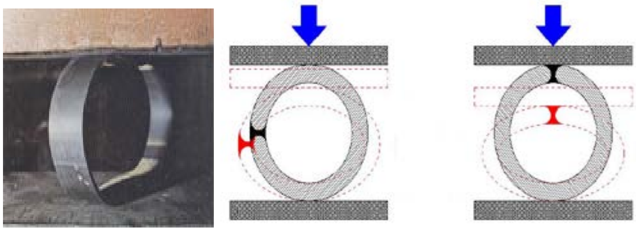


Fig.9 *Schematic illustration of flattening test*

During flattening testing, in some rings were occurred cracks or breaks in the weld area in the position (90^o and 0^o) before specified height (h=76.2mm) according to API. Figure 10 shows the results of the flattening testing of all tested specimens.

Correlation between squeezing amount (Sa) and flow angle ($\alpha_1+\alpha_3$), Figure 11 (red rectangle) shows that optimal values of squeezing amount (Sa) are in the range 2.5-3.5mm for manufacturing of HFERW pipes Ø114.3x5.21mm from high strength steel coils J55 according to API in line L-16, at the pipe mill Newco IMK-Ferizaj, Kosova.

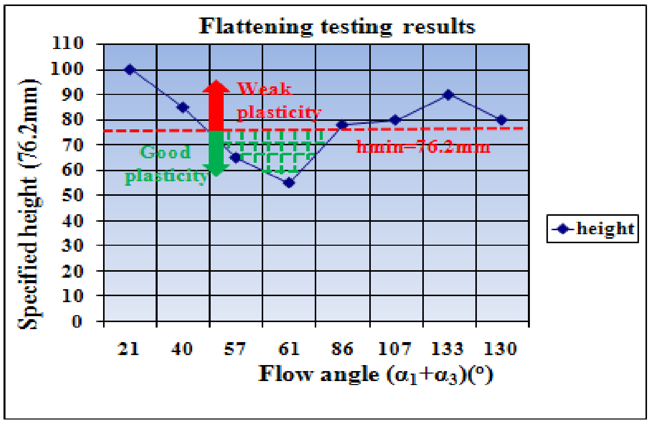


Fig.10 *Plasticity of the welded joint*

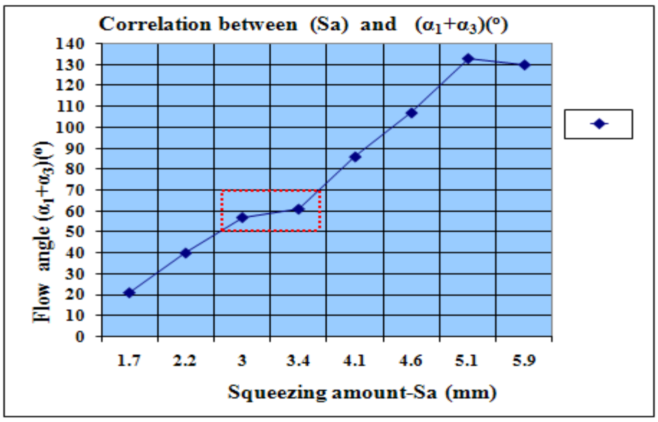
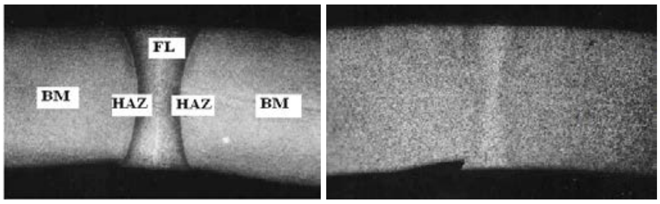


Fig.11 *Correlation between Squeezing amount (Sa) and flow angle* ($\alpha_1+\alpha_3$)

The shape, width and uniformity of the weld area presented in Figure 12.



Nital 10X Nital 10X

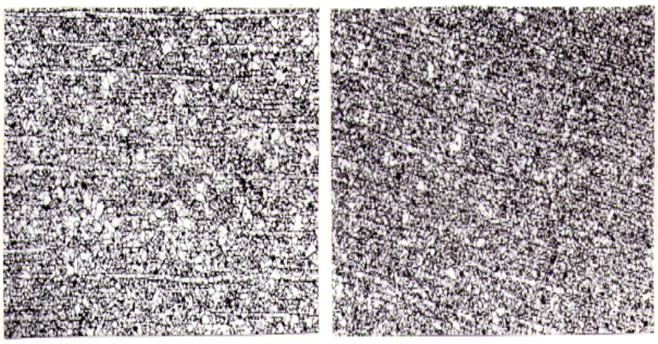
(a) (b)

Fig.12 *Macrostructure of a cross-section weld* area

Macrostructure in Figure 12a shows a cross section of a typical high frequency electric resistance weld of the longitudinal steel pipes in the as welded condition prior to heat treatment. The width of the weld is uniform from top to bottom, indicating that the heat energy input was uniform. The fusion line (FL) or bond line (BL) is vertical to the wall thickness and is usually light colored because it is very low in carbon. Due to high temperature, the carbon amount at the fusion line oxidizes, leaving the iron without carbon to darken it. This part of the weld area called decarbonisation layer or light area [8].

Adjacent to the fusion line (FL) is the heat affected zone (HAZ) where the materials is affected by the heat of the welding process. The heat affected zone (HAZ) is shaped like an hourglass as a result of the heat generated by the high frequency current. Macrostructure in Figure 11b indicates that after normalizing heat treatment, the forge weld areas is indiscernible from the rest of the base metal (BM).

Microstructure of the base metal (BM) and heat affected zone (HAZ) are shown by the photomicrographs in Figure 13. The photomicrograph on the left shows the microstructure of the base metal (BM), whereas the photomicrograph on the right shows the microstructure of the heat affected zone (HAZ) after normalizing heat treatment. The base metal (BM) has fine grained ferrite-pearlite microstructure with some bands in the entire the wall thickness. The heat affected zone (HAZ) has also fine grained ferrite-pearlite microstructure as a result of the proper normalizing heat treatment.



Nital BM 100X Nital HAZ 100X

Fig.13 *Microstructure of a cross-section weld area*

Flow lines and flow angles, Figure 13 illustrates the influence of the forge pressure in the weld area.

The flow lines are visible in all metallographic specimens and the degree of upset is different, depending from the intensity of plastic deformation of squeeze weld rolls. Figure 13 shows flow lines, respectively flow angles from some characteristic metallographic specimens of HFERW pipes Ø 114.3x5.21mm.

4. Conclusion

Following conclusions can be drawn from the present study:

Plastic deformation during high frequency electric resistance welding (HFERW) plays principal role on the microstructural changes of the welded joint. These microstructural changes affects the mechanical properties of the welded joint, particularly the strength and plasticity.

Cold plastic deformation is present in the entire manufacturing process of high frequency electric resistance welding (HFERW), from the beginning to the end of the manufacturing process, almost in all manufacturing operations, where directly or indirectly participates on the development of these operations at room temperatures and affects the mechanical properties of the base metal (BM) and welded joint.

Hot plastic deformation is present in the welding point, where directly affects the microstructure evolution of high frequency electric resistance welding (HFERW) and the consequent changes in the relationship between the microstructure of the welded joint and mechanical properties, strength and plasticity.

5. References

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