International Journal of Technical Research and Applications e-ISSN: 2320-8163,
www.ijtra.com Volume 3, Issue 3 (May-June 2015), PP. 280-285

EFFECT OF WELDING PROCESS AND POST WELD HEAT TREATMENTS ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF AISI 431 MARTENSITIC STAINLESS STEEL

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***Abstract* - Evaluation of mechanical properties and metallurgical changes, which occur in AISI 431 martensitic stainless steel as a result of the welding processes consisting of electron beam welding (fusion welding) and friction welding (solid state welding) is carried out. In addition, the influence of post weld heat treatments on microstructure and mechanical properties has also been investigated. Weld center in EB welding exhibited a cast dendritic structure with ferrite network in a matrix of un-tempered martensite. In friction welding, the weld center exhibited thermo-mechanical effected structure consists of fine intragranular acicular martensite in equiaxed prior austenite grains. In both the welding processes, post weld tempering treatment resulted in coarsening of the martensite which increases with increase in tempering temperature. In the as-weld condition, both EB and Friction welds exhibited high strength and hardness and poor impact toughness. Increase in impact toughness and decrease in strength and hardness is observed with an increase in tempering temperature. However, high strength and hardness observed in friction welds as compared to EB welds, which may be due to fine grain size of the welds due to thermo-mechanical work the weld undergoes during welding. Low impact toughness is observed in friction welds as compared to EB welds, due to presence of fine grained martensite.**

***Key words:* Martensitic stainless steel; Electron beam welding; Friction welding; Tempering temperature; Microstructure; Mechanical properties.**

I. INTRODUCTION

Martensitic stainless steels are widely used when the application requires good tensile strength, creep and fatigue strength in combination with good corrosion resistance. They have been primarily used as structural material in various industry sectors, various parts in steam turbines, gas turbines and petro chemical equipment.

Conventional arc welding characteristics of martensitic stainless steels have been examined by several researchers [1-4]. Though these processes can be employed for welding of martensitic stainless steels, special precautions are necessary to avoid hydrogen cracking and the propensity of forming fine and brittle martensite even in normal air cooling conditions [5].

These steels can be used as structural material and hence focus was thrown to use the material in the as welded condition by reducing the carbon content [1,6]. However, at low carbon levels, the steel becomes fully ferritic which exhibits extensive grain growth in the weld and heat affected zones of fusion welds. Further, the toughness and ductility of these steels welded by conventional welding processes are low and they do not effectively respond to post weld heat treatments due to high ferrite content.

Research is focused to improve toughness in these steels by controlling heat input, employing multi-pass deposition to encourage additional austenite formation and tempering of martensite in the reheated areas [5,7]. Both preheat and post weld heat treatments (PWHT) can be employed to reduce the hardness of these martensitic regions thereby ensuring the structural integrity of the weld region during service. Optimum combination of high strength and high toughness in the steel can only be achieved under carefully controlled heat treatment conditions.

Electron beam welding process has a lower heat input, and hence a greater control is expected over grain coarsening and distortion. Solid state welding process like friction welding due to its slow cooling rate can offer a solution to the problem of low toughness encountered in conventional fusion welding. Hence this study is focused on the metallurgical changes, which occur in AISI 431 martensitic stainless steel as a result of the welding processes consisting of electron beam welding (fusion welding) and friction welding (solid state welding). In addition, the influence of post weld heat treatments on microstructure and mechanical properties has also been investigated.

II. EXPERIMENTAL PROCEDURE

A. Material

The parent material employed in this study is martensitic stainless steel type AISI 431 whose chemical composition is 0.17C-0.6Si-1.0Mn-17.0Cr-2.0Ni-0.03S-0.04P(wt.%). The material was received in the form of 20 mm diameter rods in fully annealed condition.

For preparing welds by electron beam welding, as received rods were forged at 1200^0C into 5 mm thick plates. The forged plates were annealed at 670^0C for 1 hour and air cooled prior to welding.

B. Welding Processes

In the present study, electron beam welding (high power density fusion welding) and continuous drive friction welding (solid state welding) processes are employed.

C. Electron Beam Welding

Autogenous bead on plate full penetration electron beam welds were made in 5mm thick plates of AISI 431 martensitic stainless steel. The welding parameters employed for EB welding are given in Table 1. Initial low power welding has been adopted to preheat the material.

Machine settings/ parameters	
Gun to work distance (mm)	283
Accelerating Voltage (kV)	55
Beam Current (mA)	35 mA (first pass for pre heating) ; 65mA (for penetration)
Focus	Slightly above the surface
Speed (m min^{-1})	1.0
Vacuum level (mbar)	10 $^{-4}$ mbar and less
Heat Input (J min^{-1})	214.5

Table 1. Welding parameters for EB welding

D. Friction Welding

Welding was carried out on a continuous drive rotary friction welding machine with continuous variable speed capability up to 2400 rpm. The maximum axial force of the machine was150 KN.

Prior to welding, the mating faces of all the specimens were machined perpendicular to the rotational axis and the samples were degreased with acetone and dried. The weld parameters employed to weld 20 mm diameter rods are: Friction force – 30 kN, Upset force – 50 kN, Rotational speed – 1350 rpm and burn - off –5 mm.

E. Post weld heat treatment (PWHT)

Welded samples were austenitized at 950 ^{0}C for one hour followed by air cooling. The air cooled samples were subsequently subjected to various tempering treatments at 400^{0}C (HT/400), 600^{0}C (HT/600) and double tempering at 670^{0}C + 600^{0}C (HT/DT) for two hours followed by air cooling. For comparison purpose parent metal was also subjected to similar heat treatment.

F. Metallography

The welds were subjected to standard metallographic sample preparation to examine the microstructure under LEITZ optical microscope and stereomicroscope. To observe the microstructure in the etched condition gleseresia (glycerol–15ml, HCl-10ml, HNO_3-5ml, and acetic acid-5 ml) was employed for friction welds and Kallings reagent (cupric chloride-1.5g, HCl-33ml, ethanol-33ml and distilled water-33ml) was employed for EB welds. After different mechanical tests the fractured surfaces were examined under scanning electron microscope (SEM).

G. X-Ray Diffraction

The phases present in the parent metal and welds in various conditions were identified by X-ray diffraction using Philips PW 3020 machine with Cu Kα radiation. Retained austenite (γ_r) content in the welds and parent metal in various heat treated conditions was estimated using Stress Tech 3000 X-ray system using Cr Kα radiation. The volume fraction of austenite was estimated from measurements of the integrated intensities of martensite, austenite and delta ferrite peaks assuming they are the only phases present.

H. Mechanical testing

Tensile strength, hardness and Charpy 'V'-notch impact properties of welds were evaluated. ASTM Standard specimen configurations were employed for tensile and impact testing. Hardness measurements included survey of hardness across the joint interface at the centre.

III. RESULTS AND DISCUSSION

A. Visual examination

Visual examinations of welded joints revealed that, the welds are of high quality and were free from cracks, incomplete bonding and other micro-structural defects.

B. Microstructure and XRD analysis

The transverse sectional view of the welds in the as-welded condition along with micro structural details in the centre and fusion boundary region of EB welds are presented in Fig. 1 and in the centre, mid-radius and periphery regions of friction welds are presented in Fig. 2. EB welds exhibited cast dendritic structure with ferrite network in a matrix of un-tempered martensite (Fig. 3). The as-welded microstructure contains about 10% dark regions within a martensitic matrix. Friction welds in the as-welded condition exhibited thermo mechanical effected structure which consists acicular martensite in equiaxed prior austenite grains at the periphery region, while the central region contains fine intragranular martensite.

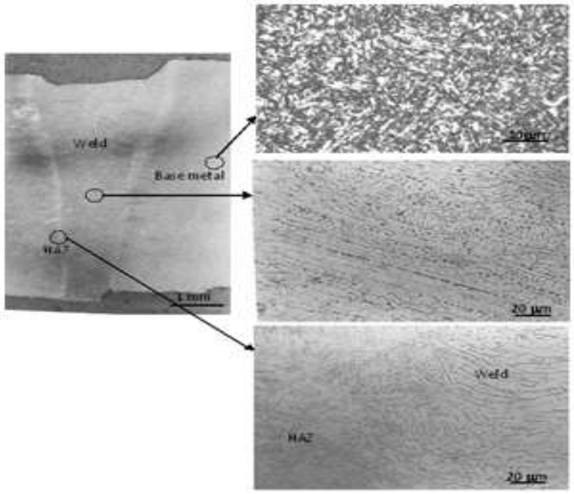

Fig. 1 Electron beam weld and its cross sectional view (as-welded condition)

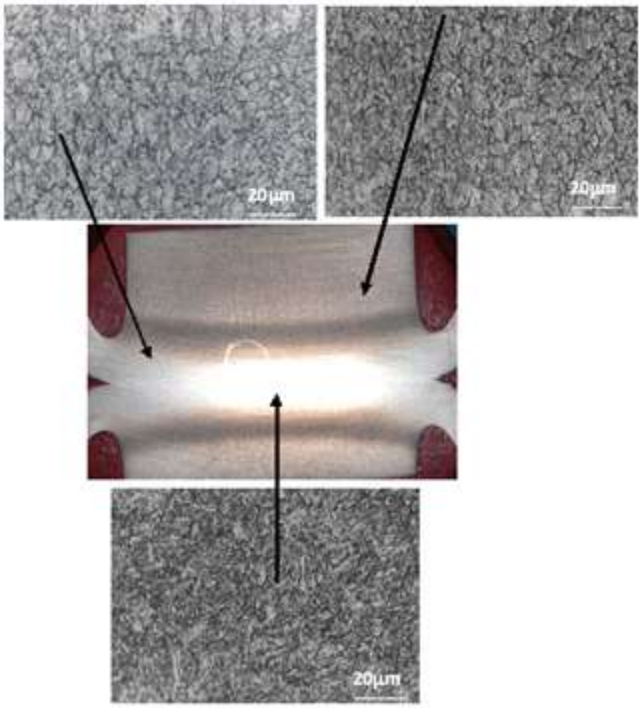

Fig. 2. Friction weld and its cross sectional view (as-welded condition)

The microstructures of the central region of welds in different post weld heat treatment conditions are presented in Fig. 4 (EB welds) and 5 (friction welds). From the figures it is revealed that with heat treatment, dendritic microstructure features in EB welding disappeared. The martensitic microstructure in both EB and friction welds experienced coarsening after heat treatment. The degree of coarsening increased with an increase in the tempering temperature.

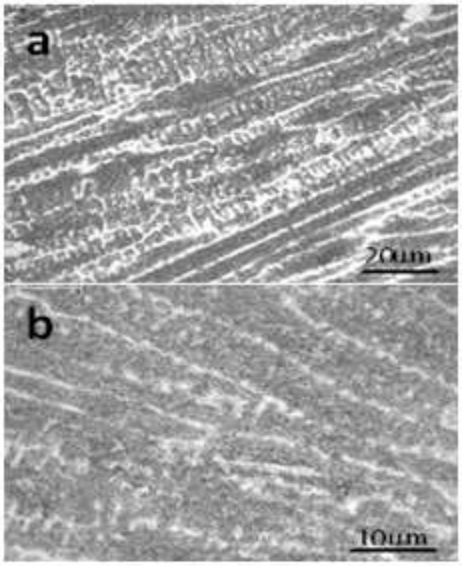

Fig. 3 Optical microstructure of EB welds in as-weld condition. a) 500x b) 1000x

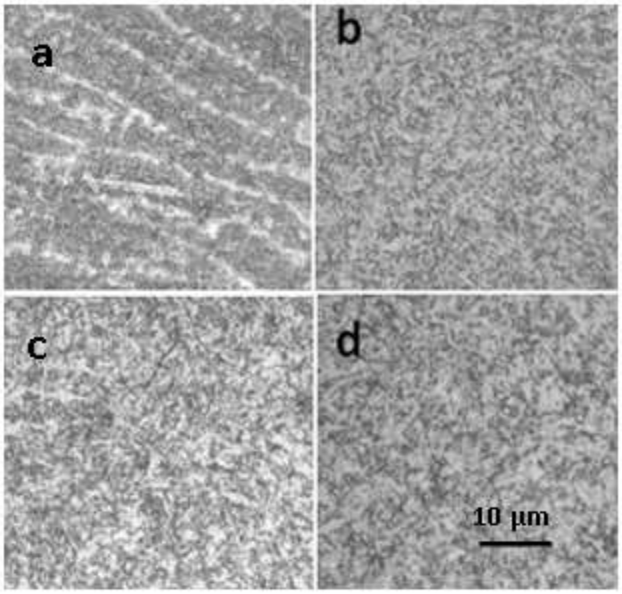

Fig. 4 Optical microstructures of EB welds (central region) (a) As-weld (b) HT/T400 (c) HT/T600 (d) HT/ T (670+600) conditions

Material condition	Phases Present (hkl)		
	Parent Metal	EB welds	Friction weld
As- received	Martensite (110) Austenite (200),(220),(311)		
As-weld		Martensite (110) Austenite (200),(220),(311) Ferrite (200),(221)	Martensite (110) Austenite (200),(220),(311)
HT/400	Martensite (110) Austenite (200),(220),(311)	Martensite (110) Austenite (200),(220) ,(311) Ferrite (200),(221)	Martensite (110) Austenite (200),(220),(311)
HT/600	Martensite (110)	Martensite (110) Ferrite (200),(221)	Martensite (110)
HT/DT	Martensite (110)	Martensite (110) Ferrite (200),(221)	Martensite (110)

Table 2. Various phases present in parent metal and weld in different heat treated conditions.

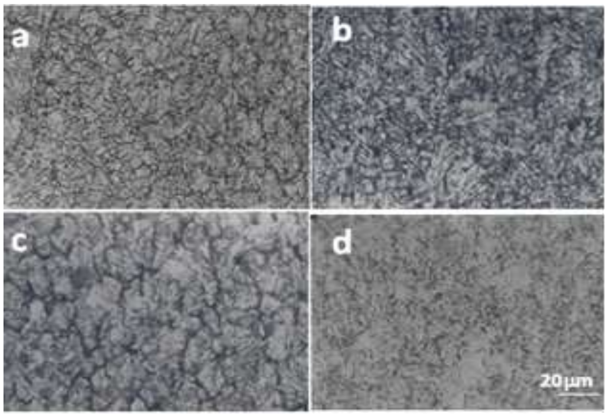

Fig. 5 Optical microstructure of friction welds (central region) (a) as-weld (b) HT/T400 (c) HT/T600 (d) HT/T(670+600) conditions

X-ray diffraction data summarized in Table 2 reveals the presence of delta ferrite and retained austenite along with martensite in EB welds and presence of retained austenite with martensite in friction welds. The effect of post weld heat treatment (PWHT) on the distribution of phases is also evident from the table.

Material condition	0.2 % Yield strength (MP		Ultimate tensil strength (MP		Elongation %	
	EB welds	FW welds	EB welds	FW welds	EB welds	FW welds
As-weld	730	859	1050	996	6.9	12
HT/400	1162	1158	1432	1448	15.3	14
HT/600	794	831	1010	1038	5.0	14
HT/DT	664	749	929	971	6.8	17

Table. 3 Variation in Retained austenite in parent metal and welds in different post weld heat treatments.

The influence of PWHTs on retained austenite is presented in Table 3. It is observed that retained austenite content is high in as weld condition and it is reduced with increase in PWHT. The high austenite percentage in the as weld condition is due to the fact that the welding experiences high temperatures, and at these temperatures carbon exists in the form of solid solution. Carbon is an austenite stabiliser and reduces Ms temperature, as alloying elements which are austenite stabilisers lower Ms temperature. Tempering at 400^0C did not result in significant reduction in retained austenite content. The reduction of retained austenite content in double tempered condition to the level of 2% can be attributed to the transformation of retained austenite to martensite during first tempering and decomposition of this martensite to ferrite and carbides during subsequent low temperature tempering.

C. Hardness

Hardness survey across EB and Friction welds in the as welded and different post weld heat treated conditions are shown in Fig. 6. In the as-welded condition the weld and HAZ regions exhibit higher hardness than the parent metal. The high temperatures experienced in welding allow the carbides to get dissolved and a carbon rich martensite formed that results in higher hardness. Hardness is observed to decrease with PWHT. Hardness reduction is predominant at high tempering temperatures. In HT/DT the hardness of the weld, HAZ and parent metal is equal. Tempering at 400^0C is ineffective in reducing the hardness. Hardness plots reveal that hardness of friction welds is slightly more as compared to EB welds in all the conditions. This may be due to fine grained microstructure of friction welds as compared to EB welds.

D. Tensile properties

The tensile properties of both EB and friction welds in different post weld heat treatments are presented in Table 4. From the results it is observed that in all the conditions, friction welds exhibited higher tensile strengths as compared to EB welds except in as-weld condition. From the elongation data it is observed that EB welds in general have low ductility as compared to friction welds in the corresponding PWHT conditions with the exception of weld in HT/400 condition in that, the EB weld exhibits higher ductility than the friction weld in the same heat treated condition.

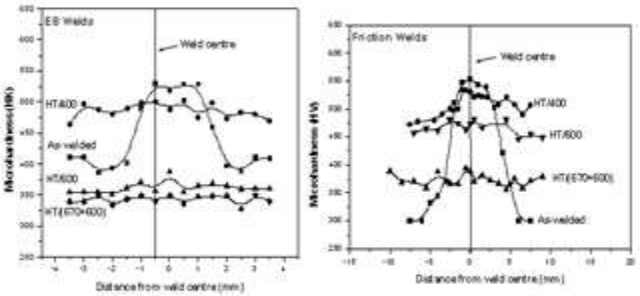

Fig. 6. Micro hardness survey across the weld joint (a) EB weld (b) Friction weld

Material condition	Impact toughness (Joules)	
	EB welds	Friction welds
As-weld	32	4
HT/400	24	15
HT/600	52	45
HT/DT	72	68

Table 4. Tensile properties of EB and friction welds (FW) in different heat treated conditions

Material condition	Retained Austenite (%)		
	Parent metal	EB welds	Friction welds
As-received	16		
As-weld		18	24
HT/400	12	14	18
HT/600	5	8	10
HT/DT	<2	<2	<2

Table 5. Impact properties of EB and Friction welds in different heat treated conditions

High transverse strengths and elongations of friction welds may be due to fine grain microstructure and absence of δ-ferrite. Presence of significant amounts of δ-ferrite in EB welds resulted in low transverse strength and ductility, and also lower corrosion resistance [8-9]. The high tensile strength in EB welds in as-weld condition as compared to as-welded friction welds is thought to be due to presence of carbon in solid solution which increases the strength and hardness.

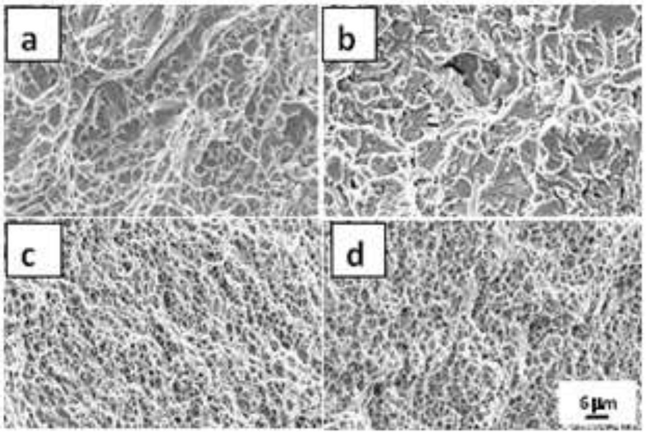

Fig. 7 Fracture features of impact samples of EB welds in various heat treated conditions (a) as-weld (b) HT/T400 (c) HT/T600 (d) H/T(670+600)

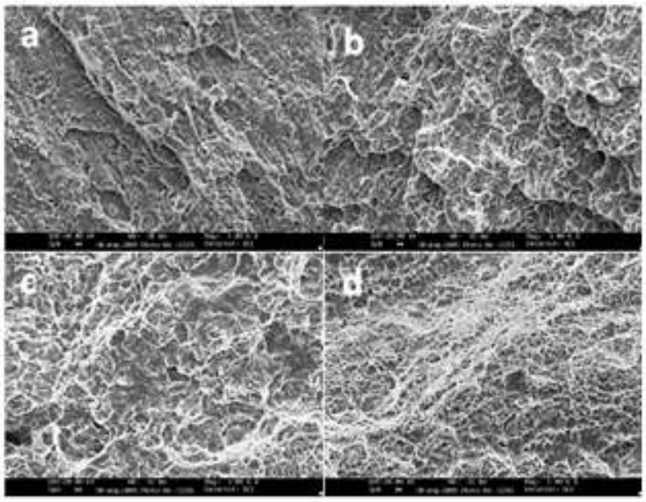

Fig. 8. Fracture features of impact samples of friction welds in various heat treated conditions (a) as-weld (b) HT/ T400 (c) HT/T600 (d) HT/ T(670+600)

E. Impact toughness

The impact properties of EB and friction welds are presented in Table 5. Welds in as-weld condition exhibited lower impact toughness. Post weld heat treatments resulted in improved toughness. The toughness is in the order: HT/DT > HT/600 > HT/400. Double tempering resulted in maximum improvement in toughness. Fractographs presented in Fig. 7 and Fig. 8 suggests that ductile features increased with an improvement in impact toughness. Improvement in toughness was accompanied by a corresponding decrease in hardness and strength which is similar to other engineering metals and alloys [10-19]. Intergranular cracks observed in 400^{0}C tempered condition suggest that the material experienced temper embrittlement.

The observed reduction in strength and improvement in toughness at high tempering temperatures is thought to be due to tempering of martensite to ferrite and alloy carbides.

Friction welds did not respond to heat treatments as much as EB welds, as revealed from toughness trends. This behaviour could be due to combined effects of fine grain size and aligned microstructural features that developed due to the application of axial pressure in these welds (Fig. 9).

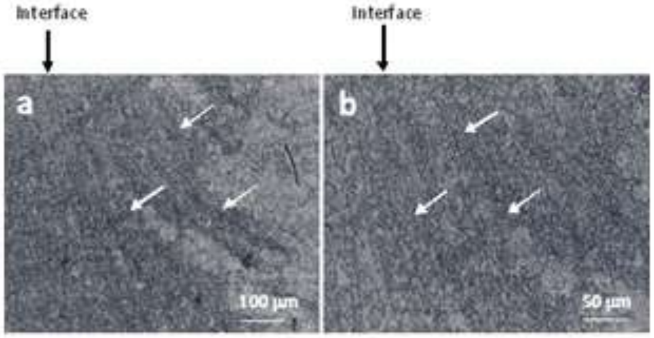

Fig.9. Typical optical micrograph at the interface of the friction weld (as-welded condition) arrow indicates aligned grain structure (a) low magnification (b) higher magnification

IV. CONCLUSIONS

AISI 431 martensitic stainless steel can be successfully welded by both friction welding and electron beam (EB) welding processes.

EB welding resulted a cast dendritic structure which consists of ferrite network in a matrix of un-tempered martensite. In friction welding, the weld centre exhibited thermo-mechanical effected structure consists of fine intragranular acicular martensite in equiaxed prior austenite grains.

Presence of δ-ferrite along with martensite and retained austenite phases is observed in EB welds, where as friction welds resulted only martensite and retained austenite phases.

In all the specimens, martensitic microstructure experienced coarsening when subjected to post weld heat treatments. The degree of coarsening increased with an increase in the tempering temperature.

Hardness of friction welds is slightly more as compared to EB welds in all the conditions due to fine grained microstructure.

EB welds exhibited lower tensile strengths and elongation rates as compared to friction welds due to course grained structure and presence of δ-ferrite.

Poor impact toughness resulted in both the welding processes in as welded condition. Double tempering exhibited better toughness due to coarsening of martensite during PWHT. However, friction welds did not respond to heat treatments as much as EB welds as revealed from toughness trends due to combined effects of fine grain size and aligned microstructural features.

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