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Corrosion Resistance of Low-Alloy Steel After Conducting ElectroSlag Remelting and Homogenization Process

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Abstract: *Daily increase in development of steel industries has raised the demand for higher quality products. To meet this, researchers have exploited various processing methods, one of the most important of which is ElectroSlag Remelting (ESR). Corrosion resistance of steels are influenced by number of factors specially the presence of segregations and impurities. ESR improves physical and mechanical properties of steels due to suitable solidification conditions as well as reduction of void inclusions content. The aim of this work is to study the effect of ESR and homogenization on corrosion resistance of low-carbon steels. To reach this purpose, the prepared samples in this study are subjected to a polarization test. In order to eliminate the banding segregations that are resulted of hot-rolling process, a number of samples were subjected to homogenization heat treatment under 1200 °C for 4 h. It was observed that remelted steels in this study showed a better corrosion resistance behavior as a result of the appropriate solidification condition and the absence of inclusions.*

Keywords: *Electro Slag Remelting, Corrosion Resistance, Segregation, Solidification*

INTRODUCTION

One of the most significant remelting methods is ElectroSlag Remelting. In this process, first, the electrode is melted drop-wise due to the heat resulted from electrical slag. Then, the drops of molten metal are casted in appropriate crucible. Finally, the sample is solidified with a high rate (Donachie et al., 2002; Nafziger, 1976). The thermal source that causes the surface of electrode to melt is the slag, consisting CaF_2 and other oxide additives (Hoyle, 1982). Also, an AC current is used in this process (Hoyle, 1982). In general, the steels that undergo ESR have less content of voids and segregations (Plockinger, 2005). The effects of ESR and steels are studied by Medovard and Gerard (Gerard, 1975; Medovar, 1974).
The possibility of formation of banding segregation in hot-rolled steels is high. This type of segregation is observed in rolled and forged steels (Krauss, 2003; Grange, 1971). Presence of this type of segregations effects the mechanical properties as well as corrosion resistance of steels (Osorio et al., 2002; Osorio, Mater.Sci.Eng. A, submitted for publication). To reduce the amount of segregations, homogenization treatment in different temperatures and times can be used (Grange, 1971). Also, presence of inclusions and impurities is another reason for poor mechanical properties and corrosion resistance in steels (Lott et al., 1989). Exploiting ESR results in reduction and even elimination of inclusions and segregations (Plockinger, 2005). In studies performed by Mitchel (2005) and Dong (2007), the effect of control of solidification in ESR on the quality of

prepared ingot is studied. Factors such as depth of melt pool and Local Solidification Time (LST) are effective on the difference between dendrites and presence of segregations. In total, reduction of melt pool reduces the LST and consequently the gap between dendrites, and amount of segregations (Paton, et al. 2004; Chang and Li, 2008). Microstructural segregation in low-carbon and low-alloy steels is the reason for segregation of interstitial alloying elements during the solidification of dendrites (Smith, 1993; Turkdogan and Grange, 1970). Elements such as magnesium, chromium and molybdenum are considered as elements which result in banding segregation (Smith, 1993; Turkdogan and Grange, 1970). The concentration difference between center and surface of solidified dendrites results in a series of parallel bands during rolling and forming processes (Doherty and Melford, 1966; Grange, 1971). The variation of behavior of austenitic transformation in the bands results in layerd microstructure with separate layers of martensite, ferrite, and bainite. Numerous research works have shown that Mn is a key element in formation of banding segregation in low-alloy steels (Grange, 1971; Leslie, 1981). Voldrich et al. (1974) have shown that during cooling of low-alloy steels, carbon migrated from low-Mn regions to high-Mn regions. Increasing cooling rate and size of austenite grain size reduces the chance of banding segregation (Thompson and Howell, 1992). Caballero et al. (2006) have studied the morphology of bands (thickness and geometry). Temperature and timing of homogenization heat treatment, and type of forming process are effective factors in determining the morphology of bands (2006). In casted pure metals, corrosion resistance behavior only depends on morphology of microstructure and grain size. In casted alloys, however, the gap between dendrite arms can be more influential than microstructure morphology and grain size with regard to corrosion resistance behavior. Low gap between dendrites and low amount of segregations and inclusions effects the corrosion resistance behavior of alloys (Osorio et al., 2002; Osorio, Mater.Sci.Eng. A, submitted for publication). The aim of this research is to study effects of ESR process, and presence of segregations and inclusions on corrosion resistance behavior of Low-Alloy steels.

Materials and Methods

The primary ingot was melted using an induction furnace with an inert gas atmosphere having a capacity of 10 Kg. ESR was used to obtain a low-impurity steel. The voltage was 23-25 V, the current intensity was 140-180 A, and the chemical composition of slag was 70% Al_2O_3-30%CaF_2 in a copper mold with the rotation of water. Chemical compositions of the non remelting (Sample1) and remelting steels (Sample2) were obtained from different parts of the samples using Quantometry test. The results are revealed in table 1.

Table 1: Chemical compositions of the steels (%Wt).

	C	Si	Mn	Cr	Ni	Mo	Cu	V	Al	P	S	Balance
Sample1	0.24	1.45	1.58	1.10	1.19	0.25	0.98	0.13	0.047	0.029	0.030	≈92.97
Sample2	0.24	1.04	1.31	1.10	1.19	0.25	0.98	0.13	0.047	0.027	0.012	≈93.67

The non-remelted and remelted steel ingots with thicknesses of up to approximately 17mm were hot rolled at a temperature range of 900-1000°C. To achieve this, first, both remelted and non-remelted samples were preheated at 1200 °C for 4 h. Then, the thickness of samples was reduced from 50 mm to 17 mm through three-step hot-rolling processes at a temperature range of 950-1000 °C. Finally, the hot-rolled samples were cooled to room temperature in air.

To homogenize the microstructure of samples, both remelted and non-remelted ones, and reduce the amount of segregations, a homogenization process was performed on them at 1200 °C for 4 h and was followed by air-cooling. Since both the rolled and the homogenized samples were cooled down in air and in a continuous manner, JIMAT PRO software was used to predict their microstructure.

A 2% Nital etch solution was used to study the microstructure of prepared steels. An optical microscope, model OLYMPUS PMG3™, was used to take the microscopy images. Also, a scanning electron microscope

(SEM), model Cam Scan MV 2300, equipped with an electron gun and with a voltage range of 15-20 KV was used to obtain microscopy images at high magnifications and to perform EDX analysis. To study the corrosion resistance behavior, samples of 1×1×1 cm^3 dimension were cut out of the prepared steels, and were tested using a polarization machine, model BHP2063+, after immersion in a saline solution (NACL 3%).
The abbreviations of the steels used in this research are listed in table 2 to better investigate their properties.

Table 2: Abbreviations of the steels used in this research.

Steels used in this research	Abbreviation
Remelted	ESR
non-Remelted	nESR
Remelted and homogenized at 1200 °C	ESR-H1200ºC
non-Remelted and homogenized at 1200 °C	nESR-H1200ºC

Results and Discussion

Optical microscopy image, SEM image and EDX analysis of nESR steel are shown in Figures 1 and 2, respectively.

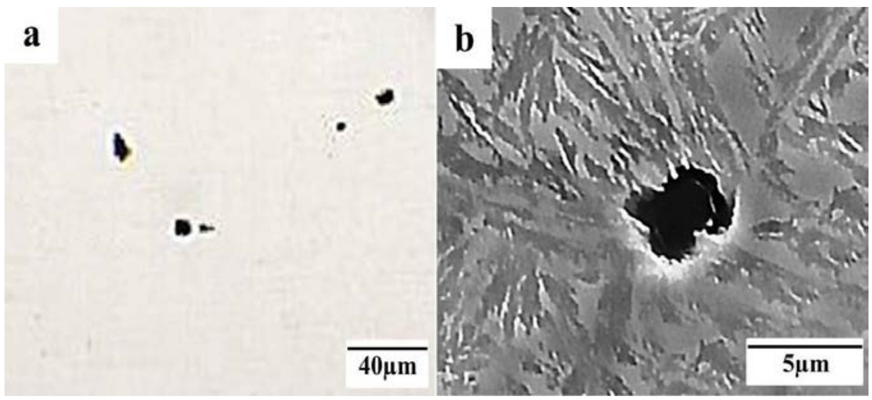

Figure 1: a) optical micrograph b) SEM micrograph of the inclusions.

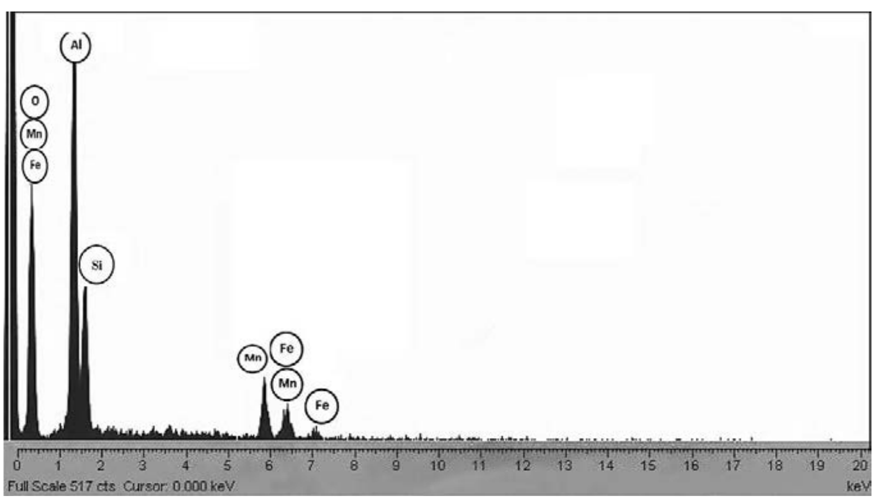

Figure 2: EDX analysis of inclusions in the nESR steel.

The observed inclusions in nESR steel are made of AL_2O_3 and size 20±2 µm. I should be mentioned that the polishing was done in cutting fluid (cutting oil) instead of regular Al_2O_3 containing polish solution to avoid any possible external contamination of Al_2O_3. The metallography investigation revealed the absence of presence of any inclusions or impurities in the ESR processes steel.

CCT graphs were obtained using the JMARPRO software to predict the possible transformations after hot-rolling process and/or homogenization treatment at 1200 ºC and are shown in Figure 3. Since the chemical compositions of remelted and non-remelted samples were similar, only one single CCT graph is drawn in this study.

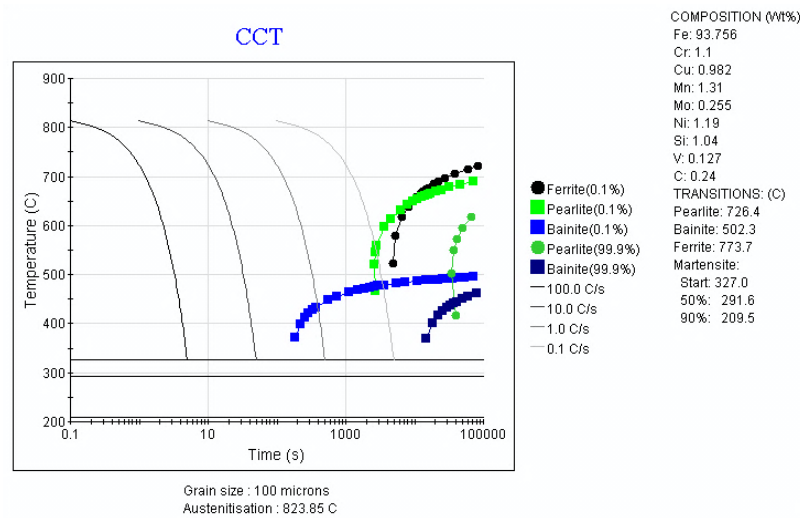

Figure 3: CCT diagram obtained using the JMAT PRO software for the studied steels.

By investigating the cooling rate of steels in this study, the cooling rate of hot-rolled and homogenized steels at 1200 ºC were 0.4 and 0.6 $\frac{°C}{s}$, respectively. The metallography results of the prepared steels in this study are shown in Figures 4.

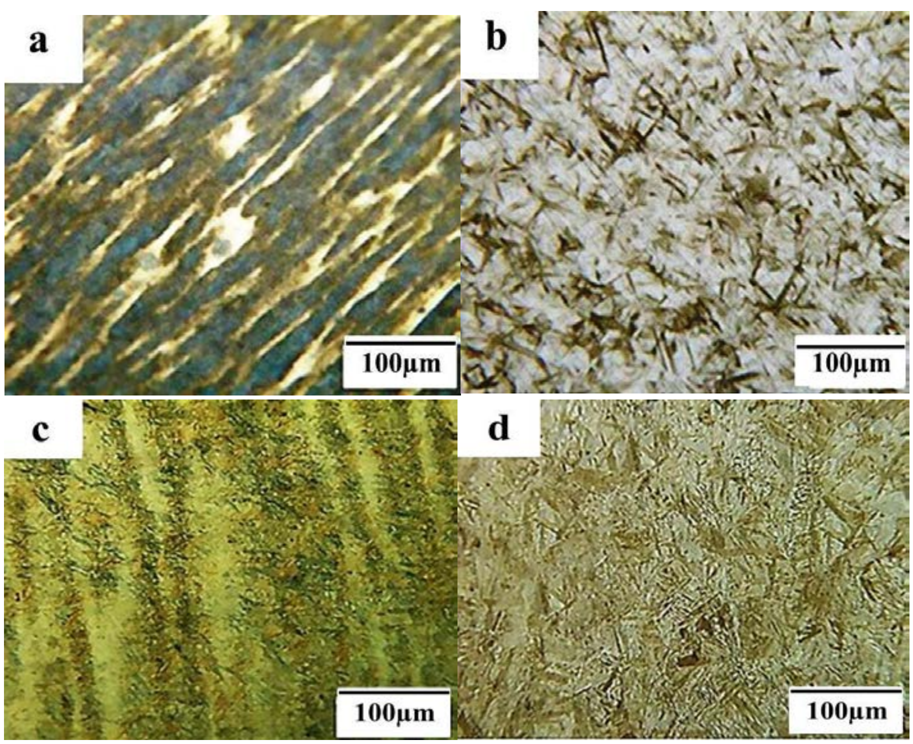

Figure 4: Optical micrographs of samples
a) non-homogenized b) homogenized nESR steels. c) non-homogenized and d) homogenized ESR steels.

Regarding the results obtained from metallography studies, we notice the presence of bainitic sheaves in the microstructure of the studied steels. The presence of bainitic sheaves in the steels has been predicted by the results of the JMARPRO software.

Figures 4 a and c show banding segregations in the hot-rolled steel. The presence of banding separations in the rolled steel is caused by the difference in the concentration of elements in the core and the surface of solidified dendrites. As shown in Figures 4 b and d, homogenization heat treatment at 1200 °C for 4 h resulted in banding segregation for the studied steels. By performing homogenization operations, the opportunity for the uniform distribution of the elements and reduction of the difference in the concentration of the elements in the core and the surface of solidified dendrites is provided. Reducing the difference in the concentration of the elements in the core and the solidified dendrites has led to the removal of banding segregation for the studied steels.

In order to investigate the effect of both remelting and banding segregation on the corrosion resistance of the steel, the steel samples were subjected to polarization test. The results of the polarization test are shown in Figure 5 and table 3.

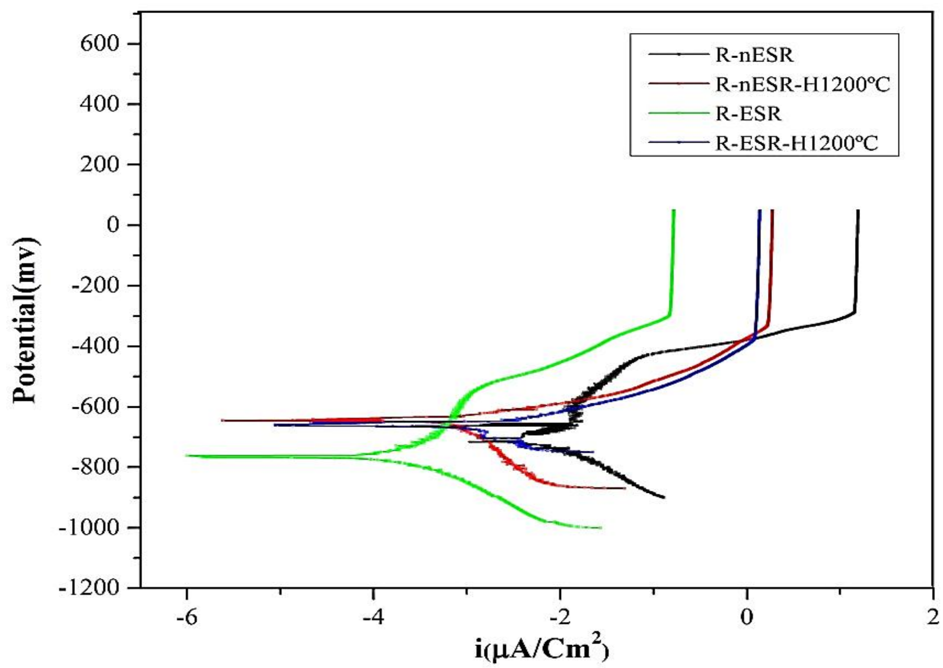

Figure 5: Results of the polarization test.

Table 3: Results obtained from Tafel diagrams for the investigated steels.

Type of Steel	iCorrosion (μA/Cm2)	ECorrosion (mA)
nESR	0.342	-730
ESR	0.221	-770
ESR-h1200 °C	0.130	-650
nESR-h1200 °C	0.194	-670

Since ESR-processed steels have no impurities and solification conditions in these steels were controlled, the increase in corrosion resistance in ESR steels has been predictable. Since the cooling rate of the ESR process was controlled and the casting was carried out in a cylindrical metallic mold with a low-thickness, the cooling rate was high due to the fact that the metal mold was surrounded by a copper coil and placed on a copper plate that played the role of a refrigerant, it has been expected to have directional cooling for ESR steels (Nafziger, 1976; Krauss, 2003; Grange, 1971). The localized solidification time (LST) in ESR steels was low due to the nature of the ESR process, and the reduction of LST resulted in reduction of the gap between dendrites and this gap between dendrites is further reduced by the hot rolling process (Nafziger, 1976; Krauss, 2003; Grange, 1971). Since the cooling rate is inversely related to the degree of segregation, the segregation is reduced in the ESR steels due to the high cooling rate. The reduction of segregations is effective on the corrosion resistance of the steels and leads to an increase in the corrosion resistance of the ESR steel. As shown in Figure1, in nESR steels, there are inclusions of the Al2O3 type, and no inclusions were found in ESR steels. The absence of inclusions in the ESR steels has been effective in increasing the corrosion resistance of these steel and has led to an increase in the corrosion resistance of these steels compared to nESR steel. As shown in Figures 4b and d, homogenization heat treatment has led to the removal of banding segregations. Removal of banding segregations by performing homogenization heat treatments has been effective in increasing the corrosion resistance of homogenized steels. As shown in Table 3, ESR-H1200°C and nESR-H1200°C steels have a better corrosion resistance than the other steels. ESR-H1200°C steel has a better corrosion resistance than the nESR-H1200°C steel because of its lack of inclusions.

Conclusions

1. ESR steels have higher resistance to corrosion due to the absence of inclusions and suitable cooling conditions.
2. The presence of banding segregations in rolled steels has reduced the corrosion resistance of these steels.
3. The homogenization heat treatment at 1200 °C for 4 h resulted in the removal of banding segregations for the investigated steels.
4. Among all the investigated steels, the ESR-H1200ºC steel had the highest corrosion resistance

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