

Effects of Inoculation in Gray Cast Iron with the Addition of Niobium from Scrap

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Casting is one of the oldest and most widely used manufacturing processes in industry; however, it is known for its high consumption of natural resources and the generation of waste and pollutants. Given the growing need for sustainable practices, this work proposes the reuse of metallic materials through the casting of gray cast iron ingots, using recycled scrap with the addition of niobium from a FeSiNb alloy. The inoculation technique was applied to investigate the influence of niobium on the microstructure and mechanical properties of the cast material. Metallographic and machining tests were carried out to evaluate the quality of the recycled material. The results indicate significant potential in using recycled materials combined with alloying elements such as niobium to improve metallurgical performance and reduce the environmental impact of casting production.

Keywords: Cast Iron. Foundry. Sustainable Manufacturing. Sound Level.

Casting is recognized as one of the oldest manufacturing processes used by humankind. Despite its historical and industrial significance, the process still faces major challenges related to the excessive consumption of natural resources and the generation of waste and pollutants [1,2]. In this context, the search for sustainable solutions has become essential to mitigate the environmental impacts associated with casting. However, replacing conventional materials with more environmentally friendly alternatives faces obstacles such as limited technical knowledge, a lack of available options, and specific market demands [2]. Aiming to contribute to the sustainability of the metallurgical sector, this study proposes an investigation into the effects of varying the addition of recycled niobium from FeSiNb-based scrap in the casting process. The use of recyclable materials in this context represents a promising alternative to reduce environmental impact without compromising the performance of final products [3,6,7].

Cast Iron

Cast iron is a metallic alloy primarily composed

of iron, carbon, and silicon, and may also contain elements such as manganese, sulfur, and phosphorus. Its classification is based on the shape of the graphite and the fracture appearance, which influence its mechanical properties [8]. The chemical structure of cast iron is mainly influenced by carbon and silicon. Carbon controls graphite formation, while silicon acts as a graphitizing agent, promoting the decomposition of iron carbide. Silicon tends to push cast iron toward gray or white conditions, whereas manganese, commonly present, opposes silicon by stabilizing cementite and balancing its graphitizing effect. Manganese is also added as a desulfurizer but often stabilizes pearlite, especially in large castings. Other elements like phosphorus and sulfur play minor roles in graphitization, though phosphorus can stabilize iron carbides and phosphides, causing a white and porous appearance. Understanding cast iron metallurgy, including solidification, is essential to grasp microstructure formation and the material's mechanical properties, compromising the ability of future generations to meet their own needs [2].

Niobium and cast iron

Niobium (Nb) is a metallic element with atomic number 41, known for its unique properties such as a high melting point (2468°C) and superconductivity at very low temperatures. Its main uses include microalloyed steel production, heat-resistant

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stainless steels, and superalloys. Niobium has gained growing economic importance due to rising demand.

In gray cast iron, niobium offers several benefits when added as an alloying element: it increases mechanical strength, enhances corrosion resistance, improves machinability, reduces component weight, and boosts thermal conductivity [9]. These improvements make gray cast iron more durable, cost-effective, and suitable for demanding applications like automotive parts, engines, and heat exchangers [9]. Additionally, niobium contributes to sustainability by extending the lifespan of cast components and reducing maintenance needs

Determination and Solidification of Cast Iron Structure

The chemical structure of cast iron is mainly influenced by carbon and silicon. Carbon controls graphite formation, while silicon acts as a graphitizing agent, promoting the decomposition of iron carbide. Silicon tends to push cast iron toward gray or white conditions, whereas manganese, commonly present, opposes silicon by stabilizing cementite and balancing its graphitizing effect. Manganese is also added as a desulfurizer but often stabilizes pearlite, especially in large castings [4].

Other elements like phosphorus and sulfur play minor roles in graphitization, though phosphorus can stabilize iron carbides and phosphides, causing a white and porous appearance and the material's mechanical properties [10].

Materials and Methods

The development of the work is divided into two parts: obtaining the materials used in the research, including elements derived from scrap for the production of (a) cast iron, and (b) recycled niobium used. The experiments that make up this work were carried out in two foundry companies, which provided some of their laboratories for the addition of niobium to the iron alloy and the necessary material.

Material Selection

The choice of materials directly influences the quality of cast products. In this study, scrap-derived materials representative of industrial casting processes were used. In no study has gray cast iron GG-25 been used from scrap material supplied. According to DIN EN 1561 (1997), this material must have a tensile strength between 250 N/mm² and 350 N/mm² and a hardness between 180 HB and 250 HB.

Casting of test Specimens

All material used was separated and weighed on a precision scale. Therefore, the alloy of the material used was prepared in an induction furnace, with a temperature of around 1,480°C. Following the protocol for this type of process, a small coin-shaped sample was taken for chemical analysis, in order to adjust the desired composition. Then, the oven temperature was raised to 1,505°C for homogenization. The recycled niobium) and previously separated in the proportions of 0.2%, 0.6% and 0.8% of the 5kg volume of the sand molds was added when transferring the melt to the casting pan (Figure 1). Once you have the cast alloy and the molds, the process of pouring the pan into the molds is done manually, where a properly equipped employee pours the metallic liquid into the molds (Figure 2) made on the production line for subsequent cooling.

Metallographic Analysis

Metallography was used to examine the microstructure, which is essential for quality assurance, developing new alloys, and failure investigation. Analysis was performed using optical and electron microscopy. The metallographic test was carried out to study the influence of the addition of recycled niobium on the microstructure, which will make it possible to relate the properties to the machinability of the material. The metallographic analysis procedure was carried out in accordance

Figure 1. Cast blocks.**Figure 2.** Molds with poured metal.

with standards NBR 13284:95 (2015) and NBR 6593:81 (2015).

The microstructural characterization was carried out in the central region of the samples taken from the cast specimen, which is called half radius [8].

The preparation of samples for metallographic analysis consisted of embedding the samples and sanding them using 220 and 400 mesh sandpaper, followed by polishing in a polishing machine.

To characterize the matrix, 4% Nital was used to identify pearlite and ferrite, and to count eutectic cells, the Stead reagent was applied, which highlights phosphorus and sulfur segregations and the cell contours.

Machining

Noise levels were measured using a DEC-46 sound level meter (35–130 dB, A-weighting), consistently positioned near the operator's ear during equipment operation (Figure 3) [11].

Figure 3. Sound level.

Microscopic Imaging

Images obtained through optical and electron microscopy were crucial for quality control, process optimization, and scientific research, enabling defect identification and detailed evaluation of the microstructure of cast materials.

Machinability Test

The flank wear (VB) of inserts was evaluated to estimate tool life during the machining of a cast ingot with 0.8% Nb, using $VB = 0.3$ mm as the end-of-life criterion. A 90° milling head with four Lamina OFMT 050405 inserts was used, with one cutting edge per insert. After 10 passes, the inserts were analyzed using a scanning electron microscope. Machining parameters were: cutting speed of 230 m/min, feed per tooth of 0.39 mm, and axial depth of cut of 3.3 mm.

Results

Results for Tool Wear

The machining parameters were: cutting speed $V_c = 230$ m/min; feed per tooth $f_o = 0.39$ mm; axial cutting depth $A_p = 3.3$ mm. In Figure 3, tool wear can be seen on each of the 4 edges of the insert used in the tests, which were visualized using a scanning electron microscope.

Flank wear on cutting tools affects machining quality. This study found an average wear of $L = 0.585$ mm (Figure 4), impacting precision, surface finish, and energy use. Solutions include maintenance, proper tool selection, optimized cutting parameters, and operator training. Results show good operational performance with the tested cast material.

Results for Noise Levels

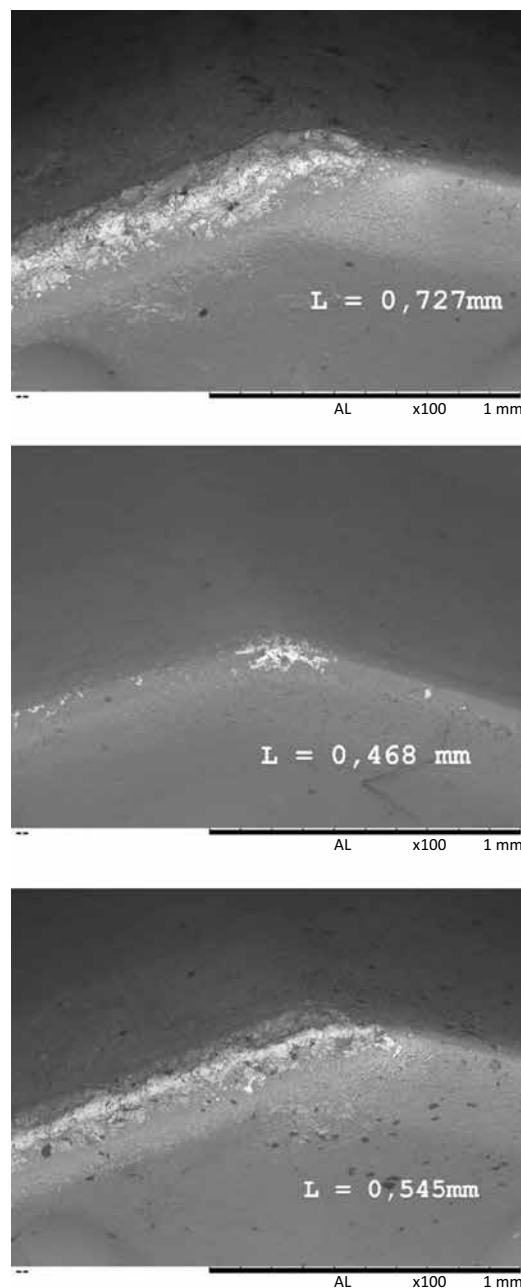
For the noise level test, 10 passes of the cutting tool were performed on cast iron containing 0.8% niobium using the same conventional milling machine. Meanwhile, the sound level meter was continuously positioned near the operator's ear throughout the test. The noise level during the test remained constant, averaging 67.4 dB (NR 15, 2019), indicating good quality of the machined material. Milling noise results from the interaction between the tool and the workpiece and can impact workers' hearing health. Controlling sound pressure is essential for safety, production efficiency, and regulatory compliance, requiring innovations and safe practices in machine tool design.

Results for Metallographic Analysis

Sample 1

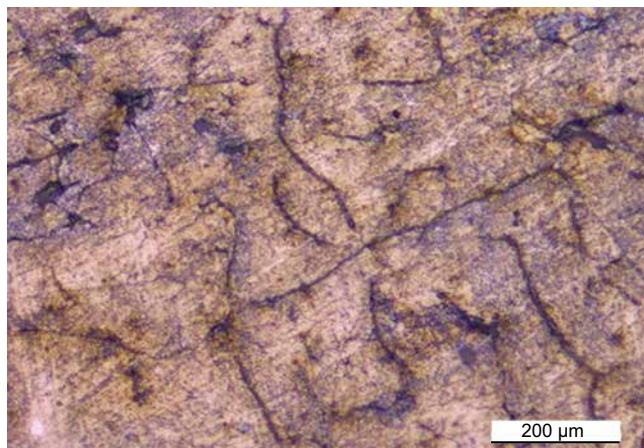
According to Figure 5, it is noted that sample 1 presents elongated black particles, which are called lamellar graphite, which are typical of gray cast iron. Lamellar graphite plays a fundamental role in improving the properties of gray cast iron, making it a material of choice in several

Figure 4. Images of the insert by SEM.



industrial applications. These benefits are mainly related to their unique microstructure and resulting mechanical characteristics.

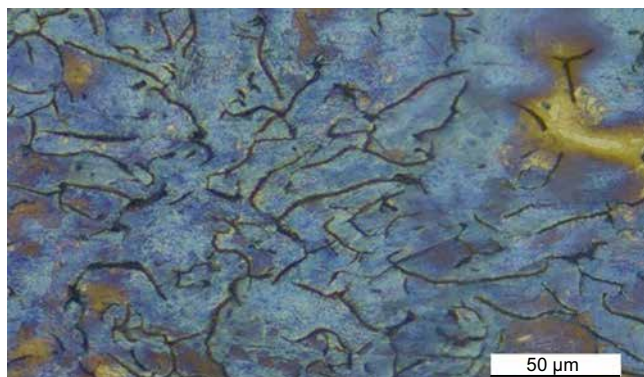
Materials with lamellar graphite have a high vibration absorption capacity, making them ideal for components subjected to dynamic loads (e.g., engine blocks, brake drums, and gearboxes). In machining, lamellar graphite reduces cutting tool wear, making the process more efficient and cost-

Figure 5. Sample 1 (0.2% Nb).

effective, especially for parts with tight tolerances [12]. The material shows corrosion resistance, making it suitable for marine and industrial environments. It also improves heat dissipation and facilitates shaping into complex geometries during casting. The combination of these properties makes gray cast iron with lamellar graphite highly durable, with a prolonged service life in many applications.

Sample 2

Sample 2, shown in Figure 6, also exhibits graphite formation and, in particular, pearlite formation. The formation of pearlite in cast iron is a metallurgical process that provides a series of significant benefits for the metallurgical industry and other applications. Pearlite is a microstructure

Figure 6. Sample 2 (0.6% Nb).

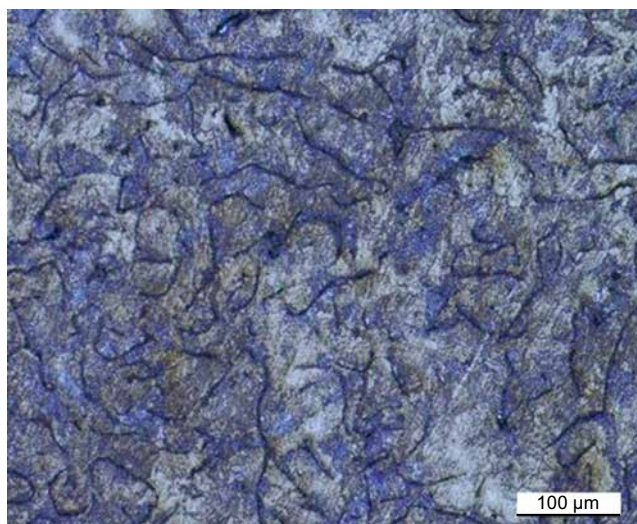
composed of alternating lamellae of ferrite and cementite (an iron–carbon compound), and its formation occurs through the controlled cooling of cast iron. Pearlite enhances the mechanical performance of cast iron by providing a balanced combination of hardness and toughness, enabling it to withstand loads, impacts, and wear moreover, pearlite formation can be controlled to meet specific requirements, ensuring wide applicability across industrial sectors [12].

Sample 3

Sample 03 (0.8% Nb) showed ferrite formation in addition to graphite and pearlite (Figure 7). Ferrite increases malleability, making machining easier, improves corrosion resistance, enhances ductility and fatigue strength, and provides good thermal and electrical conductivity, making gray cast iron more suitable for applications requiring these properties [10].

Conclusions

This study evaluated the effects of niobium addition in cast iron alloys produced from scrap, demonstrating the technical and environmental viability of this approach for the metallurgical

Figure 7. Sample 3 (0.8% Nb).

industry. Microstructural analysis revealed the presence of lamellar graphite, pearlite, and ferrite (0.8%), indicating that the composition and mechanical properties remain consistent with those obtained from virgin materials. Pearlite provided increased toughness and improved machinability, while ferrite contributed to enhanced ductility and corrosion resistance. Machinability tests showed results consistent with the literature, highlighting good surface finish quality and process efficiency. Additionally, acoustic monitoring during machining indicated noise levels below 85 dB, complying with occupational safety standards. Further studies on tool wear under varying cutting conditions are recommended to optimize the process.

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