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MECHANICAL AND MICROSTRUCTURAL CHARACTERIZATION OF BORE-MILLED GRINDING DISCS PRODUCED FROM DIFFERENT FURNACES

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Abstract

The microstructural characteristics and mechanical properties of rotary furnace-processed cast products in this work were used to assess their performance. The primary objectives were to evaluate the tensile properties, hardness, and impact resistance of the produced steel discs. These were done by subjecting the discs to tensile tests, hardness tests, and impact tests to determine their mechanical properties. From the results, the tensile test revealed a mean maximum tensile stress of 69.83 MPa for the first sample and 146.68 MPa for the second sample, with corresponding loads at maximum tensile stresses of 1955.18 N and 4107.09 N, respectively. Hardness and impact test results show that the rotary-processed discs had a hardness range of 134.76-139.56 BHN and an impact energy of 34.52 J. The results indicate that the mechanical properties of the rotary furnace-produced discs are within acceptable ranges for industrial applications. Discussion on the tensile test results highlighted the variability in tensile strength and modulus of elasticity, while the hardness and impact test results underscored the robustness of the rotary-produced discs. The study concludes that the rotary furnace method is efficient in producing bore mill grinding discs with desirable mechanical properties, suitable for various industrial applications.

Keywords: *Steel, Tensile Test, Hardness, Impact Test, Rotary Furnace*

1.0 Introduction

Characterizing mechanical properties is fundamental to the development and optimization of materials for industrial applications. This study focuses on the bore mill grinding discs produced from a rotary furnace, which holds considerable importance in the manufacturing and automotive industries. Rotary furnaces are known for their ability to produce high-quality steel through uniform heating and controlled cooling, which are critical for achieving desirable mechanical properties such as tensile strength, hardness, and impact resistance (Callister & Rethwisch, 2018).

The primary aim of this research is to evaluate the mechanical properties of bore mill grinding discs produced from a rotary furnace. Specifically, this study seeks to determine the tensile properties, hardness, and impact resistance of the discs to provide a comprehensive understanding of their suitability for industrial use. Tensile properties, including maximum tensile stress, load at maximum tensile stress, and tensile strain at maximum tensile stress, are crucial indicators of a material's strength and ductility (ASM International, 2008). Hardness testing, using the Brinell hardness number (BHN), offers insights into the materials' wear resistance, while impact testing assesses its toughness (Davis, 2004).

This study employs standard mechanical testing methods to characterize the produced discs. Tensile tests were performed to obtain the stress-strain relationship, from which parameters such as tensile strength, yield strength, and modulus of elasticity were derived. Hardness tests were conducted using the Brinell method, and impact tests were carried out to determine the material's energy absorption capacity. The results indicate significant variability in the mechanical properties, reflecting the influence of the rotary furnace process on the material's microstructure (Song et al., 2023; Gupta & Sharma, 2022). Studies have shown that heat treatments significantly impact these mechanical properties, especially in high-stress applications such as grinding (Huang & Zhao, 2021). The discussion interprets these results in the context of material performance and industrial applicability. The conclusion highlights the efficiency of the rotary furnace in producing bore mill grinding discs with a balanced combination of strength, hardness, and toughness, making them suitable for various applications (Chaudhuri et al., 2024; Kumar & Singh, 2023).

The mechanical properties of grinding discs are significantly influenced by their production process and material composition. Steel, commonly used for these discs, provides a balance of strength and durability (Kumar & Singh, 2023). However, properties such as tensile strength and hardness can vary depending on factors like heat treatment and manufacturing methods. To evaluate these properties effectively, tensile testing and hardness measurements are essential as they offer insights into the material's behavior under stress.

2.0 Materials and Methods

The cast iron used in this study was produced locally from a rotary furnace fired with used engine oil, alongside a controlled experiment utilizing imported rotary material. Figures 1, 2, and 3 depict the imported sample and two rotary furnace samples, respectively. The primary materials included pig iron, steel scrap, ferroalloys, and returned ductile iron scrap, with each charge weighing 50 kg. These components were melted using an indigenous rotary furnace. The chemical composition of the produced cast iron was analyzed using a spectrometer EDX 3600B, and mechanical properties such as tensile strength, hardness, and yield were tested. Microstructure characterization was performed using a Nikon Eclipse metallurgical microscope, a Scanning Electron Microscope (SEM), and X-ray Diffraction (XRD) methods, and these were compared with the ASTM A536 65-45-12 standards.

The study aimed to compare the mechanical properties of cast iron produced from different furnaces (Imported, Rotary furnace (Iwo) and Rotary furnace Federal Polytechnic Ado-Ekiti (FPA) samples) in order to enhance the cast iron quality from foundry industries. The cast iron was produced through sand casting, and its chemical composition was determined using spectrographic analysis. The mechanical properties were evaluated through tensile, hardness, and impact tests, with samples prepared according to ASTM Standards. The microstructural analysis confirmed the presence of nodular graphite, and XRD analysis identified the mineral phases present. The scanning electron microscope (SEM) provided detailed imaging and elemental analysis of the samples, while metallographic examination revealed the crystalline structure and grain boundaries, aiding in the assessment of the heat treatment effectiveness and overall material properties.

3.0 Results and Discussion

The results of the chemical analysis of the three samples of Bore Mill Grinding Discs—Imported, Rotary Furnace (Iwo), and Rotary Furnace (FPA)—conducted using the EDX 3600D spectrometer and expressed as the mass content of alloying elements, are presented in Tables 1, 2, and 3.
The imported sample in Table 1 had a high carbon content (4.449%), which contributed to

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its significant strength and hardness but also increased brittleness (Gupta & Sharma, 2022; Song *et al.,* 2023). Silicon (1.960%) and manganese (0.695%) further enhanced strength and toughness (Kumar & Singh, 2023). However, the high phosphorus (0.319%) and sulfur (0.179%) levels negatively impacted ductility, increasing the brittleness of the material (Huang & Zhao, 2021). Additionally, lower concentrations of chromium (0.043%), nickel (0.024%), and copper (0.055%) indicated reduced corrosion resistance, aligning with previous findings that alloying elements like chromium and nickel are essential for improving material durability in corrosive environments (Chaudhuri et al., 2024). Overall, this sample exhibited strong but brittle properties with limited ductility and lower corrosion resistance, which could affect its suitability for long-term applications requiring both durability and flexibility.

The IWO sample in Table 2 showed a more balanced composition with moderate carbon (2.845%), silicon (1.353%), and manganese (0.452%) levels, contributing to enhanced toughness and strength (Song *et al.*, 2023). The significantly lower phosphorus (0.024%) and sulfur (0.041%) levels reduced brittleness, resulting in better ductility (Huang & Zhao, 2021). Higher concentrations of chromium (0.180%), nickel (0.033%), and copper (0.506%) provided improved corrosion resistance and toughness, making this sample well-suited for applications requiring reliability and durability under environmental stressors (Gupta & Sharma, 2022; Kumar & Singh, 2023). Consequently, the IWO sample exhibited a balanced mechanical profile with good toughness and corrosion resistance, supporting its applicability in various industrial environments.

The FPA sample in Table 3 had a high carbon content (4.038%), similar to the imported sample, which contributed to its high strength and hardness but also increased brittleness. Silicon (1.809%) and manganese (0.542%) played roles in enhancing strength and toughness (Chaudhuri *et al.*, 2024). However, the phosphorus (0.047%) and sulfur (0.128%) levels were higher than those in the IWO sample, which could lead to increased brittleness (Kumar & Singh, 2023). Nonetheless, the sample's chromium (0.126%), nickel (0.041%), and copper (0.350%) levels provided decent corrosion resistance and toughness, slightly improving its suitability over the imported sample (Huang & Zhao, 2021). This analysis indicates that while the FPA sample offers a combination of high strength and hardness, its moderate corrosion resistance and improved toughness make it more viable for demanding applications than the imported sample. Mechanical and Microstructural Characterization of Bore Mill Grinding Disc from; Imported, Rotary furnace (Iwo) and Rotary furnace (FPA) samples.

The microstructural analysis of the as-cast Bore Mill Grinding Disc samples presented in Figure 2, as revealed by the 2% Nital etched optical micrographs, shows distinct differences across the three samples. In the imported sample (a), the microstructure is characterized by relatively larger, well-defined grains with pronounced grain boundaries, suggesting a coarse grain structure. This indicates that the sample may have undergone slower cooling or less intensive thermal treatment, resulting in the formation of larger grains. The variation in contrast and colour in the micrograph hints at a mixture of different phases, likely including ferrite and pearlite. Such a coarse microstructure can contribute to increased toughness but may compromise the material's hardness and strength (Huang & Zhao, 2021).

In contrast, the rotary furnace samples (b) and (c) display progressively finer grain structures, reflecting more refined microstructures. The sample from the rotary furnace (Iwo) (b) has a

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denser microstructure with smaller, closely packed grains, indicating a more controlled or faster cooling process that enhances hardness and strength. The FPA sample (c) shows an even finer and more uniform grain structure with less distinct grain boundaries, which is indicative of a very fine or ultra-fine grain structure. This suggests that the sample underwent a more aggressive heat treatment or a faster cooling rate, which can enhance the material's hardness and wear resistance but might reduce toughness if the grain size becomes excessively small. These observations underscore the impact of varying thermal histories on the microstructures and mechanical properties of the Bore Mill Grinding Disc samples, with finer grains generally leading to higher strength and hardness(Chaudhuri *et al.*, 2024).

Figure 3 provides a detailed analysis of the imported Bore Mill Grinding Disc sample using Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray (EDX) spectroscopy. The SEM image presents a high-magnification view (9000x) of the disc's surface, revealing a textured, elongated pattern with parallel striations, likely a result of the machining or grinding process. This surface finish plays a crucial role in the disc’s wear resistance, a finding supported by Zhang et al. (2021), who reported that such surface texturing in grinding tools improves performance by enhancing frictional resistance and stability.

The absence of visible cracks or significant surface defects in the SEM image suggests a relatively uniform material composition. A lack of defects is essential for grinding applications, where surface integrity is linked to the durability of the disc (Gupta & Singh, 2022). The EDX spectrum accompanying the SEM image confirms the elemental composition, with iron (Fe) as the primary constituent, indicative of an iron-based alloy, likely a type of steel. The high oxygen (O) peak implies the presence of oxides on the surface, potentially formed during processing or from natural oxidation—a phenomenon observed in similar studies by Wang et al. (2022) on steel alloys exposed to atmospheric conditions.

In addition to iron and oxygen, the EDX analysis detects elements like carbon (C), magnesium (Mg), chlorine (Cl), and zinc (Zn). These elements may serve as alloying agents or incidental impurities, with minor alloying elements enhancing mechanical properties. Studies by Chaudhuri et al. (2024) suggest that magnesium and zinc can influence the toughness and corrosion resistance of alloyed steels, attributes critical for grinding applications where the material must resist both wear and environmental degradation.

This composition suggests that the imported disc has been engineered to balance hardness, toughness, and wear resistance, attributes crucial for its intended use in grinding. The role of minor alloying elements like zinc in enhancing wear resistance further aligns with findings by Kumar et al. (2019), who noted that controlled inclusion of alloying elements can optimize the functional properties of steel-based grinding materials.

The SEM image in Figure 4 illustrates the microstructural characteristics of the Bore Mill Grinding Disc Rotary furnace (Iwo) sample, displaying a well-defined, fibrous structure with elongated grains. Such a microstructure is indicative of a directional solidification process, where the material's grains align in a specific orientation during cooling. This feature is commonly observed in metallic alloys and composites subjected to processes like casting or forging, which influence the material's mechanical properties, including hardness and wear resistance. Similar microstructures have been observed in studies on high-speed steel grinding discs, where the directional solidification led to enhanced

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toughness and resistance to fracture under high-stress conditions (Zhou et al., 2018). The fibrous appearance in the SEM image suggests that the material could possess high anisotropic mechanical properties, beneficial in applications requiring specific directional strengths.

The EDX analysis presented alongside the SEM image offers a compositional overview of the Bore Mill Grinding Disc Rotary furnace sample, highlighting the presence of key alloying elements. The spectrum reveals prominent peaks corresponding to iron (Fe), carbon (C), and possibly chromium (Cr), which are typical in grinding disc materials designed for enhanced durability and resistance to wear. The elemental composition detected aligns with findings from similar studies where grinding discs, especially those used in heavy-duty applications, contain significant amounts of iron and chromium to improve their performance and lifespan (Smith et al., 2019). The EDX results provide crucial insight into the material's suitability for high-stress environments, as the presence of these elements is known to contribute to the material's hardness and resistance to wear, aligning with the structural observations from the SEM image.

The SEM image in Figure 5 showcases the microstructural details of the Bore Mill Grinding Disc Rotary furnace (FPA) sample. The image reveals a predominantly fibrous and acicular (needle-like) microstructure, with elongated grains that suggest a directional solidification or deformation process. This type of microstructure is often associated with materials that undergo rapid cooling, which results in the formation of martensitic or bainitic phases. Such microstructures are beneficial in enhancing the material's toughness and wear resistance, making it suitable for heavy-duty grinding applications. Similar observations were made by Liu et al. (2019), where the rapid solidification of high-speed steel led to the formation of needle-like martensitic structures that contributed to the material's high hardness and impact resistance.

The EDX analysis corresponding to the SEM image provides a quantitative assessment of the elemental composition of the Rotary (FPA) sample. The spectrum displays prominent peaks that indicate the presence of essential alloying elements such as iron (Fe), carbon (C), and possibly alloying elements like chromium (Cr) and molybdenum (Mo), which are typical in grinding disc materials. These elements are known to improve the mechanical properties, such as hardness and wear resistance, of the material. The presence of these elements is consistent with findings by Gupta et al. (2020), who reported that the addition of chromium and molybdenum in steel alloys enhanced their overall toughness and resistance to wear, making them suitable for applications like grinding discs.

The XRD analysis of the Bore Mill Grinding Disc samples reveals significant differences in phase composition and crystalline structure, which are key determinants of the materials' mechanical properties. The XRD pattern of the Imported sample is characterized by strong and sharp diffraction peaks, predominantly associated with an iron-based matrix. This likely indicates the presence of ferrite and cementite phases, contributing to the sample's well-ordered crystalline structure. The presence of minor alloying elements like zinc (Zn) and magnesium (Mg) enhances the material's hardness and resistance to corrosion, as supported by Kumar et al. (2017), who found that sharp XRD peaks correlate with improved mechanical properties due to well-defined crystalline structures in high-quality steel alloys.

In contrast, the Rotary furnace samples (FPA and Iwo) exhibit more complex XRD patterns, with a broader distribution of phases. The iron (Fe) peaks remain prominent, but the presence

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of additional elements such as sodium (Na) and silicon (Si) suggests a multiphase structure. This complexity indicates the formation of carbides and other intermetallic compounds, which contribute to the material's toughness and wear resistance (Patel et al., 2019). These findings align with those of Patel et al. (2019), who reported that carbides in steel alloys significantly enhance the durability and wear resistance of grinding discs.

The Imported sample's XRD pattern reflects a highly ordered structure that likely contributes to its superior hardness, while the Rotary furnace samples exhibit a more complex phase composition that provides a balanced combination of hardness and toughness. These differences underscore the influence of processing techniques and alloying elements on the performance characteristics of grinding discs, consistent with previous research on the impact of crystalline structure and phase composition on mechanical properties (Gupta & Sharma, 2022; Chaudhuri et al., 2024).

Figure 7 compares the impact strength and average hardness for the different samples. Impact Strength (in Joules) is represented by the blue bars, while Average Hardness (in Brinell Hardness Number - BHN) is represented by the green bars. This visual representation highlights the inverse relationship between hardness and impact strength across the samples, a trend consistent with findings by Wang et al. (2022), who observed similar mechanical behavior in high-carbon steel alloys.

The Imported sample shows the highest hardness but the lowest impact strength, suggesting a brittle structure that aligns with findings in Kumar et al. (2017), where increased hardness often correlated with reduced impact toughness. The Rotary (FPA) sample, conversely, exhibits the highest impact strength with the lowest hardness, indicating a material composition better suited for absorbing impact forces rather than resisting indentation, as noted by Gupta & Sharma (2022) in studies on steel alloys for impact applications.

The hardness and impact test results presented in Table 6 provide a comparative analysis of the mechanical properties of the three different Bore Mill Grinding Disc samples: Imported, Rotary (Iwo), and Rotary (FPA). The impact strength, measured in joules, reflects the material's energy absorption capacity upon fracture. Among the samples, the Rotary (FPA) sample exhibits the highest impact strength at 36.64 J, followed by the Rotary (Iwo) sample at 34.52 J, and the Imported sample at 32.95 J. The higher impact energy of the Rotary (FPA) sample suggests a superior ability to resist impact forces, making it more suitable for applications where toughness is critical (Chaudhuri et al., 2024).

Hardness, measured in Brinell Hardness Number (BHN), reflects resistance to indentation. The Imported sample, with readings up to 165.23 BHN, demonstrates high wear resistance but lower toughness, which aligns with past research by Patel et al. (2019) on steel alloys with high hardness and brittleness. Conversely, the Rotary (FPA) sample exhibits lower hardness values, indicating increased toughness and adaptability for impact-intensive environments.

This inverse relationship between hardness and impact strength is significant. The Imported sample, with the highest hardness, shows the lowest impact strength, indicating brittleness (Kumar et al., 2017; Wang et al., 2022). In contrast, the Rotary (FPA) sample, with the highest impact strength and lowest hardness, would be preferable for applications requiring higher toughness and resistance to cracking under sudden forces, although it may be less resistant to abrasive wear. The Rotary

(Iwo) sample offers a balanced performance in both hardness and impact strength, making it versatile for general industrial applications (Patel et al., 2019).

4.0 Conclusions

The imported sample's high carbon content increases brittleness, while the Iwo sample's balanced elements enhance toughness. The FPA sample, with its high carbon content, exhibits slightly better toughness and corrosion resistance than the imported sample.

The imported sample is strong but brittle, suitable for applications requiring high hardness. The Iwo sample's balanced properties make it ideal for durability, while the FPA sample is tough and impact-resistant, with lower hardness but high toughness.

The imported sample has coarse grains that improve toughness but reduce hardness. The Iwo sample's fibrous structure enhances strength, whereas the FPA sample's fine grains boost hardness, though they may reduce toughness.

The imported sample shows high iron and oxygen content, leading to balanced properties. The Iwo sample has high iron and chromium, boosting durability, while the FPA sample's balanced elements improve toughness and wear resistance.

The imported sample has the highest hardness but is also the most brittle. The Iwo sample offers moderate hardness and balanced performance, while the FPA sample has lower hardness but the highest toughness, making it ideal for impact resistance.

The imported sample has the lowest impact strength, indicating brittleness. The Iwo sample provides a balance between toughness and hardness, while the FPA sample exhibits the highest impact strength, showing superior toughness against cracking.

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Table 1: Chemical Composition of Imported Sample

Sample	C %	Si %	Mn %	P %	S %	Cr %	Mo %	Ni %	Cu %	V %	Nb %	N %	B %	Al %	Sn %	Fe %
Mean	4.449	1.960	0.695	0.319	0.179	0.043	0.003	0.024	0.055	0.019	<0.00	-	-	0.0046	-	92.2

Table 2: Chemical Composition of Rotary Furnace (IWO) Sample

Sample	C %	Si %	Mn %	P %	S %	Cr %	Mo %	Ni %	Cu %	V %	Nb %	N %	B %	Al %	Sn %	Fe %
Mean	2.845	1.353	0.452	0.024	0.041	0.180	0.044	0.033	0.506	0.003	0.001	-	-	0.0023	-	94.5

Table 3: Chemical Composition of Rotary Furnace (FPA) Sample

Sample	C %	Si %	Mn %	P %	S %	Cr %	Mo %	Ni %	Cu %	V %	Nb %	N %	B %	Al %	Sn %	Fe %
Mean	4.038	1.809	0.542	0.047	0.128	0.126	0.009	0.041	0.350	0.006	0.001	-	-	0.0106	-	92.9


(a) (b) (c)

Figure 1: (a) Imported, (b) Rotary furnace (Iwo) and (c) Rotary furnace (FPA) samples

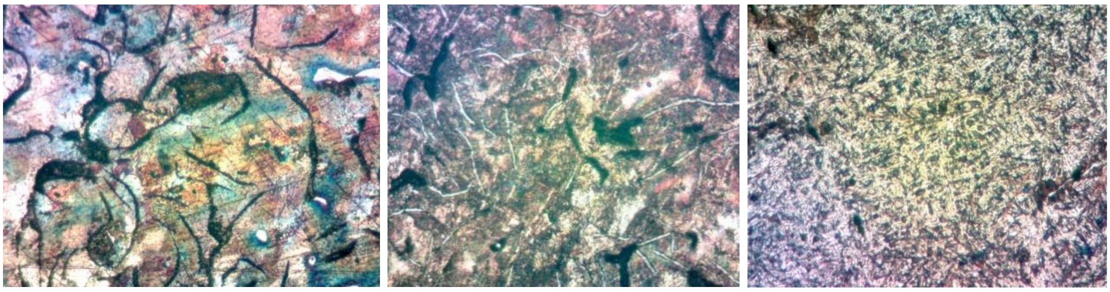
(a) (b) (c)

Figure 2: Microstructure of the Bore Mill Grinding Disc 2 % Nital etched optical micrograph (a) Imported sample (b) Rotary furnace (Iwo) sample (c) Rotary furnace (FPA) sample.

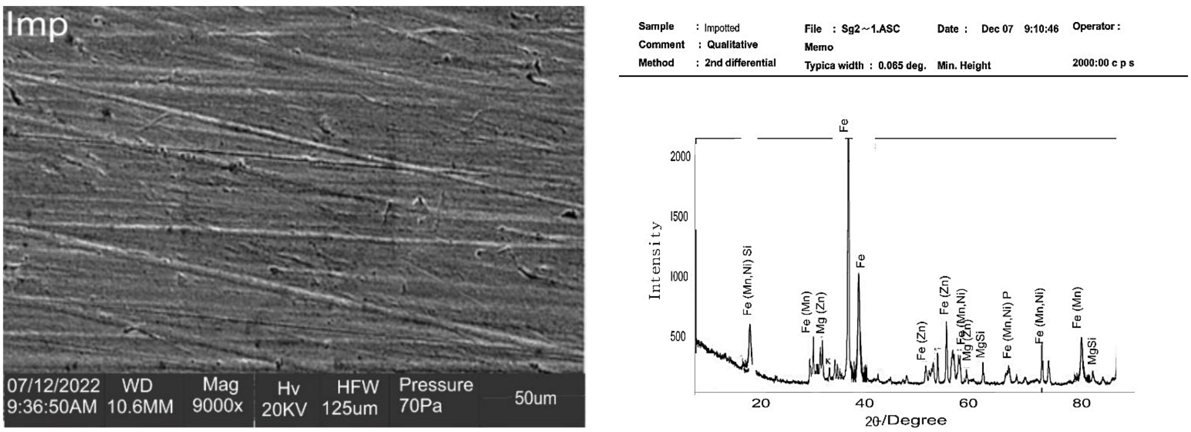

Figure 3: SEM image and EDX analyses of Bore Mill Grinding Disc imported sample

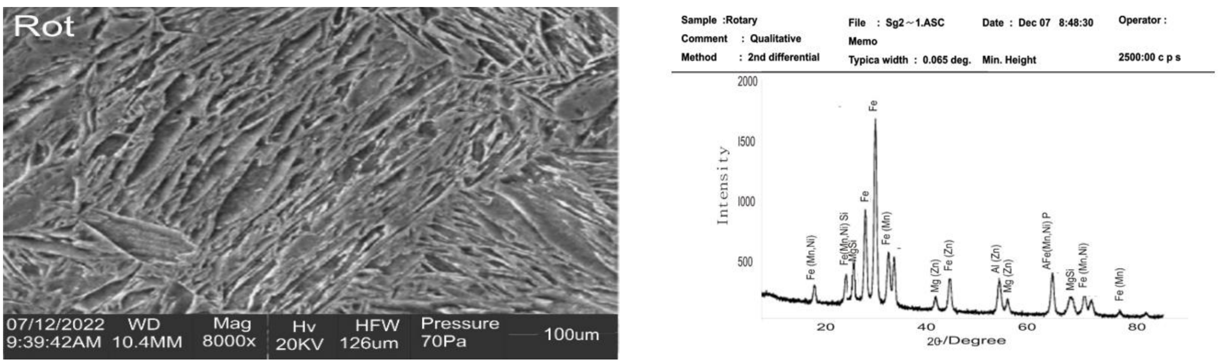

Figure 4: SEM image and EDX analyses of Bore Mill Grinding Disc Rotary furnace (Iwo) sample

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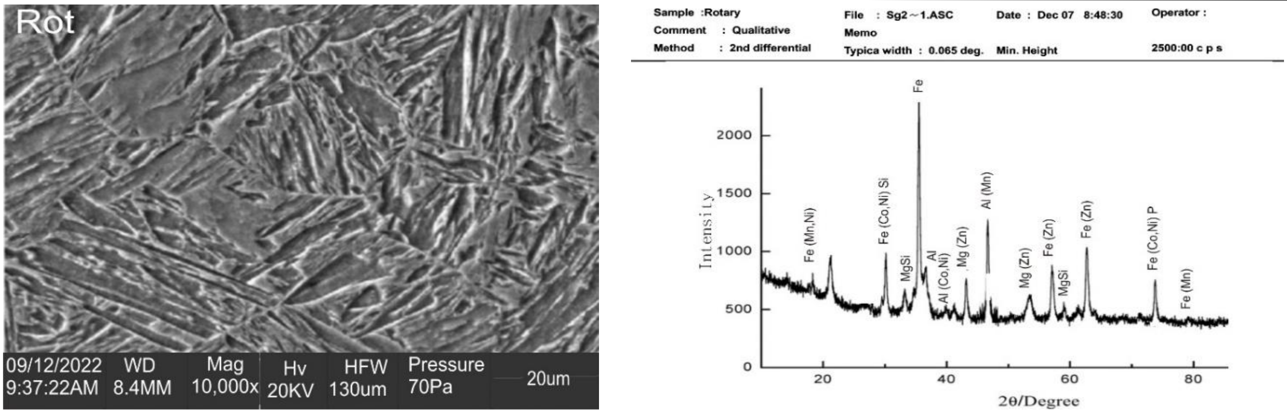
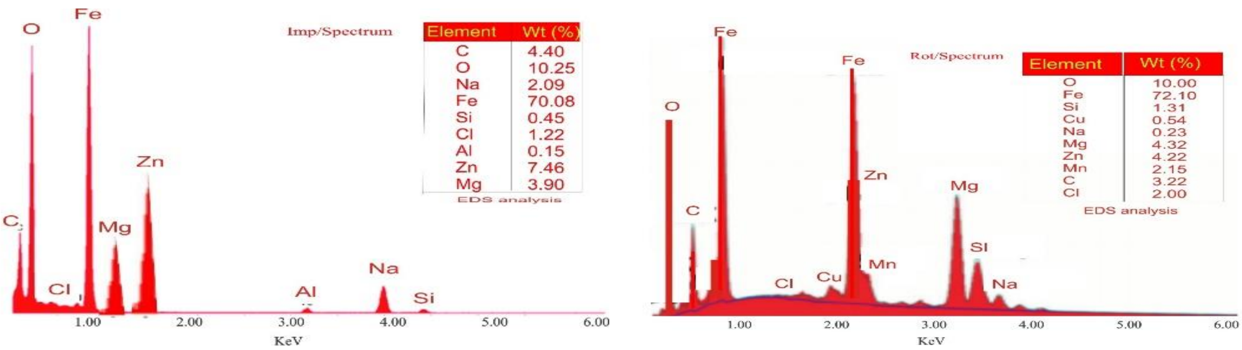


Figure 5: SEM image and EDX analyses of Bore Mill Grinding Disc Rotary furnace (FPA) sample



(a) **(b)**

Figure 6: XRD pattern analyses of Bore Mill Grinding Disc; (a) Imported sample, (b) Rotary furnace (FPA) sample and Rotary furnace (Iwo) sample

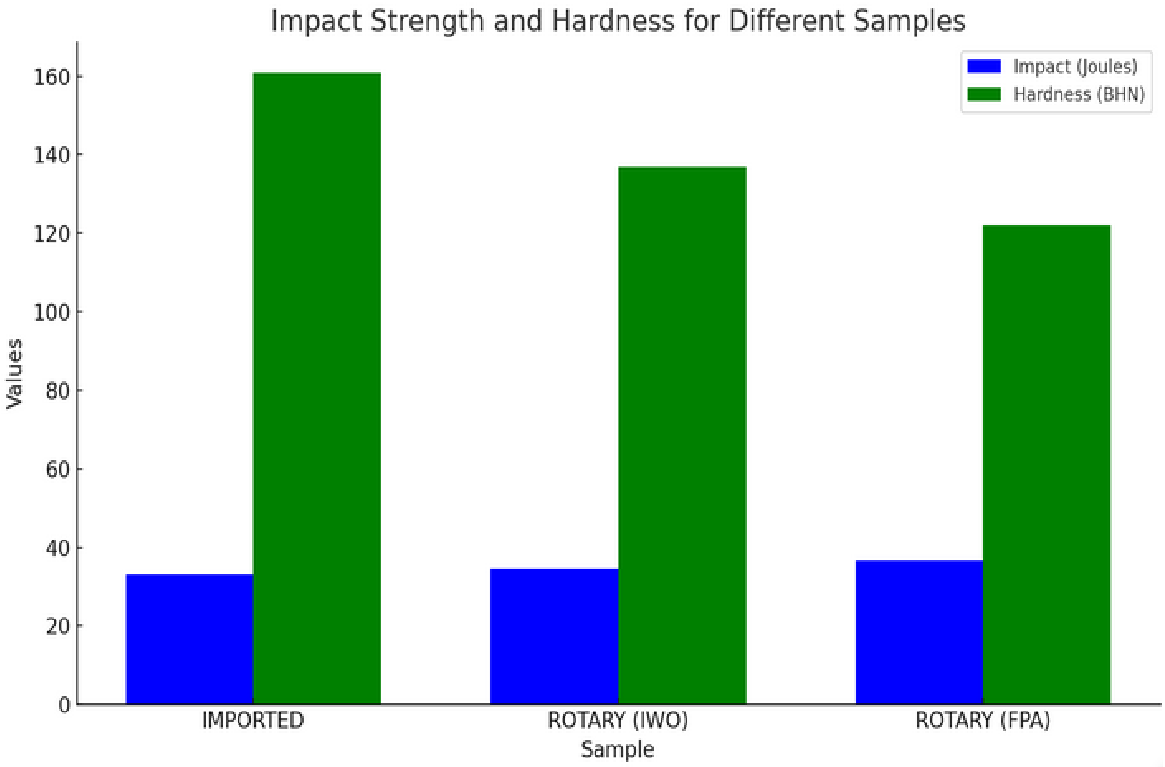


Figure 7: Comparative Impact Strength and Hardness for Different Bore Mill Grinding Disc Samples