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Mechanical Properties and Corrosion Behaviors in 3.5% NaCl Solution of Grade-A and Dual-Phase Steels Welded by FCAW

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Abstract:

The first aim of this study is to demonstrate the transformation of Grade-A steel into dual-phase steel by heat-treatment at the chosen 730°C and 800°C intercritical temperature for 60 min followed by cold water quenching. The second aim of this study is to investigate the mechanical properties and the corrosion behaviours in 3.5% NaCl solution of Grade-A and dual-phase steels welded by flux-cored arc welding (FCAW). It was carried out the mass loss measurements and investigated the micro and macrostructures of welding zone using by optical microscope.

The present study has demonstrated that Grade-A ship steel consisting of ferrite and pearlite can be successfully transformed to the dual-phase steel at the chosen intercritical temperatures. The microstructure of transformed dual-phase steel consists of island of martensite in a ferrite matrix. The Grade-A and transformed dual-phase steels were successfully joined by FCAW. The mechanical results showed that the tensile strength of the transformed dual-phase steel were higher, but lower elongation than that of the Grade-A steel. The results from the immersion test in 3.5% NaCl solution showed that the corrosion behaviours of the dual-phase and Grade-A steels depend upon the morphology of the phase constituents. The corrosion rate of the transformed dual-phase steel with ferrite-martensite structure was lower than that of the Grade-A steel with ferrit- pearlite structure. The corrosion has preferential started at fusion line and progressed towards the heat affected zone (HAZ) of the welded dual-phase and Grade-A steels.

Keywords: Grade-A steel, flux-cored arc welding (FCAW), corrosion behaviour of dual-phase steel, 3.5% NaCl solution.

1. Introduction

The shipbuilding industry has promoted high performance of ships and improved productivity in construction. It is very important to develop new steel with high the specific strength, good weldability and high corrosion resistance for construction of ship having lower construction weight, improving the fuel consumption economy and allowing greater quantities and sizes of loads. So far, the Grade-A steel was mostly employed to construct a great region of ship frame due to the being cheaper, having good weldability and high mechanical properties.

It was reported by Hayat et al. that Grade-A ship steel has been employed to transform into dual-phase (DP) steel accomplished by intercritically annealing at intercritical temperatures ranges of 730 ºC and 800ºC, and following by water quenching (Hayat, 2012). Thus, the microstructure of Grade-A consists of ferrite and pearlite, while the transformed dual-phase steels consist of ferrite and martensite. Mechanical properties of the transformed dual-phase steels are higher than the Grade-A steel. Therefore, the transformed dual-phase steels are promising candidate materials for the ship building industry because of their good weldability, high strength, low yield-to-tensile strength ratio and high strength-to-weight ratio (Hayat, 2012). It was investigated the weldability of transformed dual-phase steels joined by flux-cored arc welding (FCAW) process at the same work.

Nowadays, it was reported the corrosion performance of dual-phase steel embedded in concrete by Ismail et al. (Ismail, 2009) and Keleştemur et al. (Keleştemur, 2009), the mechanical properties and corrosion susceptibility of dual-

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phase steel in concrete by Trejo et al. (Trejo, 1994), microstructural influence on the electrochemical corrosion behaviour steels in 3.5% NaCl solution by Sarkar et al. (Sarkar, 2005) and mechanical and corrosion behaviours of plain low carbon dual-phase steels by Bhagavathi et al. (Bhagavathi, 2011). It was no any report the corrosion behaviours in 3.5% NaCl solution of the transformed dual-phase steels welded by FCAW.

The first aim of this study is to demonstrate the transformation of Grade-A steel into dual-phase steel by heat-treatment at the chosen 730°C and 800°C intercritical temperature for 60 min followed by cold water quenching. The second aim of this study is to investigate the mechanical properties and the corrosion behaviours in 3.5% NaCl solution of Grade-A and dual-phase steels welded by FCAW. It was carried out the mass loss measurements and investigated the micro and macrostructures of welding zone using by optical microscope. The pitting corrosion mechanism was described and compared with the Grade-A steel and the transformed dual-phase steel joints.

2. Experimental Procedure

The as-received hot-rolled Grade-A ship steel plates was employed to transform to the dual-phase steel. Table 1 shows the chemical compositions and mechanical properties of the Grade-A ship steel.

The Ac_1 and Ac_3 temperature limits (711-845ºC) were computed using the Andrews formula from the chemical composition of the Grade-A steel (Andrews, 1965). It was carried out the transformation of Grade-A steel into dual-phase steel by heat-treatment at the chosen relatively lower 730 °C and upper 800 °C intercritical temperatures for 60 min followed by cold water quenching. 730DP and 800DP represent the base metal at different annealing temperatures of 730 °C and 800 °C, respectively. The martensite volume fractions (MVF) of the transformed dual-phase steels are calculated by using the Clemex Vision Lite image analysis program by Nikon Eclipse L150A optical microscope.

Similar the Grade-A and the transformed dual-phase steel plates (400x150x8 mm) were joined on three different passes in the V-groove butt form by FCAW process with AWS/ASME SFA-5.29 E81 T1-Ni1 flux-cored welding wire. The schematic the single V-groove butt joint with ceramic backing is illustrated in Fig. 1.

The corrosion behaviours of Grade A and dual-phase steels non-welded and welded by flux-cored arc welding (FCAW) were studied by using immersion test in 3.5% NaCl solution. The ASTM established recommended procedure for immersion tests as covered by designation G-31 (ASTM, 2004) was employed. They were weighed before the start of the test and after completion of the test. The non-welded and welded specimens were immersed in 3.5% NaCl solution for 7, 15, 30, 45, 60, 75 and 90 days at room temperature. It was kept the corrosion solution with a constant pH value of 8 during the immersion test. The corrosion rate was calculated by weight loss method. The weight loss is converted to an average corrosion rate using the following formula:

$$CR = \frac{K \times W}{A \times T \times D} \tag{1}$$

Where CR is average corrosion rate (mm/year), K is constant (8.76 x 10^4), W is weight lost by the specimen during the test (g), A is = total surface area of the test specimen (cm^2), T is duration of exposure (h) and D is density of the specimen material (g/cm^3).

The tensile tests of non-welded and welded specimens were prepared according to TS EN ISO 6892-1 and TS EN ISO 4136:2011 specifications, respectively. The Vickers microhardness measurements were performed using a load of 200 g and a dwell time of 10 s.

3. Results And Discussion

3.1. Microstructures of Grade-A steel, dual-phase steel and weld metals

The microstructure of the as-received Grade-A steel shown in Fig. 2 reveals that the microstructure consists of uniformly distributed pearlite (dark) colonies in an equiaxed ferrite matrix (light). Figure 3 shows the microstructures of the base dual-phase steels which are transformed from the Grade-A steel. The microstructure of base dual-phase steel developed following intercritical annealing at lower temperature of 730°C is composed of light gray coloured uniform fibrous ferrite and dark coloured martensite, which is commonly termed as a fibrous structure (Fig. 3 (a)). The microstructure of base dual-phase steel developed following intercritical annealing at higher temperature of 800°C consists of islands of martensite in a ferrite matrix (Fig. 3 (b)). It is concluded that the higher and the lower intercritical annealing temperatures are influenced on the martensite morphology and distribution of the phase constituents. Similar observations were also reported in the related literatures (Sarkar, 2005 and Bhagavathi, 2011).

The image analysis exhibits that the martensite volume fractions (MVF) in the base dual-phase steels coded 730DP and 800DP are 16±5 % and 55±6 %, respectively. It shows that the MVF of the dual-phase steels increases with increasing the intercritical annealing temperatures. Similar observations were also made in the literature (Hayat, 2012).

The similar Grade-A and transformed dual-phase steels were successfully joined by FCAW process. The representative macrostructure of the weld was shown in Fig. 4. It was measured the weld face width of 12-14 mm and the weld face height of 5-7 mm.

Fig. 5 shows the microstructure of weld metal in the Grade- A and dual-phase steels joined by FCAW. It was confirmed by TEM analysis that the microstructure of weld metal was consisted of the primary ferrite phase, grain boundary ferrite (allotriomorphic ferrite), polygonal ferrite, Widmanstatten ferrite, acicular ferrite and martensite at a lower quantity (Hayat, 2012).

3.2. Mechanical properties

The microhardness profiles along the top and bottom in cross sectional horizontal to the weld direction in the similar Grade -A and dual-phase steels with different annealing temperatures of 730 °C and 800 °C welded by FCAW are shown in Fig. 6. The hardness profiles of the dual phase steels reported by Hayat et al. are also shown in the same Figure for comparison purposes (Hayat, 2012). The lowest hardness value was found in Grade-A steel, approximately 142±5 Hv. The hardness values in dual-phase steels with the tempering temperature of 730 ºC and 800 ºC were 200 ± 5 Hv and 258 ± 5, respectively.

The tensile test results of Grade-A and dual-phase steels welded by FCAW are presented in Table 2. The lowest tensile strength is exhibited by the Grade-A steel as compared the dual-phase steels. The tensile strength of dual-phase steels increases and the percentage of elongation decreases with increasing martensite volume fraction.

3.3. Corrosion properties

Fig. 7 shows the macrostructures of weld region of Grade-A and dual-phase steels welded by FCAW after immersion corrosion test in 3.5% NaCl solution. It is estimated that the galvanic couple triggered pitting reaction on the corrosion of Grade-A and dual-phase steel joints. It is observed that the corrosion failure at the weld region preferentially starts in the partially melted zone between weld metal and heat affected zone (HAZ), and prolonged towards the HAZ. Thus the partially melted zone may corrode faster than the weld metal and/or HAZ or HAZ may corrode faster than the weld metal. This is attributed that two galvanic couples are formed either between the weld metal and the partially melted zone or between HAZ and the partially melted zone. In galvanic couple between the weld metal and the partially melted zone, the weld metal acts as cathode and the partially melted zone acts anode. In galvanic couple between HAZ and the partially melted zone, HAZ acts as cathode and the partially melted zone acts anode.

In the corrosion of Grade-A and dual-phase steels in 3.5% NaCl solution, following corrosion reactions occur simultaneously.

$$\text{Anodic reaction: } Fe \rightarrow Fe^{2+} + 2e^- \tag{2}$$

$$\text{Cathodic reaction: } Fe^{+2} + 2OH^- \rightarrow Fe(OH)_2 \tag{3}$$

In 3.5% NaCl solution, sodium and chlorine ions are decomposed and then reacted with ferrous ions, thus the pH of the solution from a value of 8 to 5 decreases. Therefore, the corrosion failure of steels increases. In the present study, the pH of 3.5% NaCl solution is arranged the constant value of pH 8 in order to evaluate the performance of steels.

$$NaCl \rightarrow Na^+ + Cl^- \tag{4}$$

$$Fe^{+2} + 2Cl^- \rightarrow FeCl_2 \tag{5}$$

$$Fe^{+3} + 3Cl^- \rightarrow FeCl_3 \tag{6}$$

$FeCl_2$ and $FeCl_3$ compounds occurred at the end of the reactions are hydrolyzed. As a result of the reactions**,** hydrochloric acid (HCl) occurs.

$$FeCl_2 + 2H_2O \rightarrow Fe(OH)_2 + 2HCl \tag{7}$$

$$FeCl_3 + 2H_2O \rightarrow Fe(OH)_3 + 3HCl \tag{8}$$

The ferrous hydroxide is oxidized to ferric hydroxide ($Fe(OH)_3$) known as corrosion product.

$$Fe(OH)_2 + \tfrac{1}{2} H_2O + \tfrac{1}{4} O_2 \rightarrow Fe(OH)_3 \tag{9}$$

Table 3 shows the results of the average corrosion rates of similar the Grade-A and the dual-phase steel joints obtained from immersion test in 3.5% NaCl solution. It can be seen from Table 3 that the average corrosion rate of similar Grade -A steel joint is higher than that for the similar dual-phase steel joints. This is attributed to the number of micro and macro corrosion couples. It was observed two micro corrosion couples and two macro corrosion couples at the Grade-A steel joint. Macro corrosion couples are formed (1) between the weld metal (cathode) and the partially melted zone (anode), (2) between HAZ (cathode) and the partially melted zone (anode). Micro corrosion couples are formed (1) between lamellae cementit in pearlite (cathode) and eutectoid ferrite in pearlite (anode), (2) between lamellae of pearlite (cathode) and proeutectoid ferrite (anode). Fig. 8 shows the schematic galvanic corrosion mechanisms of similar Grade-A steel joints.

On the other hand, it was observed a micro corrosion couple and two macro corrosion couples at the dual-phase steel joints. Macro corrosion couples are formed (1) between the weld metal (cathode) and the partially melted zone (anode), (2) between HAZ (cathode) and the partially melted zone (anode). Micro corrosion couple is formed between ferrite (anode) and martensite (cathode). Fig. 9 illustrates the schematic galvanic corrosion mechanisms of similar dual-phase steel joints.

It can be seen from Table 3 that the average corrosion rate of similar dual-phase steel joint coded 730DP developed following intercritical annealing at lower temperature of 730ºC is higher than that for the similar dual-phase steel joints coded 800DP developed following intercritical annealing at higher temperature of 800ºC. This is attributed the martensite morphology and martensite volume fraction (MVF). The MVF of dual-phase steel coded 730DP is higher than that for the dual-phase steel coded 800DP.

It has been reported (Sarkar, 2005) that island-like morphology of martensite gave better corrosion resistance as compared to the network form surrounding the ferrite grains. In present study, martensite phase has similar island-like morphology in the matrix of ferrite in dual phase steel developed following intercritical annealing at higher temperature of 800 ºC. The microstructure of dual-phase steel coded 730DP developed following intercritical annealing at lower temperature of 730 °C is composed of uniform fibrous ferrite and martensite, which is commonly termed as a fibrous structure. Thus, the lower corrosion resistance is observed on the dual phase steel joint coded 730DP as compared to dual phase steel coded 800DP, in view of the structural and morphological considerations.

4. Conclusions

Grade-A ship steel was successfully transformed to the dual-phase steel at the chosen intercritical temperatures. The Grade-A and transformed dual-phase steels were also successfully welded by FCAW. The microstructure, microhardness, tensile properties and corrosion behaviours in 3.5% NaCl solution of joints have been studied in the present work. Following conclusions are drawn:

1- The microstructure incestigation shows that while the microstructure of Grade-A steel consists of proeutectoid ferrite and pearlite, the microstructure of transformed dual-phase steels consists of ferrite and martensite phases.

2- The microstructure of dual-phase steel developed following intercritical annealing at lower temperature of 730°C is composed of uniform fibrous ferrite and martensite. The microstructure of dual-phase steel developed following intercritical annealing at higher temperature of 800°C consists of islands of martensite in a ferrite matrix.

3- The tensile test results show that the tensile strength of Grade-A steel joint is lower than that of the transformed dual phase steel joints.

4- The corrosion resistance obtained from immersion tests of Grade-A steel joint were less than that for the dual phase steel joint. It is assumed two reasons. Firstly, the martensite formed in dual phase steel is structurally and compositionally closer to ferrite matrix phase. Therefore the galvanic couple formed between ferrite–martensite is weaker as compared to Grade-A steel wherein pearlite which consists of ferrite and cementite lamellae is structurally and compositionally inhomogeneous. Secondly, the number of micro and macro corrosion couples different from Grade-A steel joint and dual phase steel joint. It could be observed two macro and micro corrosion couples on the Grade-A steel joint (1) between the weld metal and the partially melted zone, (2) between HAZ and the partially melted zone, (3) between lamellae cementit in pearlite and eutectoid ferrite in pearlite, (4) between lamellae of pearlite and proeutectoid ferrite. Ont the other hand, it could be observed two macro and one micro corrosion couples on the dual phase steel joint (1) between the weld metal and the partially melted zone, (2) between HAZ and the partially melted zone, (3) between ferrite and martensite island.

5- The corrosion resistance of dual-phase steel increases depending on the increase in the volume fraction of martensite. In addition, the corrosion resistance of the dual-phase steel increases with intercritical annealing tempering heat treatment and the highest corrosion resistance take place in dual phase steel tempered at 800 °C. This is attributed to the depending upon the volume fraction and morphology of the phase constituents. The dual phase steel tempered at higher temperature of 800°C, which consists of island-like morphology in the matrix of ferrite, gives rise better corrosion resistance property than the dual phase steel tempered at lower temperature of 730°C, which consists of fibrous ferrite and martensite.

Acknowledgment

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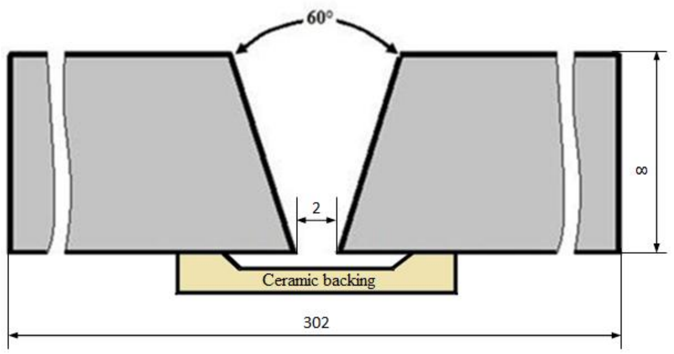

Figure 1. Schematic single V-groove butt joint with ceramic backing

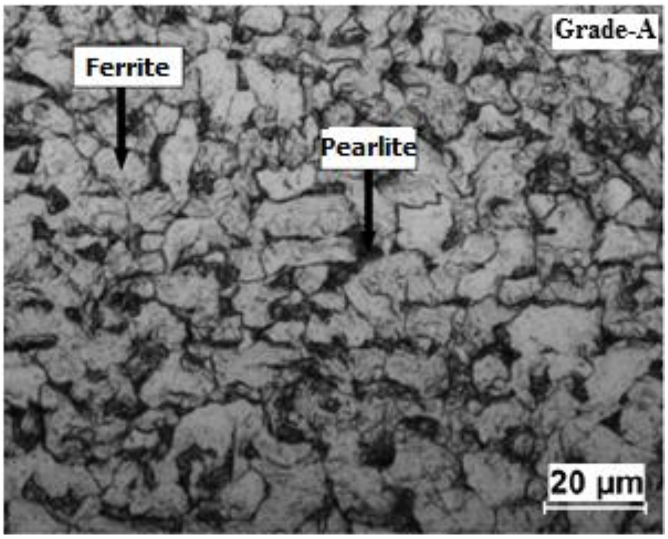

Figure 2. Microstructure of as-received Grade-A steel consisting of ferrite –pearlite structure

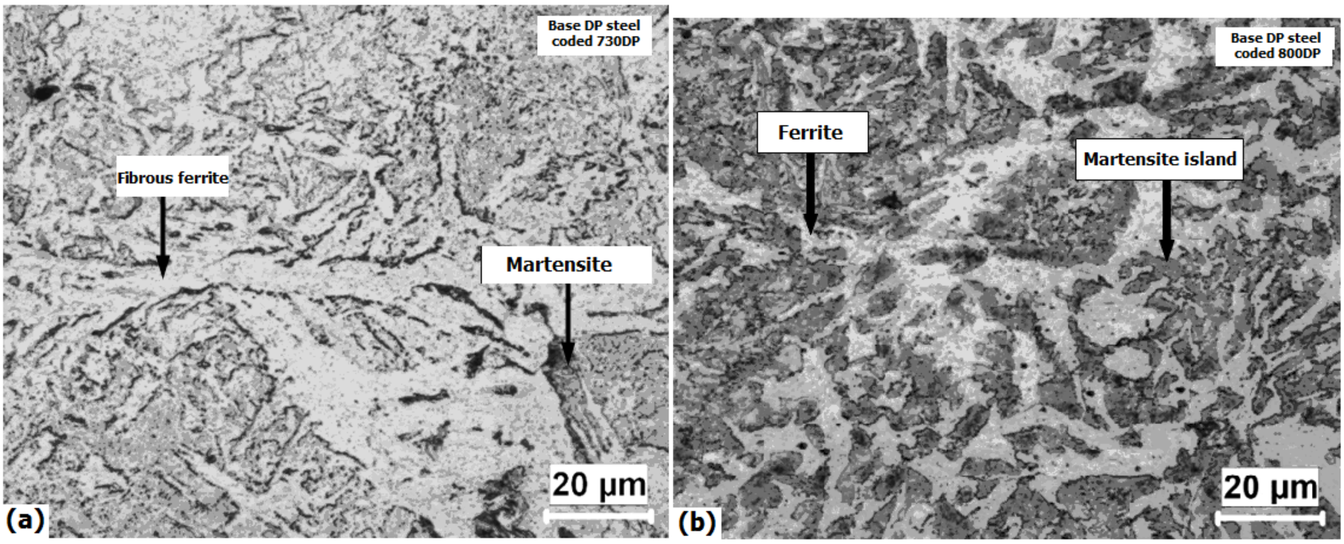

Figure 3. Microstructures of the base dual-phase steels (a) 730DP representing an annealing temperature of 730 °C and (b) 800DP representing an annealing temperature of 800 °C.

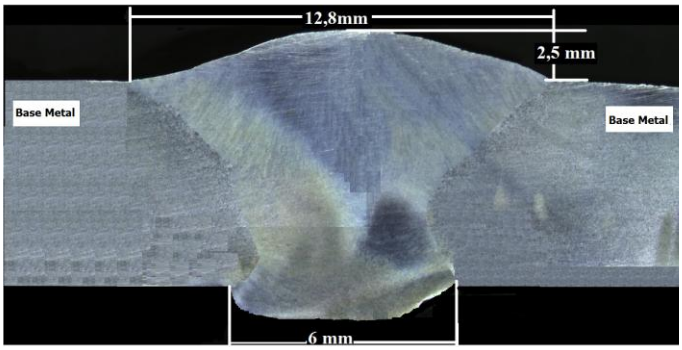

Figure 4. Representative macrostructure of the weld of Grade-A and dual-phase steel joints

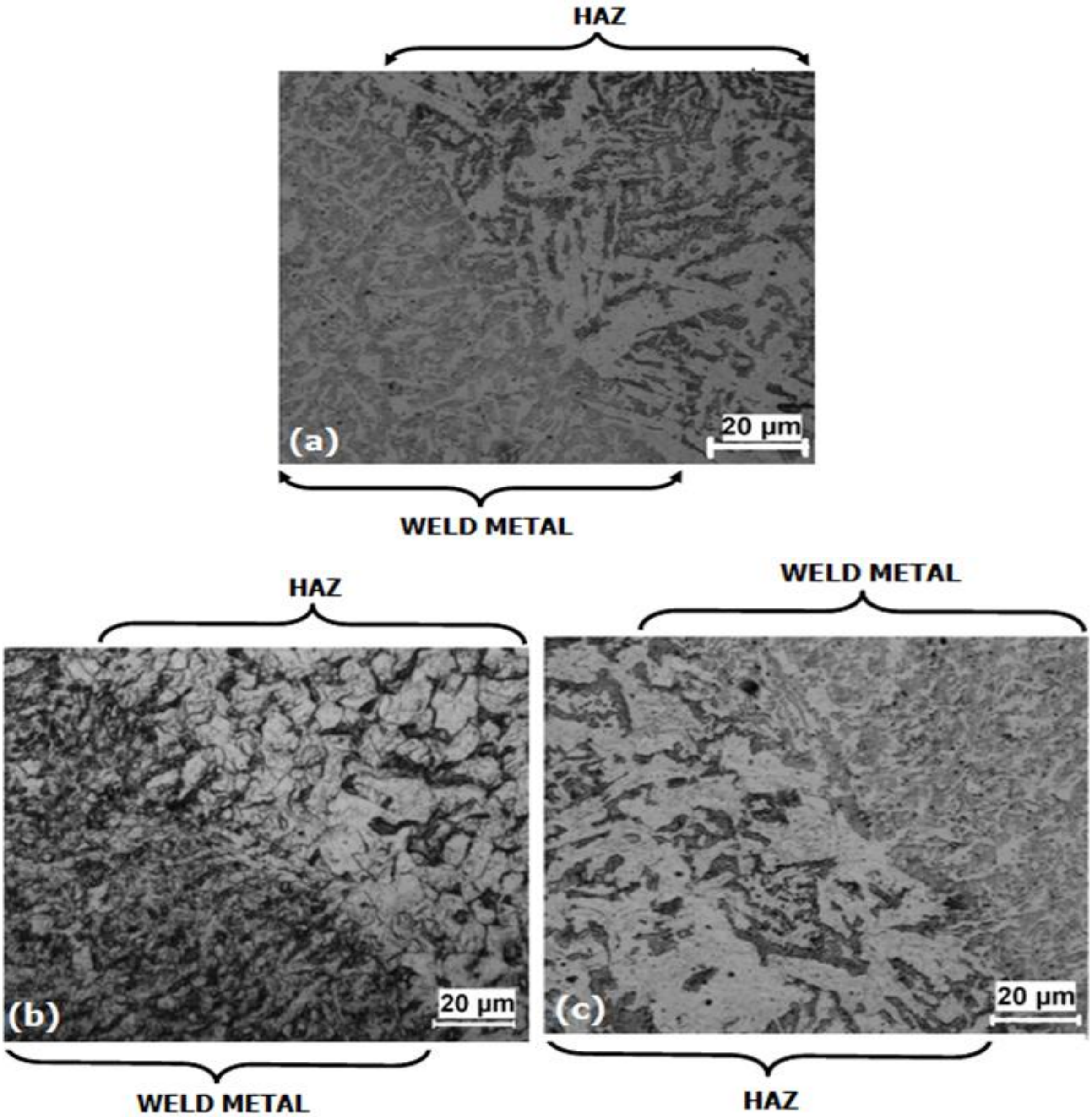

Figure 5. Weld metal and HAZ optical microstructure images of the similar Grade-A and the similar dual-phase steels welded by FCAW (a) Grade-A joint, (b) dual-phase steel joint coded 730DP and (c) dual-phase steel joint coded 800DP.

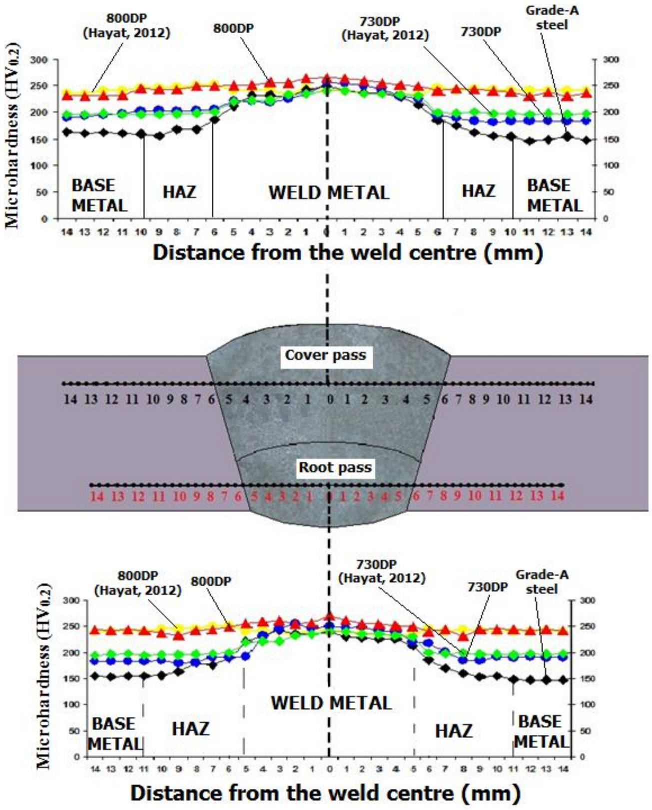

Figure 6. Hardness profiles along the top and bottom in cross-section of the Grade-A and dual phase steels

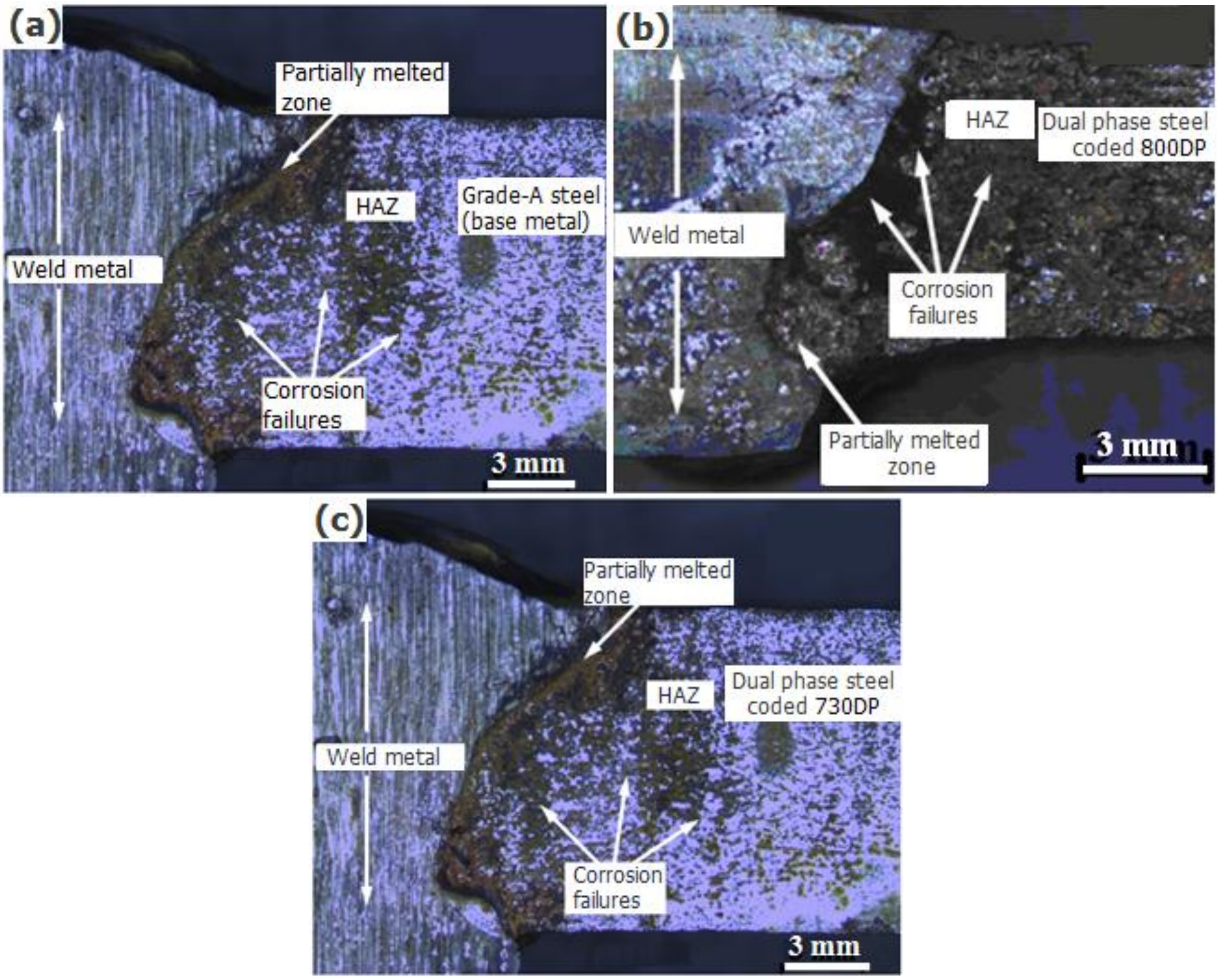

*Figure 7. Macrostructures of weld region of Grade-A and dual-phase steels welded by FCAW after 90 days immersion corrosion test in 3.5% NaCl solution; **(a)** Grade-A steel joint, **(b)** dual-phase steel joint coded 800DP and **(c)** dual-phase steel joint coded 730DP.*

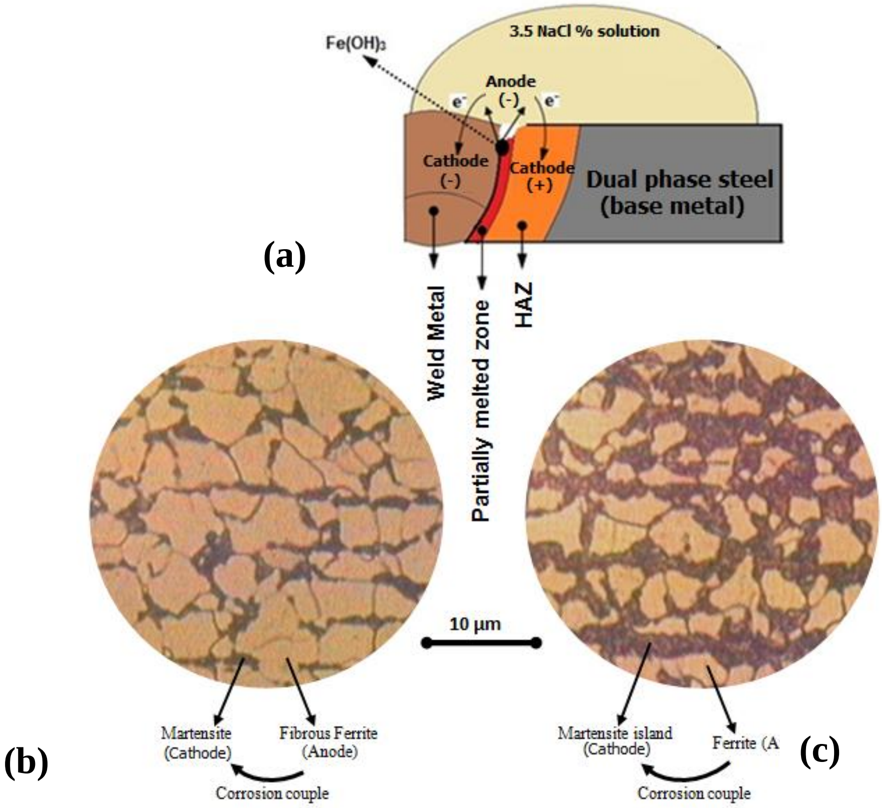

Figure 8. ***(a)*** *Schematic galvanic corrosion couples of dual phase steel welded by FCAW ((1) between the weld metal (cathode) and the partially melted zone (anode), (2) between HAZ (cathode) and the partially melted zone (anode)),* ***(b)*** *corrosion couple of base metal of dual phase steel joint coded 730DP developed following intercritical annealing at lower temperature of 730ºC (between fibrous ferrite (anode) and martensite (cathode)) and* ***(c)*** *corrosion couple of base metal of dual phase steel joint coded 800DP developed following intercritical annealing at higher temperature of 800 ºC (between ferrite (anode) and martensite island (cathode))*

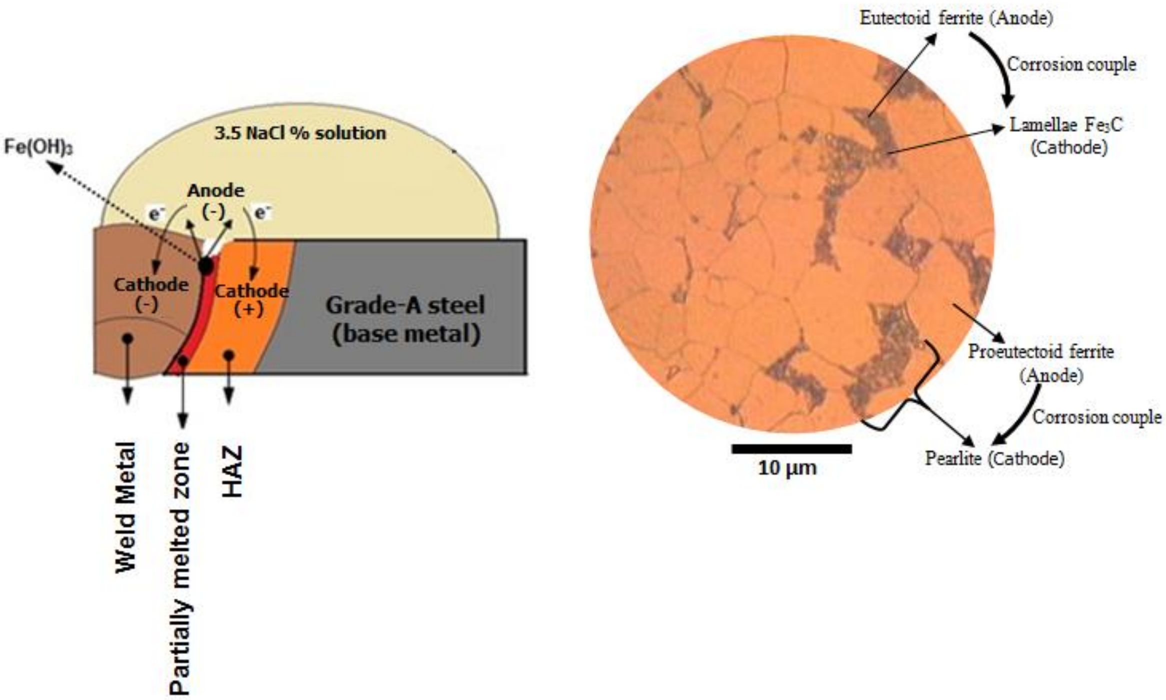

*Figure 9. **(a)** Schematic galvanic corrosion couples of Grade-A steel welded by FCAW ((1) between the weld metal (cathode) and the partially melted zone (anode), (2) between HAZ (cathode) and the partially melted zone (anode)), **(b)** corrosion couples of base metal of Grade-A steel joint ((1) between lamellae cementit in pearlite (cathode) and eutectoid ferrite in pearlite (anode), (2) between lamellae of pearlite (cathode) and proeutectoid ferrite (anode))*

Table 1. Chemical compositions and mechanical properties of the as-received hot rolled Grade-A steel

Materials	**Chemical composition (wt %)**					
	C	***Mn***	***Si***	***P***	***S***	***Fe***
Grade-A steel (ABS-P2)	0.12	0.71	0.14	0.016	0.015	Balanced
	Mechanical Properties (Erdemir, 2013)					
	Yield strength (MPa)		Tensile strength (MPa)		Elongation (%)	
	235		400 - 520		22	

Table 2. Tensile results of similar Grade-A and similar dual-phase steels welded by FCAW

Materials		**Yield strength (MPa)**	**Tensile strength (MPa)**	**Elongation (%)**	**MVF (%)**
Grade-A steel joint	Base of Grade-A steel	284±5	365±5	19	-
	Grade-A steel joint	317±5	410±5	16	
DP steel joint coded 730DP	Base of DP steel	371±6	429±4	16	16±5
	DP steel joint	490±5	580±7	13	
DP steel joint coded 800DP	Base of DP steel	345±5	437±5	14	55±6
	DP steel joint	450±5	534±5	11	

Table 3. Results of the average corrosion rates of similar the Grade-A and the dual-phase steel joints obtained from immersion corrosion test performed in 3.5% NaCl solution

Materials	Corrosion rate from immersion test (mm/year)	MVF (%)	Microstructure of base metal
Grade-A steel joint	1,334	-	Ferrite – Pearlite
DP steel joint coded 730DP	1,010	16±5	Uniform fibrous ferrite – Martensite
DP steel joint coded 800DP	0,861	52±6	Island martensite in continuous ferrite matrix