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Comparison of Two Electroslag Remelting and Homogenization Processes on the Tensile and Impact Properties of Low-Alloy Steel

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Abstract: *The Electroslag remelting (ESR) and homogenization processes influence and decrease the segregation of alloying elements in steels considerably. The objective of this study was to examine the effects of homogenizing on the strength and ductility of low-alloy steel and then to compare the obtained properties with the electroslag remelted condition. To achieve this, a set of the primary ingots were melted and cast using an induction furnace and then electroslag were remelted. The second sets of ingots were homogenized at 1200°C instead of ESR processing subsequently after casting. All of the samples were analyzed with elemental analysis and x-ray diffraction after metallography. The evaluation of mechanical properties including tensile test, impact test, and microhardness measurements were carried out on both sets of the samples. It was observed that the homogenization process has more influence on improving strength and ductility of steel in comparison with the ESR process. Finally, it has been shown that reduction of segregation, the stability of retained austenite, and reduction of the thickness of bainitic ferrite sheaves could be achieved in homogenized samples.*

Keywords: *Low-alloy steel, Homogenization, Strength, Ductility.*

INTRODUCTION

The electroslag remelting process is one of the most important methods of remelting in which the electrode melts in droplets by being subjected to electric arc heating. Then, the droplets of molten metal are poured into the crucible and undergo solidification process at high speeds. In this process, the alternating electric current is used such that the electric current passes through the electrode, the slag layer, and the solidifying ingot. In this regard, the contact made between the molten metal droplets and the slag while the droplets are passing through the slag results in the occurrence of a series of reactions between the molten metal and the slag. For instance, due to the reaction between the molten metal and CaF_2, high degrees of desulphurization take place. The aim of using ESR process is to omit inclusions and impurities, as well as to provide a directional solidification structure with lower extents of segregation (Medovar, 1974; Hoyle, 1982; Presoly et al., 2008; Donachie et al., 2002; Nafziger, 1976; Holzgruber et al., 1973; Kawakami et al., 2013; Ksendzyk et al., 1981; Plockinger, 2005; Holzgruber, 2000; Junichi et al., 1972).

During ESR process, some reactions take place due to the interactions between molten metal droplets and the electric slag. Such reactions consequently result is the omission of inclusions and impurities (ZHAO et al., 2011). In this regard, the chemical composition of slag, the value of the frequency which is applied for ESR process, the remelting rate, and the effect of the protective atmosphere are some factors that influence the omission of inclusions and impurities (Nafziger, 1976; Holzgruber et al., 1973; Kawakami et al., 2013; Ksendzyk et al., 1981). The effect of slag chemical composition and the type of deoxidant over the presence of non-metal inclusions in low-alloy steel has been studied by Mitchell et al. (1984). The results of this study showed that if the activity of SiO_2 in the slag is low, then, the amount of alumina inclusions increases. Also, too much increase in the activity of SiO_2 results in the formation of silicate-alumina inclusions. Mattar et al. (2001) examined the ESR process of tool steels and showed that the chemical composition of CaO/Al_2O_3=0/%50 slag has the highest desulphurization efficiency due to possessing proper viscosity and surface tension. Yamaguchi et al. (1973) have shown that increasing the applied frequency in ESR process results in decreasing the dispersion and area of inclusions. Also, Bonneviate et al. (1998) have shown that decreasing the remelting rate results in increasing the reaction time between molten metal and slag and consequently results in decreased extent of the presence of inclusions. The effect of the protective atmosphere on the amount of retained hydrogen and decreased extent of the presence of inclusions in the remelted steel was investigated by Chen et al. (2013). The depth of the molten bath is one of the solidification parameters which affect the quality of remelted ingots. In this regard, Chang et al. (2008) used a numerical simulation of temperature fields in electroslag remelting slab ingots and showed that decreased depth of molten bath results in decreased local solidification time and the segregation extent. Difference between the concentrations of elements at the center against the surface of solidified dendrites is responsible for segregation. Elements such as manganese, chromium, and molybdenum are among the important elements in the formation of segregation in steels (Majka et al., 2002; E.T. Turkdogan and R.A. Grange, 1970; R.D. Doherty and D.A. Melford, 1970; R.A. Grange, 1971). Voldrich et al. (C.B. Voldrich, 1947) have shown that during cooling of low-alloy steels, carbon migrates from low manganese zones to high manganese ones, which affects the formation of segregation by itself. In order to omit the segregations, have uniform elemental distribution, and increase the strength of steel, the homogenizing heat treatment is used (Krauss, 2003; Krauss, 1990). Madang-Chen et al. (Jian et al., 2009) conducted a study on the effect of homogenizing heat treatment on the H13 steel and showed that performing homogenizing heat treatment at high temperatures before the warm forging process results in the omission of a considerable amount of segregation and improves the impact resistance of the steel.

The ESR process and homogenizing heat treatment affect the structural and mechanical properties. Based on the above, the objective of the present study was to examine the effect of ESR process and homogenizing heat treatment on the microstructure and mechanical properties of low-carbon cast steel.

Materials and Experimental

The primary ingot was melted using an induction furnace with an inert gas atmosphere having a capacity of 10 Kg. A metal mold was used for pouring the metal and aligned with it the ESR process was performed in order to have a steel which is free from inclusions with lower amounts of impurity. 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. Finally, the chemical composition of steel before and after ESR was presented as in Table 1.

Table 1: The chemical composition of non-remelted and remelted samples (wt%)

	C	Si	Mn	Cr	Ni	Mo	Cu	V	Al	P	S	Balance
Without ESR	0.24	1.45	1.58	1.10	1.19	0.25	0.98	0.13	0.047	0.029	0.030	≈92.97
Afrer ESR	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^{o}C. In order to obtain structures with lower segregation and compare the effect of ESR process and homogenizing on the samples, the only rolled non-ESR samples were homogenized at 1200°C for 4 hours.

Evaluation of the primary microstructure of samples was performed after grinding, polishing, and etching samples according to the metallography process standard using an optical microscope, model OLYMPUS PMG3TM. More precise microstructural studies were conducted on Cam Scan MV 2300™ scanning electronic microscope (SEM) and line scanning analyses were carried out on the same SEM instrument when they were needed. X-ray diffraction was used for determining the volume fraction of high-carbon retained austenite within the microstructure using a BRUKER-AXS D8™ diffractometer. Following this and in order to omit the deformed layers, the XRD samples were etched and polished several times. Afterward, the amount of retained austenite was measured by using an intensity of (200), (220), and (311) austenite peaks, and (200), (211), and (220) ferrite peaks. The XRD tests were carried out in the 2θ range of 40-101° under CuK_α radiation.

Aligned with this, high-magnification SEM images and linear intercept method were used in order to define the uniform size distribution of bainitic subunits. For this purpose, a minimum of 80 measurements from 10 images at different magnifications were performed from several zones of samples and the average amount was reported.

The tensile tests were performed on the samples which were cut parallel to the rolling direction according to standard JIS Z2201. Minimum three tensile tests were used for each tensile test run such that the repeatability of the test was assured. In this regard, all tests were carried out at an ambient temperature. Moreover, Charpy impact tests were carried out according to the standard of impact test equipment model Roell Amsler™. Then, five tests were done on the notched samples with dimensions of 10x10x5mm^2 at room temperature and the reports are the average of at least three measurements. In the end, the microhardness test was carried out with a load of 100gr.

Results and Discussion

Figure 1 presents the optical microscopy (OM) images for samples as remelted, non-remelted, and homogenized at 1200°C. According to these images, the microstructural results revealed bainitic sheaves in light areas, high-carbon retained austenite, and martensite. Bainitic transformation starts by non-equilibrium bainitic ferrite nucleation and goes on by shear growth of sheaves. As the growth of bainitic ferrite goes on, its extra carbon is pushed back into the austenite. Consequently, the presence of retained carbon in solid solution results in addition of higher amounts of silicon to the chemical composition. Afterward, the bainitic transformation at high silicon amounts results in the formation of bainitic ferrite plates by shear mechanism along with the diffusion of carbon atoms into the austenite after the growth of plates. In this regard, high amounts of carbon result in M_s temperature reduction, increased volume fraction of bainitic ferrite, and stability of these phases at room temperature. According to the optical microscope (OM) images, the bainitic sheaves which are parallel with different crystallographic directions are separate from block austenite or martensite.

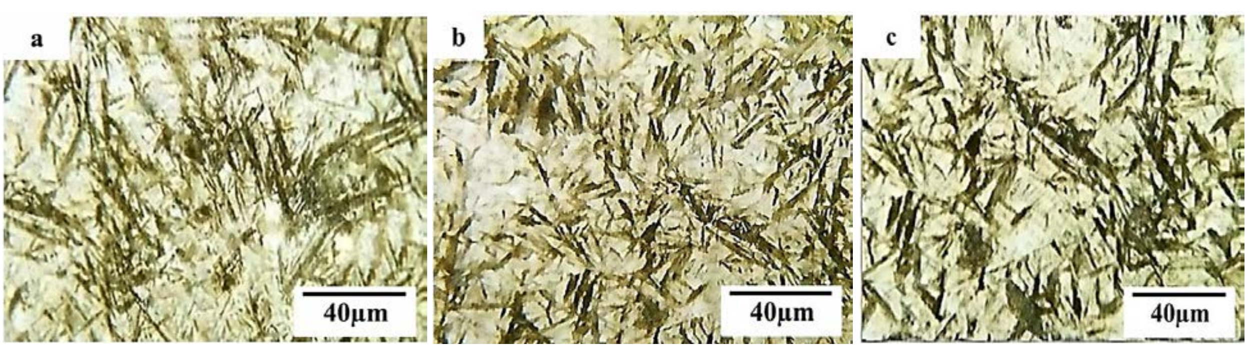


Figure 1. Optical microscope images of the studied steels
a: Without ESR, b: Without ESR-Homogenised at 1200 °C, C: After ESR.

Retained austenite has two morphologies: film and block shaped. Film-shaped austenite is in the shape of narrow films between bainitic ferrite sheaves. This type of austenite is stable due to the presence of high carbon amounts which results in improved mechanical properties. Block-shaped austenite is located between bainite sheaves; this type of austenite is unstable and is transformed due to the insertion of a small amount of stress onto brittle high-carbon martensite, which results in decreased mechanical properties. In order to distinguish between the sizes and shapes of austenite films and bainitic ferrite plates and bainitic ferrite sheaves, SEM images with high magnifications were used. Figure 2 presents the alternative layers of dark bainitic ferrite and light austenitic films which are aligned with crystal directions of each bainitic sheaf.

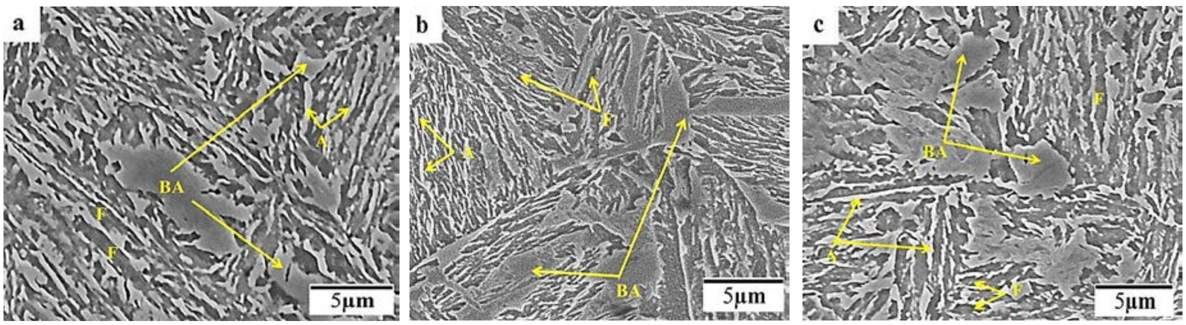
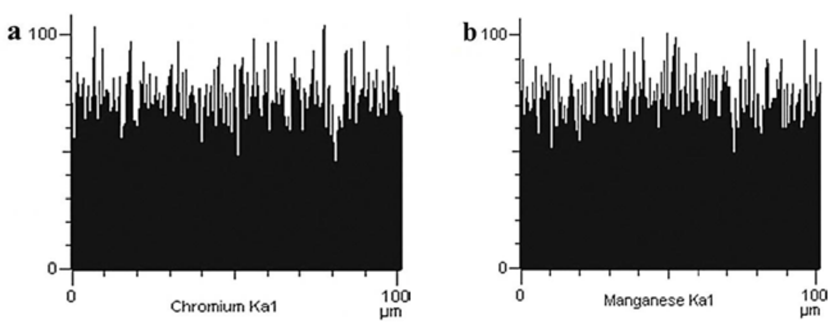


Figure 2. SEM images of the studied steels
a: Without ESR, b: Without ESR-Homogenised at 1200 °C, C: After ESR.

In order to investigate the effect of homogenizing, linear analysis of manganese and chromium elements was performed using SEM. In this regard, figure 3 shows homogenizing at 1200^{o}C for 4 hours which results in the reduction of the extent of segregation of manganese and nickel elements. Elements such as manganese, chromium, and molybdenum result in segregation. Also, the difference between the concentrations of elements at the center against the surface of solidified dendrites results in segregation during the formation operation. Considering this, the opportunity which is necessary for diffusion and even distribution of elements and decreasing the segregation extent in the microstructure is provided by performing homogenizing heat treatment.



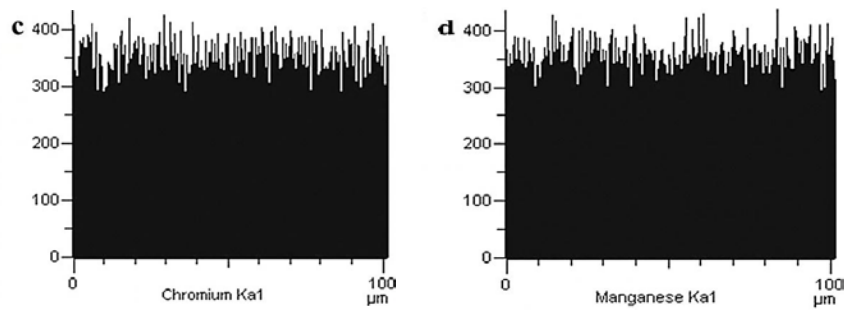


Figure 3: Elemental analysis of samples. a, b) Without ESR and c, d) Without ESR-Homogenized.

Table 2 and Figure 4 present a summary of the effects of the ESR process and homogenizing on the thickness and changes of bainitic ferrite sheaves. According to Table 2 and Figure 4, homogenizing has a higher effect on the thickness reduction and thickness changes of bainitic ferrite sheaves in comparison with the ESR process. In this regard, even distribution of elements and the strength of austenite are some of the most important effective parameters in the thickness of bainitic ferrite sheaves. As can be seen from the results of line scanning analysis of manganese and chromium elements (figure 3), homogenizing heat treatment reduces the effect of such elements on the microstructural segregation as well as the segregations in non-ESR Homogenized samples. This matter consequently results in the even distribution of elements as well as the strength of austenite. The movement of bainitic ferrite interface gets more limited by using a steel with a higher strength and thinner bainitic ferrites were obtained.

Table 2: The results of thickness measurements on ferrite sheaves

Sample Name	Average Thickness of Bainitic-Ferrite subunits (nm)
Without ESR	222.19
Without ESR-h1200°C	166.64
After ESR	185.96

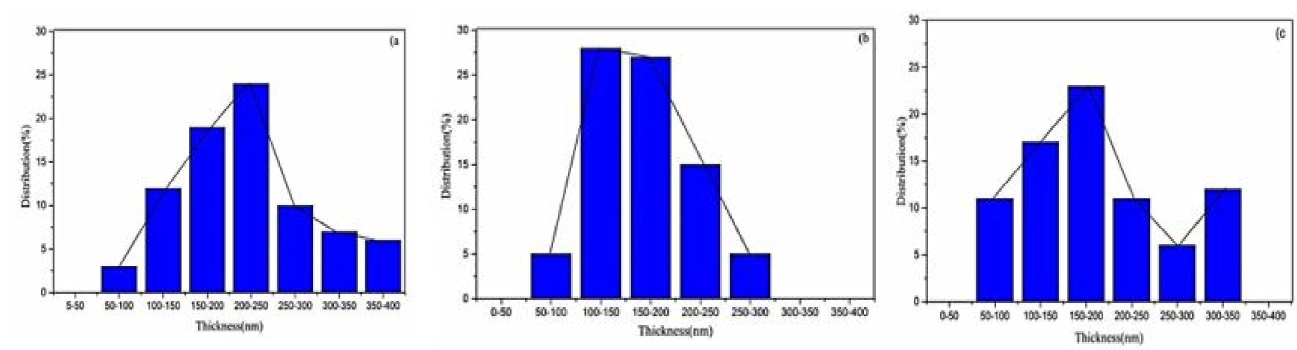


Figure 4: Distribution of the size of bainitic ferrite subunits
a: Without ESR, b: Without ESR-Hemogenised at 1200 °C, C: After ESR samples.

Low amounts of average thicknesses of bainitic ferrite sheaves after ESR in comparison with non-ESR samples is related to the nature of ESR process. ESR process results in lowering the extent of segregation of alloy elements as well as the reduction of volume fraction of inclusions and impurities. Regarding this matter, low amounts of segregation and volume fraction of inclusions after ESR have already been shown by researchers such as Chang and Medovar (Medovar, 1974; Chang, L. Z., and B. Z. Li, 2008). Reduction of local solidification times after ESR which results in the reduction of the extent of segregation of alloy elements and their even distribution in the microstructure has a direct effect over the strength of austenite and its even distribution, and consequently results in the thickness reduction and changes in the thickness of bainitic ferrite sheaves. The results obtained by measuring the bainitic ferrite sheaves in the non-ESR homogenized samples approve the results of EDX analysis. Furthermore, performing homogenization process reduces thickness and changes in the thickness of bainitic ferrite sheaves by reducing the effect of elemental segregation.

Figure 5 presents a summary of XRD results for the samples which were studied. According to these results, after ESR, samples have higher amounts of retained austenite in comparison with non- ESR samples. This is in such a way that ESR results in higher stability of austenitic-microstructure phase at room temperature. Moreover, the amount of retained austenite for non-ESR samples is lower than non-ESR Homogenized samples. It seems that homogenization heat treatment results in the stability of the amount of retained austenite in steel at room temperature, just like the ESR process.

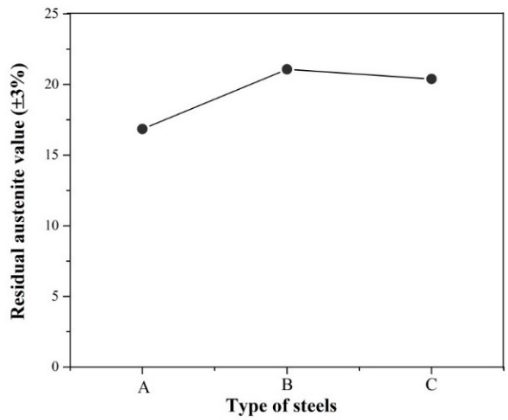


Figure 5: The residual austenite values for the studied samples
A: Without ESR, B: Without ESR-Hemogenised at 1200 °C, C: After ESR.

It seems that high amounts of retained austenite after ESR and non-ESR Homogenized samples are related to the changes in the extent of segregation as well as the even distribution of elements at different points of microstructure.

The extent of segregation of austenite stabilizer elements such as manganese and chromium in non-ESR Homogenized steel has decreased by performing the homogenizing heat treatment and this has resulted in higher stability of austenite. Additionally, high amounts of retained austenite after ESR, in comparison with non-ESR is related to the long local solidification times in such steels, reduction in volume fraction of inclusions and consequently, reduction in the extent of segregation and even distribution of elements all over the microstructure. Also, the higher volume fraction of retained austenite after ESR and non-ESR homogenized samples has resulted in decreased hardness of these samples as shown in Figure 6.

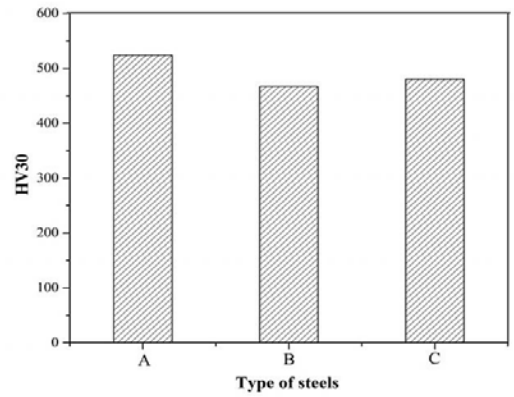


Figure 6: The results of the Micro-hardness test
A: Without ESR, B: Without ESR-Homogenised at 1200 ºC, C: ESR.

Changes in the microstructural characteristics affect the mechanical properties. Table 3 presents the results of tensile tests at room temperature. According to this table, it seems that the ESR process influences segregation reduction, thickness of bainitic ferrite sheaves, and volume fraction of inclusions. It also results in increased tensile strength in comparison with the non-ESR samples. Performing the homogenizing process at a temperature of 1200^{o}C reduces the effect of segregation of manganese and chromium elements (figure 3). Moreover, the minimum thickness of bainitic ferrite sheaves and maximum tensile strength will be provided for the homogenized samples.

Table 3: The tensile properties of the studied samples

Sample Name	Tensile Stress (MPa)	Total Elongation (%)
without ESR	1265.35	16
Without ESR-Homogenized at 1200 ºC	1450	19
ESR	1348.1	18

Figure 7 shows the fracture surfaces of the tensile test samples. The samples which have high amounts of elongation have ductile fracture structures with higher amounts and larger dimples.

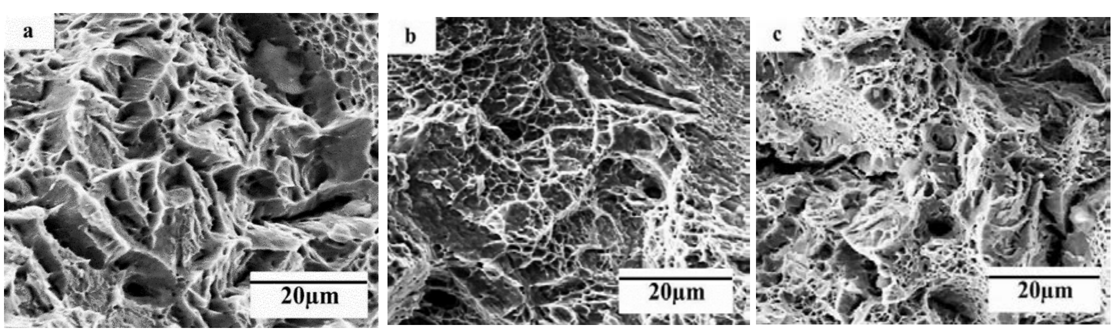


Figure 7. Fractography of the tensile test samples
a: Without ESR, b: Without ESR-Homogenized at 1200 ºC, C: After ESR samples.

Table 4 presents the impact test results related to the samples of this study. Accordingly, the results show that the samples with a higher percentage of elongation have higher fracture toughness; the reduction of segregation effects and volume fracture of inclusions during ESR process and homogenizing result in increasing impact energy after ESR and homogenized samples.

Table 4. The results of measurements on impact energy of the studied samples

Sample Name	impact energy (j)
Without ESR	42±2
Without ESR-h1200°C	63±2
After ESR	57±2

Performing homogenizing process has a higher influence over the improvement of mechanical properties and toughness in comparison with ESR process. In this regard, homogenizing at a temperature of 1200°C has higher effects on lowering the extent of segregation, even distribution of elements, decreasing the thickness of bainitic ferrite sheaves, and stability of austenite structure in comparison with ESR process. Figure 8 shows that samples with high toughness properties have a ductile fracture with fracture surfaces similar to the tensile test samples.

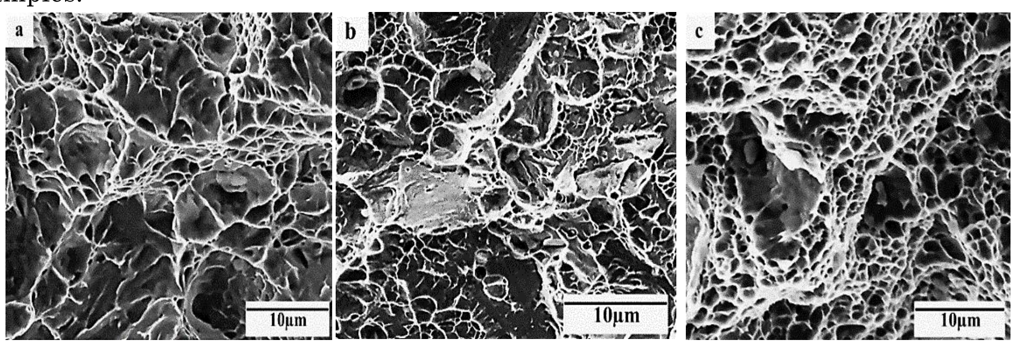


Figure 8: Fractography of impact test samples
a: Without ESR, b: Without ESR-Homogenized at 1200 °C, C: After ESR samples.

Considering the fractography results, the extent of the ductile fraction is higher after ESR and non-ESR homogenized samples, which implies improvements of tensile and toughness process by ESR process and homogenizing heat treatment.

Conclusion

Homogenizing heat treatment at 1200°C for 4 hours reduces the extent of segregation of manganese and nickel elements and has larger effects on the high stability of retained austenite compared to ESR process, resulting in the improvement of mechanical properties of non-ESR Homogenized samples in comparison with ESR samples.

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