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THE EFFECT OF WELDING CONDITIONS ON MECHANICAL PROPERTIES OF SUPERDUPLEX STAINLESS STEEL WELDED JOINTS

ABSTRACT

The tests results of superduplex stainless steel welded joints made with a different heat input, using automatic submerged arc welding (SAW) and semi-automatic flux-cored arc welding (FCAW) have been presented. Metallographic examinations, the measurements of the ferrite content, the width of the heat affected zone (HAZ) and the hardness of the welds in characteristic areas have been performed. Significant differences in the amount of ferrite in the weld metal and in the heat affected zone microstructure of joints were found.

Key words: *superduplex steel, welding, SAW process, FCAW process, microstructure*

INTRODUCTION

Duplex steels are chromium - nickel stainless steels with a ferritic-austenitic dual phase microstructure, characterized by particularly advantageous mechanical and corrosion properties [1-4,8,11,14,16,22]. Depending on the technical and economic circumstances, for the welding of duplex steels the following methods may be successfully applied: welding with coated electrodes (MMA), submerged arc welding (SAW), tungsten inert arc welding (TIG), metal active gas welding (MAG), flux-cored welding (FCAW) and also plasma arc (PAW), electron beam (EBW) and laser beam (LBW) welding [1,2,5,14,20]. The comparison of the efficiency of duplex steel welding using various processes is plotted in Fig.1.

Duplex stainless steels contain a fine microstructure of ferrite and austenite in roughly equal proportions. Arc welding operation gives more or less unwanted heat treatment of the area close to the weld. The high-temperature area of heat affected zone (HAZ) is brought to a temperature, where the material is almost fully ferritic. Upon cooling, a reformation of austenite starts in the grain boundaries and then continues in the ferrite grains. The extent of ferrite to austenite transformation depends on the steel composition and welding conditions. Higher nickel and nitrogen contents and slower cooling promote this transformation. When cooling is rapid high ferrite content can remains in the HAZ.

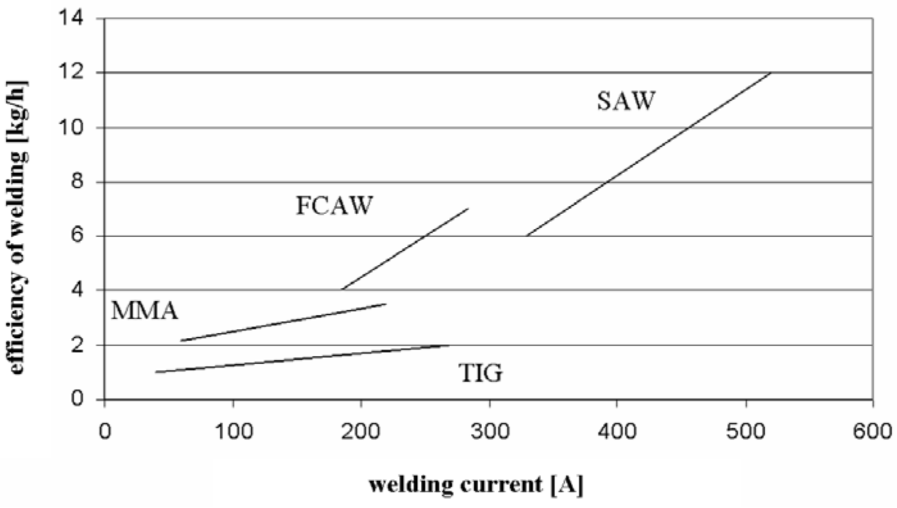

Fig. 1. Comparison of the efficiency of duplex steel welding using different methods [20]

Moreover, chromium nitrides can form within microstructure, owing to the fact that at high temperatures the solubility of nitrogen in the ferrite increases and during rapid cooling, when the solubility drops, chromium nitrides can precipitate. These particles act as initiation sites of corrosion in service.

If the heat input is too high, precipitation of intermetallic phases can occur and phase transformation ferrite to austenite can be suppressed [8]. This can significantly reduce mechanical properties and corrosion resistance of the steel. To maintain acceptable properties of the joints the ferrite content in weld metal and heat affected zone should be in the range 25-70% .

Welding of thick plates often require using more productive process like submerged arc welding. Application of this method for duplex stainless steels welding is sometimes considered to be improper, because it provides high heat input and can therefore generate too low ferrite content in the weld metal and create favorable conditions for the precipitation of intermetallic phases. Other opinions [9] say that thick plates of duplex steels can be successfully welded with the use of higher heat inputs. So far there is not clearly established the maximum heat input limit that give joints with acceptable mechanical and corrosion properties [14,12].

Flux corded arc welding is one of the latest commercial developments for the duplex stainless steels. The flux inside the wire provides a slag that protects the weld from the atmosphere, supplementing the gas shielding provided through the torch to protect the HAZ. It is suitable for out-of-position welding and for a wide range of metal thicknesses. The advantages of this method include: good mechanical properties of joints, ease of use, low cost of the shielding gas, simple cleaning of welds, is economical method because it provides high deposition rates [1,3,18,20].

Because the flux-shielded welding methods tend to produce welds of somewhat reduced toughness, resulting from the increased oxygen content in the weld metal, the FCAW filler metal is overalloyed with nickel so that the weld metal is more austenitic than the nearly balanced structure of the base metal. The shielding gases most typically used for FCAW are 75% argon - 25% carbon dioxide and 100% carbon dioxide for flat and vertical welding positions respectively.

Difficulties encountered in welding of duplex steels are: precipitates formation [13,17], cold crack formation [7,10,21] and, in a lesser extent, the formation of hot cracks [14]. This is directly related to the increase of the content of ferrite in the weld metal, as a result of the influence of the thermal welding cycle. A direct consequence of this phenomenon is a deterioration of mechanical and corrosion properties of the welded joint [6,8,22].

A crucial factor for the weldability of duplex steels is the cooling rate. The maximum values of the cooling rate are determined by the time required for the transformation of ferrite to austenite, while the minimum values are determined by the time preventing the formation of intermetallic compounds.

Regardless of the method of welding, the accepted practice is to select the consumable containing a greater amount of elements stabilising austenite - especially Ni greater about 3-4% than the base material [2,4,22]. Preferred solution is also to use as consumable alloy containing at least 60% nickel [3,16].

Another consideration is the selection of the welding heat input. It is recommended to input into the welding joint as small energy as possible [2,4]. In case of duplex steel the selection of welding heat input cannot be guided only by the literature data, which is often divergent. Each case should be considered individually and it is good practice to develop a separate welding technology [2]. Preheating is not usually recommended unless the stresses and the high ferrite and diffusible hydrogen content could lead to cracks. In that case heating to 150°C before welding may be performed [22]. Interpass temperature should not exceed 200°C however the temperature of the preheating and interpass temperature depends on the chemical composition of the steel and the thickness of the welded materials [19].

Guidelines for welding superduplex steels are similar to those for less alloyed duplex stainless steels, but it can be more difficult to obtain welding joints with expected properties. Greater susceptibility to formation of intermetallic compounds remains a concern for welded constructions. To prevent it and achieve the optimal properties of the weld it is recommended that interpass temperature should not exceed 100°C [4,5,10,16,22].

The aim of this work was to perform butt welded joints of superduplex steel with different values of heat input using FCAW and SAW processes and determine the effect of welding parameters on the structure and properties of joints.

EXPERIMENTAL

The plate 13 mm in thickness made of UR52N+ (1.4507, X2CrNiMoCuN25-6-3) superduplex stainless steel was used.

Duplex stainless steel filler metals with increased nickel content relative to the base material were selected. SAW joint was perform with the use of 2.4 mm solid wire of LNS Zeron 100X (ASME AWS A5.9/A5.9M: ER 2594) and basic non-alloyed agglomerated flux (EN 760: A AF2 63 AC H5) were used. For FCAW joints rutile flux-cored wire PREMIARC DW-25-94 (ASME AWS A5.22: E2594T1-1/4) of 1.2 mm diameter and shielding gas mixture of $Ar+CO_2$ were used.

Chemical compositions of the steel plate and consumables are presented in Table 1. Mechanical properties of UR 52N steel are presented in Table 2.

Table 1. *Chemical compositions of steel and consumables used for welding trials, wt. %*

	C	Si	Mn	Cr	Ni	Mo	Cu	N
UR52N+ acc. to the standard	0.03	Max 0.7	0.8-1.2	25.0	7.0	3.0	1.5	0.25
UR52N+ according to the control analysis	0.03	0.26	0.86	25.1	5.8	3.5	1.4	-
Zeron 100X	0.02	0.3	0.7	25.0	9.3	3.7	0.6	0.23
DW-25-94	0.03	0.5	1.18	25.7	9.6	3.8	<0.1	0.24

Table 2. *Mechanical properties of UR 52N+ steel (at 20°C)*

$YP_{min.}$ [MPa]	TS_{min} [MPa]	E_{min} [%]
550	770	25

Two butt joints were performed using 2Y for SAW and Y for FCAW edge preparation (Fig. 2a,b). SAW joint was filled with two beads and FCAW joint with five beads with the use of heat input as indicated in Table 3. Heat input was calculated as:

$$Q = \frac{U \times I}{v_s} \times \eta$$

where η - coefficient of efficiency of the process is: $\eta_{FCAW} = 0.8$; $\eta_{SAW} = 1.0$

The interpass temperature was in all cases limited to 100°C maximum. Welded plates were X-rayed and crack tested, and found to be satisfactory with B quality class according to PN-EN 25817.

Table 3. *Welding parameters of butt joints*

Run	Filler metal ∅ [mm]	Welding current I [A]	Arc voltage U [V]	Welding polarity	Travel speed v_s [mm/s]	Heat input Q [kJ/mm]
FCAW						
1	1.2	150	23	DC (+)	3.5	0.79
2	1.2	180	24	DC (+)	3.0	1.15
3	1.2	180	24	DC (+)	2.5	1.38
4	1.2	180	24	DC (+)	5.0	0.69
5	1.2	180	24	DC (+)	5.0	0.69
SAW						
1	2.4	440	29	DC (+)	6.5	1.96
2	2.4	500	30	DC (+)	6.5	2.31

RESULTS AND DISCUSSION

Metallographic examinations

Cross sections of welds were prepared using standard methods. Microstructures were obtained by light optical microscopy using Beraha reagent as an etchant. The macrographs of welded joints are presented in Fig. 2c,d. Macroscopic observations showed correct cross-sectional geometry and proper structures of the welded joints. Total dilution was estimated as 55% for 2Y joint and 38% for Y joint. The amount of dilution can significantly influence the mechanical properties of welded joints through alternations in chemical composition of weld metal and changes in microstructure.

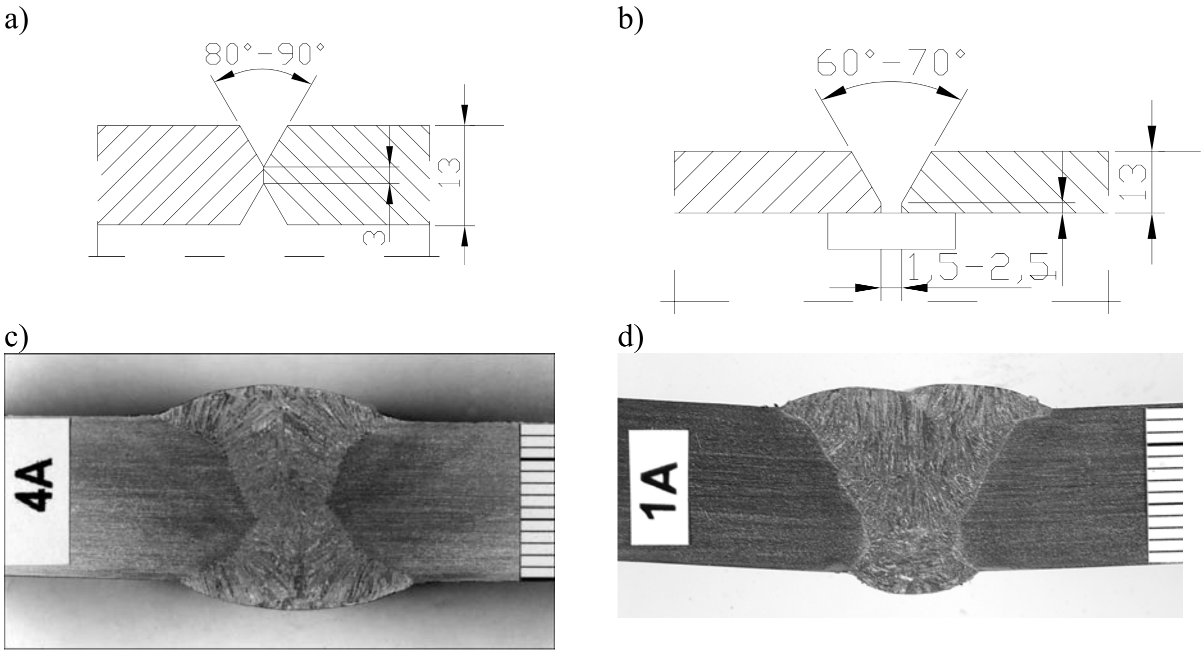

Fig. 2. Edge preparation for butt welded joints; a) 2Y, b) Y, c) cross section of SAW welded joint d) cross section of FCAW welded joint

In the metallographic examinations three aspects were considered. Firstly the general microstructures of welds were assessed in particular: the presence of intermetallic precipitates, amount of secondary austenite and ferrite to austenite ratio. Secondly, the width and structure of heat affected zones, and in the end, the solidification pattern of the root beds was examined with special attention to any solidification cracking.

Structures of weld metal in both joints were similar. During solidification of duplex weld metal almost completely ferrite structure is formed. Further cooling initiates the formation of the austenite phase nucleating at the ferrite grain boundaries. In examined welds a dendritic microstructure developed in fast cooling conditions (Fig. 3). More globular structures were observed in areas exposed for lower cooling rates and with a less pronounced heat flow direction. In the root of the welds secondary austenite occurs, which is formed from ferrite as a result of the influence of the thermal cycle during realization of subsequent weld beads (Fig. 3b). No intermetallic phases were recorded in weld metal of both joints.

Heat affected zone microstructure could be critical for welded joint properties. For examined welds the very narrow zones of about 100-400 μm were observed (Fig. 3c). The ferrite content in that zone was significantly higher in comparison to bulk weld metal.

Microstructure consists of lamellar austenite precipitates that surround equiaxial ferrite grains. Part of the austenite precipitates formed within the ferrite grains.

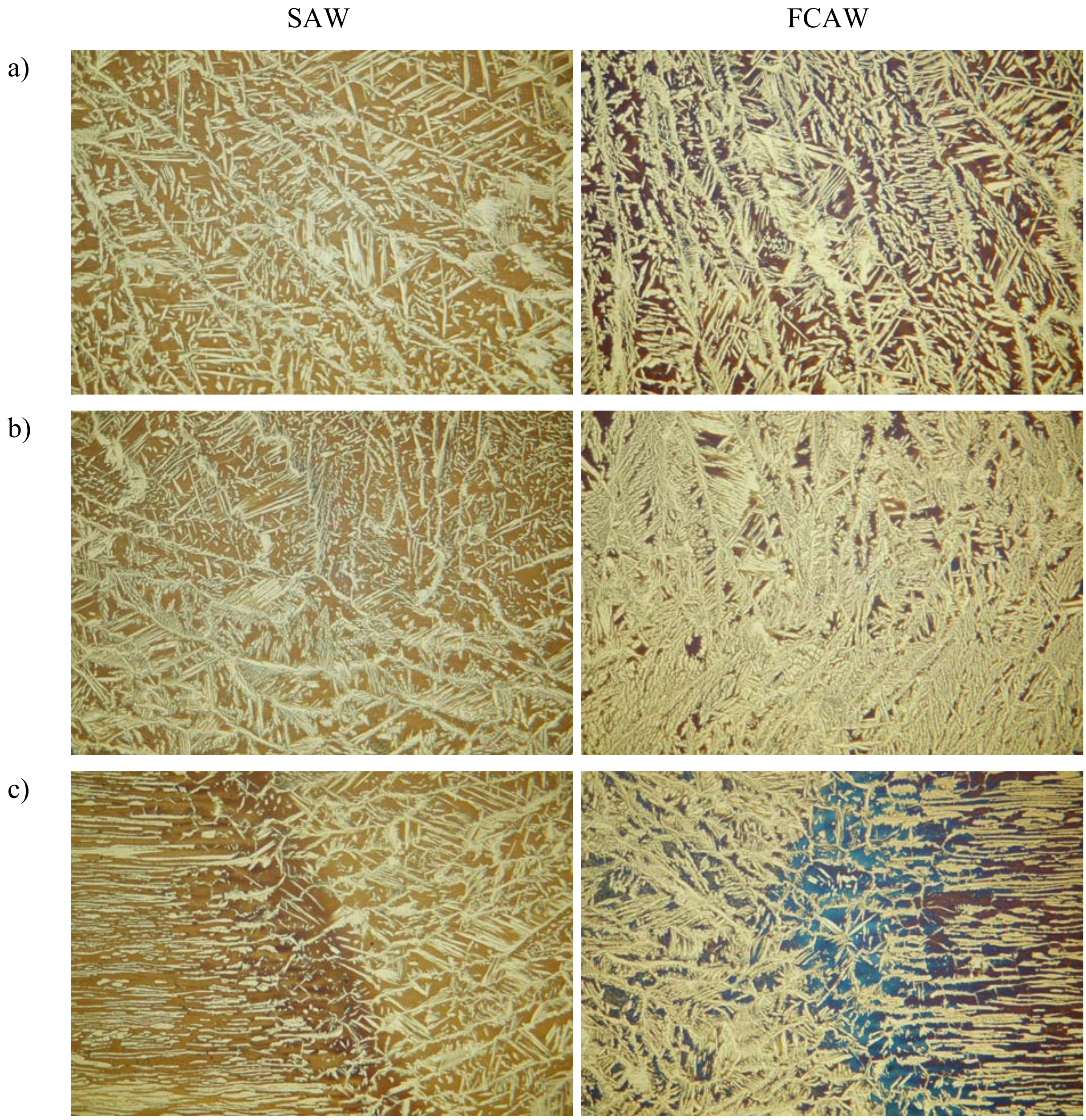

Fig. 3. Microstructure of SAW and FCAW welded joints of superduplex stainless steel. a) weld metal – face line of the weld, b) weld metal – root line of the weld, c) HAZ of the weld. Magn. 100x

The ferrite content in weld microstructures has been determined by metallographic examination using quantitative metallographic analysis. The structure was analysed at five points on the cross section of the welds in order from face of the weld to the root. The results are shown in Table 4.

The average ferrite content in the base material microstructure was 55.2%. Heat affected zones exhibit rather high ferrite content. Average ferrite content in SAW joint was 70,4% and 67,0% in FCAW joint. Big difference in heat input generated during FCAW and SAW welding methods had no great influence on ferrite amount in HAZ. Ferrite content of 70% in the HAZ should be regarded as a high, but due to a very low dimensions (width) of this zone the influence on the mechanical properties of the whole joint can not be significant.

Table 4. *Ferrite content in characteristic areas of welded joints*

	BASE METAL [%]	SAW welded joint		FCAW welded joint	
		HAZ [%]	WELD [%]	HAZ [%]	WELD [%]
Face	55.2	70.32	66.18	66.39	54.03
↓	56.3	67.02	61.10	64.47	53.67
	50.8	68.21	63.82	67.46	48.86
	59.8	72.59	59.08	67.87	45.95
Root	54.1	73.61	62.16	68.67	43.77

Ferrite content was not uniform in the weld metal of tested joints. Decreasing amount of ferrite in the direction from the face to the root of the welds was found. This phenomena is connected with the generation of secondary austenite during re-heating. Smaller amount of ferrite was found in the FCAW weld metal (Table 4).

Hot cracks were not observed in weld metal deposits. Liquation cracking is in most cases associated with a combination of high restraint and weld structure. Weld metals solidifying partly as ferrite shows high resistance to hot cracks formation.

The measurement of the width of HAZ was performed in the direction perpendicular to the fusion line. Three measurements in five lines on both sides of the welds were performed. For the FCAW joint HAZ width is between 0.075 mm and 0.279 mm while the width of HAZ for SAW joint is slightly wider and ranges between 0.104 mm and 0.393 mm (Table 5).

Table 5. *The results of measurements of HAZ width of welded joints*

Line number	Width of HAZ [mm]			Average width of HAZ [mm]
FCAW				
1	0.178	0.115	0.170	0.154
2	0.259	0.255	0.195	0.236
3	0.146	0.144	0.112	0.134
4	0.205	0.279	0.175	0.220
5	0.086	0.075	0.089	0.083
SAW				
1	0.153	0.172	0.233	0.186
2	0.300	0.230	0.151	0.227
3	0.316	0.286	0.277	0.293
4	0.393	0.298	0.357	0.349
5	0.104	0.180	0.174	0.153

Hardness measurements (HV5) were performed in three lines - 2mm from the face of weld, in the middle of the plate thickness and 2mm from the root of the weld. In each zone of the welded joint at least three impressions were made. The results are shown as graphs in Fig. 4 and Fig. 5.

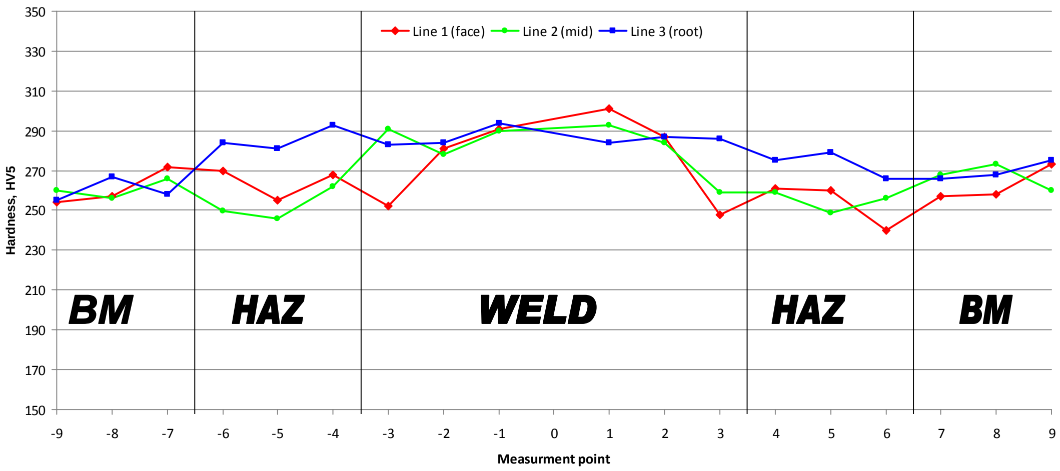

Fig. 4. Hardness distribution across FCAW welded joint

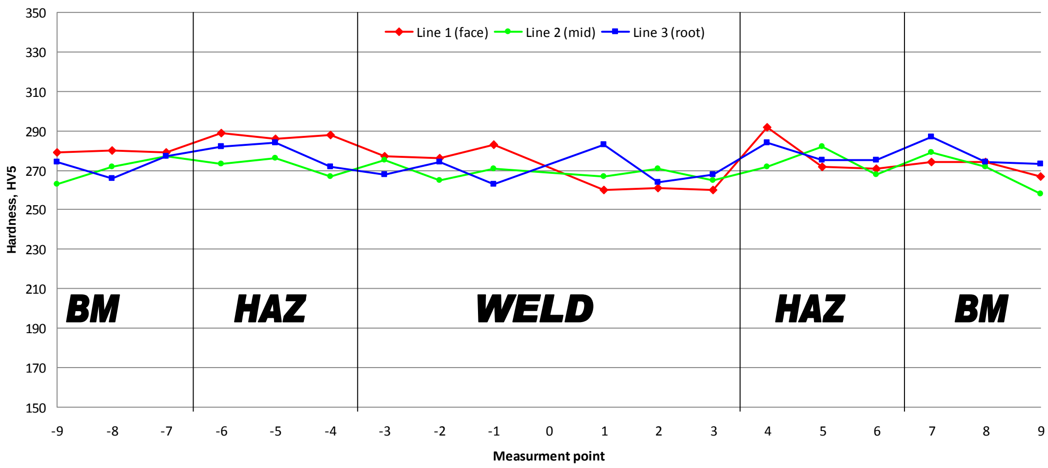

Fig. 5. Hardness distribution across SAW welded joint

The increased hardness was recorded in weld metal of FCAW joint. This is probably associated with a greater amount of secondary austenite in the microstructure. There was no increase in HAZ hardness in neither of welded joints. This may be due to difficulty in precisely measuring of this narrow zone. Hardness distribution across SAW joint is rather homogeneous and hardness results are similar for all weld areas. No significant differences between the hardness of the weld root and the face of weld were observed.

CONCLUSIONS

1. The butt welding technology of superduplex stainless steel was developed with the use of FCAW and SAW methods with different values of heat input, 0.98 kJ/mm and 2.13 kJ/mm respectively.
2. Heat affected zones in both welded joints were extremely narrow. Greater heat input in SAW method resulted in only a slight increase in the thickness of this zone.
3. The ferrite content in the FCAW weld metal is less than in SAW weld metal. It is due to secondary austenite formation during re-heating from subsequent runs.

4. Ferrite content in the HAZ of both joints reaches to about 70%. Big difference in heat input generated during FCAW and SAW welding methods had no a great influence on ferrite amount in HAZ.
5. Neither intermetallic phases nor hot cracks were observed in weld metal of both joints.
6. There were no significant differences in hardness of SAW and FCAW welded joints.

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