PRODUCTION OF COMPOSITE BASED FRICTION MATERIALS USING WASTE GG25 CASTING MATERIAL FOR SAFETY CLUTCHES IN AVIATION APPLICATIONS

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ABSTRACT

PRODUCTION OF COMPOSITE BASED FRICTION MATERIALS USING WASTE GG25 CASTING MATERIAL FOR SAFETY CLUTCHES IN AVIATION APPLICATIONS

In the aviation sector, clutch linings, which provide efficient and safe transmission of power between aircraft engines and other components, have critical importance in terms of both performance and environment when produced using sustainable materials. The aim of this study is to develop composite clutch lining materials incorporating GG25 waste metal fibers, for use in aircraft clutch systems. Developed with a sustainable production approach, these linings support both material recycling and offer important advantages such as wear resistance. In this study, microstructure analyses, mineral phase analyses and thermal analyses were performed in order to obtain a detailed perspective on the raw materials used in commercial composite-based clutch linings. The components that constitute the composite friction material suitable for aviation applications were determined in line with the obtained characterization studies and the knowledge gained from the company R&D studies. Samples produced by powder metallurgy method were abraded with ball-on type abrasion tester and friction coefficient and abrasion resistance were determined. Optical microscope and SEM-EDS analysis images taken from the worn surfaces were evaluated. As a result of the evaluations, the samples using GG25 casting waste offer similar properties to steel in terms of friction coefficient and density but are behind in terms of hardness and wear resistance. These results reveal that recyclable casting waste can be successfully evaluated instead of expensive steel fibers. It is anticipated that the idle metal fibers can effectively provide the balance of friction, wear and cost and meet sufficient performance in standard applications.

Keywords: Safety clutch material, Composite facing production, GG25 Casting Material, Material Recycling.

ÖZET

HAVACILIK UYGULAMALARINDA EMNİYET KAVRAMALARI İÇİN ATIK GG25 DÖKÜM MALZEMESİ KULLANILARAK KOMPOZİT ESASLI SÜRTÜNME MALZEMELERİNİN ÜRETİMİ

Havacılık sektöründe uçak motorları ile diğer bileşenler arasındaki gücün verimli ve güvenli bir şekilde aktarılmasını sağlayan kavrama balataları, sürdürülebilir malzemeler kullanılarak üretildiğinde hem performans hem de çevresel açıdan kritik öneme sahiptir. Bu çalışmanın amacı, uçak debriyaj sistemlerinde kullanılmak üzere GG25 atık metal lifleri içeren kompozit debriyaj balatası malzemeleri geliştirmektir. Sürdürülebilir bir üretim yaklaşımı ile geliştirilen bu balatalar hem malzeme geri dönüşümünü destekler hem de aşınma direnci gibi önemli avantajlar sunar. Bu çalışmada, ticari kompozit esaslı karama balatalarında kullanılan hammaddeler hakkında detaylı bir bakış açısı edinebilmek amacıyla mikroyapı analizleri, mineral faz analizi ve termal analiz gerçekleştirilmiştir. Havacılık uygulamalarına uygun kompozit sürtünme malzemesini oluşturan bileşenler, elde edilen karakterizasyon çalışmaları ve firma AR-GE çalışmalarından sağlanan bilgi birikimi doğrultusunda belirlenmiştir. Toz metalurjisi yöntemi ile üretim yapılan numuneler ball-on tipi aşınma test cihazı ile aşındırılmış ve sürtünme katsayısı ve aşınma direnci belirlenmiştir. Aşınan yüzeylerden alınan optik mikroskop ve SEM-EDS analiz görüntüleri değerlendirilmiştir. Değerlendirmelerin sonucunda, GG25 döküm atığı kullanılan numuneler, sürtünme katsayısı ve yoğunluğu açısından çeliğe benzer özellikler sunsa da sertlik ve aşınma direnci bakımından daha geridedir. Bu sonuçlar, pahalı çelik liflerin yerine geri dönüştürülebilir döküm atıklarının başarılı bir şekilde değerlendirilebileceğini ortaya koymaktadır. Atık durumdaki metal liflerinin, sürtünme, aşınma ve maliyet dengesini etkin bir şekilde sağlayabileceği ve standart uygulamalarda yeterli performansı karşılayabileceği öngörülmektedir.

Anahtar Kelimeler: Emniyet kavrama malzemesi, Kompozit balata üretimi, GG25 Döküm Malzeme, Malzeme Geri Dönüşümü.

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SYMBOL LIST

Symbol	Definition
λ	X-ray Wavelength
d	Distance Between Diffracting Planes
θ	Angle Between Incident Rays and Diffracting Planes
W	Weight
m	Mass
g	Gravity of Earth = 9,80665 m/s2 (32,1740 ft/s2)
A	Contact Area of the Sample
π	Pi number = 3.14159265359
r	Radius of the Sample
P	Applied Pressure Force
Δm	Mass Loss
ΔV	Volume Loss
m_1	Weight of the Material Before Wear
m_2	Weight of the Material After Wear
ρ	Density
k	Wear Rate
F	Load
d'	Distance
μ	The Coefficient of Friction
μk	Kinetic Friction Coefficient
μs	Static Friction Coefficient
Fk	Kinetic Friction Force
Fs	Static Friction Force

LIST OF ABBREVIATIONS

Abbreviations	Definition
R&D	Research and Development
CNC	Computer Numerical Control
GG25	The Cast Iron Alloy
OM	Optical Microscope
SEM	Scanning Electron Microscope Analysis
EDS	Energy Dispersive X-Ray Spectroscopy Analysis
XRD	X-Ray Diffraction Analysis
TGA	Thermogravimetric Analysis
NAOs	Non-Asbestos Organic
US	The United States of America
Ti	Titanium
UTS	Ultimate Tensile Strength
PL	Proportional Limit
VHN	Hardness
cp	Values of Commercially Pure
EL	Elongation
MMC	Metal Matrix Composite
FTIR	Fourier Transform Infrared Spectroscopy
ASTM	American Society for Testing and Materials
ZnO	Zinc Oxide
SiO_2	Quartz
$SrSO_4$	Strontium Sulfate
ZnS	Zinc Sulphide
Fe_2O_3	Hematite
Fe	Iron
C	Carbon
Si	Silicon
Zn	Zinc
Mg	Magnesium

Abbreviations	**Definition**
Ca	Calcium
S	Sulfur
O	Oxygen
ZnO	Zinc Oxide
Al	Aluminum
NBR	Nitrile Butadiene Rubber
$BaSO_4$	Barite
$CaCO_3$	Calcite
Fe_2O_3	Iron Oxide
Al_2O_3	Alumina

CHAPTER 1

INTRODUCTION

The aviation sector is a field that requires advanced technologies and precision engineering. In this field, it is of great importance for aircraft engines to operate efficiently and maintain high levels of performance. The correct transfer of power between the engine and other components plays a critical role in terms of flight safety and fuel efficiency. This is where aircraft clutch systems come into play. Aircraft clutch systems are used to efficiently transmit engine power and protect the engine by separating this power when necessary. This requires an approach that targets the development of clutch systems and pads in the aviation sector. In this context, the aviation sector has an important opportunity to achieve the goal of becoming a more effective player in the global market. Composite clutch pads make it possible to effectively evaluate the opportunities in the aviation sector with their features such as durability, lightness and high temperature resistance. In this direction, composite pads contribute to the achievement of the high-performance standards needed in the sector, while also supporting environmental sustainability with the idea of using waste raw materials in production. The use of inactive metal fibers in the production of composite pads both contributes to sustainable production processes and offers advantages in terms of performance. Inert metal fibers increase the wear resistance of the pads thanks to their strong mechanical properties, while they provide critical features such as lightness and heat resistance when incorporated into the composite structure. This approach supports both material recycling in highly engineered areas such as aviation and improves the performance and life of clutch systems.

In this study, comprehensive characterization studies were carried out in order to obtain detailed information about the compositions of commercial composite-based clutch pads. These studies include various analysis methods to determine the chemical contents of the components that make up the friction material. Microstructure analyses performed with Optical Microscope (OM) and Scanning Electron Microscope reveal the microscopic properties of the material; Energy Dispersive X-Ray Spectroscopy (SEM-EDS) is used to analyze the chemical compositions of the components. In addition, phase analysis performed with X-Ray Diffractometry (XRD) helps to understand the crystal structure of the material, while thermal behaviors were examined with Thermogravimetric Analysis (TGA).

The components that make up the composite friction material suitable for aviation applications were determined in line with the characterization studies obtained and the knowledge gained from the company's R&D studies. Based on the determined formulation, it is aimed to support material recycling and improve the performance and life of clutch systems by using GG25 casting CNC manufacturing waste instead of traditional steel fibers. Production was carried out using powder metallurgy method under fixed production conditions by preparing 6 different recipes with 200 μm steel fiber and 500 μm-1 mm material sized GG25 casting waste. GG25 casting offers an important alternative in friction material production thanks to its mechanical properties. Casting waste reduces environmental impacts and raw material costs. Thus, both sustainable material use will be provided, and the recycling process will be contributed by evaluating industrial waste.

In order to evaluate the effect of the use of GG25 casting waste in clutch lining formulations on clutch performance, wear amounts and friction coefficient were determined with a ball-on type wear tester. Optical microscope and SEM-EDS analysis images taken from the worn surfaces were evaluated. Thus, the effect of the use of casting waste on material properties was statistically interpreted.

The experimental tests and calculations made and the literature resulted in a very high convergence. This proves that the experimental work on physical performance was analyzed correctly. As a result, the use of casting waste does not negatively affect the wear and grip performance of the material at the optimum point and also exhibits an environmentally friendly approach. These results have shown that recyclable machining casting waste can be successfully evaluated instead of expensive steel fibers. With this project, an important step will be taken to meet the needs of the automotive industry and create a more sustainable future.

CHAPTER 2

LITERATURE REVIEW

2.1. Safety Clutch Mechanisms used in Aviation Applications

A clutch transfers the kinetic energy of a spinning crankshaft from a power source to the transmission and wheels. Slipping happens during interaction and produces heat. The clutch absorbs the heat and dissipates it into the environment. As a result, a clutch is a static friction pair that slides briefly during gear shifts or other interactions. Friction materials are used in a number of applications to regulate the acceleration and deceleration of vehicles and machines. These materials can be found in a variety of applications, including tiny construction equipment clutches and large airplane brakes (Kumar et al. 2021).

Trucks and off-road vehicles frequently feature big drum brakes; however some are equipped simply with front disc brakes. These brakes often work at greater friction levels and temperatures than passenger automobiles. Large airplanes have disc brakes constructed of sintered friction material. Friction materials can be resin- or rubber-bonded composites containing asbestos, metallic fibers, or a mix of these fibers (Jacko and Rhee 2000).

Brakes and clutches work in both dry and wet situations. In dry friction couples, the heat created is often passed to the surrounding air and structural parts before being eliminated. Wet friction couples, on the other hand, are often operated in oil, which absorbs heat and keeps the pair cool (generally below 200°C). The fluid may also trap worn debris (Jacko and Rhee 2000).

Safety clutch mechanisms used in cars and aviation applications are crucial to ensure that powertrain systems run safely, efficiently, and for an extended period of time. Safety clutches regulate power transfer between the engine and other components, safeguarding the system against unanticipated events such as overload, sudden stops, or crises. These systems improve vehicle safety and contribute to the long-term functioning of components by decreasing wear. Safety clutches used in both ground vehicles and airplanes are intended to meet sector-specific criteria and to endure varying operating circumstances.

Overload limiting clutches, for example, are used in vehicles to safeguard sensitive components such as the engine and transmission by preventing power transmission in the case of a sudden overload. Such devices are critical, particularly in off-road vehicles and heavy-duty trucks, where the risk of overloading is significant under challenging driving circumstances. The overload limiting clutch contributes to lower maintenance costs while boosting vehicle safety. Figure 2.1 depicts a disc braking system using friction materials. As seen in this image, the braking function is achieved by squeezing friction materials into the disk using a piston.

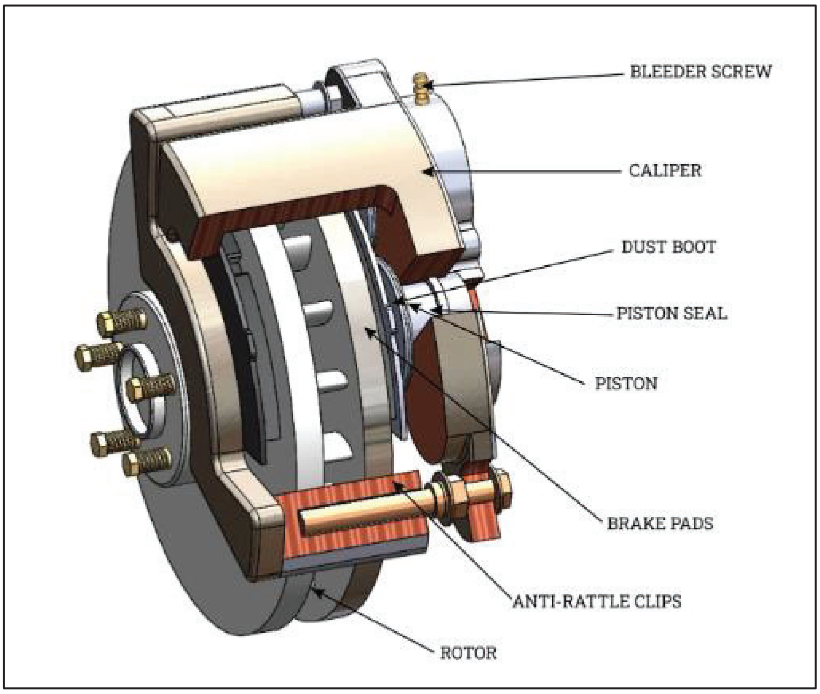


Figure 2.1. Disc Brake Used in Vehicles (Source: Zhang et al. 2022)

In the aviation sector, safety clutch mechanisms are an essential part of flight safety. Freewheel clutches, which connect aircraft engines and propeller systems, allow the propellers to spin freely in the case of an engine failure, allowing the aircraft to land safely even if one of its engines fails. Furthermore, in high-stress conditions like turbulence or when emergency braking is required, safety clutches safeguard the engine and offer overload resistance. Clutch systems used in aviation are built of materials that can withstand high temperatures and pressures, allowing them to operate safely at high altitudes. In the aviation industry, an example of safety clutch mechanisms is shown in Figure 2.2.

Figure 2.2. Disc Brake Used in Aviation Industry (Source: Agrawal 1986)

Clutch systems in airplanes are typically hydraulic or electric. Hydraulic clutch systems, which move control surfaces using fluid pressure, are often chosen in big commercial aircraft. Electric clutch systems, on the other hand, employ electric motors or actuators to move control surfaces, and they are widely used in contemporary and light aircraft. Both systems are rigorously studied and tested during the design and production phases since they are important to the aircraft's controllability and safety. Safety clutch mechanisms used in aviation applications are crucial to guaranteeing flight safety and preventing system overload. These systems are employed to reduce unexpected load shifts or excessive forces, particularly in components like engines, propellers, and gearboxes.

2.2. Clutch Facing Types According to Raw Materials Used

Until the mid-1970s, the most commonly used friction material for brakes and clutches was organic materials. These compounds were usually asbestos-based and consisted of 30-40% organic components (Jacko, Tsang and Rhee 1984). Asbestos was preferred among friction materials due to its high temperature resistance, high coefficient of friction and cost advantage. However, since the respirable fibers of asbestos caused serious health risks (such as mesothelioma and asbestosis), it was banned in many countries from the 1980s onwards (Thives et al. 2022). Today, asbestos has been largely replaced by organic, Kevlar, ceramic, metal-based and composite materials. These materials provide high performance and longevity while causing less harm to health and the environment. The choice of these materials is made according to the area of use and performance requirements of the vehicle (Khan et al. 2024). Today, brake pads can be classified as follows according to the raw materials used:

2.2.1. Asbestos Based Organic Materials

Materials called asbestos-based organic materials (ABOSM) are utilized in industrial settings to improve wear resistance and friction. However, the usage of materials containing asbestos has gradually declined and is prohibited in many countries due to the health dangers associated with asbestos. Asbestos is a long-fiber mineral with inherent fire resistance and durability.

Therefore, they have historically been employed as friction materials, particularly in industrial machinery and the automotive sector. However, many nations have limited or outright prohibited the use of asbestos because it has been shown to be a carcinogen that can cause major health issues. Alternatives free of asbestos have taken their place. Asbestos has been replaced by synthetic fibers, organic resins, metal powders, and other materials that offer comparable wear and friction resistance. These new materials are safer and better for the environment (Kumar and Gnanaraj 2024) (Quamar and Sarkar 2024) (Sachin, Sanjay and Digvijay 2023) (Chaurasiya, Ramakumar and Balasubramanian 2023).

2.2.2. Asbestos-Free Organics Materials

Since utilizing asbestos is undesirable, organic friction materials devoid of asbestos have been manufactured. Other supplements are frequently utilized in place of asbestos, and NAOs (Non-Asbestos Organic) exist in a range of formulations. Other fibers or materials with various qualities may be used as reinforcements. Typically, asbestos is replaced with a significant number of fibers free of asbestos. This is due to variances in processing and the fact that asbestos cannot be fully replaced by a single substitute fiber (Khan et al. 2024). With the ban on asbestos, organic materials such as fiberglass, resin, rubber and carbon began to be used as friction materials. These materials offered a safer option thanks to their asbestos-free structures. These materials, which are usually combined with chemical binders, have a structure suitable for daily use. They have a high coefficient of friction and a soft structure, which provides a smoother grip. Asbestos-free organic brake pads are an environmentally friendly option. They are cost-effective, operate quietly and have a soft structure. However, their resistance to heat is low, so they are not preferred in high-performance vehicles. They are preferred in passenger vehicles and city driving.

2.2.3. Metal Based (Sintered) Materials

Metal-based pads are produced by combining metal powders such as steel, copper and iron with a high temperature sintering method. It stands out with its high wear resistance and heat resistance. However, it can be noisy, cause rotor wear and is expensive. It is used in heavy-duty vehicles, trucks and motorcycles that carry high torque and load.

2.2.4. Semi-Metallic Materials

Introduced in the late 1960s, carbon-metallic materials—also known as semi-metallic-became more popular in the middle of the 1970s and, by the 1980s, were preferences for use in more than 90% of US passenger cars and light trucks' front axles. The weight percentage of iron and/or steel components in these products is often greater than 50%. Originally, iron powder with a tiny quantity of steel fibers made up the majority of nearly all semi-metals (Dong et al. 2024). Following that, little amounts of iron powder were combined with huge volumes of steel fibers. To improve the material's performance, a range of property modifiers are used, such as graphite powders, organic or rubber particles, and ceramic powders. The mixture is also supplemented with the resin binder required to keep the ingredients together (Dong et al. 2024). Semi-metallics outperformed the asbestos-based organic materials. They replaced with more constant friction, improved wear resistance, longer life, and quieter operation. Semi-metallic friction materials, consisting of sintered metals and synthetic fibers shown in Figure 2.3, are the most durable type of friction materials.

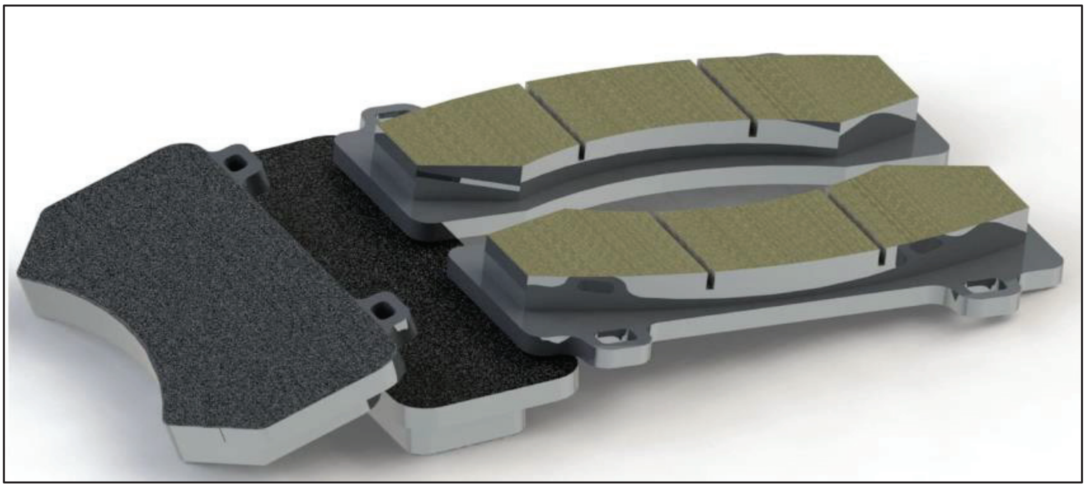


Figure 2.3. Semi-Metallic Friction Materials (Source: Jadhav et al. 2019)

2.2.5. Carbon Composite Materials

Carbon, often known as graphite, is a thermally stable material with low density and high specific heat. Carbon is a desired friction material due to its properties. As a result, various companies produce carbon fiber-reinforced carbon matrix composites, which are used mostly in racing automobiles and airplane clutches (Yu and Jiang 2024). Three forms of carbon are often included in carbon composites: carbon fibers, carbon produced by a phenolic-based resin’s-controlled pyrolysis, and carbon that fills the pores using chemical vapor deposition (Yu and Jiang 2024). Carbon-carbon pads are made of high-performance materials such as carbon fiber and carbon powder. Braking performance is at a high level. It is extremely resistant to heat, lightweight and high performance. However, its cost is high, so it is only preferred in special applications and is not suitable for daily use.

2.2.6. Ceramic Materials

Ceramic pads are produced with ceramic fibers, copper fibers and binding resins. Thanks to its high temperature resistance, it does not lose performance in overheating situations. Ceramic fibers are combined with organic materials in friction materials to provide high temperature resistance and low wear properties. Ceramic pads have become popular especially in performance vehicles and sports cars. They have a low environmental impact thanks to their long life and less dust production during braking.

2.2.7. Kevlar Materials

Kevlar pads are produced using high strength Kevlar fibers. In the 1990s, Kevlar began to be used in friction materials due to its high strength and wear-resistant structure. Kevlar has become an ideal choice especially for commercial vehicles and heavy-duty vehicles due to its low dust production, durability and lightness.

2.2.8. Composite Materials

Composite friction materials are produced by combining different materials (organic, metallic and ceramic). In this way, a balancing friction performance is provided by utilizing the advantages of each material. Composite materials aim to reduce wear on the rotor while increasing friction performance. However, they are more expensive than organic pads. They are used especially in commercial vehicles, passenger cars and light-duty vehicles. These pad types are preferred in different vehicles according to driving conditions and performance requirements. The most suitable pad type for the vehicles is selected by considering factors such as the purpose of use, the performance of the vehicle, price and durability. For example, while organic and composite pads are generally preferred in passenger cars, ceramic and carbon-carbon pads are used in high-performance vehicles.

2.3. Materials Used in Composite Clutch Facing

Composite materials are often composed of a number of distinct components linked together. These components often comprise a matrix material with a high coefficient of friction, such as a resin-based matrix. This matrix material is typically reinforced with fibers made of carbon fiber, glass fiber, or, in rare cases, metallic fibers. The distribution of reinforcing fibers throughout the material is crucial to defining the mechanical qualities and performance of the finished product. These reinforcing strands make the pad more durable, robust, and heat resistant. The fillers and additives in composite clutch linings improve friction performance and wear resistance. This complex mix of materials is frequently carefully chosen and adjusted through a variety of tests to achieve the necessary friction characteristics, durability, and performance.

Figure 2.4. Materials Used in Composite Clutch Facing (Source: Hee et al. 2005)

Composite buildings deliver more strength with less weight than traditional materials, increasing fuel economy and lowering total costs. Furthermore, structural integration of these materials allows for greater design freedom, hence expanding innovation prospects. In this regard, composite materials are extremely important in the aircraft application. Figure 2.4 provides a representative image of the materials utilized in composite clutch linings.

In the industry, raw friction materials are classified into four categories: friction material binders, reinforced fibers, friction material fillers, and friction performance modifiers (Gurunath and Bijwe 2007).

2.3.1. Friction Material Binders

Binders are fasteners that support and reinforce the structure of composite clutch pads. Typically, organic, phenolic, epoxy, or polyester resins are utilized. The chosen binder must be very heat resistant (Sudhakaran and Bijoy 2023). It also increases the durability of the facing by providing mechanical strength and wear resistance. Low resin concentration leads to poor physical properties for composite clutch linings.

Consequently, when changing the physical properties of the lining such as porosity and hardness, the resin ratio should be taken into consideration as it is critical to the intended performance and durability of the lining (Lionetto, Moscatello and Maffezzoli 2017).

2.3.2. Reinforcements

Reinforcements improve the mechanical longevity of the pad by supporting the load applied during friction (Gümüş 2012). High-strength materials like carbon fiber, glass fiber, and aramid fibers are commonly employed to improve strength and performance.

These fibers increase wear and temperature resistance by increasing the mechanical qualities of the face. Metallic fibers, like copper and steel, enhance friction performance and heat absorption, extending the pads' lifespan (Anbunathan, Perumal and Senthilkumar 2019).

2.3.3. Friction Material Fillers

Fillers improve or stabilize properties, increase manufacturability, and reduce costs (Sudhakaran and Bijoy 2023). Organic fillers enhance mechanical properties, while inorganic fillers improve hardness, thermal resistance, and chemical resistance. Common fillers include mineral fillers, ceramic powders, and glass spheres.

2.3.4. Friction Performance Modifiers

Friction modifiers improve the friction performance of the pad by raising the coefficient of friction or lowering undesired effects (Sudhakaran and Bijoy 2023). Examples include graphitized materials, metal powders, and mineral additions. Lubricants, such as molybdenum disulfide or graphite, improve friction performance by reducing wear and heating, thereby extending the pad's life (Anbunathan, Perumal and Senthilkumar 2019). Abrasives, including silica, sand, quartz, alumina, boron carbide, aluminum oxide, and silicon carbide, improve friction performance and surface roughness. They improve the contact surface between the pads and the clutch facing, resulting in more efficient friction and heat dissipation during braking. However, excessive usage might have unwanted consequences, thus cautious selection and application are required (Kocabaş 2012). Research has demonstrated that abrasive qualities such as size, hardness, and shape have a substantial impact on wear rate, with high melting temperature materials usually demonstrating high wear resistance (Hu, Meng and Liu 2014). High humidity can enhance abrasive wear by around 15%, and water vapor has a comparable impact (Chen et al. 2018).

2.4. Use of Recycled Raw Materials in Composite Production

The utilization of recycled metal raw materials in composite manufacture is a significant way for lowering costs and guaranteeing the sustainable use of natural resources while minimizing environmental effect. Today, growing environmental consciousness and industrial demands drive novel composite production techniques that recycle scrap metal elements. This recycling technique enables the production of high-performance composite materials for applications such as automotive, aviation, construction, and electronics.

Metal recycling involves processing discarded metals and incorporating them into composite matrices in the form of fibers or powders. Cast iron (e.g., GG25) and recycled steel fibers are particularly excellent reinforcements for increasing composite mechanical strength. Steel fibers offer wear resistance and rigidity, while cast iron powders like GG25 promote heat dissipation. These recovered materials have been effectively employed in automobile braking systems as well as construction applications. For example, composites made from recycled metals in the automobile sector make car parts lighter and more durable, enhancing fuel economy and lowering pollutants.

Growing worries about industrialization and resource depletion have prompted the metal recycling sector to expand. Increasing demand for metals from the automotive sector, expanding worldwide power, and developing environmental concerns are projected to boost the metal waste management market in the coming years (Liu and Keoleian 2020).

Bulei et al. (2021) addressed the most efficient techniques of recycled aluminum alloys for composite applications. Their study focused on the production of ceramic particle reinforced aluminum alloys using the liquid mixing (Vortex method) process in metal matrix composites. They concluded that this process offers economic benefits as it requires fewer procedures, less time and less energy, while also allowing the use of widely available and cost-effective recycled matrix alloys.

Enginsoy et al. (2020) aimed to develop hybrid metal matrix composites made from recycled AA7075 aluminum and copper powder as a cost-effective and industrially usable alternative material for electric motor components that require high wear and strength. As a consequence, the microstructure, strength, and wear resistance of samples produced by sintering and forging processes were enhanced, and the experimental and finite element analysis findings agreed. Figure 2.5 illustrates the service life of a metal.

Graedel et al. (2011) presented an analysis of the recycling rates of 60 metals, with the goal of evaluating the effectiveness of metal recycling operations and identifying priority areas for worldwide recycling rate improvement. The study found that end-of-life recycling rates (EOL-RR) for several metals were less than 50%, and recycled content (RC) rates were usually low, indicating areas for development and the necessity of sustainability initiatives to promote recycling efficiency.

Bauer et al. (2010) aimed to study the possibility for safe recycling in dentistry by assessing the impact of recasting titanium (Ti) alloys on mechanical characteristics, microstructure, and fracture surfaces. Recasting raised the ultimate tensile strength (UTS), proportional limit (PL), and hardness (VHN) values of commercially pure (cp) Ti while decreasing elongation (EL); hence, recasting was determined to be cost-effective and safe for use in dentistry.

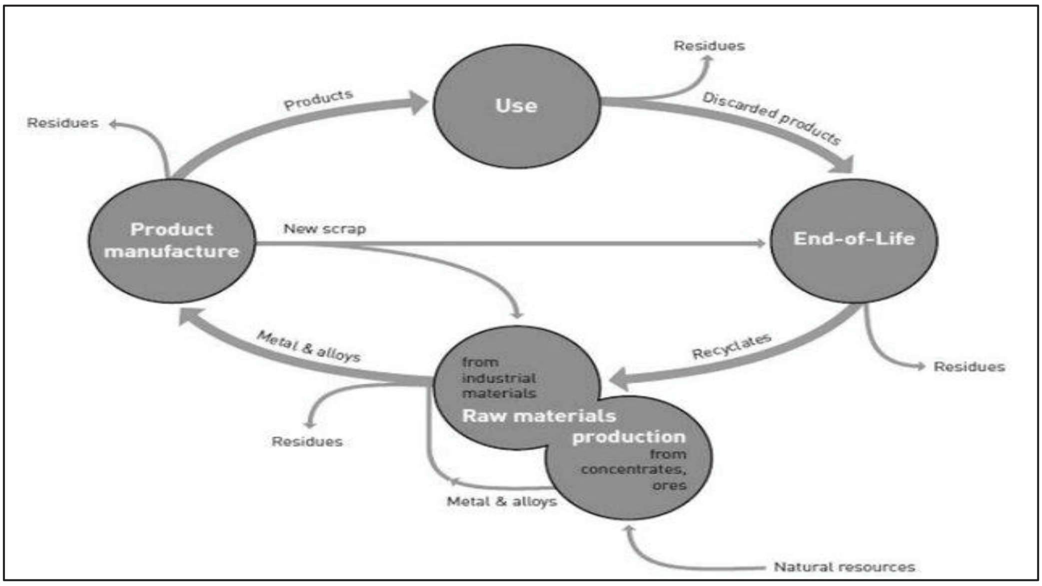


Figure 2.5. The Life Cycle of a Metal's Use (Source: Fthenakis et al. 2009)

The desire for lighter automobiles globally is driving the growth in the transportation sector. This has led to a preference for using alloyed steel and iron parts (like GG25) in automobiles or replacing them with similar composite materials. In this study, it is aimed to create a composition that supports recycling. Based on this, the idea of using metal sawdust waste emerged from the operations applied to semi-finished parts observed within Dönmez Debriyaj Sanayi ve Ticaret AŞ and the formation of significant amounts of sawdust waste. The idea of evaluating the resulting metal sawdust waste in an idle state supports targeted recycling. It is based on the GG25 casting pressure plate, which was produced in 8000 units in 2024 within the company. The semi-finished product, which is 20.6 kg in casting form, becomes 17.8 kg of product after turning, drilling and balancing processes. The amount of waste corresponding to 2.8 kg per product reaches 22.4 tons per year.

2.5. Tribological Properties of the Raw Materials Used in Friction Materials

The term tribology was introduced in 1960 to link three important interdisciplinary research areas: friction, lubrication and wear (Manu, Guptaand and Jayatissa 2021). 'Tribology' derives from the Greek term 'tribos' meaning wear or sliding

(Lisiecki 2019). The economic impact of friction losses has given impetus to the eventual unification of these different branches under a common definition (Tichy and Meyer 2000). The main goal of this discipline is to increase the durability of materials by minimizing the negative effects during engagement (Ertan and Yavuz 2005). Tribology has an important application in the aviation industry. Friction and wear reduction technology enables aircraft to travel longer distances and consume less fuel, making aviation environmentally friendly and economical. In this direction, the approach focuses on the development of new materials and coatings. In addition, the correct design of tribological systems is also important because correctly designed systems can reduce energy consumption, extend their life and ensure environmental friendliness.

Wear resistance and friction force are fundamental concepts in tribology and significantly affect the performance of materials in engineering applications. These two concepts are especially critical in industries such as automotive, aerospace, and manufacturing. Wear resistance refers to the ability of a material to withstand mechanical effects such as friction and abrasive forces, while frictional force describes the resistance encountered when one surface passes over another.

Wear resistance describes how well a material can withstand surface interactions. High wear resistance is crucial to ensuring the long-term and reliable performance of a material. Wear-resistant materials generally exhibit high hardness and smooth surface properties. Czichos et al. (2019) emphasize that wear resistance is related not only to the hardness of the material, but also to factors such as surface smoothness, lubrication conditions, and environmental influences. Hard materials generally exhibit lower wear, while softer materials tend to wear faster. However, very hard materials can sometimes be prone to cracks and fractures, making material selection a complex process. Wear testing methods are used to measure the wear resistance of materials. Some common methods include pin-disc, block-ring, and wear tests. These tests involve the interaction of two surfaces under a given force to determine the rate at which the material wears. Understanding how different materials respond to wear is important to guide material selection or surface treatment techniques.

Wear is the permanent changes that occur on the surfaces of materials. These changes can cause damage and wear to the surfaces and shorten the life of the worn surfaces (Yukio and Kato 2008). Wear can be caused by three conditions: surface-to-surface contact (frictional wear), surface contact with a foreign substance (abrasive wear), and erosion by corrosive elements. Increased speeds and loads necessitate tighter tolerances for machine system dependability and longevity, as well as the limitation and management of wear.

According to research performed by several organizations, friction accounts for around 20% of global energy output (Holmberg and Erdemir 2017). The first documented study on friction was conducted by Thermistius in 350 BC and showed that rolling friction is less than sliding friction due to the torque produced by the friction force ($\mu k < \mu s$). Friction force is a measure of the resistance encountered when one surface slides over another. Friction is divided into two categories: static friction and kinetic friction. Blau (2001) defines static friction as the resistance between objects before they start moving, while kinetic friction refers to the resistance created when objects start moving. Static friction is generally higher than kinetic friction. The friction force is affected by a variety of factors, including the roughness of the contacting surfaces, material properties, surface pressure, and lubrication conditions.

The coefficient of friction (μ) is the ratio of the friction force to the normal force applied to the surface and is used to evaluate the friction performance between pairs of materials. Moreover, the friction force always leads to energy loss, thus reducing the system efficiency. Therefore, reducing friction, like minimizing wear, is very important in many engineering applications. Friction materials must have the ability to stop a moving vehicle quickly and safely under various conditions. During this process, kinetic energy is converted into thermal energy by friction systems (Sudhakaran and Bijoy 2023) (Borawski 2020). Lastly, lubrication is started a gaseous, liquid, or solid lubricant to reduce friction and wear and to remove heat and debris created through the sliding course (Lancaster 1990).

The relationship between wear and friction is complex and not always linear. Generally, higher friction leads to increased wear, but in some cases, the structure of the material or the application of lubrication can reduce wear despite higher friction forces. Czichos et al. (2019) explain that wear rates generally increase with increasing friction forces, but that material and environmental conditions can alter this relationship. Lubricants, in particular, can reduce both friction forces and wear rates. Consequently, balancing wear resistance and friction force is critical to the performance and longevity of engineered systems. Proper control of these two factors provides significant benefits, particularly in terms of energy efficiency, maintenance costs, and system reliability. As tribology continues to grow in importance across industries, particularly in aerospace, there is increasing focus on the development of advanced materials. One important area where these materials are applied is the production of composite clutch surfaces. The following section examines the materials used in composite clutch surfaces and how their properties contribute to their performance.

The effect of the resin on wear resistance depends on both the structure of the material and the operating conditions. When the resin is correctly selected, it can increase wear resistance, but it can have a negative effect if it deteriorates at high temperatures (Nassar et al. 2022). When used in the right amount, graphite can reduce wear and provide smooth friction, but excessive use can negatively affect wear resistance (Ibrahim et al. 2024). Quartz provides resistance to wear due to its high hardness. This property supports less wear of composites under friction and thus a longer life (Zurowski et al. 2021). Talc is a low-hardness material and can negatively affect wear resistance when exposed to abrasive particles. Composites with a high talc content can become more vulnerable to wear (Rathaur, Patel and Katiyar 2019). Zinc sulfide may not have sufficient lubricating properties in some applications. It can negatively affect wear resistance, especially under friction conditions, if not combined with other fillers (Ertan and Yavuz 2011).

2.6. Production of Composite Facing by Powder Metallurgy Method

Composite materials are materials made by mixing several components that have complimentary qualities. Composite clutch linings are one of these materials, and they are commonly utilized in important applications such as brake systems, particularly in the automobile sector. Fibers (such as carbon fiber and glass fiber), fillers, friction modifier additives, and phenolic resin are common components found in composite clutch linings. The procedures employed in the manufacture of these linings are critical in terms of boosting durability and giving the appropriate performance characteristics. Powder metallurgy is one of the most regularly utilized technologies for producing composite clutch linings. The powder metallurgy technology combines metal and nonmetal powders to create metal matrix composite (MMC) powders. It is a manufacturing technology that allows for the creation of metal matrix composite components by molding powders into certain shapes and sintering at high temperatures, i.e. combining with heat treatment. The benefits of powder metallurgy are significant. First and foremost, items may be manufactured with high accuracy and near-net form, reducing the requirement for subsequent procedures. Furthermore, powder metallurgy is effective at creating components with complicated and intricate geometries while still providing great efficiency in mass production. Furthermore, combining metal powders can provide diverse material characteristics, allowing for the creation of composite materials or multifunctional goods. However, powder metallurgy does have certain limits. It may raise costs due to its reduced efficiency in small-scale production. Powder metallurgy has four fundamental stages: mixing, pressing, sintering, and secondary processes. Figure 2.6 depicts the steps of the powder metallurgy process. Prior to mixing and blending, the powder's appropriateness for the powder metallurgy process is evaluated and tested. Flow rate, density, compressibility, and strength are all taken into consideration.

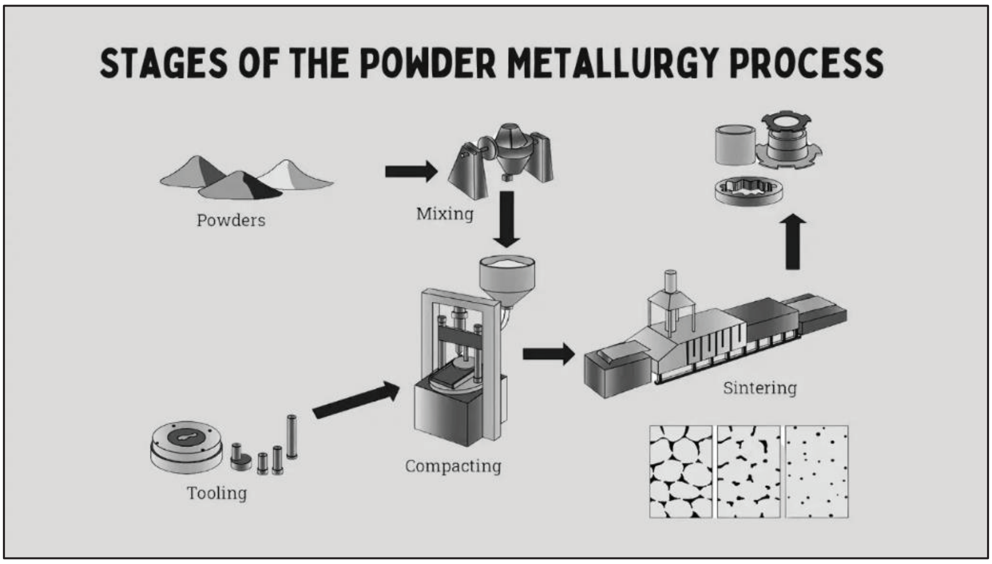


Figure 2.6. Stages of the Powder Metallurgy Process (Source: Sadeghi et al. 2021)

2.6.1. Mixing of Powders

In the first stage, the powders whose appropriateness has been determined are blended to get the desired composition and qualities. It is critical to distribute these components uniformly in order to develop materials with the correct qualities. Effective mixing aids in maintaining the required qualities of the coating material, but the true issue is to ensure that the reinforcement element is equally distributed in the matrix and to strengthen the link between the reinforcement and the matrix. The mixing technique and time have a considerable impact on the distribution of the reinforcing ingredient as well as the powder's qualities (Williams 1968).

2.6.2. Forming of the Mixed Powder into a Compact

After mixing, the homogeneously dispersed powder mixture is squeezed under high pressure using hydraulic or mechanical presses and customized molds to get the required form. This procedure often involves one-way compression. Because the molding process has a direct impact on the friction material's qualities, the pressure and temperature must be adjusted accordingly (Manu, Guptaand and Jayatissa 2021). This pressing process, which typically occurs at temperatures ranging from 140 to 250 °C, impacts the friction material's characteristics and enhances resin hardening and material durability (Kim, Seok Kim and Jang 2003). The amount of compaction pressure required for each type of metal or non-metal powder varies according to its properties.

2.6.3. Sintering of the Compact to Enhance Integrity and Strength

Sintering is a heat treatment procedure in which the compressed object is subjected to temperatures high enough to allow loose particles to combine and join, resulting in a solid part. In this process, the pressed material is kept at a specific temperature and humidity for a set amount of time. During this process, the resin within it completely solidifies, allowing the material to achieve its intended mechanical qualities and to form a whole.

2.6.4. Secondary Operations

Secondary procedures are used in powder metallurgy to improve the mechanical characteristics and surface quality of a product after it has been sintered. These procedures include densification, heat treatment, machining, and polishing. Densification strengthens the component, whilst heat treatment adds hardness and wear resistance. Surface coatings prevent corrosion, whereas machining produces accurate measurements. In addition, unique techniques like oil impregnation enable the component to lubricate itself. These secondary procedures maximize the qualities of the final product based on the application's needs.

CHAPTER 3

EXPERIMENTAL METHOD

Material characterization procedures are basic research and analytical methods for determining the physical, chemical, and mechanical characteristics of a material. These procedures yield precise information on the material's structural properties, composition, surface structure, thermal behavior, mechanical strength, and other relevant characteristics. Material characterization is crucial during the design, manufacture, processing, and performance assessment stages. Scanning electron microscopy (SEM) is one of the most popular characterization procedures because it allows the surface structure of the material to be viewed and evaluated at high resolution. SEM allows for detailed examination of the material's morphological characteristics, porosity rate, surface roughness, and component interactions. Furthermore, analytical methods such as energy dispersive spectroscopy (EDS) can be used to determine the material's composition. X-ray diffraction (XRD) is another significant technique for analyzing the crystal structure and phase composition of the material. XRD helps to detect crystal phases by determining the material's crystallographic characteristics. This approach is frequently used in solid state physics research, materials fabrication, and polycrystalline structure characterization. Other characterization procedures include thermogravimetric analysis (TGA) studies. These strategies are crucial for better understanding and optimizing the material in a variety of ways. The physical attributes of the material include appearance, shape, size, and structural characteristics.

3.1. Chemical Analysis

Chemical analysis of clutch linings is extremely important for vehicle performance and safety. These techniques help determine how the lining components work and in what kind of environmental conditions they perform best. In particular, material knowledge and evaluation of factors such as wear, and temperature resistance are critical in automotive engineering and applications. Some of the chemical analyses are as follows.

3.1.1. Optical Microscope (OM)

The optical microscope, sometimes known as the "light microscope," is a device that employs visible light and a series of lenses to expand pictures of microscopic objects. This type of microscope is the earliest model of microscope and have been developed in its current compound form in the 17th century (Di Gianfrancesco 2017). It is frequently used by material scientists in the examination of metallic materials and is called metallography. An optical microscope can be used to examine the surface structure and wear modes of the clutch lining. By examining the wear, cracks and surface roughness on the surface of the clutch lining, it is observed how these parts deform over time. Information is obtained about the lining and material homogeneity of the lining.

3.1.2. Scanning Electron Microscopy and Energy Dispersive X-ray Spectroscopy (SEM-EDS)

SEM/EDS allows for the analysis and morphological characterization of both organic and inorganic material surfaces. An electron beam with a high voltage is focused on the sample. The interaction between the sample and the electron beam causes the emission of radiation in the X-ray spectrum, which is unique to an element. High-speed qualitative elemental analysis is made possible by this method. The intensity of the radiation that the sample emits can likewise be used to determine the quantity (Newbury and Ritchie 2013). The clutch lining's surface wear and microscopic cracks are examined using SEM. Elemental analysis can be performed with EDS, the elemental composition of surface contaminants and material components formed as a result of wear can be determined, which helps to understand the wear mechanisms of the pad. In this study, it is used to perform elemental analysis of organic and inorganic components.

3.1.3. X-ray Diffraction Analysis (XRD)

XRD is an important material characterization method used in the analysis of crystal structures. In XRD analysis, X-rays are sent to a sample at a certain angle and the pattern resulting from the diffraction of these rays depending on the atomic arrangement in the crystal structure is examined. When X-rays pass through a crystal structure, they are diffracted at certain angles depending on the distance between the atoms (d-line). The relationship between the diffraction angle and wavelength is determined using Bragg's Law ($n\lambda = 2d \sin\theta$).

The peak values obtained from this diffraction pattern provide information about the crystal structure of the material. Each peak in the XRD pattern originates from a certain plane of the material and the position of the peak indicates the properties of the crystal structure of the material (Khan et al. 2020).

3.1.4. Thermogravimetric Analysis (TGA)

The mass variations of clutch lining components under heat are examined using TGA. The thermal stability of the clutch lining and the evaporated components can be determined using TGA. It is possible to ascertain how heating the material impacts the lining's durability by measuring the amount of mass lost.

3.2. Characterization of Commercial Friction Material

In this work, material characterization investigations were conducted on Trimat MN2221 composite-based clutch linings to get extensive information about the compositions of commercial composite-based clutch linings. Before the chemical analysis examinations, as seen in Figure 3.1, samples were taken from the sections and surfaces of the samples with a precision cutting disc, then molded using Bakelite and the sample preparation process was carried out by sanding the surface of the samples.

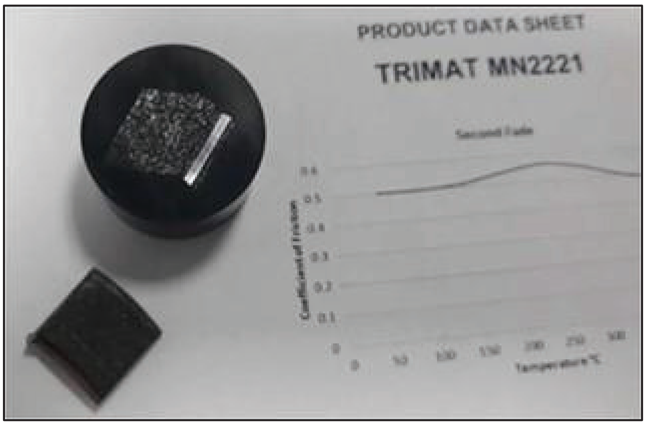


Figure 3.1. Prepared by Taking the Surface and Cross Section of Commercial Friction Facing

Phase analysis, an important material characterization method used in the analysis of crystal structures, was performed in the central research laboratory. Different crystal phases in the content of the material were determined. Comments were made on the minerals and metal alloy phases in the content of the composite. In addition, comments were made on material safety with factors such as the intensity and width of the peaks. The analysis and results are shown in Figure 4.1.

In the study, the sample microstructure was examined under an optical microscope and the particles in the matrix, their sizes and morphologies were determined. Then, the distribution of the microstructures in the composition was examined under a scanning electron microscope. SEM analysis, one of the primary techniques used in material characterization, enabled the assessment of morphology, porosity, surface roughness, and interactions between components by imaging and analyzing the material's surface structure at high resolution.

Then, EDS, a method utilized in tandem with scanning electron microscopy, was used. This determines the elemental distribution of the material and provides detailed chemical information by measuring the amount of each element. Thermal analysis investigations were conducted as a continuation of the analyses to investigate the sample's mass losses under temperature. In light of the investigations conducted, detailed information was obtained about the compositions used in clutch linings and characterization interpretations were made in the light of this information in the result.

3.3. Sample Preparation and Production Stages

The components that constitute the composite friction material suitable for aviation applications were determined in line with the characterization studies and the knowledge gained from the company's R&D studies. Based on the determined formulation, it is aimed to support both material recycling and improve the performance and life of the clutch systems by using GG25 casting CNC manufacturing chip waste instead of traditional steel fibers. 6 different recipes were prepared with different ratios of steel fiber and GG25 casting waste in 500 µm and 1 mm material sizes.

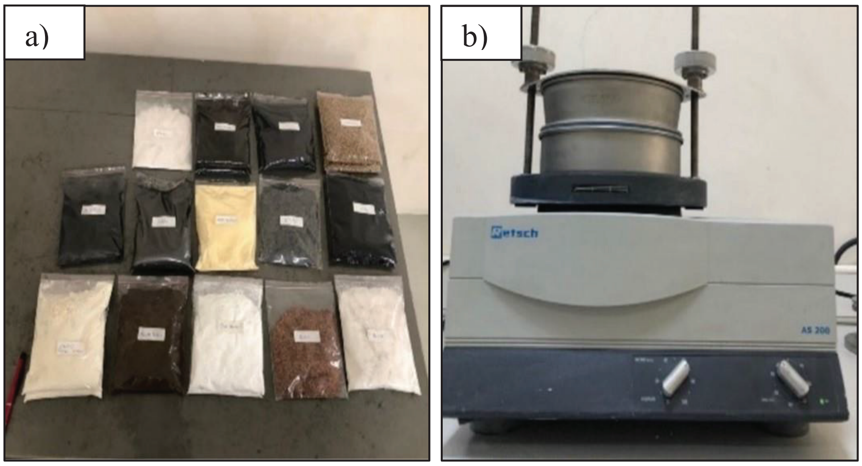


Figure 3.2. a) Prepared Raw Materials, b) Retsch (A5200) Sifter Device

Then, production was carried out with the powder metallurgy method under fixed production conditions in line with the prepared recipes. Before preparing the sample mixtures, in order to obtain metal fibers in the desired sizes, the GG25 material, which was found in the form of large metal sawdust, was separated into maximum sizes of 500 µm and 1 mm by passing through 500 µm and 1 mm sieves with the Retsch (A5200) device. The prepared powder samples and the device in which the sieving process was performed are given in Figure 3.2.

Then, 6 different sample mixtures were prepared with raw materials in different proportions in line with the determined recipes. The mixing process of the prepared powder raw materials was carried out homogeneously by processing at 700 rpm for 1 minute in the L3046 brand industrial mixer given in Figure 3.3.

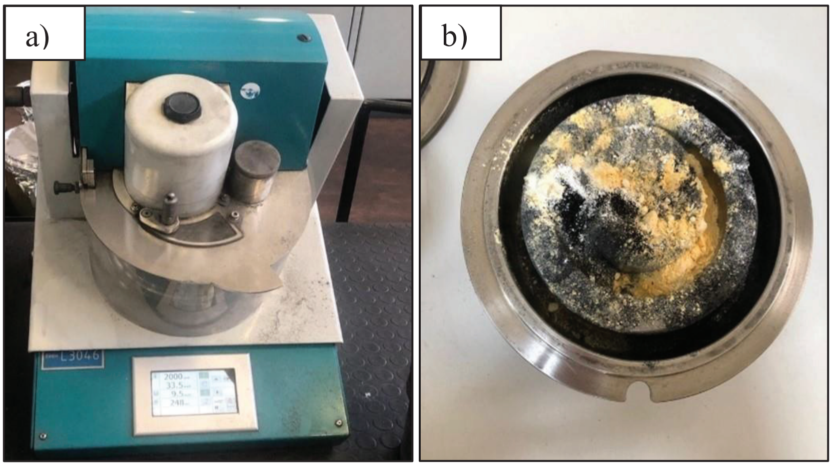


Figure 3.3. a) L3046 Mixer Device, b) Homogeneous Raw Material Mixture

Then, the sample is prepared by heating the mold in a laboratory oven until it reaches 160°C to reach the desired temperature before pressing. After the mold has achieved the necessary temperature, it is removed from the oven, and roughly 10 grams of the powder combination, which offers adequate homogeneity in the mixer, is taken and filled into a 25 mm diameter and 10 mm thick mold.

Figure 3.4. Pressing Process in Hydraulic Press Machine

Then, the mold was pressed in the hydraulic press machine in Figure 3.4 under 6-7 tons of pressure for 15 seconds. Finally, the test samples are subjected to a sintering process for 8-10 hours in a laboratory oven set at 180 ˚C to obtain their final shape.

Support was received from Manisa Celal Bayar University and Eren Balatacılık Sanayi ve Ticaret A.Ş. regarding the devices used during the production of friction surfaces. Then, the samples produced according to the determined recipes were subjected to friction tests and chemical analyses. The production and testing process is schematized in Figure 3.5 for a better understanding of the methods and steps used.

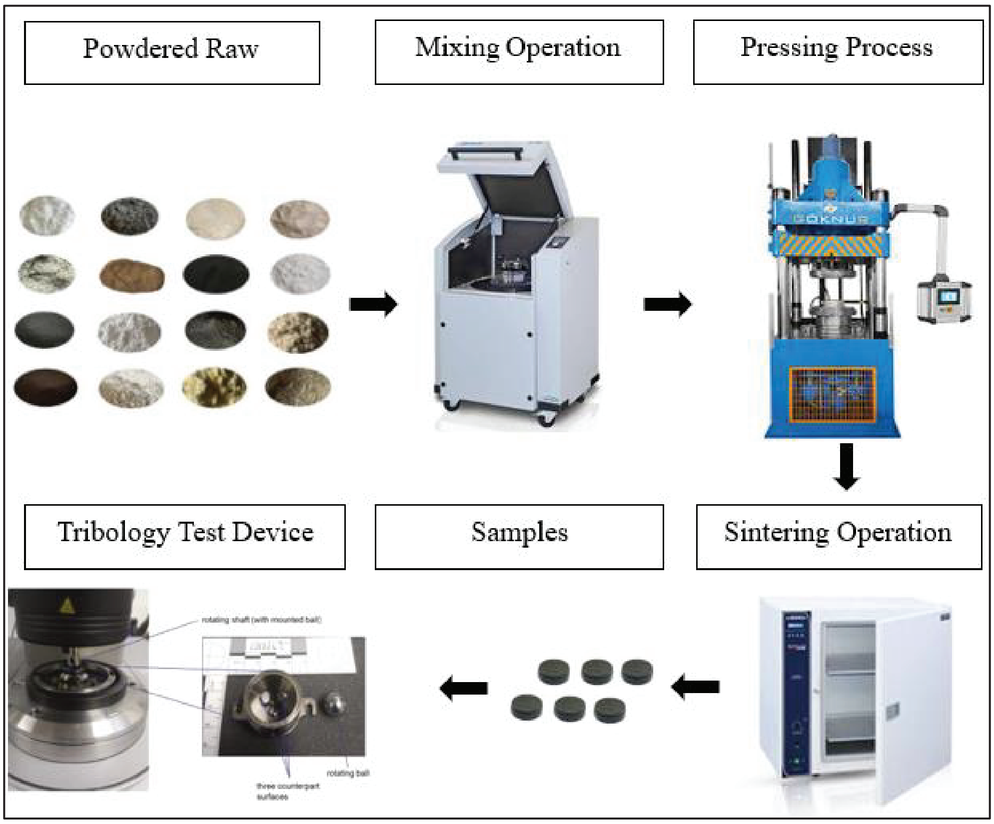


Figure 3.5. Production Flow Chart (Source: Di Gianfrancesco 2017)

3.4. Tribology Testing with Ball-on Disk Type Testing Device

One performance test used to measure a material's durability and wear resistance is the wear test. The degree of wear and surface alterations are measured over a predetermined amount of time when the material is exposed to friction or wear forces. This test assesses the material's lifespan, coefficient of friction, and surface quality.

The ball-on-disc geometry is frequently used to analyze different material combinations by comparing wear values at the equal sliding distance under the same nominal experimental circumstances (e.g. normal load, sliding velocity, ambient temperature, and composition) (Du et al. 2022) (Czichos, Becker and Lexow 1987). In principle, this can be achieved by experimentally estimating wear constants, which are defined only by the worn volume and do not depend on the geometry of the contact surfaces. A frequently procedure is used for constant An, flat on flat geometries (in common ball on disc tests k1 and k2 are usually determined by post-test profilometry and/or microscopical analysis, using the overall volume loss). More advantages are the non-linear nature of the model (allowing in principle better accuracy than usual linear fits) and the circumstance that in addition to real-time recording of the cumulative wear height h(t) and of the friction force F(t), only a small number of profilometric measures may be necessary to determine tribological coefficients (Meozzi 2006).

The ball on type disc tester was used in the wear and friction testing to evaluation the tribological characteristics of the grip surface materials, after the sample preparation process was completed. A laboratory test tool called the disc tester analyzes the friction coefficient data produced by the motion of material surfaces. Essentially, this gadget comprises of a disk and a ball. The disk is often composed of metal and has a smooth surface. On the other hand, the ball is often constructed of a hard substance that causes friction and wear while revolving on the disc.

During the test, the disc is spun, and the ball follows a predetermined course on it. Friction and wear are measured by the number of traces or wear particles created on the disk surface. This testing equipment is commonly used to compare the friction and wear properties of various materials, to influence material selection, and to undertake tribology research (friction, wear, and lubrication). In order to determine the performance behaviors of the test samples, 5 mm radius and 1050 steel disc was used as an abrasive in the Ball-on disc device shown in Figure 3.6. Throughout the test, care was taken to ensure that the disc component was in complete contact with the sample.

In addition to the size and surface quality of the test sample utilized during the test, other elements influencing the test include applied force, sample rotation speed, contact point distance from sample center to disk, temperature, and ambient conditions. The test was carried out under laboratory conditions at 20 °C and 50% humidity. Considering that an aircraft landing on the runway travels an average of 1500-2000 m, the distance parameter to be covered was determined as 2000 m. The samples were subjected to a disk with a load of 10 N and a linear speed of 25 cm/h (Akdoğu 2010). The parameters used are presented in Table 3.1. In the ASTM G99 test, the amount of wear is measured by calculating the weight loss by measuring the sample before and after it is placed in the device.

Table 3.1. Ball on Disk Type Wear Tester Tribo Parameters

Conditions	Linear Speed	25.00 [cm/s]
	Normal Load	10.00 [N]
	Stop Condition	2000.00 [m]
	Acquisition Rate	0.10 [Hz]
Sample Static Partner	Dimension	10.00 [mm]
	Geometry	Ball
	Abrasive Disc	1050 Steel
Environment	Temperature	20.00 [°C]
	Humidity	50.00 [%]

The samples were weighed on a scale with an accuracy of 0.0001 gr prior to the test, and their weights were assessed after wear to quantify mass loss. Table 4.5. shows the mass changes of the different samples. The friction coefficient data graphs recorded by the device are in Table 4.4 and the wear rates are created and evaluated in the results section in Table 4.5.

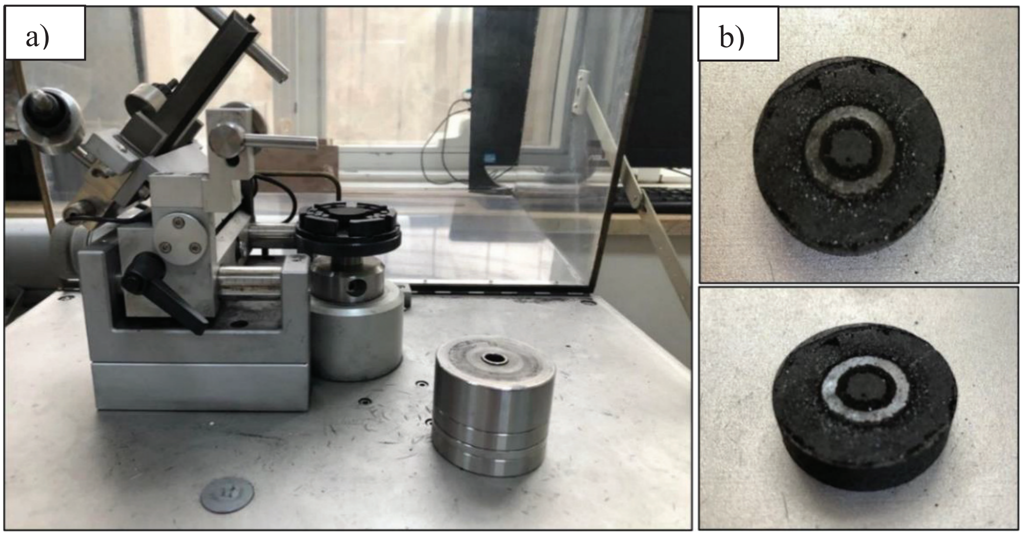


Figure 3.6. a) Tribology Test Device, b) Worn Test Specimen Used in the Experiments

Based on the physical measurements of the samples before wear, the initial weight, contact surface area and applied pressure force of each sample were determined. The mass of each sample was calculated using formula 3.1, the contact areas of the samples were determined with formula 3.2 and the pressure force applied to these areas was detailed with formula 3.3.

$$W = m.\,g\ [N] \tag{3.1.}$$

$$A = \pi.r^2\ [mm^2] \tag{3.2.}$$

$$P = W/A\ [N/mm^2] \tag{3.3.}$$

The samples were subjected to abrasion at a distance of 2000 m by following the basic parameters and mass and volume losses were determined using formulas 3.4- 3.5.

$$\Delta m = m_1 - m_2\ [gr] \tag{3.4.}$$

$$\Delta V = \Delta m/\rho\ [gr/mm^3] \tag{3.5.}$$

The wear rate is found by dividing the wear volume calculated with formula 3.5 by the applied load and distance as in formula 3.6.

$$k = \Delta V/F.d\ [mm^3/Nmm] \tag{3.6.}$$

3.5. Physical Analysis

Density testing is an analysis that determines the ratio of the mass of a substance to its unit volume for the purpose of identifying and quality control. Usually, the mass of the tested sample is determined with a precision balance and the volume is determined by using a water immersion method or a measuring cylinder. This test determines if the material is light or dense.

A hardness test determines how much resistance the surface of a material displays under varied stresses. This test measures the material's hardness, toughness, and wear resistance. Hardness varies according on the material's microstructure, composition, and processing processes. Hardness is defined by the degree of indentation or depression caused by a force applied to the material's surface and is often measured using techniques such as Brinell, Rockwell, Vickers, and Shore D. Another physical test, surface roughness testing, detects abnormalities, protrusions, and indentations on a material's surface. This test evaluates the surface quality of the material and determines the amount of smoothness necessary for various applications. This testing is performed by methods such as profilometry, visual inspection or laser scanning, and the roughness of the surface is expressed by parameters such as Ra (average roughness) and Rz (maximum height).

3.5.1. Density Calculation Experiments

Density calculation was performed using the mass-volume relationship to determine the lightness and density of the material. First, volume calculation was performed from physical measurements of the samples before abrasion. Then, density calculations were performed using Formula 3.5 in accordance with the measurements recorded before abrasion on a 0.0001 gr precision scale (Gümüş 2012). The physical measurements of the samples before abrasion, volume and density calculation results are recorded in Table 4.6.

3.5.2. Hardness Tests

The hardness test is used to determine the hardness, toughness, and wear resistance of a material by evaluating how resistant its surface is to various stresses. The hardness of the material is determined by the degree of indentation created by the force applied to its surface. This test can also be used as a critical parameter in the design and manufacturing stages, helping to predict the performance of the material under different conditions.

While hardness is measured with methods such as Brinell, Rockwell, Vickers and Shore D, measurement with other devices has become difficult due to its composite-based structure. For this reason, the SHORE D Calibration Set in Figure 3.7 was preferred for hardness measurement in composite wear surface samples. Hardness measurements were performed three times from different parts of the samples. To reduce external mistakes, the averages and standard deviations of the measured hardnesses were determined. Table 4.7 displays the results.

Figure 3.7. Hardness Test Device SHORE D Calibration Set

3.6. Microstructural Investigations After Wear Test

Microstructural studies entail evaluating and describing a substance or system using a microscope. These examinations establish the material's internal structure, crystal structures, grain size and form, porosity quantity and distribution, chemical composition, and other microscopic parameters. Before the microstructural analyses of the samples to be made from the worn surface and cross-section, sample preparation was carried out by taking sections from the samples with a wire saw as in Figure 3.8.

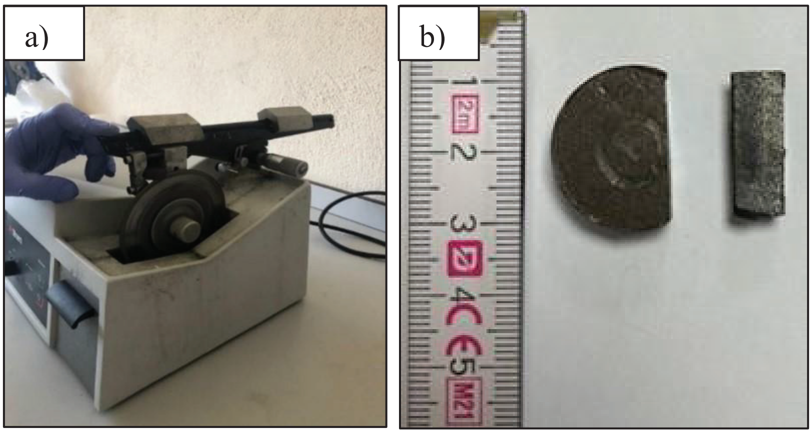


Figure 3.8. The Process of Sectioning with a) Wire Saw, b) Sectioned Sample

After the sample preparation process of the clutch lining samples was completed, an optical microscope in the Izmir Institute of Technology laboratory was used to examine the modes of the sample's worn surface structure. By examining the wear, cracks and surface roughness on the surface of the clutch lining, it was observed how these parts deformed over time. Sample examinations performed under an optical microscope are as shown in Figure 3.9. In order to examine the crystal phase contents of the materials in continuation of the microstructural examinations, scanning electron microscope examinations were carried out at different magnifications with the support of Izmir Institute of Technology Central Research Laboratory, and then Energy-dispersive X-ray spectroscopy analysis was performed on certain portions of the samples from which SEM pictures were acquired (Çolak and Turhan 2016).

Figure 3.9. Sample Examination with an Optical Microscope

CHAPTER 4

RESULTS AND DISCUSSION

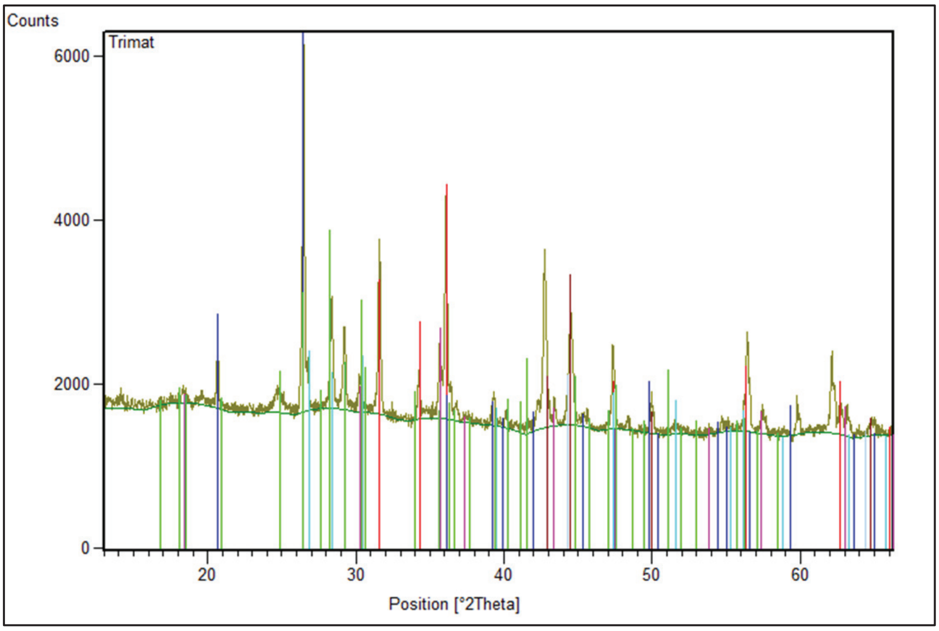
4.1. Results of Characterization of Commercial Friction Materials

Within the scope of characterization studies of commercial friction materials, X-Ray Diffraction (XRD) analysis, Optical Microscope (OM) Analysis, Scanning Electron Microscope (SEM) analysis, Energy Dispersive X-ray Spectroscopy (EDS) analysis and Thermogravimetric (TGA) analysis were carried out.

4.1.1. X-Ray Diffraction (XRD) Analysis of Commercial Friction Materials

XRD is an important material characterization method used in the analysis of crystal structures. This analysis provides information about the crystal structure of the material. Each peak in the XRD pattern originates from a specific plane of the material and the position of the peak indicates the properties of the crystal structure of the material.

The peak values formed as a result of the mineral phase analysis of the commercial friction material and the chemical formulas of the compounds with the highest score corresponding to these peak values are listed in Figure 4.1. The compounds with the highest score among the possible phases found in the sample are listed from top to bottom according to the scale factor. The rates of presence of these crystals in the composite are included in the score section. When the list obtained from the analysis is taken into consideration, it can be interpreted that there are many different crystals in the composite content. In the obtained data, acicular/layered minerals such as Zincite (ZnO), Quartz (SiO_2) and Strontium Sulfate ($SrSO_4$) are the first three minerals to pick in the graph, which indicates their intense presence in the composition. The composition includes graphite, zinc sulphide (ZnS) as lubricants and hematite (Fe_2O_3) as abrasives. It has been observed that short glass fibers and metal slags/powders (Iron (Fe) alloy) are the reinforcing materials. Finally, phyllogopit (vermiculite), antigorite (talc, serpentine) are the fillers.



Accepted Ref. Pattern: 03-065-750

N..	Visi...	Ref. Code	Compound Name	Chemical Formula	SemiQ...	Score
1	✓	01-079-0208	Zincite, syn	Zn O	-	48
2	✓	01-074-1811	Quartz	Si O2	-	49
3	✓	00-044-0375	Strontium Sulfate	Sr S O4	-	44
4	✓	01-075-1547	Wurtzite 2\ITH\RG, syn	Zn S	-	32
5		01-073-0603	Hematite, syn	Fe2 O3	-	25
6	✓	01-086-2267	Trevorite, syn	Ni Fe2 O4	-	44
7	✓	01-089-4185	Iron	Fe	-	37
8	✓	03-065-7509	Iron Vanadium	Fe9 V	-	43

Figure 4.1. XRD Phase Analysis Result

4.1.2. Optical Microscope (OM) Analysis of Commercial Friction Materials

The polished cross-section images of the commercial composite clutch lining MN2221 sample manufactured by Trimat Ltd, used in various industrial areas, taken under an optical microscope at 100 µm magnification are shown in Figure 4.2. Approximately 25-30% of long shiny particles of different shapes are thought to be metallic. As seen in Figure 4.3, the main base of the composition is resin and it is seen that it also contains fine micron-sized particles in dark and shiny tones.

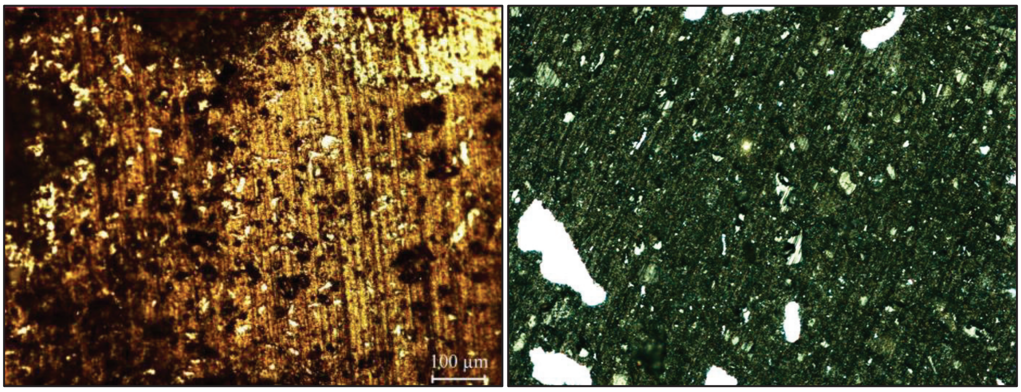


Figure 4.2. Images of the Sample Under an Optical Microscope Taken at 100X Magnification

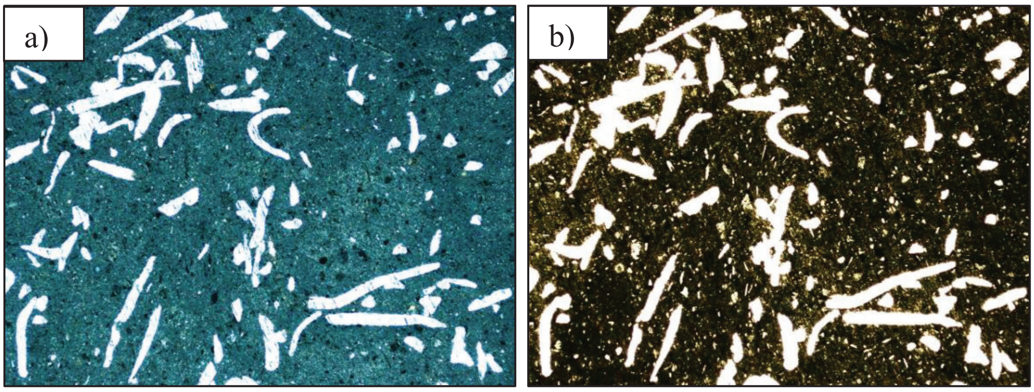


Figure 4.3. Images of the Sample Recorded at 50X Magnification Using an Optical Microscope, a) Dark Field Mode, b) Bright Field Mode

Within the matrix shown in Figure 4.4, structures were found that included shining metallic particles, long, thin fibers, and shiny/dark mineral particles of various sizes and shapes. In this case, it can be seen that the content of the friction surface consists of different types of raw materials such as metallic, fiber, mineral and resin. These raw materials determine not only the friction performance of the surface, but also its mechanical strength and thermal stability. In particular, combining raw materials in the right proportions can directly affect the operating life and reliability of the system. It also has a significant effect on the wear resistance of the surface.

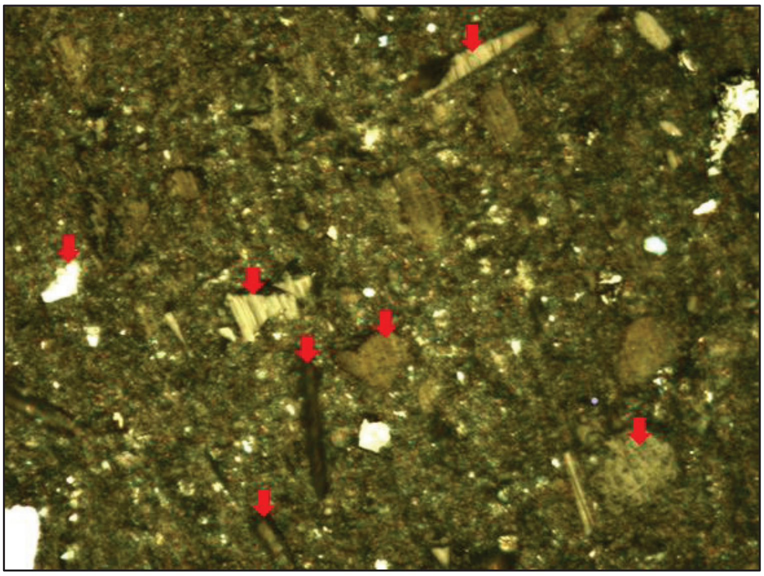


Figure 4.4. Sectional Image of the Sample Under an Optical Microscope Taken at 500X Magnification

4.1.3. Scanning Electron Microscopy- Energy Dispersive X-ray Spectroscopy (SEM-EDS) Analysis of Commercial Friction Materials

In this section, SEM-EDS analysis studies were conducted in order to identify the composite's chemical composition and microstructure. The SEM images produced from various portions of the commercial sample shown in Figure 4.5 at magnifications ranging from 500 to 5000 reveal that the long thin particles in the shape of chips are metallic fibers. The sizes of these particles can reach up to 400 microns and are generally 100 microns and below. In addition to the metal fibers, the brake pad sample also shows smooth glass fibers that are gray in color and smaller than 100 microns. Apart from these, it is seen that the body has various particles with varying large and small morphologies. These particles are smaller than 50 µm and have densely distributed angular, fibrous and angular shapes. In addition, there are particles in both bright and dark tones with extremely small particle sizes. It is essential that the friction lining examined contains a high percentage of iron element. In addition, when element C (carbon) is present, organic resin, carbonaceous and carbonate compounds are found in the body.

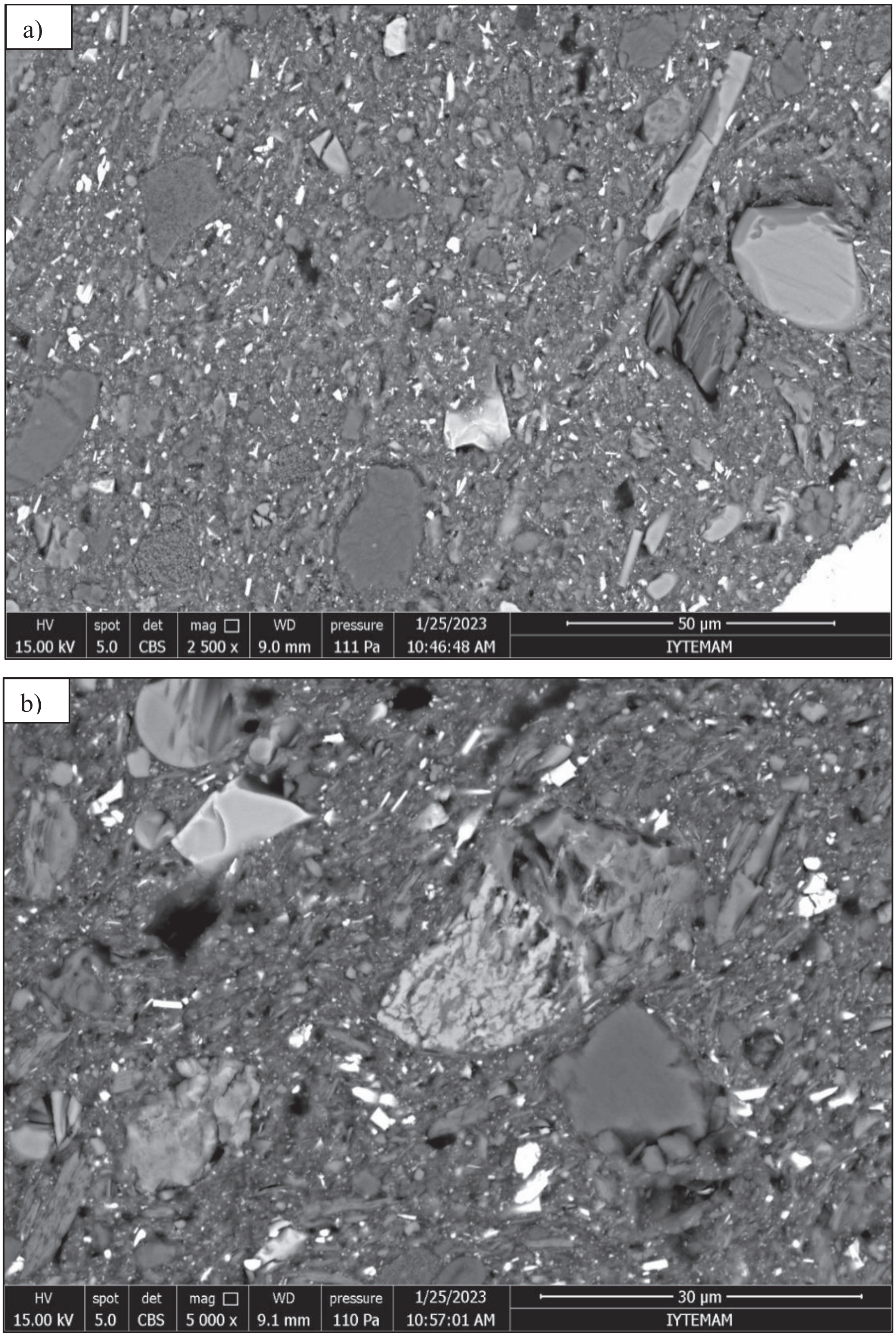


Figure 4.5. SEM Images Acquired from the Slice at Various Magnifications, a) at 500X Magnification, b) at 5000X Magnification

Figure 4.6 shows the SEM images of commercial friction material obtained from the cross-section and the EDS results obtained from this SEM image are as in Figure 4.7 and Figure 4.8. The particles with metallic iron were identified as Fe alloy, comprising alloy components like Mn, Cr, and W, based on SEM-EDS analysis.

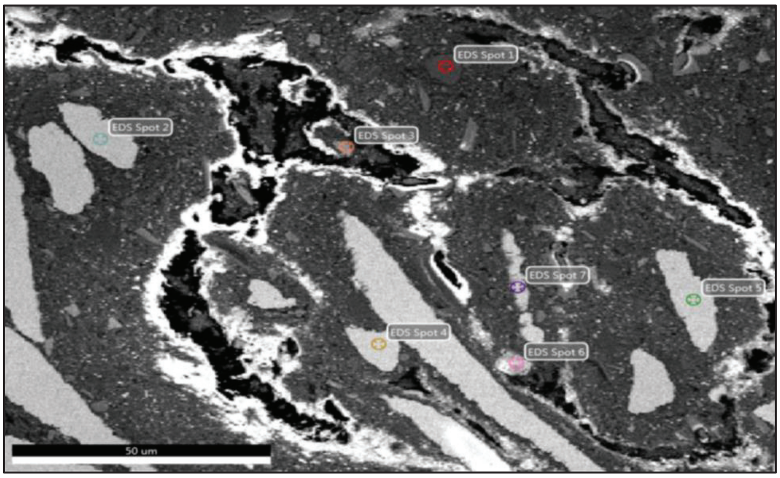


Figure 4.6. SEM Image of Sample Taken at 50 μm Magnification

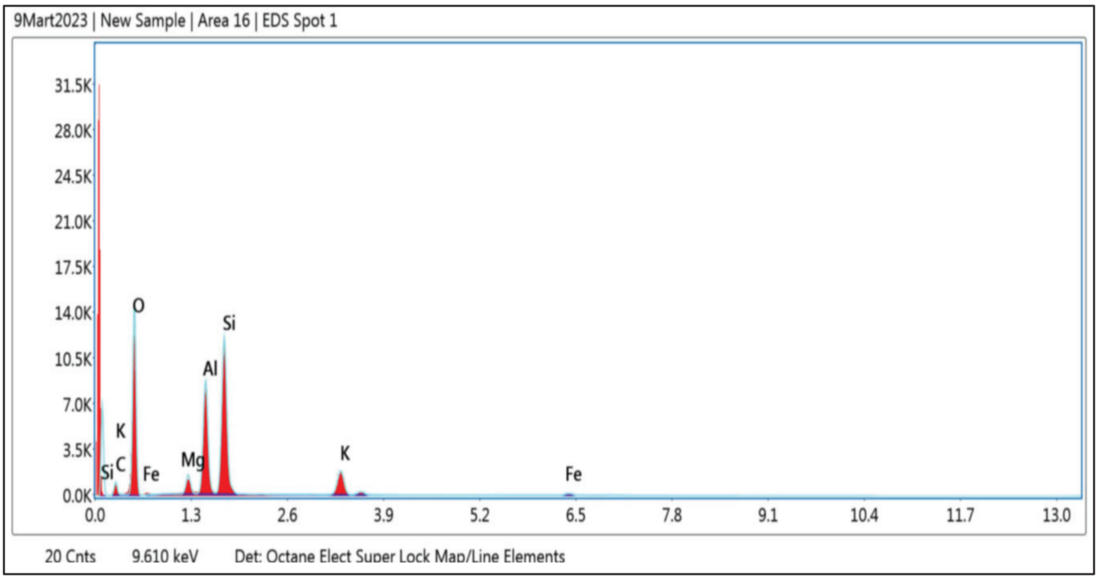


Figure 4.7. EDS Result of the Sample in the Spot1 Region

The particles that include Si and O can be classified as quartz particles. These are the constituents of the tiny, vividly colored ZnS and ZnO particles found in the Zn-containing clutch lining. In addition, it might be said that the particles that comprise Si, Al, and Mg are fillers and silicate minerals.

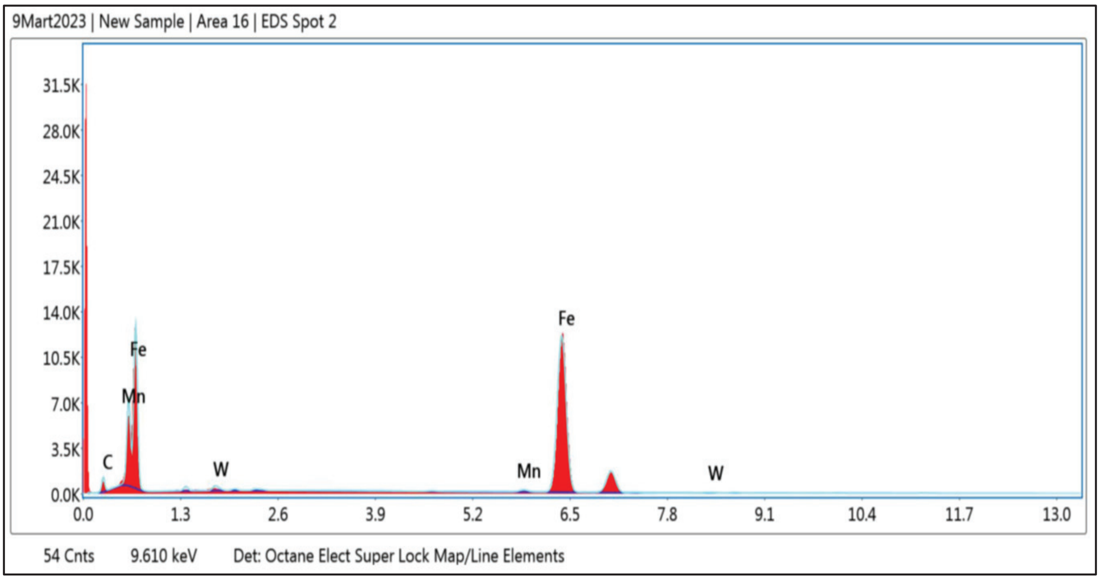


Figure 4.8. EDS Result of the Sample in the Spot2 Region

The existence of elements and compounds from the crystalline phases found in the XRD examination was verified by a regional SEM-EDS analysis of the friction sample's cross-section.

4.1.4. Thermogravimetric (TGA) Analysis of Commercial Friction Materials

Because the studied material is an organic composite, heat analysis was used to quantify the quantity of resin and disintegrated components. The thermal investigation revealed temperature-dependent weight loss responses in the commercial friction sample heated to 1000 °C, as illustrated in Figure 4.9. The sample lost around 15% of its weight between 350 and 450 °C. This reaction is hypothesized to be caused by polymer resin degradation and/or mineral dehydroxylation. This results in the presence of approximately 10% to 15% phenolic resin in the structure of the composite. TGA has been used in literature to describe the permanent, light, and moderate-moderate degradation produced following heat treatment of a phenol formaldehyde (phenolic) resin. The breakdown temperatures observed in the resin structure complement our findings (Kmita et al. 2016). It is possible that the reaction around 600-650 °C is a result of thermal decomposition of calcite. A mass loss of approximately 5% occurred in this temperature range, indicating that the composite contained 5% calcite. The decomposition of calcite at this temperature and the release of carbon dioxide are considered to be the main cause of the observed mass loss. This process confirms the decomposition temperature of calcite in the composition of the material, while also shedding light on the thermal properties of the composite. In addition, these analyses play an important role in understanding the changes that the material may experience at high temperatures.

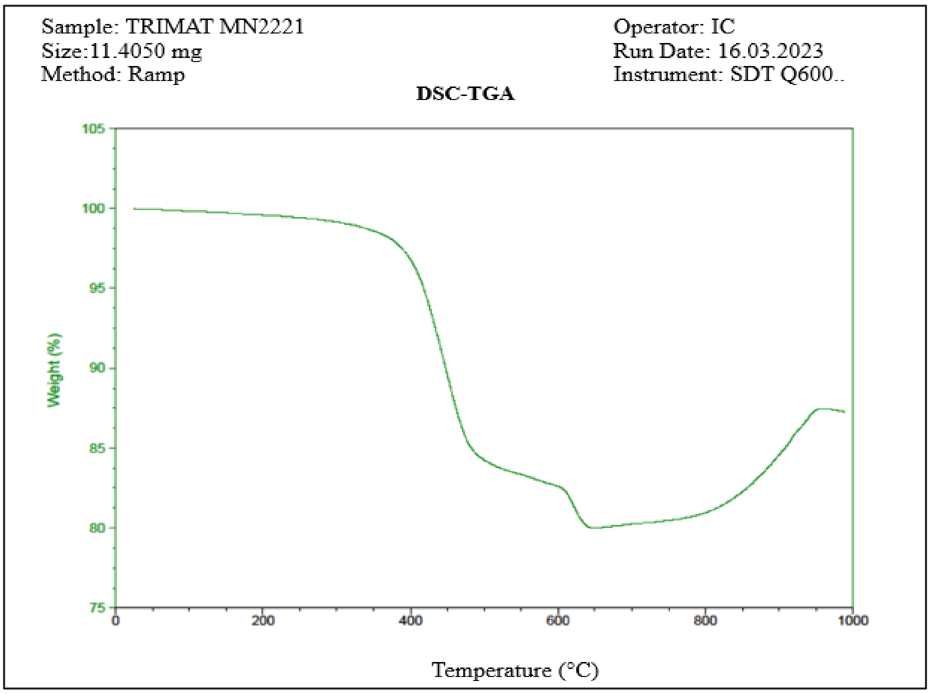


Figure 4.9. TG/DTA Analysis Results

The overall weight loss up to 650°C is around 20%. The oxidation of Fe-based metals accounts for the weight increase when the temperature rises over 700°C. Between 700-1000°C, a mass increase of 8.5% and 25% occurred, which indicates that the presence of Fe metal is approximately between these values.

4.2. Determining Composite Friction Facing Formulation

Table 4.1 shows the composition and percentages of the friction sample obtained during the characterization experiments. In line with the know-how gained from the company's previous R&D studies, the effect of the raw material ratios used in clutch linings on the performance of the produced friction samples was investigated. This research aimed to evaluate the effects of material ratios on the friction coefficient, wear resistance and thermal stability. The obtained data provided important information that will guide future optimization studies.

Table 4.1. Raw Materials Used in Facing Sample Production

Percentage of Materials [wt%]		
Binders	Total amount of Binders (22.5%)	Phenolic Resin
		Rubber Dust
		NBR
Reinforcements	Non-Metallic Fibers (%2.5)	Glass Fiber
	Metallic Fibers (%20)	Steel Fiber
		GG25 Casting Waste
Fillers	Total amount of filler (35%)	Barite (BaSO4) or SrSO4
		Calcite (CaCO3)
		Zinc Oxide (ZnO)
		Iron Oxide (Fe2O3)
		Talc: Magnesium Silicate Hydr.
		Expanded Vermiculite
Friction Modifiers	Lubricants (%12.5)	Zinc Sulfide (ZnS)
		Graphite
	Abrasives (%7.5)	Alumina (Al2O3)

It has been found that Alumina, an abrasive raw material, has an optimal application impact on friction materials and improves clutch performance. The components that constitute the composite friction material suitable for aviation applications were determined in line with the know-how obtained from the characterization studies and the company's R&D studies.

Based on the determined formulation, it was aimed to support both material recycling and increase the performance and life of clutch systems by using GG25 casting

CNC manufacturing chip waste instead of traditional steel fibers. 6 different recipes were prepared with steel fiber and GG25 casting waste in different ratios in 500 µm and 1 mm material sizes. The samples were created using various variations of these raw materials, namely steel fiber and GG25 casting waste, at ratios ranging from 0% to 20% by mass, respectively. The inclusion ratios of steel fiber and GG25 casting waste samples into the composite and the raw material dimensions are as given in Table 4.2.

Table 4.2. Proportions of Steel Fiber and GG25 Casting Waste Samples in Composite

	Steel Fiber		GG25 Casting Waste	
Sample No.	Percentage of Materials [mass%]	Fiber Diameter [µm]	Percentage of Materials [mass%]	Fiber Diameter [µm]
1	-	<200µm	20	<500µm
2	5	<200µm	15	<500µm
3	10	<200µm	10	<500µm
4	15	<200µm	5	<500µm
5	20	<200µm	-	<500µm
6	-	<200µm	20	<1mm

The amount of waste generated during the processing of GG25 casting pressure plate, which is produced in 8000 units per year by Dönmez Debriyaj Sanayi ve Ticaret AŞ, is considered as a potential recycling source. During the production process, semi-finished parts, which are 20.6 kg in casting, are reduced to 17.8 kg by turning, drilling and balancing processes, resulting in approximately 2.8 kg of waste per product. This amount of waste, which reaches a total of 22.4 tons per year, is considered as a metal sawdust that can be recycled. This approach supports sustainable production goals while also providing solutions to waste management needs. It supports the reuse of processed sawdust waste, contributes to the circular economy and reduces environmental impact. This approach minimizes the consumption of resources.

Table 4.3. The Amount of Metal Sawdust Generated in GG25 Pressure Plate Processing

Stock Name	Quantity [Piece]	Weight [kg]
Balancing Operation	1	17.8
Turning + Drilling Operation	1	18.1
GG25 Casting Material	1	20.6

4.3. Performance Results of the Produced Friction Samples and Their Evaluation

In this section, hardness and density values were determined with 6 different samples produced depending on the determined pad compositions, and the wear and the pads' friction properties were investigated using a pin-on-disc wear instrument. Then, optical microscope images and SEM-EDS analyses taken from the worn and sectioned surfaces of the samples were examined. The samples produced within the scope of the study include steel fibers with a grain size of 200 µm and GG25 casting waste separated with a grain size of 500 µm-1 mm below. In the sample recipes (1 to 5), the effects of steel fibers and GG25 casting waste on the material were evaluated. In addition, in the 1st and 6th samples, the effects of GG25 casting waste with different grain sizes on the material properties were investigated.

4.3.1. Evaluation of Coefficient of Friction in Ball-on Disc Test

Abrasion tests were carried out on a disk testing machine to assess the friction and wear properties of materials with varying ratios and to assist material selection. In this experiment to investigate the wear and friction behaviors of test items, the Ball-on disc device depicted in Figure 3.6 was utilized as an abrasive with a 5 mm radius and a 1050 steel disc. In addition to the size and surface quality of the test sample utilized during the test, other elements influencing the test include applied force, sample rotation speed, contact point distance from sample center to disk, temperature, and ambient conditions. The experiment was conducted out under laboratory settings of 20 °C and 50% humidity.

Throughout the experiment, care was taken to ensure that the disc section was in complete contact with the sample. The test was performed at a linear speed of 25 cm/h, a distance of 2000 m and a load parameter of 10 N (Akdoğu 2010).

As a result of the tribology test performed on friction samples to evaluate the tribological properties of materials, the device outputs the friction coefficient values based on the sample path. The friction coefficient graphs are created according to the data of the device and the path followed. The applied compressive forces are calculated using formulas 3.1, 3.2 and 3.3 according to the load used and the contact area of the sample, as shown in Table 4.4. These calculations allow to analyze the friction behavior in more detail and provide an understanding of the factors affecting the durability of the sample. In addition, these data provide an important basis for comparing the performance of different material combinations. The results can be used to improve material design and to produce more efficient solutions in applied engineering.

Table 4.4. Friction Coefficient Outputs and Pressure Force Calculations

Sample No.	Start [μ]	Min [μ]	Max [μ]	Mean [μ]	Std. Dev.	Mass [gr]	Weight [N]	Pressure Force [N/mm^2]
1	0.129	0.129	0.547	0.45	0.091	10.001	98.076	0.19979941
2	0.183	0.183	0.654	0.556	0.095	10.031	98.371	0.21475375
3	0.165	0.165	0.640	0.567	0.093	10.127	99.312	0.19880232
4	0.182	0.182	0.730	0.638	0.107	10.625	104.196	0.20890972
5	0.199	0.199	0.743	0.639	0.099	10.143	99.469	0.21272453
6	0.146	0.146	0.528	0.429	0.103	10.139	99.430	0.20014739

The mean friction coefficient statistics of the friction samples obtained from the experiment are visualized in Figure 4.10.

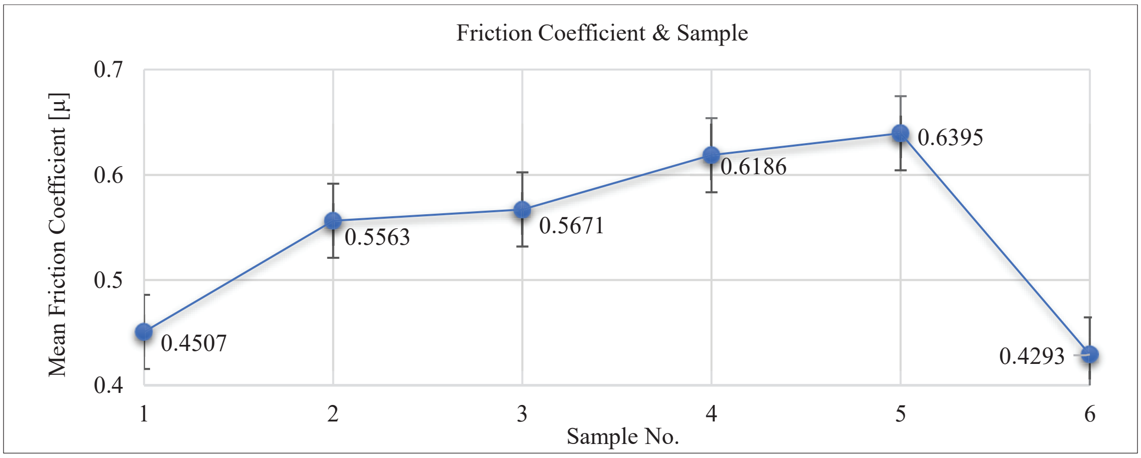


Figure 4.10. Mean Friction Coefficient- Sample

Comparison of friction coefficient statistics of friction samples depending on distance is visualized in Figure 4.11. This graph clearly shows the changes in performance of the samples by comparing friction coefficient values at different distances. In addition, it can be visually analyzed how the fluctuations in the friction coefficient are shaped according to material properties and applied conditions.

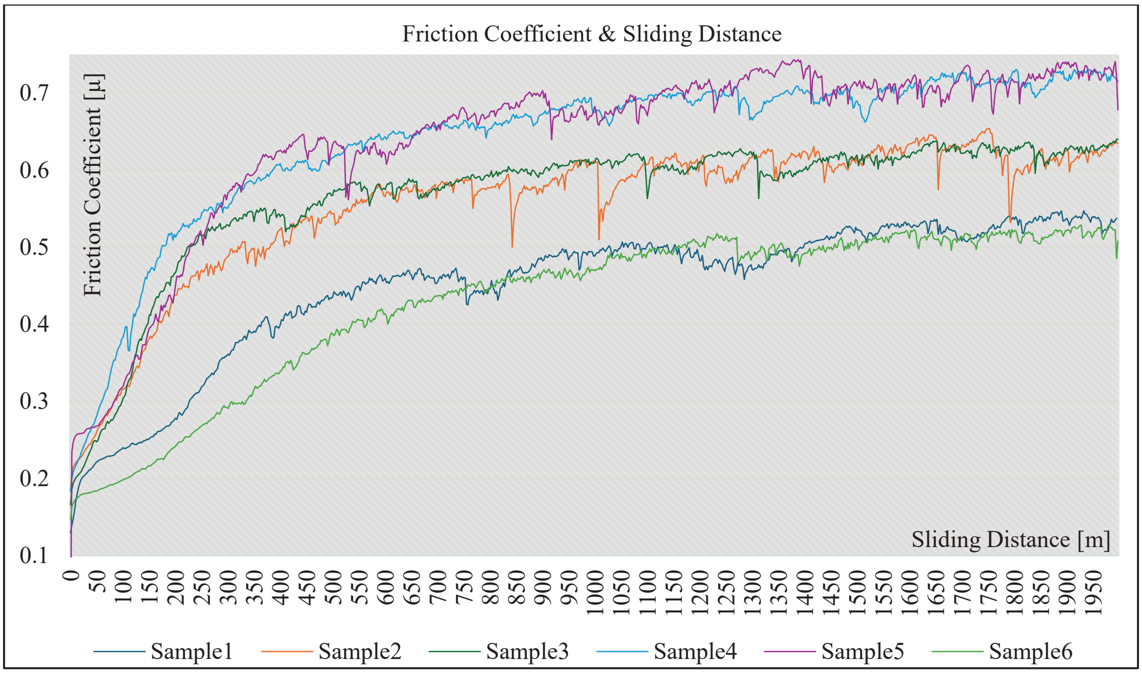


Figure 4.11. Comparative Friction Coefficient vs. Distance Result of Samples

The changes in the friction forces read on the pin-on-disc device during the wear test are as shown in Figure 4.11. First of all, since the sample surface had to be completely accustomed to the rotating disc and all points of the surface had to be in contact, the initial values had lower friction forces, but the sample achieved a better contact surface in the later stages and exhibited a higher friction force. While a friction coefficient of around 0.10 μ was observed at the beginning, this value increased to around 0.70 μ in the later distances. The coefficient of friction of steel fibers may vary depending on the type of steel used, but generally remains in the medium-high range (around 0.3-0.6). This feature allows steel fibers to provide high performance, especially in brake and clutch applications. When the coefficient of friction forms a good bond with the composite matrix, it provides a reliable holding power (Ramalingam et al. 2022) (Ertan and Yavuz 2011) (Sugözü and Dağhan 2018). GG25 cast iron also has a similar coefficient of friction and can reach a value in the range of approximately 0.3-0.5. Due to its lamellar structure, it shows a stable performance in the coefficient of friction and is preferred as a friction composite in brake discs. However, it may not provide as high friction strength as steel fibers (Demir 2020) (Düzce and Samtaş 2021).

As a result of the friction tests, when the comparative friction coefficient graph of the samples is examined in Figure 4.11, it is seen that the friction coefficient decreases proportionally with the increase in the amount of GG25 sawdust waste, and the lowest friction coefficient values are seen in the 1st and 6th samples containing 20% GG25 sawdust waste. This situation reveals that the samples using GG25 sawdust waste show lower wear and heating tendencies compared to traditional materials.

The highest friction coefficient values are observed in the 5th sample containing 20% steel fiber and in the 4th, sample containing 15% steel fiber and 5% GG25 sawdust waste. It is observed that the sample with the least deviation in the friction coefficient value and providing stabilization is the 3rd sample using 10% steel fiber and 10% GG25 sawdust waste. The friction coefficient, which shows close values in the 2nd and 3rd samples; increased the GG25 casting waste by 5%, provided more stabilization in the material. In this case, it can be commented that the friction coefficient provided by steel fiber and GG25 sawdust waste used in equal proportions is more balanced compared to other correlations.

In addition, the effect of metal fiber grain size on the friction coefficient was examined with the 1st and 6th formulas using 20% GG25 sawdust waste. It was observed that the GG25 sawdust waste used in 500 µm grain size increased the friction coefficient value more compared to the one used in 1 mm grain size. In this way, it is understood that the ideal size of the grain size has a balancing and increasing effect on the friction coefficient. In this case, a result supporting the literature study was obtained. When the increasing friction coefficient and the stabilization of the friction coefficient are taken into consideration, it can be commented that the 3rd sample using steel fiber and GG25 sawdust waste in equal proportions is the ideal recipe.

4.3.2. Wear Measurement and Calculation in Ball-on-Disc Test

According to the ASTM G99 standard, the amount of wear was calculated by weighing the beginning and end weights in the experiment. Before the experiment started, the initial sample weight and the final weights after 2000 m of wear were weighed on a scale with 0.0001 gr precision. The mass loss was calculated using the data collected from the wear test and equations 3.6 and 3.7. The wear rate was found by dividing the wear volume calculated using formula 3.6 by the applied load and distance as in formula 3.7. Table 4.5 shows the samples' mass losses and wear rates. In addition, the percentage of wear loss was calculated based on the mass and volume of the materials using the collected data, and this information was supported by visuals. These calculations helped determine which material was more durable and long-lasting by comparing the wear resistance of different types of materials.

Table 4.5. The samples' Mass Losses and Wear Rates

Sample No.	Mass Before Wear [gr]	Mass After Wear [gr]	Mass Loss [gr]	delta D mm^3	Wear Rate [mm^3/Nmm]	Wear (%)
1	10.0010	9.9958	0.0052	2.37873316	0.000118937	0.0520
2	10.0318	10.0303	0.0015	0.63702156	3.18511E-05	0.0150
3	10.1279	10.1274	0.0005	0.23801074	1.19005E-05	0.0049
4	10.6258	10.6237	0.0021	0.95423793	4.77119E-05	0.0198
5	10.1430	10.1420	0.0010	0.43334218	2.16671E-05	0.0099
6	10.1399	10.1377	0.0022	1.04559898	5.22799E-05	0.0217

The obtained results and calculation statistics are shown in Figure 4.12 with the amount of wear-sample graph.

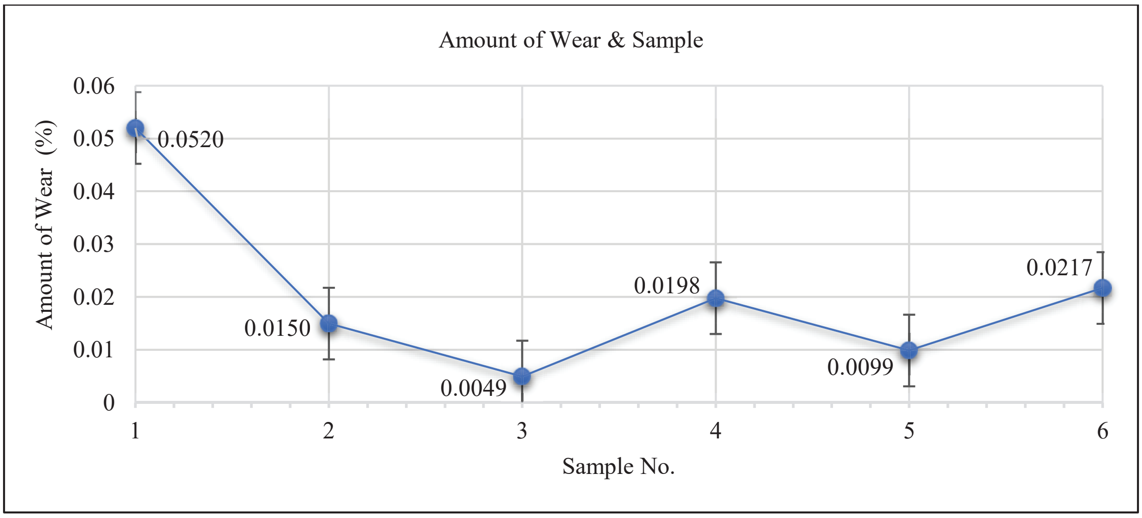


Figure 4.12. Amount of Wear -Sample Graph

Steel fibers are very strong in terms of wear resistance thanks to their high hardness and strength. Steel fibers, which are frequently used in friction applications, reduce surface wear thanks to their hardness and impact resistance. Therefore, they provide advantages in intensive friction applications such as brake pads and clutch systems operating under high temperatures and pressure. GG25 cast iron is resistant to wear due to its lamellar graphite structure, but its wear resistance is lower than steel fibers.

It can wear faster when exposed to high impact and continuous high pressure. Therefore, GG25 cast iron is mostly used in applications such as standard brake discs (Ertan and Yavuz 2011) (Sugözü and Dağhan 2018) (Demir 2020).

When the wear amounts graph according to samples is examined in Figure 4.12, it is observed that the wear amount decreases and the resistance to wear increases as the GG25 casting waste ratio decreases in general terms, which confirms the literature. However, when the graph is examined carefully, an increase in the wear amount is observed in the 4th sample. It is thought that this anomaly is due to the fact that the samples cannot be produced with equal precision under different environmental conditions.

In addition, when the effect of metal fiber grain size on the wear resistance of the sample was examined with formulas 1 and 6 using 20% GG25 sawdust waste, it was observed that the GG25 sawdust waste used in 500 µm grain size provided higher wear resistance compared to the one used in 1 mm grain size.

4.3.3. Density Calculation

Density calculations were conducted using the mass-volume relationship, which involved determining the volume in accordance with the physical measurements collected before abrasion. Table 4.6 shows the initial physical measurements, volume, and density calculation findings for the samples. The visualization of the densities of the samples manufactured with similar diameters and heights, the values of which are given in Table 4.6, is as in Figure 4.13.

Table 4.6. Density Calculation Based on Mass-Volume Relationship

Sample No.	Starting Mass [gr]	Diameter [mm]	Height [mm]	Volume [mm^3]	Density [gr/cm^3]
1	10.0010	25.00	9.32	4574.94	2.186
2	10.0318	24.15	9.30	4259.98	2.355
3	10.1279	25.22	9.65	4820.67	2.101
4	10.6258	25.20	9.68	4827.99	2.201
5	10.1430	24.40	9.40	4395.39	2.308
6	10.1399	25.15	9.70	4818.79	2.104

The density of steel fibers is approximately 7.85 g/cm³, which is higher than GG25 cast iron. The high density of steel fibers can increase the weight of composite materials; however, this is an advantage in terms of providing mechanical strength (Gao, Sun and Morino 1997). The density of GG25 cast iron is approximately 7.2 g/cm³. The lower density makes GG25 preferred in applications with weight restrictions. This feature is especially advantageous in applications requiring lightness, such as brake discs in the automotive sector.

When the comparative density graph of the samples in Figure 4.13 is examined, the density value of the 5th composition, which was prepared similarly to the commercial sample and contained 20% steel fiber, was measured as 2.308 g/cm³. In general, it was observed that the decrease in the GG25 casting waste ratio caused an initial increase in the density values of the samples. This is because the density of GG25 sawdust waste in casting form is lower than that of steel in fiber form.

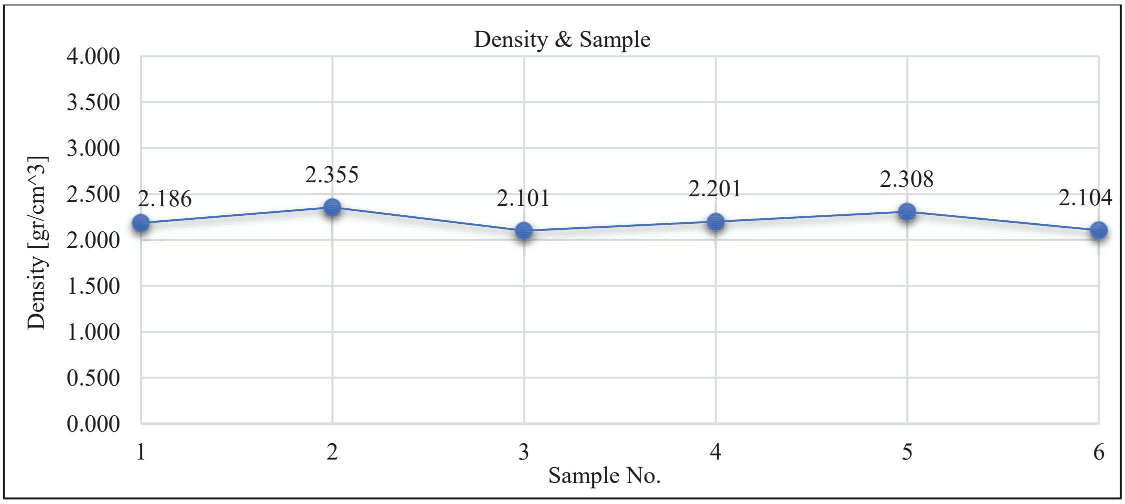


Figure 4.13. Density & Sample Graph

However, a density decrease was observed in the transition from sample 2 to sample 3. It is thought that this anomaly is due to the fact that the samples could not be produced with equal precision under different environmental conditions. When the density ranges were examined, the highest density value was measured as 2.355 g/cm³ and the lowest density value was measured as 2.101 g/cm³.

The difference between these two values is 0.230 g/cm³, which corresponds to a change of approximately 10%. This small density difference is a factor that makes it difficult to interpret density differences due to changing raw material ratios. The use of lower density metals such as GG25 casting waste can reduce sample weight and have effects on grip performance. Especially critical factors such as fuel efficiency and carrying capacity can be directly affected by these changes.

In addition, the effect of GG25 casting waste with different grain sizes on material density was examined in samples 1 and 6. It was observed that increasing grain size in sample 6 gave lower results in density values.

4.3.4. Hardness Measurement

The hardness of the samples was measured using the SHORE D Calibration Set measuring technique. Hardness measurements were taken three times on various areas of the samples. The measured hardnesses and standard deviations were then averaged to reduce external errors. Table 4.7 shows the results. The hardness values of steel fibers generally vary between 200-400 HB. This feature makes steel fibers highly resistant to wear and deformation.

Table 4.7. Hardness Test Results (Each Value is Based on Three Measurements)

Sample No.	Mass1	Mass2	Mass3	Average	Standard Deviation
1	76	77	77.5	76.8	0.764
2	79	78	78.6	78.5	0.503
3	80	79	79.0	79.3	0.577
4	81	81	81.0	81.0	0.000
5	81	82	81.8	81.6	0.529
6	77	78	77.5	77.5	0.500

Steel fibers stand out in applications that require working under extreme loads and temperatures. In contrast, the hardness range of GG25 cast iron is 180-250 HB. This value is lower than steel fibers and makes it difficult to replace steel fibers in applications requiring hardness.

However, the lower hardness of GG25 provides advantages in terms of machinability and milling. In comparison, steel fibers are preferred for applications requiring higher hardness, tensile strength and impact resistance. For this reason, it is generally used in high-performance brake and clutch composites. GG25 cast iron, on the other hand, provides advantages in applications requiring medium-level durability, such as standard brake discs, thanks to its affordable cost and sufficient hardness level.

According to Table 4.7, Shore-D hardness values of friction samples vary between 76.8 and 81.6, which means a difference of approximately 5.8%. The highest hardness value was measured as 81.6 Shore in the 5th sample containing 20% steel fiber. The 4th sample, containing 15% steel fiber and 5% GG25 casting raw material with sub-500 µm grain, ranked second with a hardness value of 81.0 Shore. Sample 1, which had the highest amount of GG25 casting waste, showed the lowest hardness value with 76.8 Shore. In support of the literature, samples using steel fiber generally have higher hardness values compared to those using GG25 casting waste. Hardness is a critical parameter in terms of grip performance. High hardness increases the resistance of the material to deformation and significantly reduces wear, ensuring long life of the systems.

Therefore, materials with high hardness values are of great importance in terms of both safety and performance and should be tested continuously. Especially in sectors that require high safety standards such as aviation, the stability of material hardness and the preservation of wear resistance are of vital importance for system reliability (Majcherczak, Dufrenoy and Berthier 2007).

4.3.5. Optical Microscope (OM) Analysis of Test Samples

The worn surface and the cross-section of the worn samples were examined in detail using an optical microscope (OM) at 100 µm in order to examine the surface morphology, determine the material loss and analyze the wear mechanisms in detail. The data obtained during the examination were evaluated to provide a better understanding of the changes in the material structure as well as the microstructural deteriorations and the characteristic features of wear, and the optical microscope images taken during this process are given in Figures 4.14-4.19 for comparative analysis. In addition, factors such as cracks on the surface during wear, deformations in the microstructure and material loss rates were carefully examined and their effects on material performance were investigated.

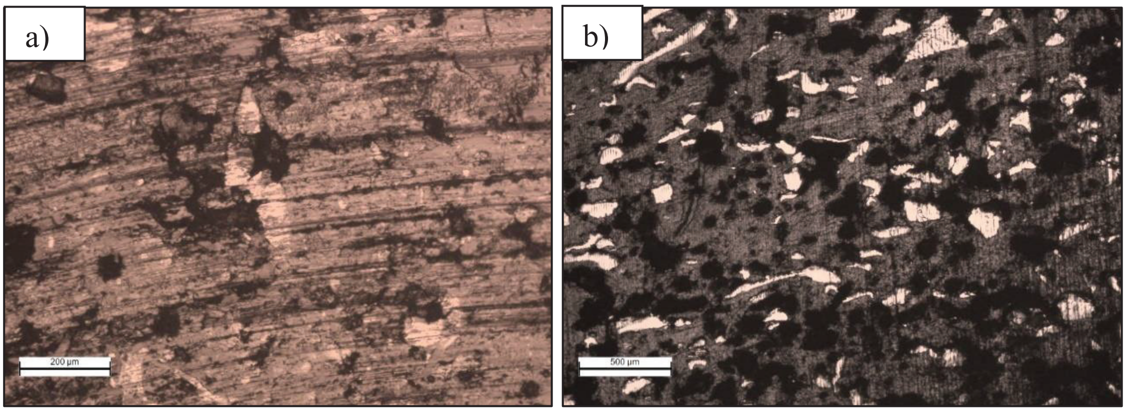


Figure 4.14. Optical Microscope Images of Sample1, a) From the Worn Surface, b) From the Sectioned Surface

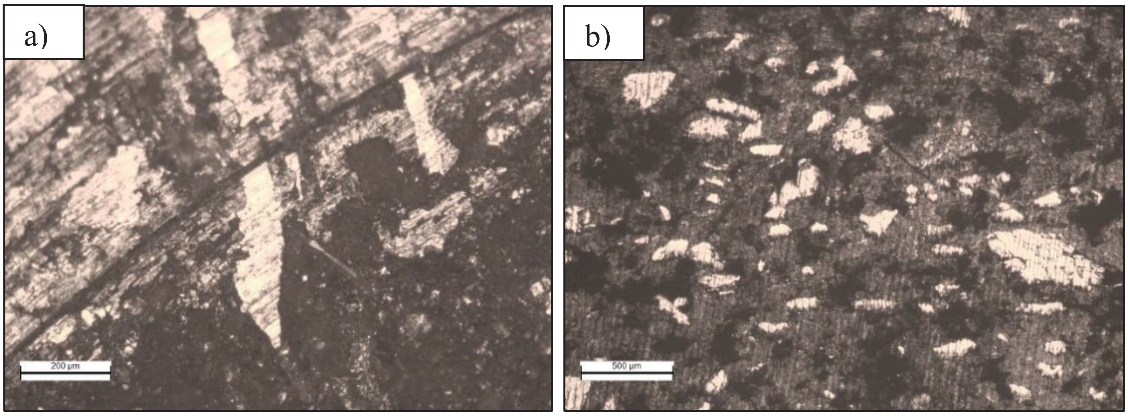


Figure 4.15. Optical Microscope Images of Sample2, a) From the Worn Surface, b) From the Sectioned Surface

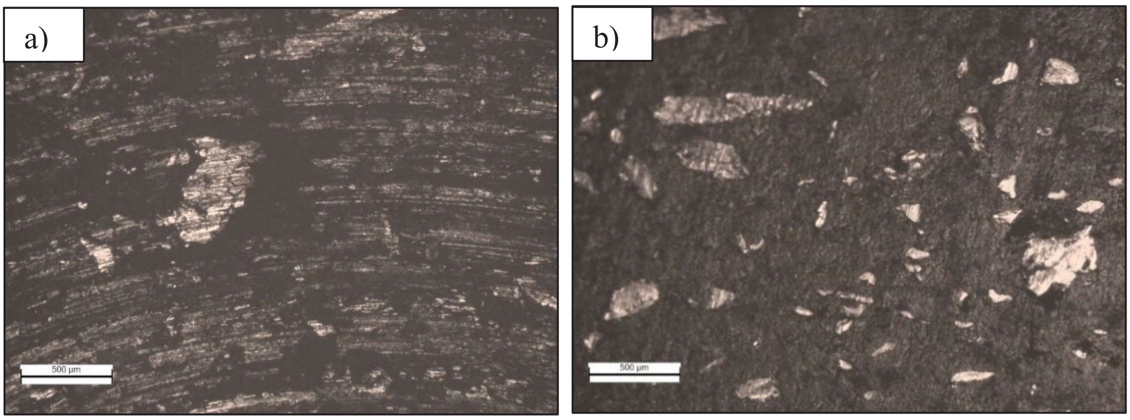


Figure 4.16. Optical Microscope Images of Sample3, a) From the Worn Surface, b) From the Sectioned Surface

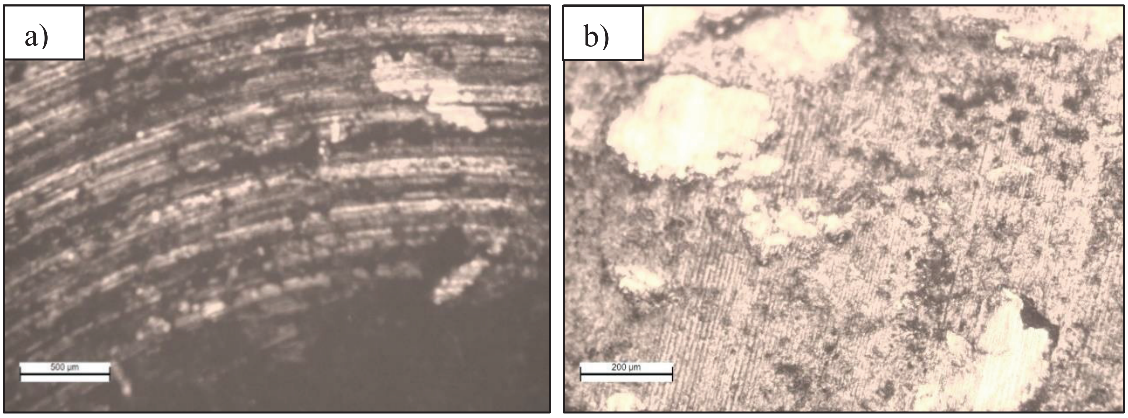


Figure 4.17. Optical Microscope Images of Sample4, a) From the Worn Surface, b) From the Sectioned Surface

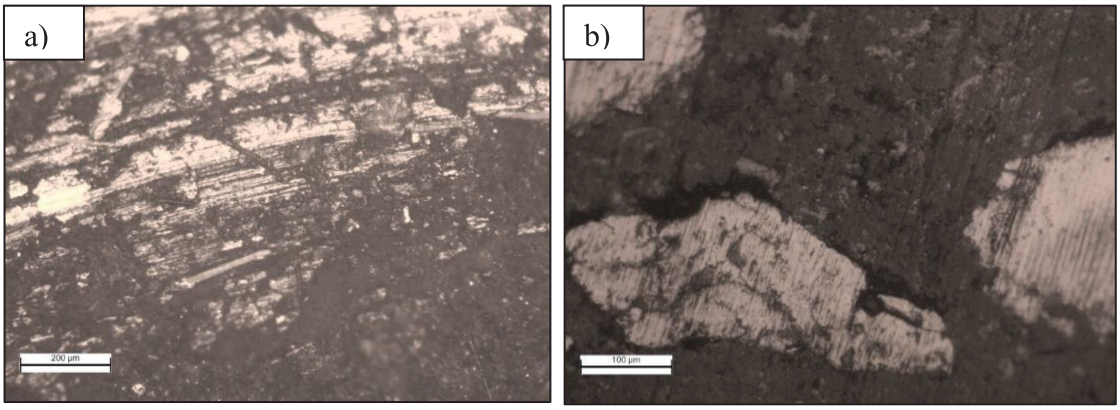


Figure 4.18. Optical Microscope Images of Sample5, a) From the Worn Surface, b) From the Sectioned Surface

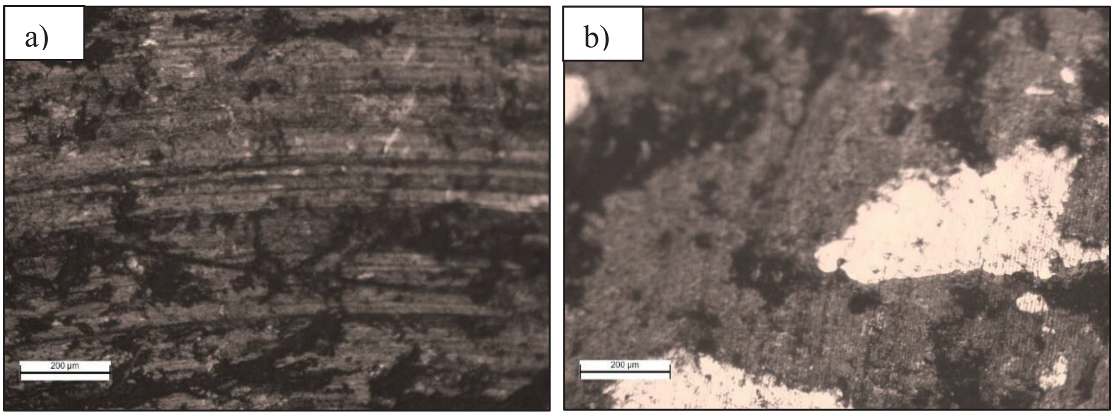
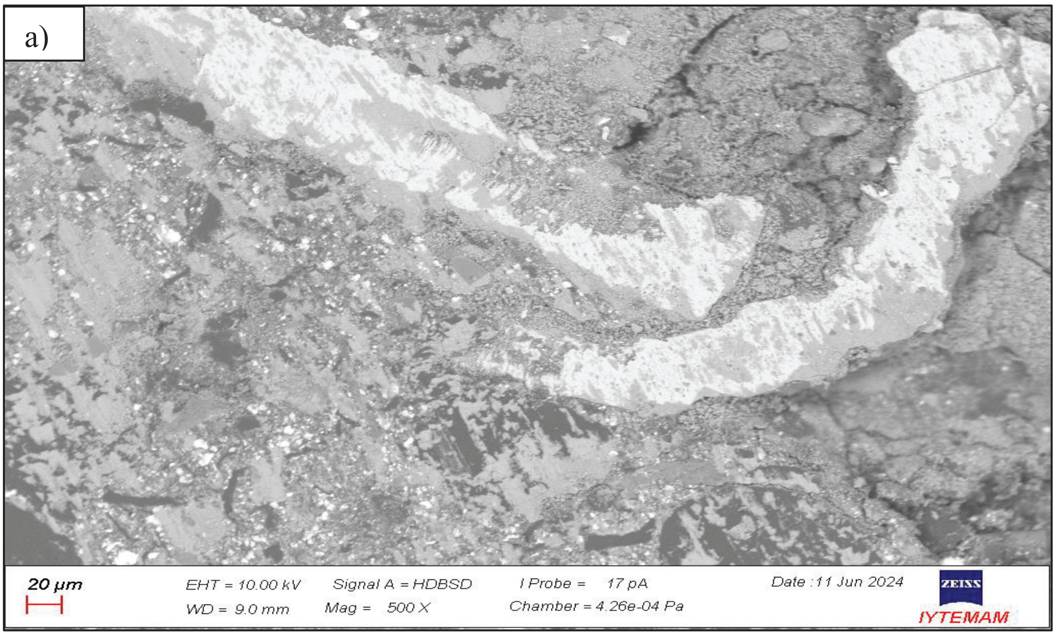


Figure 4.19. Optical Microscope Images of Sample6, a) From the Worn Surface, b) From the Sectioned Surface

4.3.6. Microstructural (SEM-EDS) Analysis of Test Samples

In this section, the worn and cut surfaces of the materials were examined using a scanning electron microscope. In Figures 4.20-4.25, the findings for each sample are shown separately.



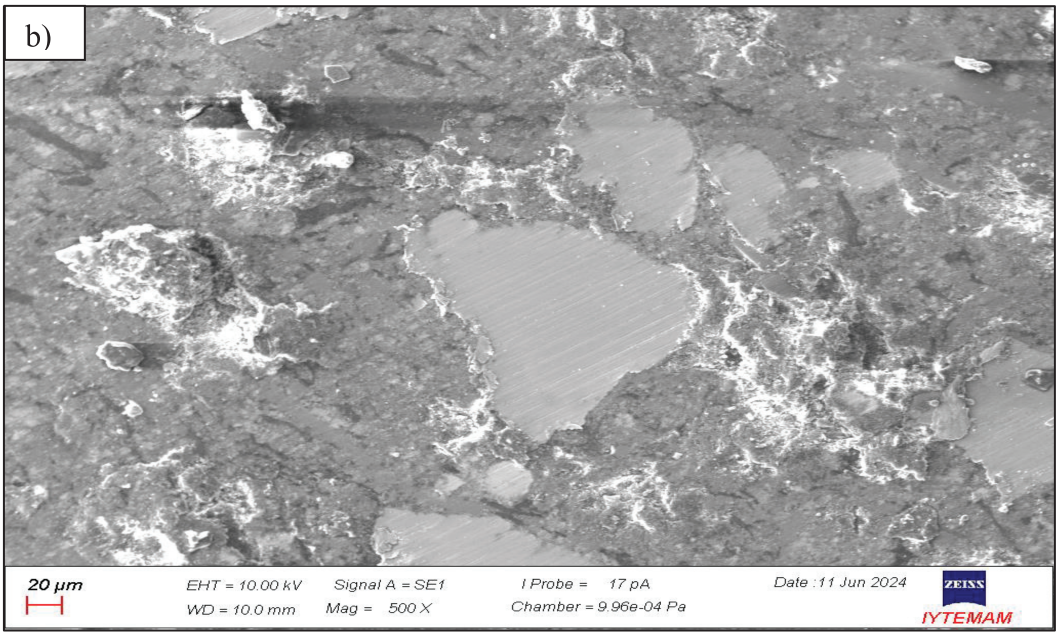


Figure 4.20. SEM Images of Sample1, a) From the Worn Surface, b) From the Sectioned Surface

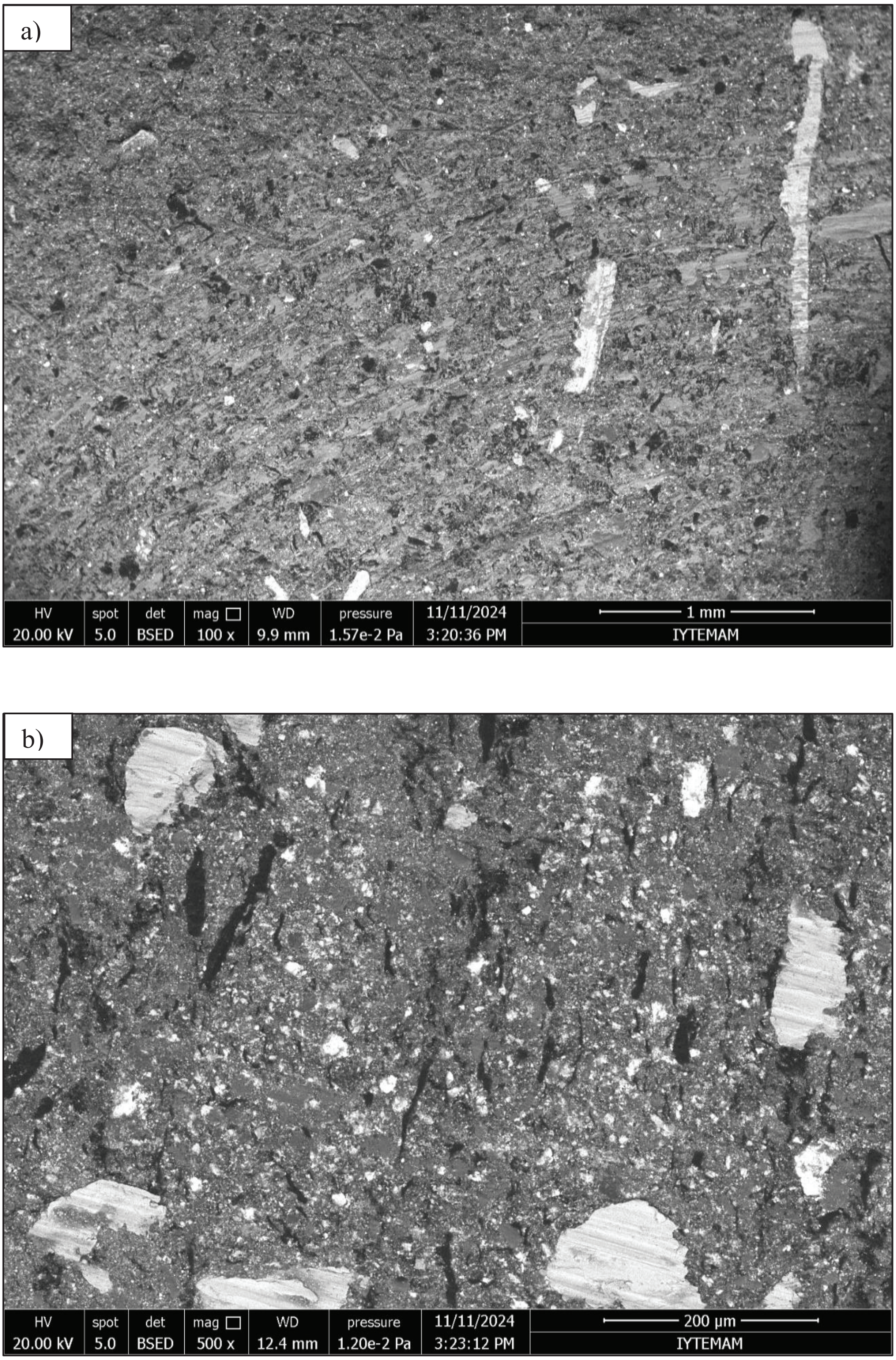
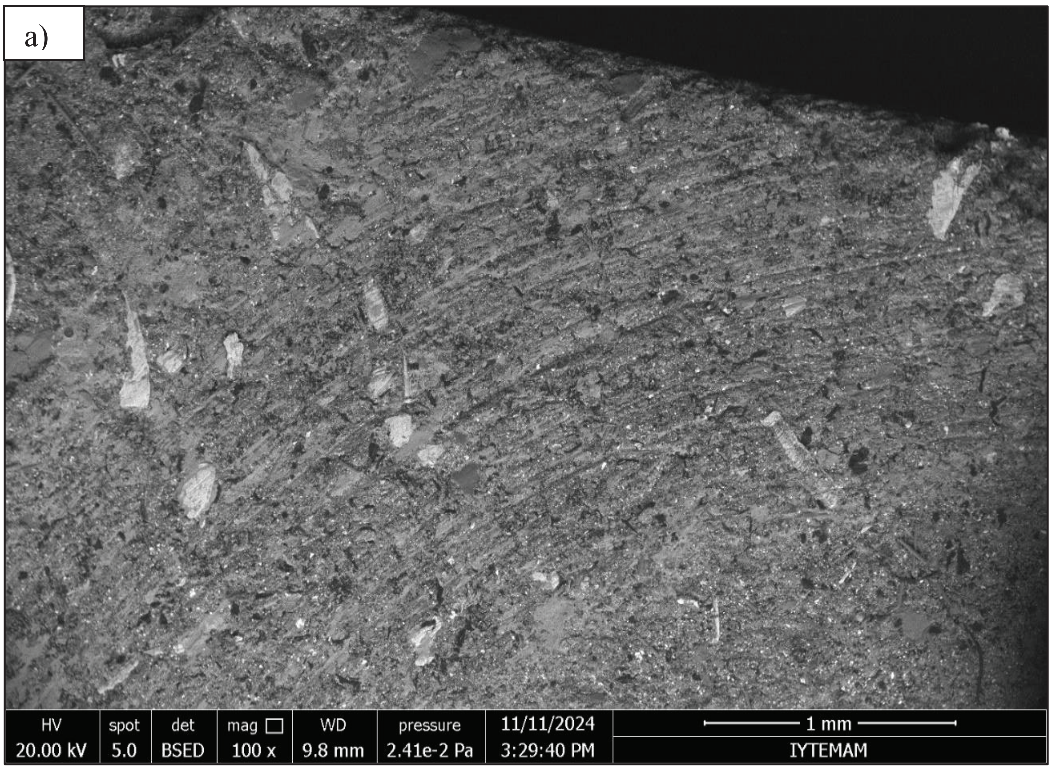


Figure 4.21. SEM Images of Sample2, a) From the Worn Surface, b) From the Sectioned Surface



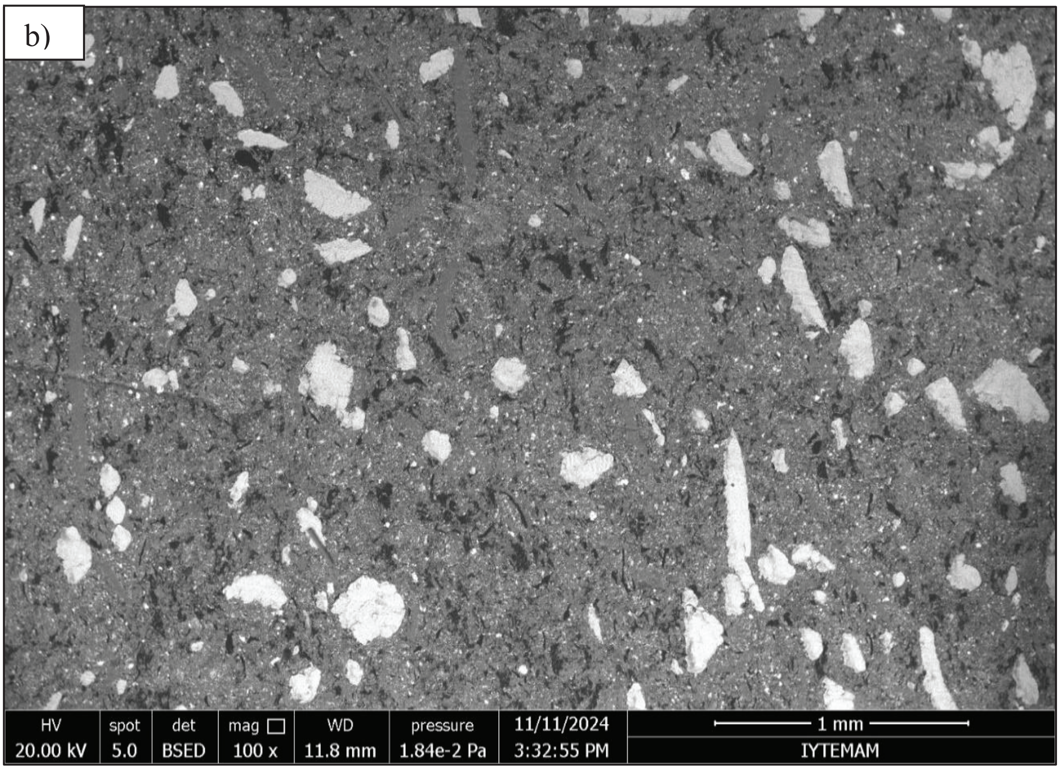


Figure 4.22. SEM Images of Sample3, a) From the Worn Surface, b) From the Sectioned Surface

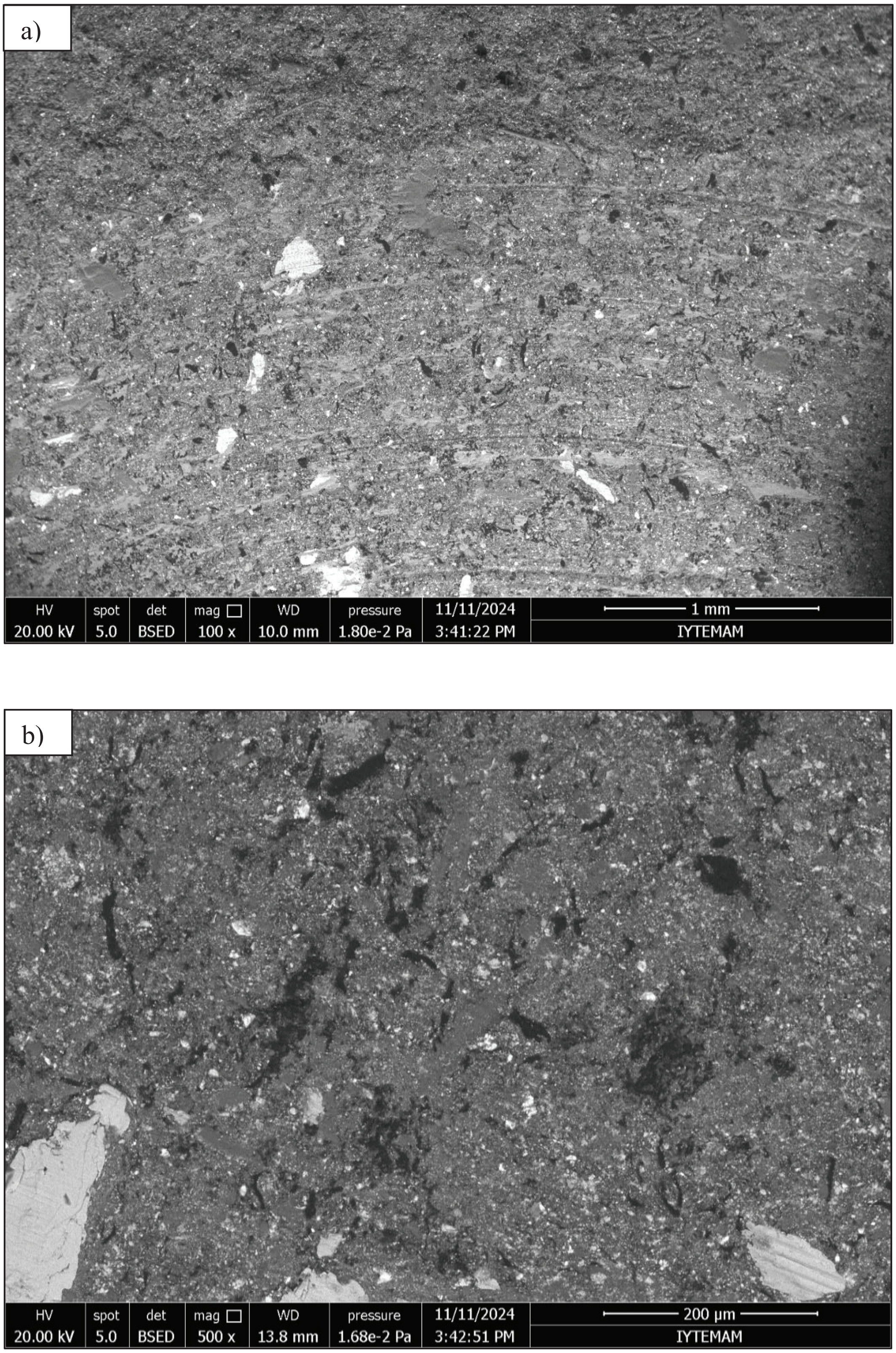


Figure 4.23. SEM Images of Sample4, a) From the Worn Surface, b) From the Sectioned Surface

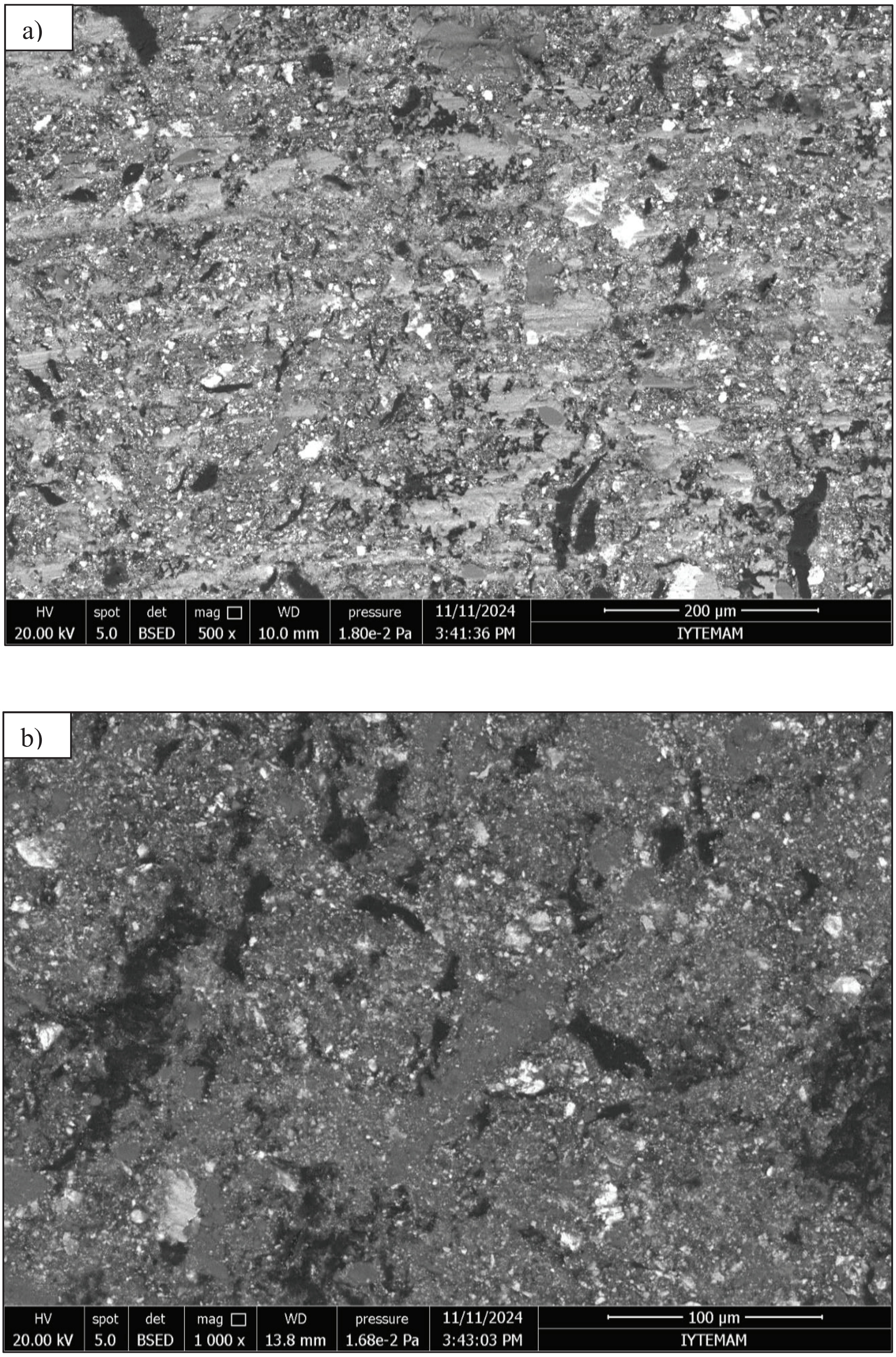
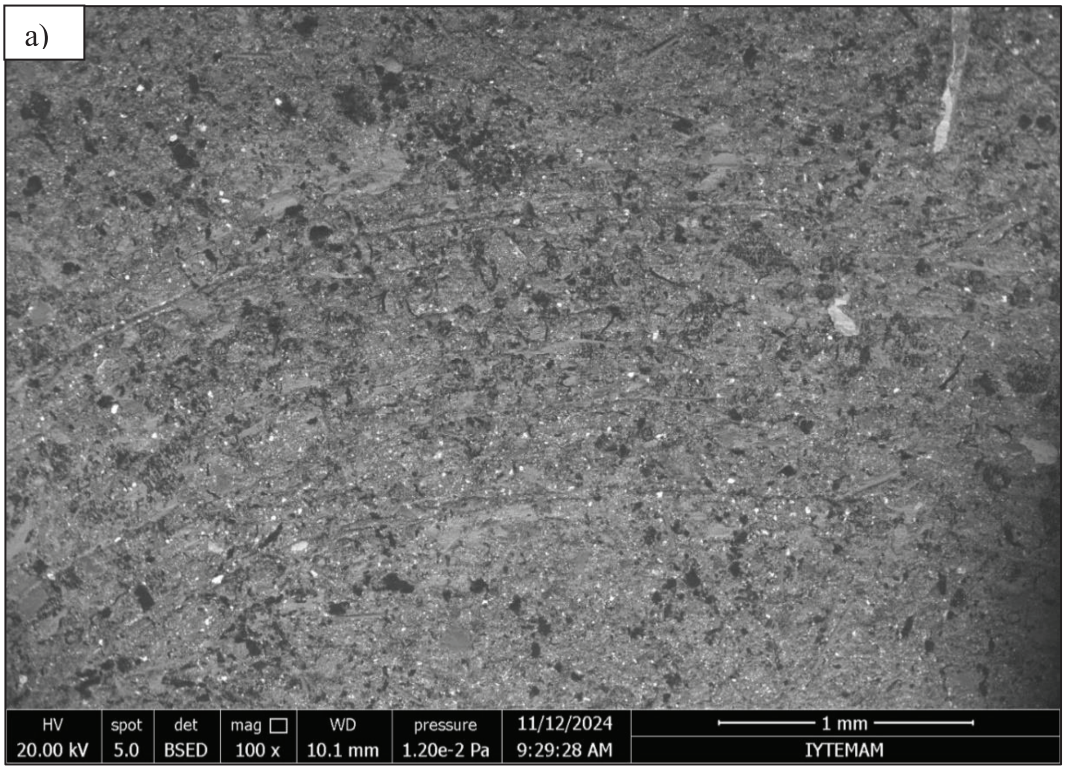


Figure 4.24. SEM Images of Sample5, a) From the Worn Surface, b) From the Sectioned Surface



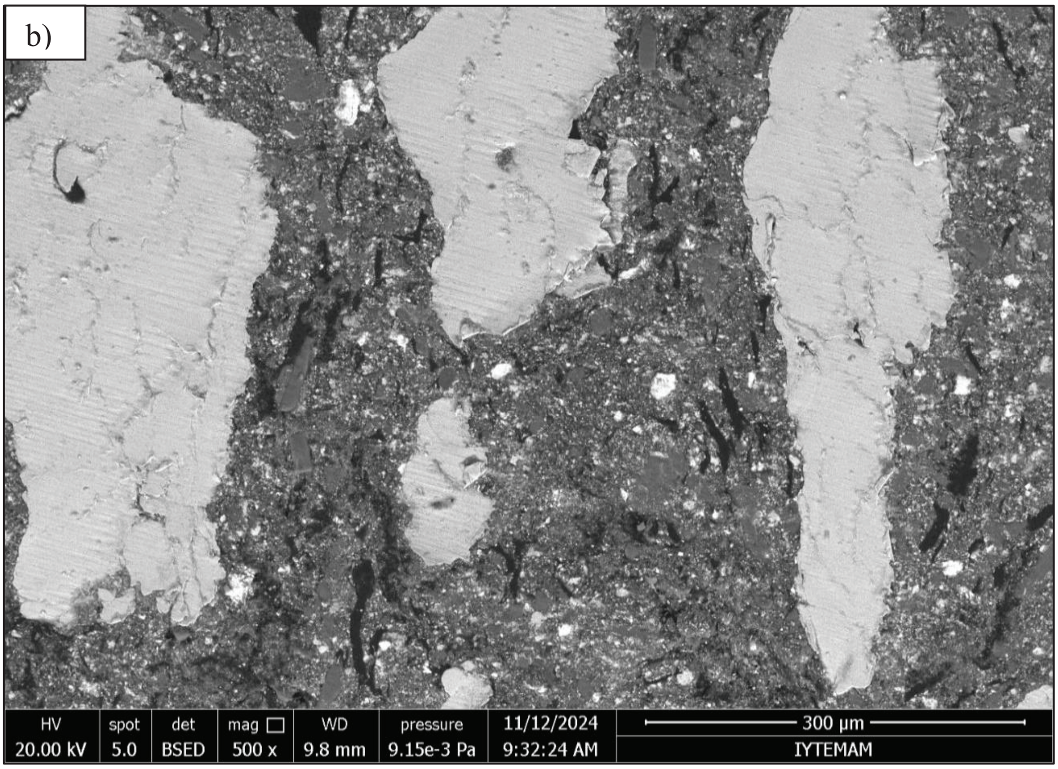


Figure 4.25. SEM Images of Sample6, a) From the Worn Surface, b) From the Sectioned Surface

In this section, the worn and cut surfaces of the materials were examined using scanning electron microscopy and energy dispersive X-ray Spectroscopy. The findings for sample2 are shown separately in Figures 4.26-4.27.

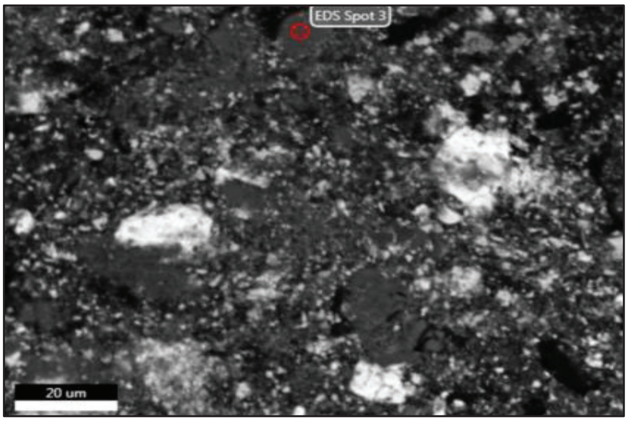


Figure 4.26. SEM Image of Sample2 at 20µm.

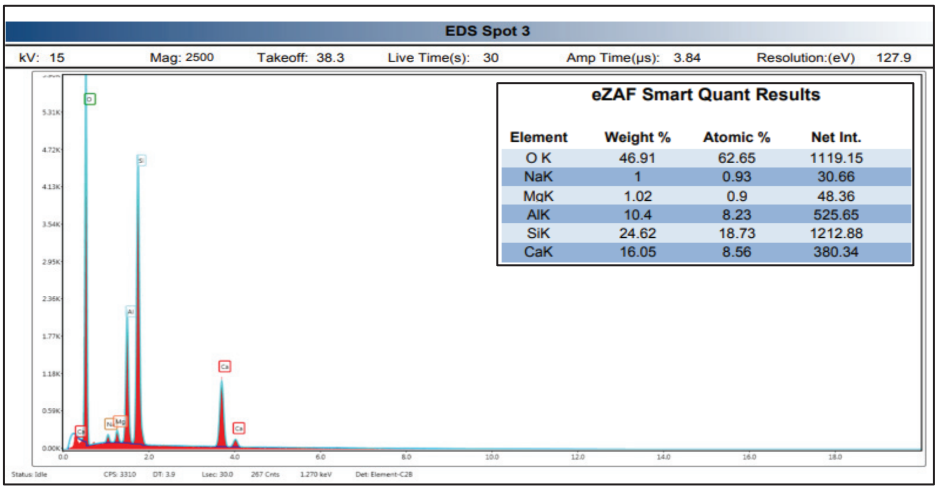


Figure 4.27. EDS Images of Sample2 Taken from Spot

As seen in the figures taken with SEM, it is clear that sample 6 containing 20% GG25 casting waste in 1 mm size has more porosity than sample 1 containing 500 µm casting waste. When sample 5 containing 20% steel fiber is compared to sample 1 containing 20% GG25 sawdust waste, it is seen that sample 5 has less porosity. This situation somehow reveals the high-volume difference between samples 1 and 5. In addition, samples 3, 4 and 5 have less volume difference than samples 1, 2 and 6. When the SEM figures are examined, it is seen that sample 5 has the least volume difference and porosity according to the volume increases. Microstructure images taken from the surface of sample 1 before wear and after sample 1 was subjected to wear are shown in Figure 4.28. When these images are inspected, it becomes evident that the abrasion has a considerable effect on the sample and that the surface has been abraded. It is understood that the smooth surface seen in the first Figure has lost its effect. After the abrasion test, the surface of the material appeared to have a less porous structure as a result of the friction effect and friction marks formed during the test were observed. Due to the continuation of the friction process, the surface gained a smoother appearance with a plaster-like effect.

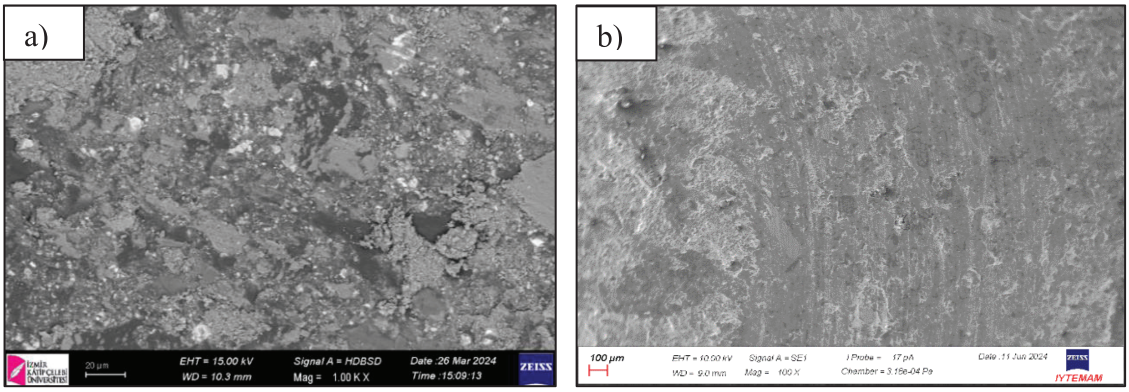


Figure 4.28. a) SEM image of Sample 1 taken from a) Original Surface, b) Wear Surface

CHAPTER 5

CONCLUSIONS

As a result, in accordance with the purpose of the study, composite clutch lining compositions to be used in aircraft clutch systems were produced using metal sawdust fibers. Developed with a sustainable production approach, these linings both support material recycling and offer important advantages such as wear resistance and high temperature resistance. In this study, comprehensive characterization studies were carried out in order to obtain a detailed perspective on the raw materials used in commercial composite-based clutch linings. These studies include various analysis methods to determine the chemical contents of the components that make up the friction material. Microstructure analyses performed with Optical Microscope (OM) and Scanning Electron Microscope reveal the microscopic properties of the material; Energy Dispersive X-Ray Spectroscopy (SEM-EDS) is used to analyze the chemical compositions of the components. In addition, phase analysis performed with X-Ray Diffractometry (XRD) helps to understand the crystal structure of the material, while thermal behaviors were examined with Thermogravimetric Analysis (TGA). The company has knowledge on the effect of the raw material ratios used in clutch linings on the performance of the friction samples produced with the know-how obtained from previous R&D studies. The components that constitute the composite friction material suitable for aviation applications were determined in line with the characterization studies obtained and the knowledge obtained from the company's R&D studies. Taking the determined formulation as a reference, GG25 material, which creates approximately 22.4 tons of waste per year as a result of CNC processing within the company Hammer Clutch, was used instead of the traditional steel fibers used in the composition. Six different recipes were prepared with different ratios of steel fiber and GG25 casting waste in material sizes below 500 µm and 1 mm. The samples were manufactured by powder metallurgy method using raw materials in mass ratios ranging from minimum 2.5% to maximum 20% and varying particle sizes as specified in Table 4.1.

In order to evaluate the effect of the use of GG25 casting waste in clutch lining formulations on clutch performance, the wear resistance and friction coefficient of the sample were determined with a ball-on type wear tester. Optical microscope and SEM-EDS analysis images taken from the worn surfaces were evaluated. Thus, the effect of the use of casting waste on the material properties was statistically interpreted.

As a result of the friction tests, when the comparative friction coefficient graph of the samples is examined in Figure 4.11, it is seen that the friction coefficient decreases proportionally with the increase in the amount of GG25 sawdust waste. The lowest friction coefficient values were observed in the 1st and 6th samples containing 20% GG25 sawdust waste. The highest friction coefficient values are observed in the 5th sample containing 20% steel fiber and in the 4th, sample containing 15% steel fiber and 5% GG25 sawdust waste. It is observed that the sample with the least deviation in the friction coefficient value and providing stabilization is the 3rd sample, which used 10% steel fiber and 10% GG25 sawdust waste. The friction coefficient, which shows close values in the 2nd and 3rd samples, provided more stabilization in the material by increasing the GG25 casting waste by 5%. In this case, it can be commented that the friction coefficient provided by the steel fiber and GG25 sawdust waste used in equal proportions is more balanced compared to other correlations.

In addition, the effect of metal fiber grain size on the friction coefficient was investigated with formulas 1 and 6 using 20% GG25 sawdust waste. It was observed that the GG25 sawdust waste used with a grain size of 500 µm increased the friction coefficient value more compared to the one used with a grain size of 1 mm. In this way, it is understood that the ideal size of the grain size has a balancing and increasing effect on the friction coefficient. In this case, a result supporting the literature study was obtained. Based on this evaluation, future studies can be carried out to obtain higher friction coefficient values by using metal waste in smaller grain sizes. Considering the increasing friction coefficient and the stabilization of the friction coefficient, it can be commented that the 3rd sample, which uses equal proportions of steel fiber and GG25 sawdust waste, is the ideal recipe.

When the graph of wear amounts according to samples is examined in Figure 4.12, it is observed that as the GG25 casting waste ratio decreases, the amount of wear decreases and the resistance to wear increases, which confirms the literature. However, when the graph is examined carefully, an increase in the amount of wear is observed in sample 4. It is thought that this anomaly is due to the fact that the samples cannot be produced with equal precision in different environmental conditions. In addition, when the effect of metal fiber grain size on the wear resistance of the sample was examined with formulas 1 and 6 using 20% GG25 sawdust waste, it was observed that the GG25 sawdust waste used in 500 µm grain size provided higher wear resistance compared to the one used in 1 mm grain size.

When the comparative density graph of the samples in Figure 4.13 is examined, the density value of the 5th composition, which was prepared similarly to the commercial sample and contained 20% steel fiber, was measured as 2.308 g/cm³. In general, it was observed that the decrease in the GG25 casting waste ratio caused an initial increase in the density values of the samples. This is because the density of GG25 waste sawdust in casting form is lower than that of steel in fiber form. However, a density decrease was observed from the 2nd sample to the 3rd sample. This anomaly is thought to be due to the fact that samples cannot be produced with equal sensitivity under different environmental conditions. When the density ranges are examined, the highest density value is measured as 2.355 g/cm³ and the lowest density value is measured as 2.101 g/cm³. The difference between these two values is 0.230 g/cm³, which corresponds to a change of approximately 10%. This small density difference is a factor that makes it difficult to interpret density differences due to varying raw material ratios. The use of lower density metals such as GG25 casting waste can have effects on grip performance by reducing sample weight. Critical factors such as fuel efficiency and payload capacity in particular can be directly affected by these changes.

Additionally, the effect of GG25 casting waste with different grain sizes on the material density was investigated in samples 1 and 6. It was observed that increasing grain size in sample 6 resulted in lower density values.

According to Table 4.7, the shore-D hardness values of the friction samples vary between 76.8 and 81.6, which means a difference of approximately 5.8%. The highest hardness value was measured as 81.6 shore in the 5th sample containing 20% steel fiber. The 4th sample, containing 15% steel fiber and 5% GG25 casting raw material with grains below 500 µm, ranked second with a shore hardness value of 81.0. Sample 1, which has the highest GG25 casting waste ratio, showed the lowest hardness value with 76.8 shore. In support of the literature, samples using steel fiber generally have higher hardness values compared to those using GG25 casting waste.

Hardness is a critical parameter for grip performance. High hardness increases the material's resistance to deformation and significantly reduces wear, ensuring long-term system life. Especially in industries that require high safety standards, such as aviation, maintaining material hardness stability and wear resistance is vital for system reliability.

When the cross-sectional images of the samples before and after abrasion are examined, it is seen that abrasion has a significant effect on the sample and clearly reveals that the surface has been abraded. It is understood that the smooth surface loses its effect after abrasion. After the abrasion test, it was seen that the surface of the material had a less porous structure as a result of the friction effect and the friction marks formed during the test were observed. Due to the continuation of the friction process, the surface gained a smoother appearance with a plaster-like effect.

As a result of the evaluations, it was concluded that the samples using GG25 casting waste had lower hardness and wear resistance compared to the samples using steel fiber. Although GG25 cast iron offers similar properties to steel in terms of friction coefficient and density, it is behind in terms of hardness and wear resistance. Therefore, GG25 cast iron, which offers lower cost and machinability advantages, provides sufficient performance in standard applications. In particular, it effectively provides friction, wear and cost balance. As a result of the analyses, when the effects of using GG25 casting waste instead of steel fiber on grip performance were evaluated, the 3rd sample, which provides stability and high values in the friction coefficient and high protection against wear resistance, was determined as the most suitable formulation.

The calculations made with experimental tests and the literature resulted in a very high convergence. This proves that the experimental study on physical performance was analyzed correctly. As a result, the tribology tests conducted show that the inactive metal fibers used instead of steel fibers do not negatively affect the wear and grip performance at the optimum point and also contribute to the recycling process by evaluating industrial waste and exhibiting an environmentally friendly approach. GG25 casting offers an important alternative in the production of friction materials thanks to its mechanical properties. These results have shown that recyclable casting waste can be successfully evaluated instead of expensive steel fibers. With this project, an important step will be taken to meet the needs of the automotive industry, reduce raw material costs and create a more sustainable future.

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