Mechanical and wear behavior of self-lubricating hybrid metal matrix composite(MMC)

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Abstract. This study investigates the mechanical and wear behavior of self-lubricating mixed metal matrix composites (MMCs) by focusing on magnesium reinforced with graphene nanoparticles (GNP) and silicon carbide (SiC). The aim of this study was to explore the potential of magnesium as a base material for advanced applications due to its lightweight and strength properties, while combining GNP for improved lubrication and SiC for increased mechanical strength. Samples were prepared and analyzed using powder metallurgy techniques and the results showed that while GNP improves self-lubrication, it reduces the strength of the material. However, the addition of SiC counteracts this effect and improves the hardness and overall mechanical properties of the composite. This study provides insights into the future development of lightweight, durable and self-lubricating materials for the automotive and aerospace industries.

Keywords: Self-lubricating composites, Magnesium alloys, Graphene nanoplatelets (GNP), Silicon carbide (SiC), Powder metallurgy, Wear resistance, Mechanical properties, Lightweight materials, Hybrid metal matrix composites (MMC), Corrosion resistance.

1. Introduction

The demand for lightweight, high-performance materials has significantly increased, especially in sectors such as aerospace, automotive, and electronics, where energy efficiency and durability are critical. Aluminum alloys[1] have been widely used due to their superior strength, corrosion resistance, and heat tolerance. However, magnesium alloys are emerging as a more sustainable alternative, offering even lighter weight and comparable strength. These alloys also contribute to reducing emissions, aligning with global sustainability efforts.

One challenge with magnesium alloys is their susceptibility to wear, limiting their lifespan. To address this, graphene nanoplatelets (GNP), known for their excellent lubrication and thermal properties[2], have been introduced as reinforcements. GNP can reduce friction and improve durability by forming a lubricating film on the alloy surface. However, at higher concentrations, GNP tends to agglomerate[3], weakening the mechanical properties of the alloy.

This study explores the addition of silicon carbide (SiC) alongside GNP in magnesium alloys to counterbalance the mechanical drawbacks[3]. SiC's hardness and wear resistance[4], combined with GNP's self-lubrication, aim to create a hybrid metal matrix composite (MMC) with enhanced mechanical and wear properties. Using powder metallurgy techniques, this research focuses on improving the bonding between the matrix and reinforcements, optimizing the composite for lightweight, durable, and high-performance applications.

2. Materials and method

2.1 Starting material

Pure Mg powder and GNPs were used as element material in this research, and the SiC was also used to comparison. Besides, the PVA was set in the mixer as a binder

2.2 Synthesis of composite materials

The samples used in this experiment were prepared using powder metallurgy, chosen for several reasons. First, it is the preferred method for manufacturing refractory metals, their compounds,

pseudo-alloys, and porous materials. Second, it allows the production of final-sized blanks with minimal additional processing, resulting in material savings and reduced costs. The powder metallurgy process starts with preparing the raw powder, which can be done through mechanical or physicochemical methods. Mechanical methods include crushing and atomization, while physicochemical methods involve processes like electrochemical corrosion, reduction, vapor deposition, and electrolysis, with reduction, atomization, and electrolysis being the most common. In this experiment, mechanical methods were used. Once the powder is prepared, it is molded into blanks, with pressurized molding being the most common approach. Pressurized molding was used here to minimize material usage and cost. After forming the blanks, they undergo sintering, a crucial step that enhances their physical and mechanical properties by heating the shaped blanks. Sintering can involve unit or multi-system processes, with multi-system liquid-phase sintering using lower temperatures for fusible components. Specialized sintering processes include melt impregnation and hot pressing. After sintering, post-treatment processes like finishing, oil dipping, heat treatment, and mechanical processing are employed. Rolling and forging may also be used after sintering to improve results. In this study, laboratory tests on physical properties were necessary, so careful post-processing was crucial to ensure optimal performance and characterization[5].

Weighing was done with a standard electronic balance, ensuring that different test papers were used for each sample. The three experiments involved pure magnesium (10.33 g), magnesium with 3% GNP (10.0771 g and 0.326 g), and magnesium with 3% GNP added 15% SiC (10.01 g, 0.32 g, and 1.54 g)[6]. Each sample included 2% PVA binder, which helped form the samples without flaking, as shown in Figure 1. The Mg, Mg-GNP, and Mg-GNP-SiC mixtures were placed in separate beakers, and 20 ml of acetone was added to each to aid in mixing. Magnetic stirrers were introduced to each beaker, and the mixtures were stirred for 30 minutes at 650 rpm. The equipment was deep enough to prevent splashing, as any material loss could affect the accuracy of subsequent tests. After mixing, the mixtures were dried overnight in an oven at 80°C. The next morning, the Mg-GNP samples were ground clockwise with a mortar and pestle for about 15 minutes, ensuring the powder had a dimensional error below 0.001 mm and surface roughness of 0.4 to 0.1 μm, achieving a minimum Ra of 0.012 μm. This step improved particle accuracy, allowing better compaction and a more thorough examination of the SiC addition's effect on lubricity. The discs were thoroughly cleaned after each sample to avoid contamination. GNP’s lightweight nature caused it to stick to the discs due to van der Waals forces, requiring ultrasonic cleaning to remove residue. The same method was applied to the Mg-GNP-SiC samples, and the grinding process was repeated until all test equipment was cleaned and the desired results were achieved.

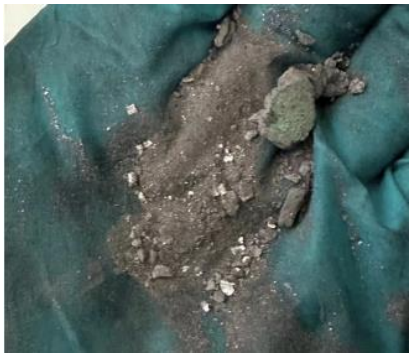


Figure 1. Flakes



Figure 2.Ultrasonic Stirrer



Figure 3. Grinding Dish

After the grinding process, the next step involves preparing the powder into flake samples through a technique known as powder metallurgy. Powder metallurgy offers distinct chemical, mechanical, and physical properties that cannot be achieved using traditional melt casting methods. This method enables the production of porous, semi-dense, or fully dense materials, as well as various products like oiled bearings, gears, cams, guide rods, and tools, using a less cutting-intensive process.To carry out this process, specific equipment is required, namely a press die and its corresponding press machine. The press die is initially assembled according to the configuration shown in Figure 4. Then, a sample of Mg-GNP powder is poured into the hole of the die (note that there are two small cylinders, with the first one placed in the hole before pouring the powder). Subsequently, the second cylinder is filled with an adequate amount of sample powder and placed in the hole. Additionally, a long cylindrical stick is inserted into the cavity to apply pressure on the two small cylinders and the sample powder. The entire setup is then positioned on the tablet press machine.The process begins by turning the first knob. This knob allows the scales used to hold down the press die to gradually descend as pressure is applied to the rocker. Therefore, the first knob should be opened initially, and the rocker should be swung to ensure that the scales press down on the abrasive system first. Afterward, the first knob is tightened, and the second knob is opened. The second knob is responsible for applying additional pressure by swinging the rocker while maintaining the weight in place. At this stage, the scales are already pressed against the apparatus. With the first knob loosened and the rocker swung to the appropriate extent, continuous pressure is exerted once the second knob is released. The pressure is set to 10 tons, and the second knob is tightened when the gauge indicates 10 tons, as shown in the diagram. This pressure is maintained for five minutes. After five minutes, the second knob is unscrewed to release the pressure, allowing the press die to be removed from the press machine. Next, the die is flipped over, and the open cylinder is placed in its original position, where the press bar was previously located. The original press base is removed from the top, and the initial press bar is placed

in the upper hole of the current press die. Finally, the press die is placed on the press base again. At this point, the second knob can be released once more to allow the scales to return to their resting position. Carefully extract the device used for powder metallurgy, ensuring not to reverse the up and down direction of the press. Remove the open cylinder to reveal the two short cylinders and the primary sample within. During the forming process, several issues may arise. First, it is crucial to be cautious when pouring the powder into the holes to prevent any spillage around the holes. This ensures that excess powder does not become trapped in the die after pressing, which could impede its functionality and make it difficult to open. Excessive powder can also cause blockage. Once the powder forms a casing within the equipment, it becomes challenging for the equipment to operate correctly. Severe casing may lead to an overload of the press, resulting in a reaction force and oil leakage, which can cause significant damage to the testing equipment. If you find that PVA has been added but the sample still appears as shown in Figure 1, it is possible that the grinding accuracy and time were not sufficient and that larger particles were present during the pressing process, which can lead to cracking and fragmentation [7].



Figure 4. Cold Compaction Die

After the formation of the primary samples, the next step involves sintering. Sintering is a well-established process that converts powdered materials into dense bodies. It has been widely used for producing ceramics, powder metallurgy, refractory materials, and ultra-high temperature materials. Generally, the densified body obtained through sintering consists of crystals, glassy phases, and pores within its microstructure. The sintering process directly impacts grain size, pore size, shape, and the distribution of grain boundaries in the microstructure, thereby influencing the material's properties. In the preparation of inorganic solid compounds using solid-phase reactions, the diffusion process typically governs the reaction rate, requiring high temperatures for efficient progress. Conversely, lower temperatures can result in less effective sintering. It is also crucial to isolate oxygen during sintering to prevent the oxidation of magnesium (Mg) in the presence of air, as it significantly affects the process. The primary samples are placed in a crucible, which is then positioned in the sintering apparatus and subjected to a temperature of 675°C. After two hours, the first batch of samples is removed and replaced with the second batch. It is important to note that individual samples should be sintered one by one in the equipment, rather than simultaneously, to prevent contamination and ensure accurate results. Following the second round of sintering, the crucible is gently shaken to assess the integrity of the sintered samples. Inadequate grinding or insufficient pressure during molding can lead to sample breakage after sintering.

The subsequent step involves further processing of the product, which comprises two steps. The first is the mosaic inlay of the sample, using metallographic inlay materials. Metallographic inlay refers to the consumables used during the inlay stage of metallographic examination. Sample preparation involves sampling, inlaying, coarse and fine grinding, polishing, etching, and specific considerations for each step. Proper execution of the metallographic process directly affects the accuracy of test results. In extreme cases, incorrect procedures can lead to false structures and misleading conclusions. Hence, the metallographic process is crucial. Modern metallographic analysis methods are widely used in the quality analysis of solid materials, and the control and optimization of the process have advanced. Metallographic inlay materials have evolved, incorporating various technologies based on the tested materials. These inlays can be classified as hot inlays and cold inlays [8]. Thermal inlays typically consist of thermally cured resins and functional

fillers. A thermal inlay machine applies heat and pressure to solid samples after cooling to complete the inlay process. Resin options include phenolic, acrylic, epoxy, and honeydew resins, while fillers encompass mineral powders, glass fiber powders, ceramic powders, pigment indicators, copper powders, and graphite. On the other hand, cold inlays don't involve heating and are achieved using a two-component mixture of room-temperature curing resins and functional fillers. Cold inlays are commonly used for samples sensitive to temperature or pressure, such as plant and animal samples, plastics, rubbers that can soften or undergo physical changes under heat, and metals that can experience structural changes from low-temperature tempering. Cold inlay resins include epoxy and acrylic types, while fillers consist of mineral powders, glass fiber powders, pigment indicators, and more.

Regardless of the type of inlay, they serve three main functions in metallographic sample preparation. First, they allow for sample fixation to facilitate orientation of the viewing surface. Second, they support the sample during grinding and polishing. Third, inlays help standardize the sample shape, making it easier to clamp during grinding and polishing. For this test, thermal inlay was chosen due to its convenience, sustainability, and suitability. Hot mounting involves embedding the resin and sample using heat and pressure into a regularly shaped sample of fixed size. Before inlaying, the surface is cleaned with acetone or ultrasound to remove oil, impurities, rust, and contaminants, improving the sample's adhesion to the inlay. After cleaning, the sample should be wiped or dried with a hairdryer. The dry and clean sample is placed on the inlay barrel of the hot inlay machine, and the inlay table is lowered. The appropriate amount of resin powder is added, and in this experiment, Lab Testing Technology Ltd.'s thermal inlay resin was used. The amount of resin added should correspond to the desired height of the final inlaid sample (approximately 20 mm). The cover is tightly closed, and the sample is heated to 180°C and subjected to approximately 250 bar of pressure. After adjusting the parameters and waiting about 10 minutes (heating-holding-cooling process, as seen in Figure 5), the sealing lid is opened, the test bench is raised, and the specimen is removed.

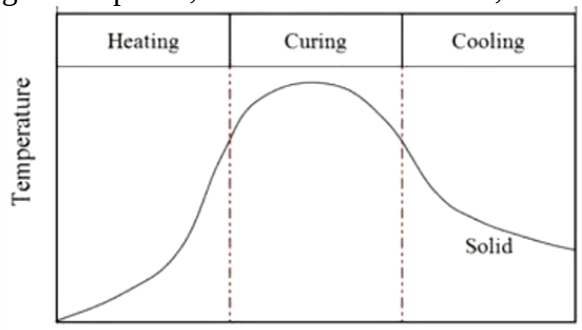


Figure 5. Heating-holding-cooling Process

When performing inlaying, several important points should be considered. First, the size of the inlay should be adjusted to fit the thermal inlay barrel diameter, leaving a distance of 3-5 mm from the barrel edge. The height of the sample inlay should be approximately 20 mm, allowing for convenient handling. For thin slices, sheets, small cylindrical shapes, and irregular samples, a tool should be used to hold the slices, and multiple samples can be inlaid simultaneously with gaps between them. In this experiment, different samples will be individually heat-set to minimize errors, and the use of a slice holder is crucial to ensure intact sample removal. Once the inlaying process is completed, the next step is polishing. This involves using a flexible polishing tool and abrasive particles or other polishing media to finish the surface of the workpiece [9]. Polishing does not improve the dimensional or geometrical accuracy of the workpiece but aims to achieve a smooth surface or a mirror-like shine. Sometimes, polishing is also employed to remove the shine and create a matte finish. The polishing process involves smoothing the workpiece's surface using abrasives and machinery.

To begin the polishing process, the polishing machine is started, and the wheel is set to rotate clockwise at 250 RPM. The tap on the polishing machine is turned on, allowing water to drip slowly onto the wheel. Adding a small amount of water continuously during polishing helps prevent

overheating and the blowing up of the sample. It also carries away the debris generated during polishing, thereby avoiding sample contamination.

The first step in polishing is to use 400-grit sandpaper. Care should be taken to maintain regular intervals when applying pressure to the sample during polishing to ensure a smooth effect. After sanding with 400-grit sandpaper for approximately 30 minutes, the sample should exhibit noticeable sanding marks. It is important to keep the wheel rotating in the same direction and at the same speed to avoid creating complex scratches on the sample's surface due to changes in the wheel's rotation direction. Complex scratches can make it difficult to assess the degree of polishing and hinder the observation of the sample's structure in the SEM (scanning electron microscope) for easy analysis.

After stopping the wheel, the 400-grit sandpaper is replaced with 800-grit sandpaper, and the polishing process is repeated. Occasional observations should be made to ensure the complete coverage of the 400-grit marks by the 800-grit sandpaper. The wheel is then stopped again, and 1200-grit sandpaper replaces the 800-grit sandpaper. This procedure is repeated until the 800-grit marks are fully covered by the 1200-grit.

Once the wheel is stopped, the 1200-grit sandpaper is replaced with a polishing cloth. A polishing compound is added to the part of the cloth used for polishing, and the polishing machine is turned on again. By applying certain pressure and using the polishing agent, a softened layer forms on the workpiece's surface due to the corrosive medium in the agent. The abrasive grains in the polishing solution grind the softened layer, resulting in a polished surface that is conducive to subsequent SEM observation, while also providing a more metallic appearance to the sample surface.

2.3 Structural Testing of Samples

The primary method used in this experiment to analyze the structure of the samples was scanning electron microscopy (SEM). SEM is a precise instrument that allows for high-resolution analysis of micro-zone morphology. It plays a crucial role in materials research and is extensively employed to study the morphological structure, interface conditions, damage mechanisms, and prediction of material properties across various materials. With SEM, it is possible to directly investigate crystal defects and their formation processes, observe the atomic arrangement within metallic materials and their actual boundaries, examine boundary movement under different conditions, and analyze damage caused by crystals during surface mechanical processing and radiation exposure, among other applications.

SEM is characterized by its ability to provide a large depth of field, high-resolution imaging, visually intuitive representation, a strong sense of three-dimensionality, a wide range of magnification options, and the capability to rotate and tilt samples in three dimensions for examination. It also offers the advantage of accommodating a wide range of sample types, causing minimal damage or contamination to the original sample, and enabling the simultaneous acquisition of morphological, structural, compositional, and crystallographic information.

The primary objective of using SEM in this experiment is to observe whether the addition of graphene nanoplatelets (GNP) effectively encapsulates the magnesium (Mg) samples, thereby ensuring a certain level of self-lubrication and preventing corrosion of Mg upon contact with air, which could reduce its lifespan. Furthermore, it aims to determine whether the addition of silicon carbide (SiC) leads to the integration of individual substances, enhancing lubricity and overall strength. Additionally, SEM will allow for separate analysis of Mg and GNP for further investigation and evaluation[10].

To begin, power on the machine and wait for the hardness testing software to start. This may take a few minutes. Once the login page appears, click on it. In this experiment, the Vickers hardness test will be conducted to measure the hardness of the materials. In material science, hardness refers to "the property of solid materials to resist permanent deformation" and is an important mechanical characteristic. It represents the local resistance of a solid to external objects penetrating its surface and serves as a comparative index for the hardness or softness of different materials. Different hardness standards exist due to variations in measurement methods, and the measured hardness

represents different material properties. For instance, the indentation hardness measured in metals reflects their resistance to plastic deformation, while in ceramics and mineral materials, it reflects their ability to resist damage. Therefore, the mechanical meanings and units of various hardness standards differ, and there is no fixed conversion relationship between them. However, they can be compared through experiments. Hardness testing is a simple and practical method in mechanical performance tests. In order to replace certain mechanical performance tests with hardness tests in production, a more accurate conversion relationship between hardness and strength is required.

Vickers hardness is measured using a diamond prism indenter with an angle of 136 degrees between opposing surfaces. The indenter is pressed into the specimen's surface under a specified load (F) for a set duration, and the length of the resulting indentation diagonal (d) is measured. The surface area of the indentation is calculated, and the average pressure on that area provides the Vickers hardness value (HV) of the metal [11]. During actual measurements, no calculations are needed, as the hardness value can be directly obtained by referring to a lookup table based on the measured d value. The Vickers hardness test was introduced in 1921 by Robert L. Smith and George E. Sandland of Vickers Ltd., UK. It is a standard for indicating the hardness of a material. The test applies a load of 49.03 to 980.7 N using a square cone-shaped diamond indenter at an angle of 136 degrees, and the indentation's diagonal length is measured to calculate the hardness value using a formula. Vickers hardness is suitable for determining the hardness of larger workpieces and deeper surfaces. It also includes small-load Vickers hardness for thin workpieces, tool surfaces, or coatings, as well as micro Vickers hardness with a test load of less than 1.961 N for metal foil and extremely thin surface layers. HV is used for microscopic analysis.

In this experiment, a load of one kilogram will be applied, and the automatic objective option will be selected due to the small sample size. It is important to note that excessive inlay during the heat-setting stage can result in a sample that is too high, leading to potential tipping during the hardness test. This could damage the sample, the machine, and most likely the probe. Therefore, it is crucial to repeatedly confirm the stability of the sample before the test to prevent the test surface from tilting and causing equipment damage. After setting the method, select an existing quadruplet from the position menu and click "Measure" to await the results. For accuracy, manual adjustment of the test range may be necessary after measurement to avoid errors in automatic identification. Repeat these steps for pure Mg, Mg-GNP, and Mg-GNP-SiC alloys to measure their respective Vickers hardness.

The hardness test can effectively analyze and address the mechanical properties of pure magnesium after adding different fillers. The Vickers hardness test can help solve the initial problem, which is understanding the influence of fillers on the mechanical properties of pure magnesium.

3. Results and Discussion

3.1 Visual Analysis of the Surface

Before conducting all the tests, the metal can first be observed with the naked eye. At this point, the alloy shows a relatively good metallic luster after being polished, which is an important criterion for lubricating performance. As shown in Figure 6 below, the surface of some samples appears smooth, with voids and cracks being difficult to detect. The alloy exhibits relatively good metal characteristics, indicating that it will likely have good self-lubricating properties.



Figure 6. Surface of Sample

3.2 SEM Test

The results of the SEM test are shown in Figure 7. When examining the SEM images, it was observed that the morphology of pure magnesium (Mg) appeared spherical, but with the addition of graphene nanosheets (GNP), the shape became irregular. However, despite the irregular shape, the SEM images still showed a smooth surface. This suggests that the GNPs envelop a larger mass of magnesium powder, leading to the formation of an irregular three-dimensional structure driven by van der Waals forces during the powder metallurgy process. Furthermore, the SEM results indicated that the high surface area of GNPs facilitated better mixing with magnesium, resulting in a structure where GNPs encapsulated the magnesium. This shape implies fewer connections between individual particles, and the intermolecular interactions are not sufficiently strong to withstand various unexpected scenarios in practical applications. In other words, without the addition of silicon carbide (SiC), the overall mechanical properties of the alloy tend to decline.

However, it was observed that the agglomeration of pure GNPs was minimal, indicating that the previously observed tendency for GNPs to agglomerate was effectively addressed through improved stirring and meticulous grinding, leading to further enhancements in the mechanical properties of the samples. The improved fusion between GNPs and magnesium, rather than agglomeration, contributed to the enhanced mechanical properties of the alloy.

Analyzing the SEM results of SiC-incorporated samples, it became evident that there was intermolecular extraction between individual molecules, albeit with limited GNP aggregation. This observation suggests that the pre-existing agglomeration issue of GNPs was effectively mitigated through enhanced stirring and meticulous grinding. Additionally, the presence of the GNP coating acted as a protective layer, preventing the fracture of SiC particles and reducing surface damage. According to Azzat[3], the addition of GNPs weakens the mechanical properties of Mg alloys. However, SEM analysis reveals that the overall mechanical properties improve with further SiC incorporation. This indicates that SiC, serving as a secondary filler, counteracts the mechanical strength reduction caused by GNPs and instead enhances the overall mechanical strength.

The Mg structure, encompassing both GNP and SiC particles, further verifies that the homogenization and grinding processes result in better powder bonding, thereby strengthening the material's mechanical properties through tighter cohesion. Regarding self-lubrication, the introduction of GNPs imparts self-lubricating capabilities to the alloy, albeit at the expense of reduced mechanical properties. However, SEM examination after the addition of SiC demonstrates noticeable intermolecular extraction, suggesting that SiC incorporation theoretically establishes a lubricating protective film. Simultaneously, extraction occurs between GNPs and Mg. The presence of this protective film not only enhances the overall mechanical strength but also addresses the issue of GNP loss during the self-lubrication process in the original Mg-GNP alloy. In other words, the protective film minimizes the wear of the lubricating material while maintaining its self-lubricating ability. By employing this structural safeguard, potential damage to equipment and increased friction resulting from debris generated by wear in the Mg-GNP alloy are effectively minimized.

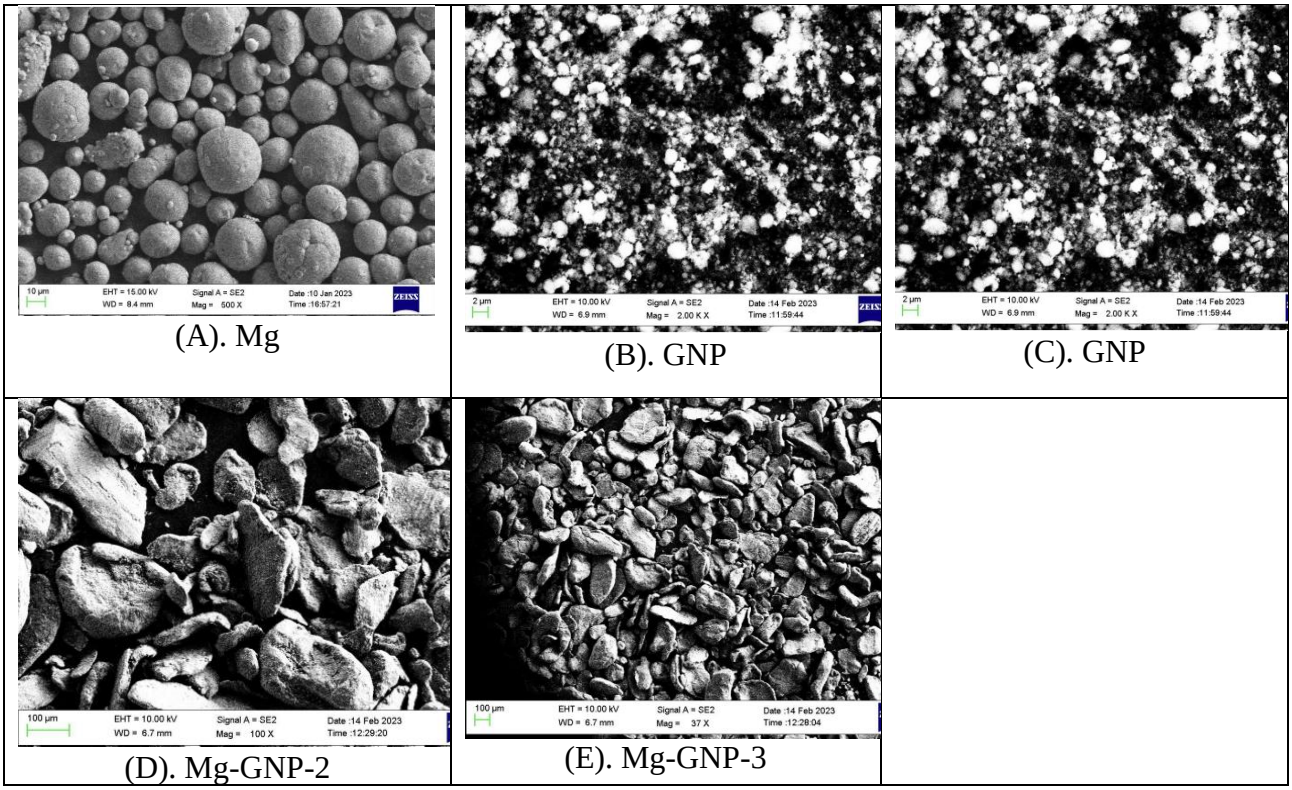
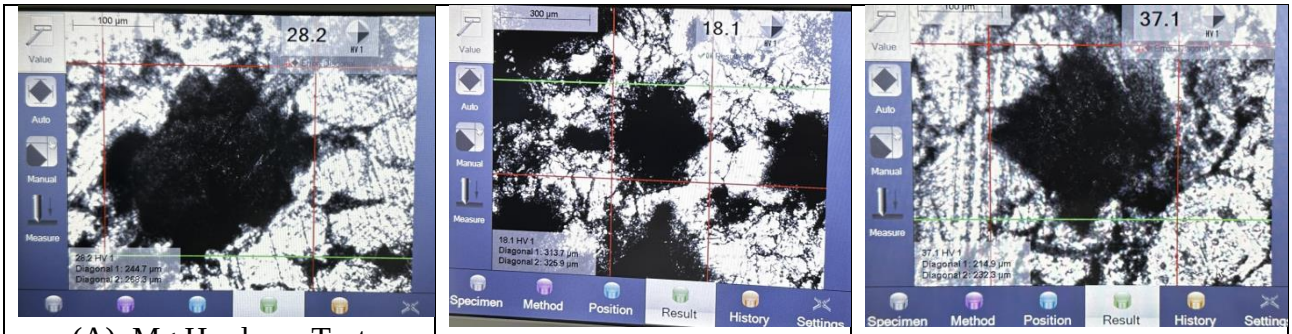


Figure 7: SEM Test

3.3 Hardness Test

The results of the hardness test are shown in Figure 8. The final Vickers hardness of pure Mg is approximately 28.3 Kgf/mm², while the Vickers hardness of Mg-GNP is approximately 18.7 Kgf/mm². Finally, with the addition of SiC, the Vickers hardness of the alloy increases to 37.1 Kgf/mm². It is clear that as GNP is added to pure Mg, followed by SiC, the overall material hardness first decreases and then increases. This means that while the addition of GNP to pure Mg improves its lubrication properties, it substantially reduces the hardness of pure Mg, which is already not a very hard metal. This reduction in hardness limits the potential applications of Mg. In contrast, the subsequent addition of SiC, a material with high hardness, results in a significant increase in Vickers hardness, which aligns with the SEM results.

The inclusions and mosaic relationship between Mg, GNP, and SiC not only protect the surface friction layer but also increase the overall hardness of the material. The formation of the protective layer directly contributes to a harder alloy. In other words, this demonstrates that the addition of SiC improves the reduction in strength and hardness caused by GNP. Even so, according to Tabor's[12] metal hardness ranking test, even with the addition of SiC to Mg-GNP to improve mechanical properties, the hardness of the magnesium alloy remains much lower than that of most metals commonly used in production. This suggests that further research is necessary to significantly improve the hardness of magnesium alloys if their range of applications is to be expanded, and if the low density and high sustainability of magnesium alloys are to be better utilized.



(A). Mg Hardness Test

(B). Mg-GNP Hardness Test

(C). Mg-GNP-SiC Hardness Test

Figure 8: Hardness Test

3.4 Discussion

In this section, the experimental errors are analyzed and discussed, and directions and methods for further experimentation are explored.

The small number of experimental groups made the results prone to chance. The experiments were set up with three groups: pure Mg, Mg-GNP, and Mg-GNP-SiC, forming a complete control, but the number of samples in each group was too small. If the measured data deviated from predictions, it was difficult to determine whether this was due to objective facts or operational errors.

The light mass of GNP led to significant losses during preparation. During powder preparation, a large amount of black material was left in the test paper, beakers, and grinding dishes. This indicates that a lot of GNP remained on the experimental apparatus, and since only a small amount of GNP was used as a filler in this experiment (to prevent agglomerates from forming at high concentrations), even a small loss could have affected the final results.

The samples were fragmented to varying degrees during the pressing and sintering process. This suggests that the samples did not fully take on the cylindrical shape expected during the process. This result was partly due to the particles causing fractures, but the amount of binder used was also likely a key factor. It is possible that the concentration of PVA added was too low, which prevented the samples from achieving the desired cylindrical shape during the forming and sintering process.

The surface of the samples was not ideal for this experiment. The polished samples had a good metallic luster and low porosity, but still differed from the ideal condition. Surface cracks and porosity in the samples are an indication of their self-lubricating capability, meaning that the self-lubrication performance of these powder metallurgy samples still needs improvement. In particular, the surface cracks and porosity will be key issues for further experiments.

It was difficult to find an ideal field of view in the SEM test. One unmentioned factor during the experiment was that the polishing process may not have been sufficiently timed, which meant that traces from previous polishing were not completely removed. Additionally, the polishing cloth may not have been used effectively at the end. These issues resulted in a poor surface condition of the samples, making it difficult to observe a clear field of view in the final SEM test.

There was no direct measurement of the improved level of self-lubrication. This experiment indirectly inferred, based on SEM microscopic analysis, that the formation of a protective layer and the avoidance of scratches and debris would further improve the self-lubrication level of the original Mg-SiC. However, more intuitive methods, such as measuring the coefficient of friction, were not used to directly determine the increase in self-lubrication.

The main method for improving the level of powder mixing could not be accurately identified. Various methods, such as better stirring and finer grinding, were used in this experiment to improve the level of powder bonding. A good level of powder bonding was observed in the final test performance, but the optimization methods were not analyzed using a controlled variable approach, meaning that each method's effectiveness in improving powder bonding was not thoroughly assessed.

4. Conclusion

In this experiment, pure magnesium, Mg-GNP, and Mg-GNP-SiC were prepared using powder metallurgy and analyzed through SEM and hardness testing. The primary focus was on addressing the existing problems of Mg-GNP and finding solutions to some of these issues.

One of the main issues was the powder bonding problem. In this experiment, a low concentration of GNP was used to reduce the agglomeration effect typically seen with higher GNP concentrations. To ensure that GNP could microscopically encapsulate the Mg, form a protective layer after the addition of SiC, and capture the SiC particles, better homogenizing equipment was employed, and careful grinding was conducted before molding. As a result, SEM analysis showed almost no GNP agglomeration, and the desired protective layer was achieved.

Another challenge was related to the mechanical properties of the material. While the addition of GNP gave pure magnesium excellent characteristics such as corrosion resistance and self-lubrication, the mechanical properties of Mg-GNP were somewhat degraded compared to pure magnesium. To address this, SiC was added in the same ratio as the original alloy, which effectively improved the overall mechanical properties of the alloy.

The Mg-GNP alloy displayed good self-lubricating properties, but its lower hardness led to increased scoring and debris during the lubrication process. This, in turn, increased friction and significantly limited the service life of equipment. To overcome this issue, SiC was added to increase the hardness of the samples, reducing chip and scratch generation during use, thereby improving the self-lubricating ability of the alloy.

In addition to resolving these issues, several problems remain to be addressed and identified. In conclusion, although Mg alloys hold great potential, they will face various challenges as the process of continuous improvement advances.

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