Materials Research. 2021; 24(6): e20210299
DOI: https://doi.org/10.1590/1980-5373-MR-2021-0299

Influence of Residual Elements Contained in Steel Scrap for the Production of Nodular Cast Iron

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Received: June 20, 2021; Revised: July 26, 2021; Accepted: August 04, 2021

Nodular cast iron is a fundamental material used in engineering. It has unique properties and is one of the most produced materials in the world nowadays. The production of nodular cast iron involves melting of raw materials such as steel scrap, pig iron, machining returns and alloy irons. With the development of increasingly technological steels through the addition of chemical elements to meet a specific application, there is an increasing difficulty in acquiring steel scrap content low alloy for the production of nodular cast iron. The chemical elements present in the steel scrap favor the appearance of unwanted phases and particles. The present study evaluated the effect of the addition of the elements copper, chromium, molybdenum and nickel in levels between 0.50% w and 1.0% w in the formation of nodular cast iron microstructure. While nickel and copper were evenly distributed in the matrix, chromium and molybdenum formed carbides. In addition, chromium strongly favored the formation of perlite in nodular cast iron and molybdenum, the martensite.

Keywords: *Ductile cast iron, matrix, nodules, chemical elements addition, microstructure and mechanical properties.*

1. Introduction

Cast iron represents a family of alloys composed by graphite wrapped in a metallic matrix[1]. It is considered the 1st composite material produced by man and one of the most manufactured alloys in the world[2,3]. Due to the various possibilities for modifying the microstructure, cast irons have numerous applications, being a more viable competitor even for some steels. Nodular cast iron (NCI) is a class of cast iron in which graphite is in spherical form, or nodules[4]. Therefore, property changes are achieved by adjusting the matrix microstructure to suit a specific application. Commercial ductile cast iron may present in its microstructure ferrite, perlite, ferrite-pearlite, cementite, martensite or ausferrite[5]. These phases can be obtained in the casting process by the chemical composition of the raw material, melting temperature, pouring temperature, inoculation, nodulization, cooling rate during solidification and by heat treatments[3,5-8].

Currently, many studies have been conducted to understand the effect of chemical elements on the microstructure and properties of nodular cast iron. Especially when these elements come from the use of recyclable materials. Steel scrap is one of the main materials used in the production process of nodular cast iron.

Due to the growing demand for steels with improved properties, chemical elements are added to suit a specific application. Thus, the unwanted addition of small amounts of chemical elements occurs through the recycling of steel scrap to produce nodular cast iron[9].

This work fills a gap in knowledge about the effect of small additions of chemical elements such as copper, nickel, molybdenum and chromium, in the process of casting by centrifugation in metallic mold to produce nodular cast iron.

2. Materials and Methods

2.1. Material

In this work the material used is an automotive ductile cast iron. Its chemical composition is presented in Table 1. The main difference refers on the Mo, Cu, Ni and Cr alloys content.

2.2. Ductile irons production

The ductile irons were melted in a medium frequency induction furnace to temperature of 1450 ºC by addition of steel scrap (5 wt pct), pig iron (25 wt pct), ductile iron returns (70 wt pct), graphite, Fe-Si-75 wt pct. Spheroidizing practices was performed in a conventional sandwich method with 0.9 wt pct Fe-Mg-Si in a 120 Kg ladle capacity. Inoculation practice was performed in 3 parts, the first one in the laddle during transference of liquid metal, second one in the crucible and the last one in the mold. Additions used for this work are: Ferrochrome (56% Cr) nickel metallic, ferromolybdenum (80% Mo) copper (wire 98%). The sequence of additions can be seen in Figure 1. The metal was poured into metallic

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Table 1. Chemical compositions of ductile cast iron (wt pct).

MELT	*C*	*Si*	*Mn*	*P*	*S*	*Mo*	*Cu*	*Ni*	*Cr*	*Mg*
Ni								0.9080		
Cr									0.7420	
Mo						0.7630				
Ni/Cr								0.854	0.821	
Mo/Cu						0.771	0.734			
Cu/Ni							0.712	0.924		
Mo/Ni						0.869		0.897		
Mo/Cr						0.412			0.877	
Cu/Cr							0.504		0.558	

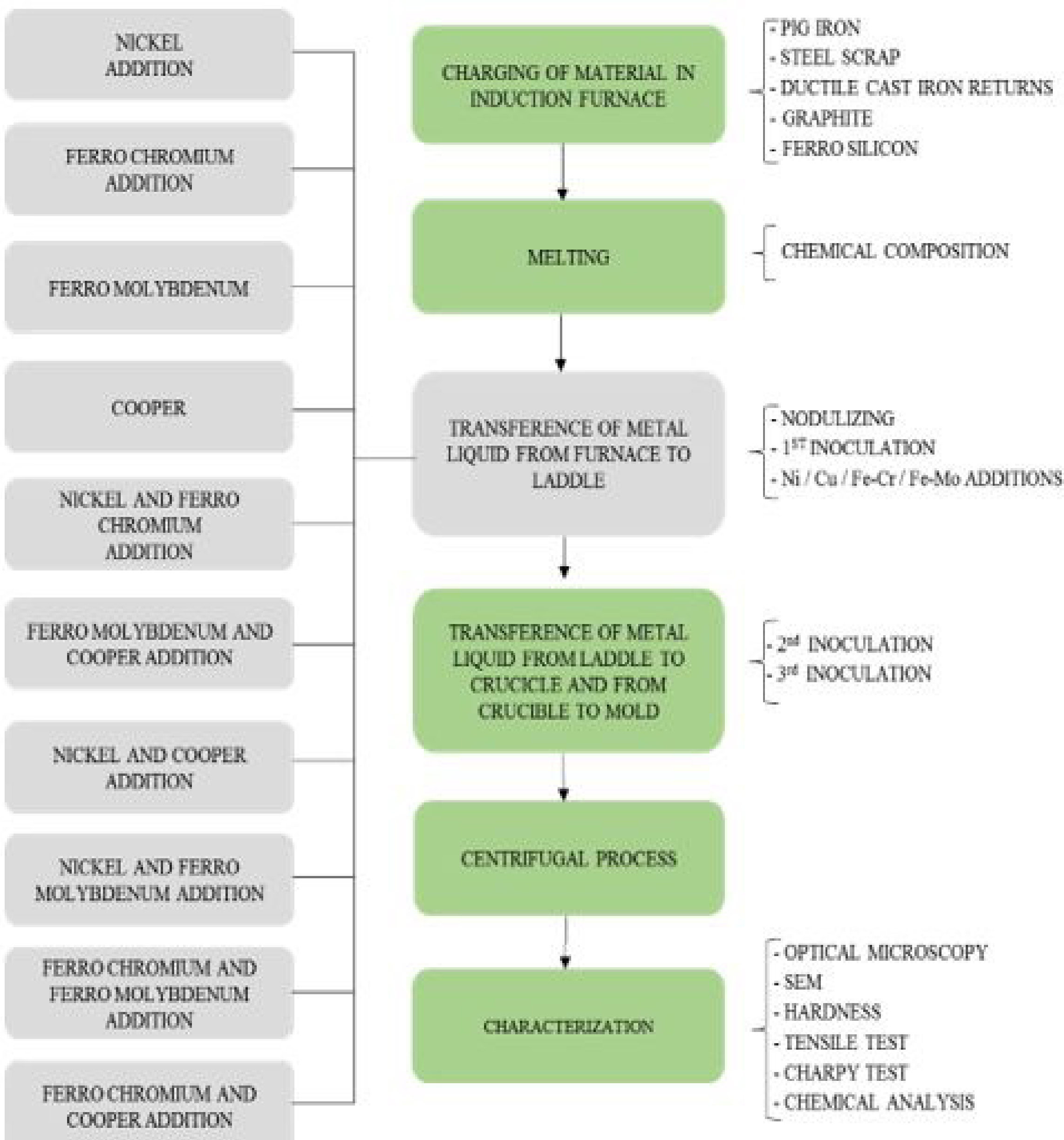


Figure 1. Route used for ductile cast iron analysis.

mold in a horizontal centrifugal machine to obtain cylindric tubes shown in Figure 2 and Figure 3. As casted dimensions are length 1,243 mm, outside diameter 115 mm and inside diameter 86 mm.

2.3. Characterization

The microstructure changing was determined by optical microscopy, scanning electron microscope (SEM), hardness, tensile test and Charpy test.

For the microstructural analysis, the specimens were ground with 120, 320, 400, 600, and 1200-grit SiC papers and polished with 3 diamond suspension, 1 µm diamond paste and colloidal silica. Then, samples were etched with a nital 2% solution to determine the microstructure using optical microscope Leica, model DMI 5000M image analyzer LAS V-4.5) and scanning electron microscope (Jeol, model JXA-840A). Tensile specimens with the dimensions shown in Figure 4 were machined in the same direction of the long of cast, Figure 5. Three tensile specimens for each condition were tested in a 250 kN hydraulic EMIC DL 3000 universal testing machine using a constant cross-head travel speed of 4 mm/min and the procedure ASTM E18-12[10] as reference.

Notched Charpy specimens, with the dimensions 55 mm x 10 mm x10 mm were machined in the same direction of the length of casted as shown in Figure 6. Charpy test was

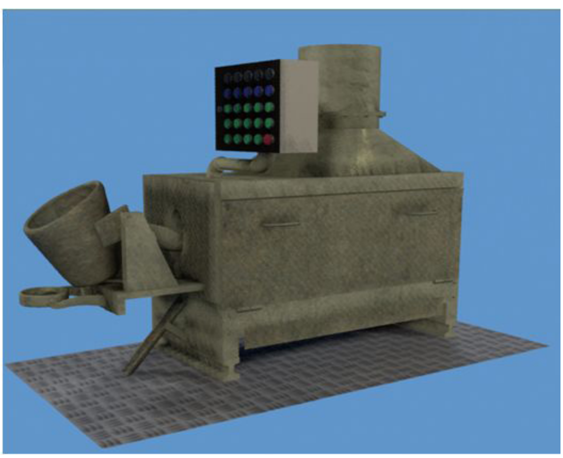


Figure 2. Centrifugal casting machine.

Figure 3. NCI in cylindric shape.

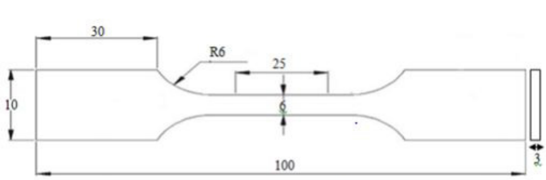


Figure 4. Tensile specimens dimensions (mm).

Figure 5. Tensile test specimen.

Figure 6. Charpy test specimens.

performed as ASTM E8M-04[11] in a Charpy tester machine model JB-300AI/C maximum energy of 300 Joules.

Hardness was performed using an OTTO WOLPERT-WERKE tester machine. Each hardness result was determined from an average of six measurements per sample with a load 100kg and a steel ball 10 mm diameter.

3. Results and Discussions

The graphite nodules were evaluated in terms of quantity, shape and size, according to the ASTM 247-16 standard[12]. Nodularization was above 95%, as calculated by Equation 1:

$$\text{Nodularization}(\%) = \frac{\text{Tipo l} + \text{Tipo ll}}{\text{Tipo l} + \text{Tipo ll} + \text{Tipo lll} + \text{Tipo lV}} \quad (1)$$

According to Murcia et al.[13] a minimum degree of nodularization of 65% is a requirement for a cast iron to be considered nodular. Another factor to be considered is the presence of graphite nodules. The best situation refers to the largest number, the most spherical shape (type 1) and the most homogeneous distribution of the nodules in the matrix, Figure 7 and Figure 8.

Type l graphite nodule is the preferred form for nodular cast iron and it is observed that it is predominant for all samples studied. This shape is desirable, as it is the one that best approaches a perfect sphere and, therefore, the one that is least susceptible to concentrating tension in service[14]. Nodules of graphite are uniformly dispersed within matrix indicating a homogeneity of properties associated with this structure, Figure 8 and Figure 9. Only exception refers to Cr/Mo addition. In this case graphite is present in lamellar form which indicates a poor nodulization performance.

Ferrite was found in all samples in this study. The maximum ferrite content (40%) was observed for the sample containing Ni. Perlite was found in all samples, ranging in content from 30% to 90%. Notably, the highest percentage values of perlite were exhibited by the samples containing chromium, between 85% and 90%The martensite was observed in 3 samples, varying in content between 35% and 50%, and molybdenum is the common element for the 3 cases, Figure 10. Martensite, in general, is present in regions with fewer nodules.The samples without chromium addition, presented bull's-eye ferrite rim around the nodules. The microstructure for each condition as shown in Figures from 11 to 19.

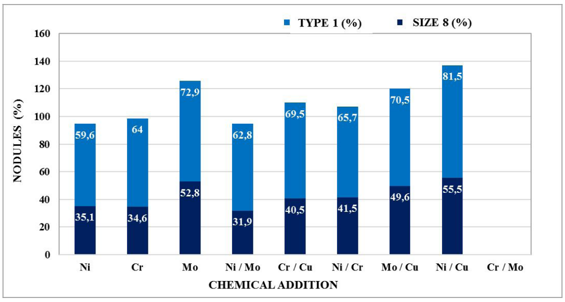


Figure 7. Nodules type and size.

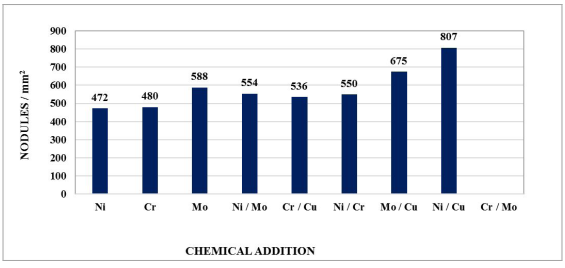


Figure 8. Nodules quantity.

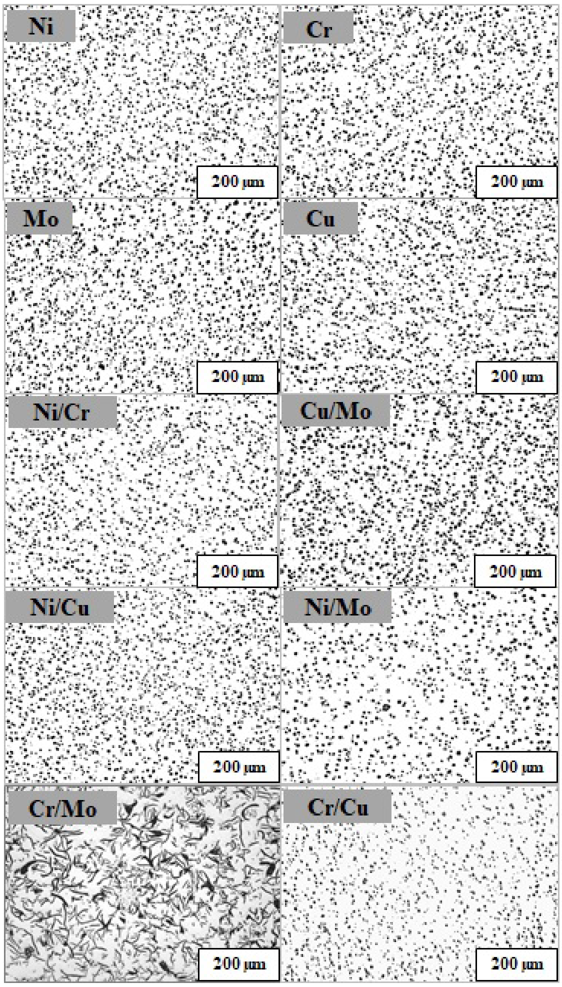


Figure 9. Graphites shapes.

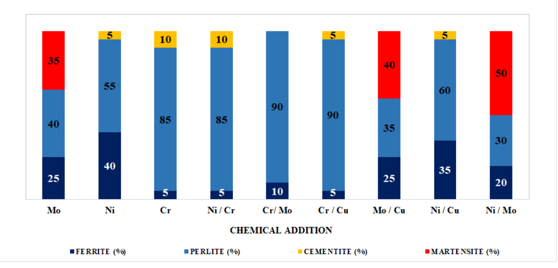


Figure 10. Matrix contents.

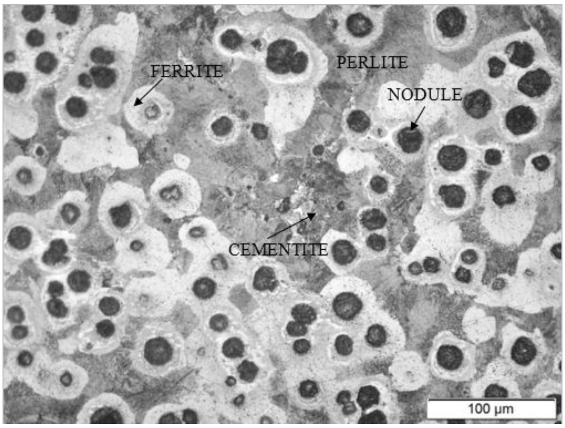


Figure 11. Matrix for Ni addition.

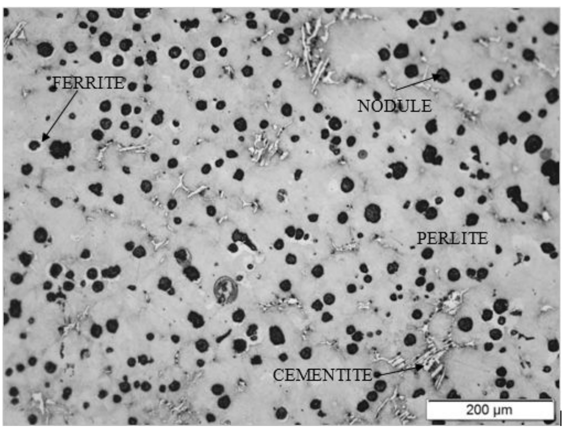


Figure 12. Matrix for Cr addition.

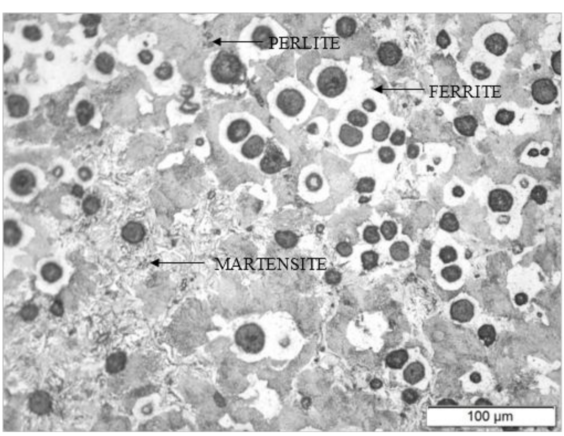


Figure 13. Matrix for Mo addition.

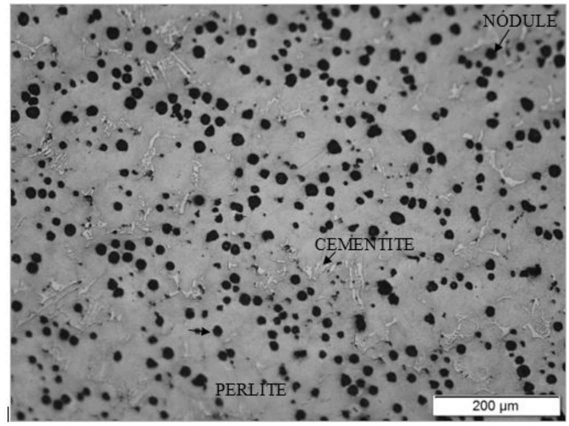


Figure 14. Matrix for Ni/Cr addition.

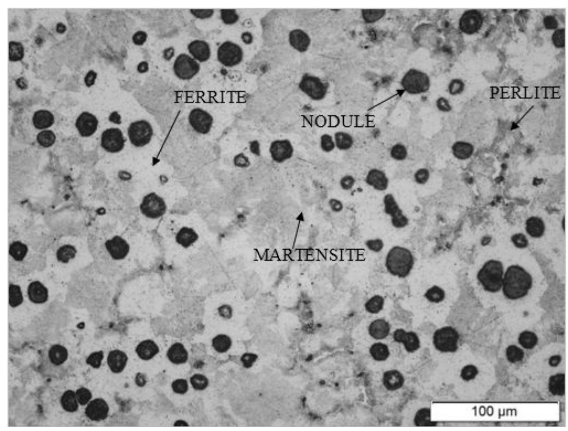


Figure 15. Matrix for Mo/Cu addition.

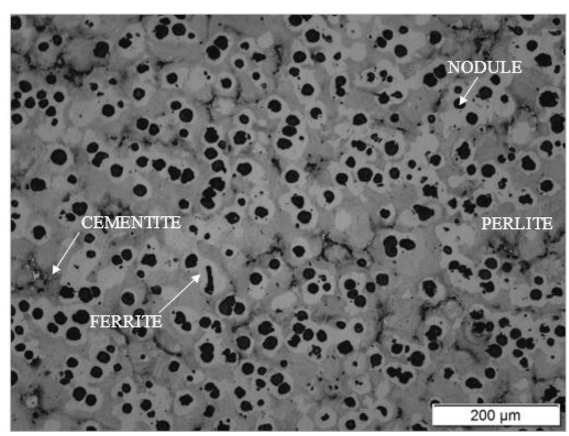


Figure 16. Matrix for Ni/Cu addition.

In accordance with EDS profile, Ni and Cu are homogeneously dispersed in the matrix as can be seen in the Figures 20, 21, 22, 23, 24 and 25. Nevertheless, in the Figure 20, Ni content decreased steeply on interface ferrite/perlite. In other hand, Cr and Mo profile in EDS analysis, shows peaks indicating Cr-rich carbides and Mo-rich carbides, as showed in Figures 22, 23, 24, 25, 26, 27 and 28. This means the segregation of Cr and Mo during solidification forms carbides around the cell boundaries and considering the cast dimension, its concentration must be limited. Mo and Cr carbides decrease the cast iron ductility. Figure 28 shows a region Cr and Mo rich carbides. In this case, Mo and Cr are homogeneously dispersed both in the matrix and in the carbide region. EDS profile for Figure 28, shows a lighter region composed by Mo-rich carbide. It means this ductile cast iron, is formed by Mo/Cr carbides and Mo carbides.

The hardness of a nodular cast iron is strongly affected by the microstructure obtained in the raw state of casting with the addition of chemical elements. According to Cho et al.[15], Mo and Ni increase hardness by solid solution. The percentage of perlite in the matrix of nodular cast iron is directly related to the presence of chromium. The highest hardness values were observed for samples containing perlite above 85%, Figure 29. Chromium increases hardness by promoting pearlite and by forming dispersed chromium carbides in the matrix.

Ferrite increases the ductility of nodular cast iron, increasing the impact resistance energy. Microstructural components of high mechanical resistance have the effect of reducing the energy of impact resistance, such as perlite and martensite. On the other hand, ductile phase such as ferrite has the opposite effect as Ni addition in Figure 30.

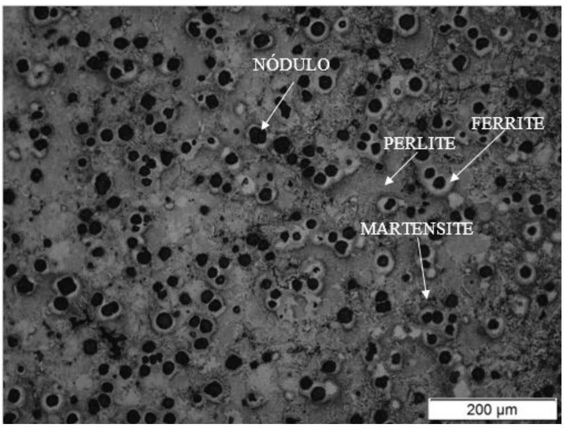


Figure 17. Matrix for Ni/Mo addition.

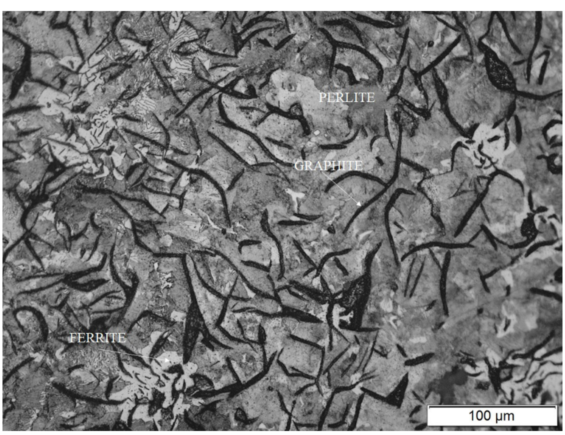


Figure 18. Matrix for Cr/Mo addition.

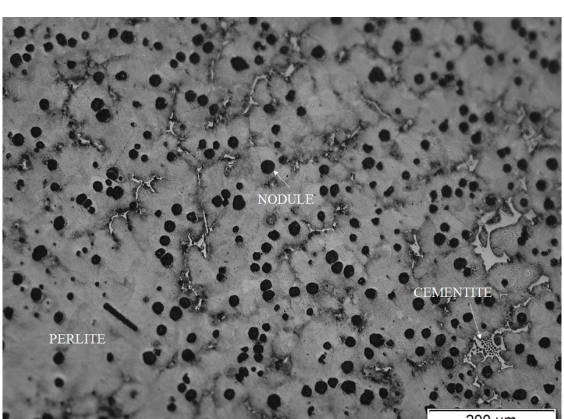


Figure 19. Matrix for Cr/Cu addition.

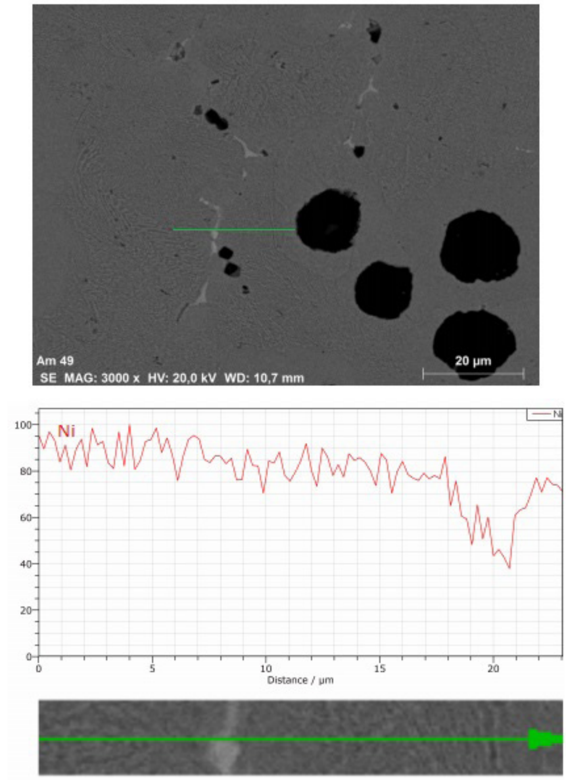


Figure 20. Ni EDS profile.

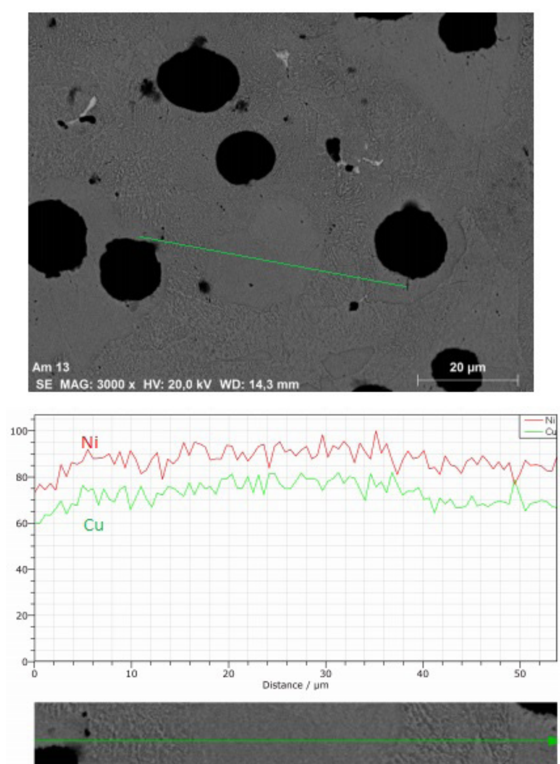


Figure 21. Ni/Cu EDS profile.

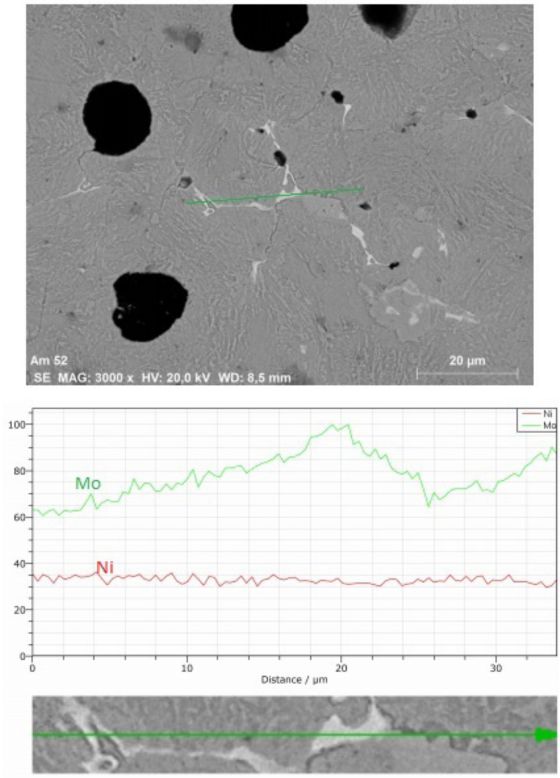


Figure 22. Ni/Mo EDS profile.

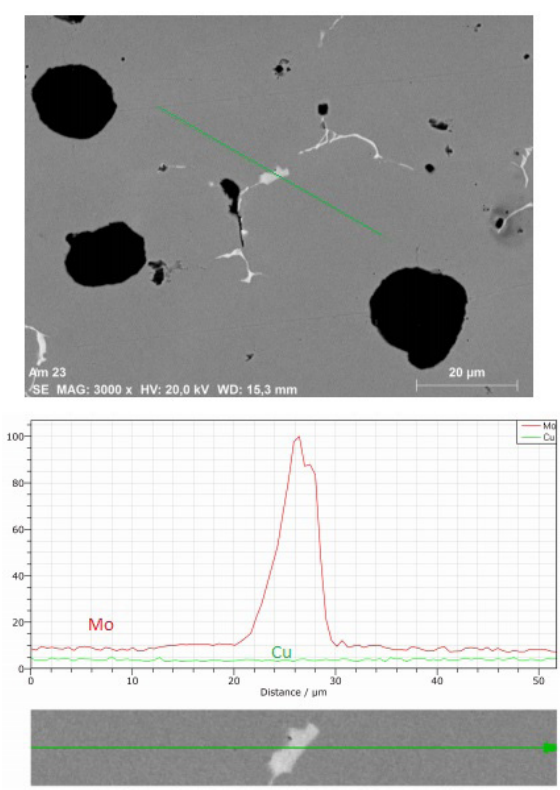


Figure 23. Mo/Cu EDS profile.

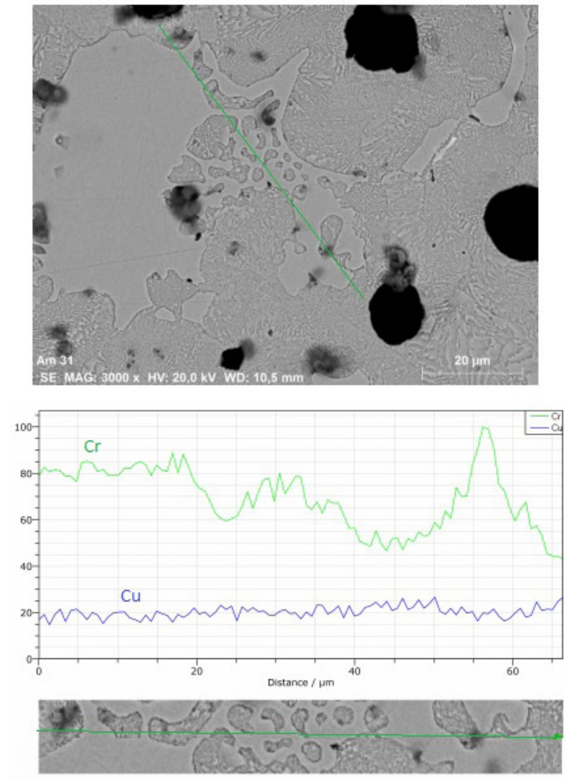


Figure 24. Cr/Cu EDS profile.

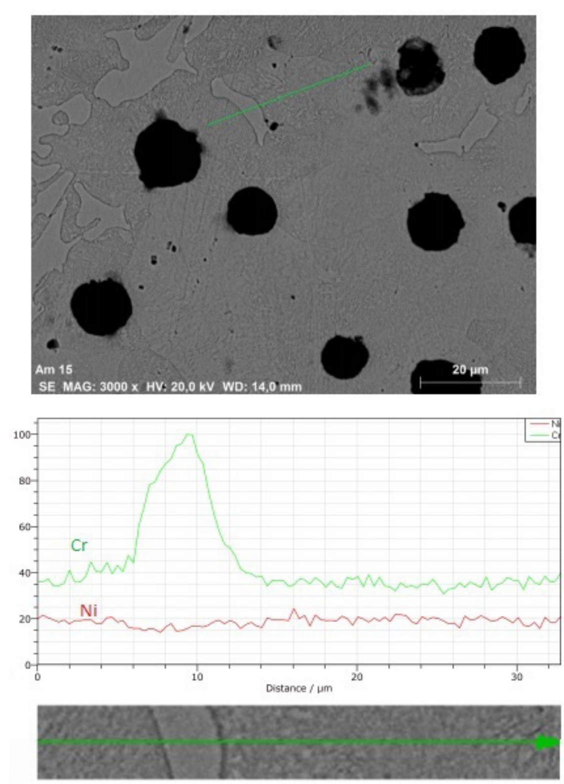


Figura 25. Ni/Cr EDS profile.

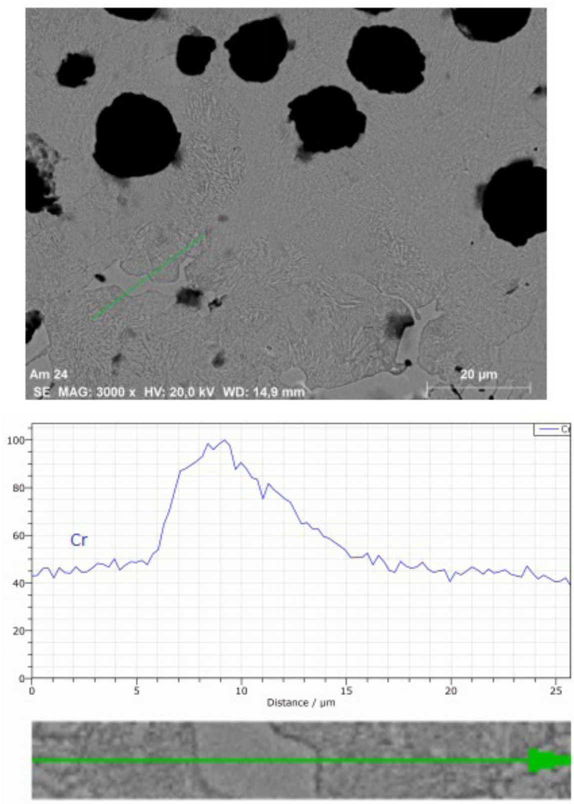


Figure 26. Cr EDS profile.

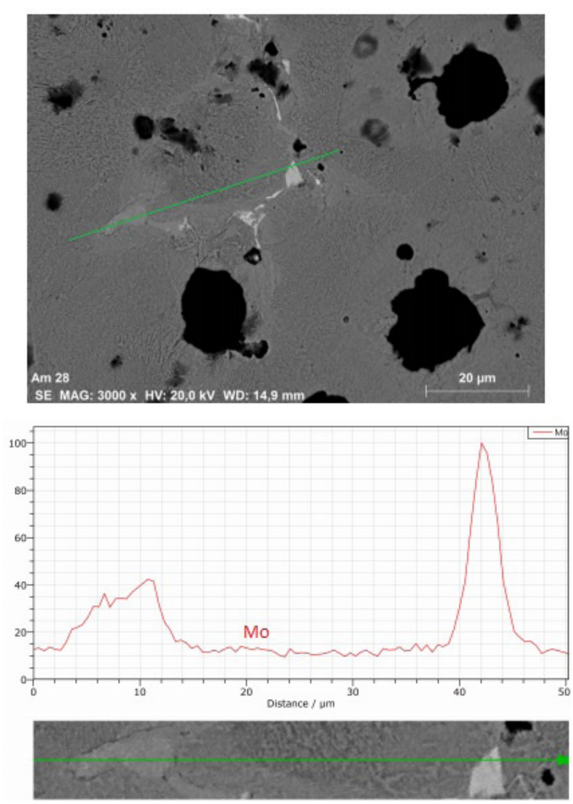
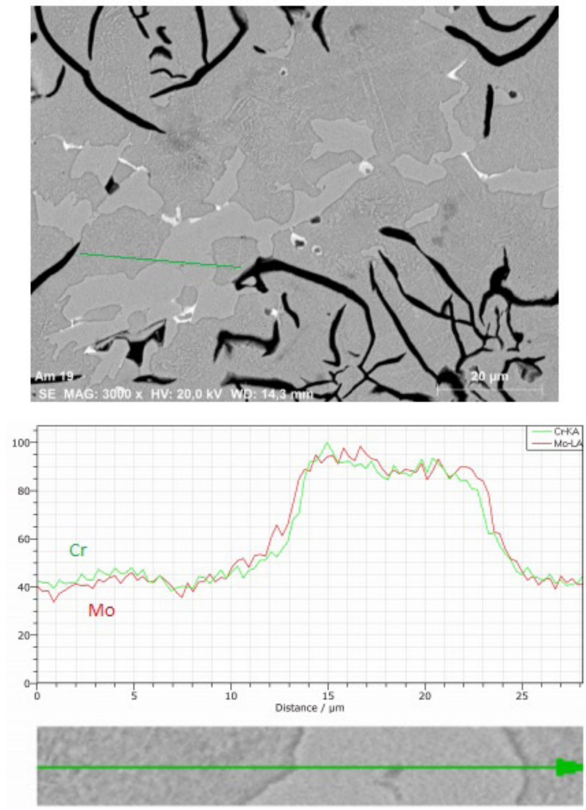


Figure 27. Mo EDS profile.



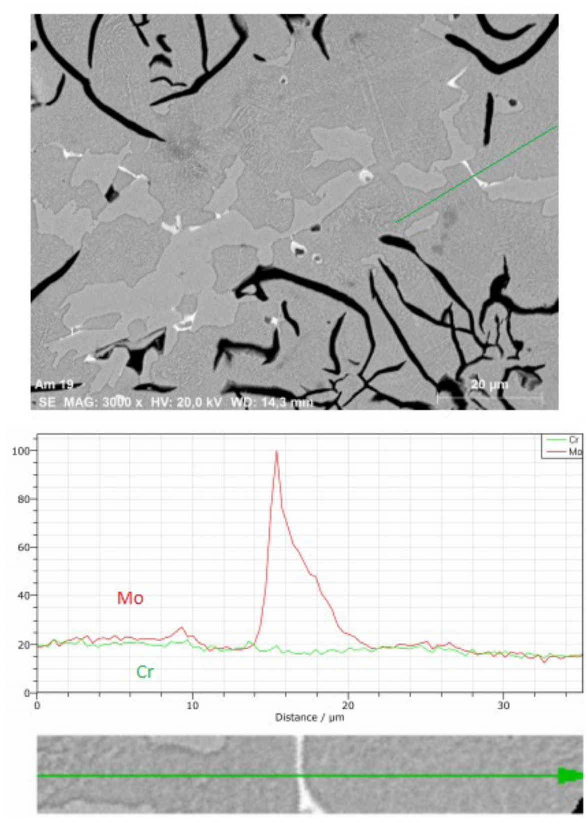


Figure 28. Cr/Mo EDS profile

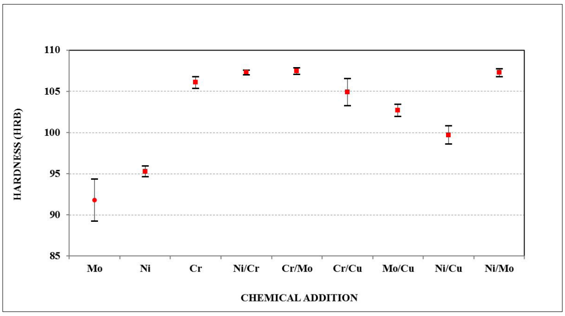


Figure 29. Hardness for each condition.

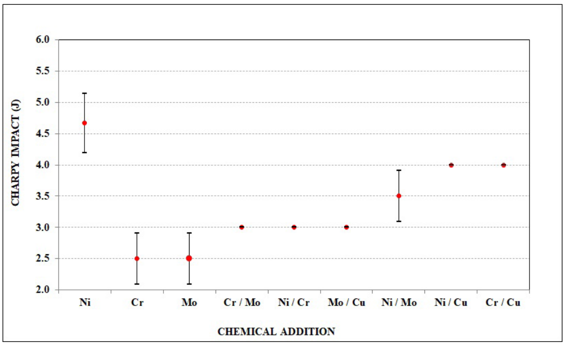


Figure 30. Charpy results for each condition.

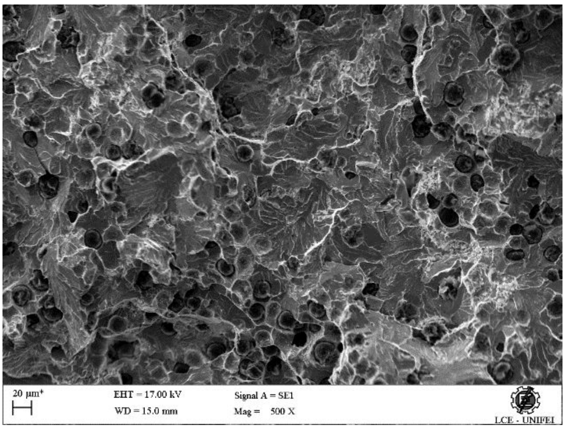


Figure 31. Fractured surface of Ni/Cu.

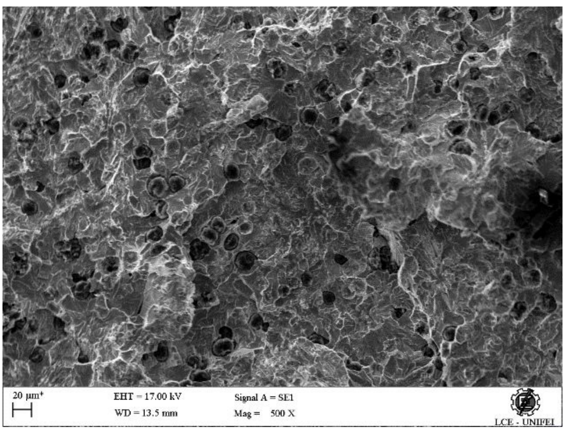


Figure 32. Fractured surface of Ni/Cr.

The analysis of the fracture surface after the charpy impact test reveals for each condition characteristics of brittle and ductile fracture and in some cases the presence of both patterns. The fractured surface depends on the phases present, that is, samples with higher levels of ferrite tend to have ductile-type fracture characteristics with plastic deformations observed. On the other hand, martensite, perlite and carbide regions tend to present a matrix with a fracture of the type cleavage river patterns as can be seen from Figure 31 to 39.

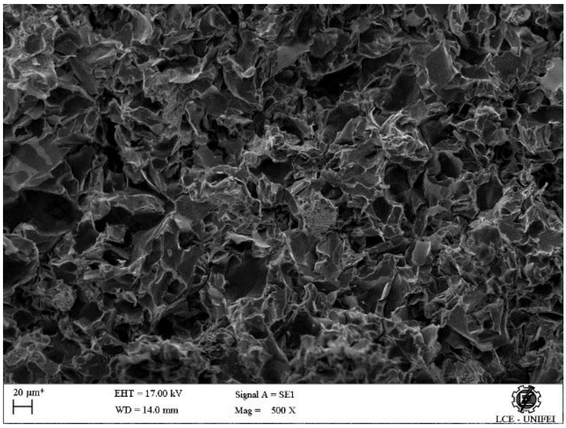


Figure 33. Fractured surface of Cr/Mo.

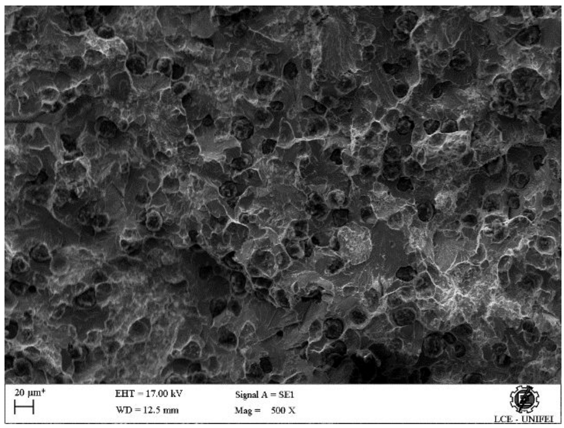


Figure 34. Fractured surface of Mo/Cu.

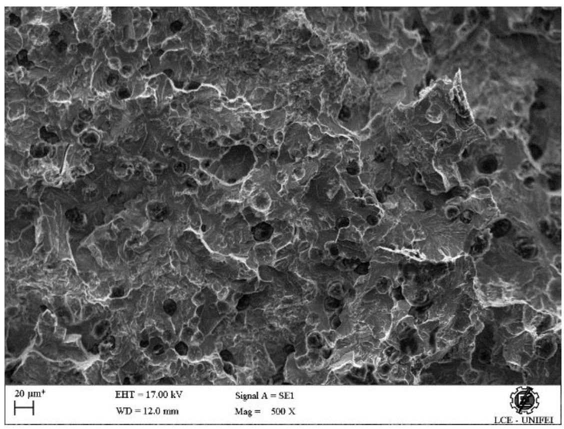


Figure 35. Fractured surface of Cr.

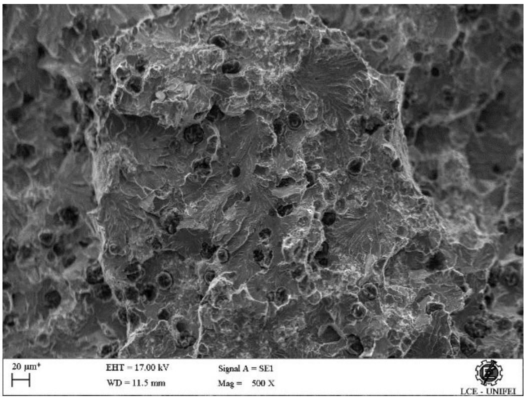


Figure 36. Fractured surface of Mo.

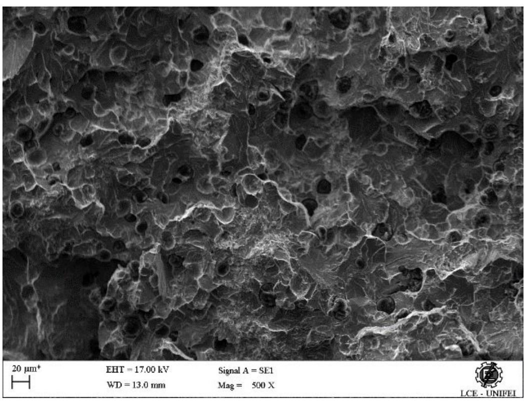


Figure 37. Fractured surface of Cr/Cu.

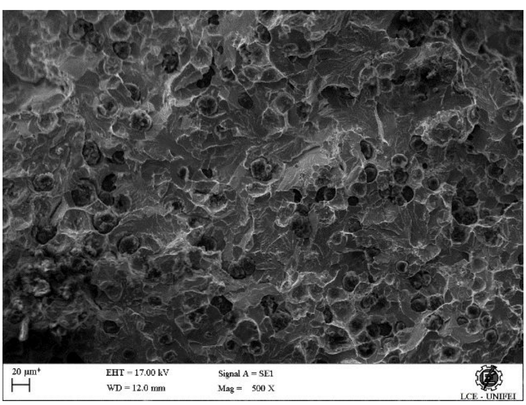


Figure 38. Fractured surface of Ni.

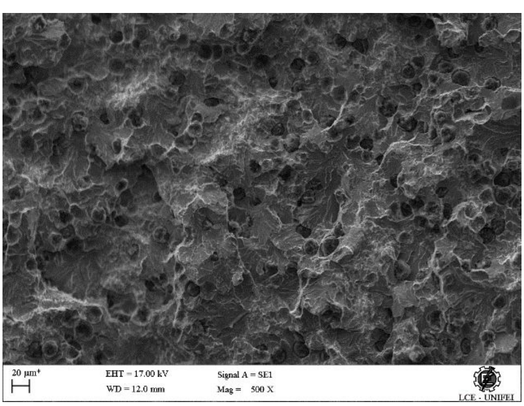


Figure 39. Fractured surface of Ni/Mo.

4. Conclusions

For processing route proposed in this work, we found that chemical elements as Cr, Cu, Mo and Ni can change modify the nodular cast iron microstructure and also mechanical properties. Although difference in nodules can be observed the main changes was met in matrix. By this reason, the use steel scrap of high quality and free of elements alloying has a main role in nodular cast iron manufacturing.

5. Acknowledgements

The authors thank the Brazilian agencies CNPq, Capes, and FAPEMIG for the financial support.

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