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RESEARCH

# Manufacture of Self-Lubricating Mechanical Parts from Al-Si Alloy Matrix Hybrid Nanocomposites

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A B S T R A C T

*Research is still being done to find solutions to the wear,abrasion and moving mechanical parts problems that persist. Production of moving and stationary parts, particularly those made of Al-Si alloy, due to their characteristics, which need for constant development. In this work, self-lubricating nano-additives were used in the manufacturing process. It was used powder metallurgy technique to fabricate the base alloy and hybrid nanocomposites. Next, by mechanically mixing ($MoS_2$) and Boron nitride (BN) in nanometer scale-level quantities as hybrid additives, 2, 4, and 6wt% were added. This was followed by pressing the mixture into a 10 mm-diameter steel mold without the use of heat. After pressing, the resultant samples are sintered at a temperature of up to 560 $C^0$ in a tube furnace that is kept free of oxygen. Argon, an inert gas that inhibits reactions, is used to protect all of these samples. The generated samples underwent to wear and abrasion tests, the resulting grains underwent analysis, and a scanning electron microscope (SEM) was used to study the surface microstructure and topography of worn samples. The results showed that the parts made with hybrid nano-additives have higher friction and wear resistances than that of the base (Al-Si)alloy. They also exhibited refine microstructure, high hardness values, and less weight loss during wear tesing. However, the addition percentage must not go above 6%. Friable phases develop in the microstructure, and it cannot pass wear testing.*



## 1. INTRODUCTION

Powder metallurgy is a common manufacturing method used for producing self-lubricating Al-Si alloys with nanoparticles. The process involves mixing the Al-Si powders with the desired nanoparticles, followed by compacting the mixture into a green part using a press. The green part is then sintered at high temperatures to form a fully dense alloy [1,2].

One of the advantages of manufacturing self-lubricating aluminum-silicon alloys with nanoparticles by powder metallurgy is the uniform distribution of nanoparticles within the alloy matrix. The mixing process can be controlled to ensure that nanoparticles are evenly distributed, giving a consistent self-lubricating layer on the surface of the alloy. Another advantage of using powder metallurgy is that it can be easily scaled up to industrial production. The process is well-established and can be automated to produce large quantities of self-lubricating Al-Si alloys with nanoparticles [3,4].

In manufacturing these materials, there are also some challenges involved through powder metallurgy. For example, high-purity powders have to be used during the process so that the alloy made from them will possess the required mechanical and tribological properties. Moreover, the sintering process might be a bit time-consuming and accordingly energy-intensive, needing proper temperature and atmosphere conditions to avoid oxidation or other unwanted effects. Overall, powder metallurgy is a promising method for manufacturing self-lubricating Al-Si alloys with nanoparticles. With further research and optimization, it has the potential to be an effective and cost-efficient method for producing these materials at an industrial scale [5].

Powder technology has been a known manufacturing method for the last century. Still, it was at a specific level and for particular alloys, as is known with brass bearings (copper-zinc). The method of powder metallurgy has become used to reduce costs for different metals and to resist bacteria in the medical industries, such as adding copper to titanium, as in the research of Youssef Al-Shammari et al. [6,7].

The same approach was used to enhance the corrosion and fatigue properties and to increase thermal and electrical conductivity of Aluminum by adding Copper to it, as in the research of K.N. Manjunath, and G.B. Krishnappa [8]. It was found in the research of Chintada et al. [9] that the powder technology method is better in damping frequencies and their absorption from the manufactured part rather than traditional Aluminum casting.

Powder technology is the best method to prepare metal matrix nanocomposites (MMNCs), with the lowest losses and the best specifications and homogeneity between the different sizes of nano and microparticles. This method is better than casting with several advantages, including the defects of isolation and cluster aggregation, which are harmful to the microstructure and thus negatively affect the mechanical properties. The goal is to manufacture self-lubricating mechanical parts, such as bearings or rotating columns that can withstand the weather conditions surrounding the moving part and thus resist mechanical corrosion [10].

The interest in self-lubricating materials, because of their great potential in friction reduction and wear protection of moving parts, has been significantly evoked in recent times. Members of the class of Al-Si alloys are widely used in automobile engines due to their excellent mechanical properties, but inherently, they are not self-lubricating. With the addition of nanoparticles to Al-Si alloy, improved self-lubricating properties of such materials have been attained [11].

One of the most promising types of nanoparticles for improving the self-lubricating properties of Al-Si alloys is graphene. Graphene has a high surface area, excellent mechanical properties, and good lubrication properties. When added to Al-Si alloys, it can form a thin, self-lubricating layer on the surface of the alloy, reducing friction and wear [12].

Another nanoparticle that has been researched to enhance the self-lubricating properties of the Al-Si alloys is CNTs. Many outstanding mechanical properties are exhibited by CNTs, including high strength and stiffness; the cylindrical geometry of CNTs offers an opportunity for them to serve as rolling elements in a lubricant matrix. When added to Al-Si alloys, CNTs can enhance the wear resistance and reduce friction, prolonging component life and improving performance [13].

In addition to graphene and CNTs, other types of nanoparticles, such as Al2O3 with graphene (as hybrid addition) have also been studied for their potential to improve the self-lubricating and wear properties of Al-Si alloys [14]. Various studies on aluminum-silicon alloys have explored the use of these nanoparticles.

Muna K.A. and Mohammad J.F. [15,16] studied the wear behavior of aluminium-silicon alloy matrix nanocomposites fabricated by powder metallurgy.

Addition of TiO2 and Al2O3 nanoparticles improved the hardness and enhanced the wear resistance of the alloy under dry sliding condition.
Nanoparticles, including boron nitride (BN) and molybdenum disulfide($MoS_2$) have been studied for their potential to improve the self-lubricating properties of Al-Si alloys. Hexagonal-Boron Nitride (h-BN) has several properties as a solid lubricant, and has a relatively low density, good thermal conductivity, high-temperature stability, and is also chemically stable. BN is known as white graphite because it has a hexagonal structure similar to Graphite, and a crystalline structure that has high lubricating properties, and making it superior to Graphite.

Molybdenum disulfide is a solid lubricant that can form a low-friction coating on the surface of the alloy, reducing friction and wear. Boron nitride is another solid lubricant that can improve the self-lubricating properties of Al-Si alloys by forming a thin, low-friction layer on the surface of the alloy [17].

Although many studies [18] in 2022 showed the capabilities of nanoparticles in enhancing the self-lubricating properties of Al-Si alloys, many challenges arise when using this material. For instance, attaining a homogenous dispersion of nanoparticles within the alloy matrix may be challenging, and compatibility with the alloy matrix must be taken into consideration. The production cost of such alloys with nanoparticles is higher compared to traditional alloys.

Zhang R., Wang H., and Zhang Y. [19] published a review paper of self-lubricating aluminium alloys reinforced by nanoparticles.. They found that the addition of molybdenum disulfide nanoparticles to an aluminum-silicon alloy improved the lubrication properties of the alloy and reduced wear rate.

The aim of this work is to study at the first: the effect of mixing molybdenum disulfide ($MoS_2$) and Boron nitride (BN) in nanometer scale with various content 2, 4, and 6wt% on the self – lubricating properties and wear behaviour of the Al-12wt%Si base alloy and hybrid nanocomposites which are fabricated by powder metallurgy (PM) technique. Boron Nitride (BN) is an abrasive material, has a long service life and observable wear resistance. The Molybdenum disulfide (MoS2) could be a 2-dimensional semiconductor matter; it is anti-wear properties, reinforces cohesion, and reduces abrasion.

The second aim is to study the wear behavior of the produced base alloy(Al-12wt%Si) and nanocomposites under dry sliding conditions. Also study the topography of worn surfaces of nanocomposites by using SEM is investigated.

## 2. EXPERIMENTAL WORK

### 2.1 Materials

In this study, the materials used are powders of different particle sizes, where the Al and Si are in micro size from Nanografi Technology, while the MoS2 and BN are in nanoparticle sizes. Table 1 shows the some characteristics of elements and compounds powders with approximate particle size and purity measurements.

**Table 1.** The characteristics of elements and compounds powders.

| Powder | Purity % | Approximate Particle size | Density gm/cm$^3$ |
|---|---|---|---|
| Aluimnum(Al) | 99.99 | 44 μm | 2.71 |
| Silicon (Si) | 99.99 | 44 μm | 2.33 |
| Boron nitride (BN) | 99.80 | 30 nm | 2.1 |
| Molybdenum disulfide ($MoS_2$) | 99.90 | 50 nm | 5.06 gm/ml at 25 ∘ C |

In this study, the metal matrix nanocomposites (MMNCs) made of nanoparticles MoS2 with BN as reinforcing phase in Al-12wt% Si alloy as matrix which have proven to raise the resistance to wear or friction and increase the hardness caused by the homogeneity in the process of mixing materials with standard micro type and nano that are less than 100 nanometers. The powder metallurgy(PM) method has become more efficient than typical casting.

In previous research by Mohammad Jabbar [20] he demonstrated an increase in wear resistance and mechanical friction with Al-Si composites, with improvement by combining Aluminum oxide ($Al_2O_3$) with Titanium oxide (TiO2). The same methods of preparation that we conducted in the current research, the mechanical mixing of the different powders, was done utilizing Zirconia balls by preparing Al-Si powder at a rate of 12% Silicon added to 88% of Aluminum does place in a plastic jar. The mixing ratio by adding the balls is 20 to one. After preparing the base alloy, nano particles, namely $MoS_2$ and BN, were added. The first mixture was made at 2wt% as a hybrid addition to the main powder, i.e., we mixed Al-12wt% Si with 1wt% $MoS_2$ + 1wt% BN. We prepared the second mixture of 4wt% by adding nanoparticles to the primary and last alloy by adding ratios of 3 + 3 of each type of nanoparticle to the original powder.

After the mixing process, it was pressed into a steel mold with a pressure of 7 tons, and the diameter of the mold was 10 mm. We got the green samples, and after that, we sinter them in an electric tube furnace type Nevola. The sintering process was carried out at temperature of 550 $^0$C and stabilized for 90 min, which is in a vacuum atmosphere, in addition to covering them with Argon gas to prevent the entry of air pollutants and oxygen at high temperatures and interaction with the produced alloy. This process lasts more than three hours, and they continue to pump Argon gas to protect the process, as shown in the diagram in figure (1).

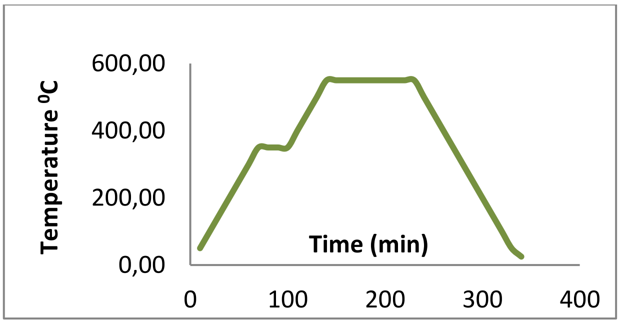



**Fig. 1.** Schematic of the relationship between time and temperature for the sintering process.

### 2.2. Tests and inspections

After conducting the primary mixing of the base alloy of Al to Si and the secondary mixing by adding nanoparticles, the mixed powder was inspected by XRD instrument type Rigaku Smart Lab X-Ray Diffractometer. Also it was examined by SEM Jeol JSM-7001F SEM which is equipped with EDS model OXFORID instrument. After the sintering process, the micro-hardness test was carried out using the Vickers equipment. Measurements of density and porosities inside the product manufactured by powder technology, were carried out by application of Archimedes' theory. Ethanol was used as a liquid for weight inside and in the air. In the wear or abrasion test, a device Type Abrasion Check Tester gibitre in compliance with ISO 4649 (ASTM D5963 Standard) was used to test the abrasive of plastic parts, but the surface used is the rough emery paper of silicon carbide with grit #60 (254 MICRONS), and this gives us a speed in consuming the sample and reduces the time in the examination, as shown in figure (2).

The wear rate of the samples was determined and measured gravimetrically. The samples were weighted before and after the abrasion wear test using a sensitive balance with an accuracy of 0.0001 g. Weight loss (ΔW) is divided by the sliding distance and the wear rate is determined using the formula (1) [21].

$$Wear\ rate\ (W.R) = \Delta W/\ \pi x D x N x t \qquad (1)$$

where: $D$ is the sliding circle diameter (cm), $t$ is the sliding time (min), $N$ is the drum or disc speed (rpm).


**Fig. 2.** (a) Abrasion Check tester gibitre instrutment, (b) The device used in the wear and abrasion tests Showing sample -counter (abrasive emery paper with #60 grit size) (254 microns).

In wear test, 3 samples were tested for each category and average values are taken and included. Figure 3 shows photographic macroscopic images of all samples used in this study.

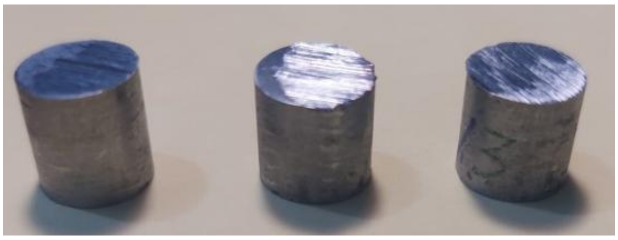


**Fig. 3.** Photographic image for 3 samples for each category that is used in the wear test.

For each sample examined, we collected the powder resulting from the friction process and then take part of this powder for examination in SEM-EDS for elemental analysis. We conducted the SEM examination of the surfaces produced after friction, and from the images of the effects of friction, we determined the type of friction produced.

## 3. RESULTS AND DISCUSSION

### 3.1 Characterization of nano composites specimens

The manufacturing of self-lubricating aluminum-silicon alloys with nanoparticles can present several challenges, including:

1. Dispersion of nanoparticles: One of the primary challenges in manufacturing self-lubricating Al-Si alloys with nanoparticles is achieving a uniform dispersion of the nanoparticles throughout the alloy. The nanoparticles must be uniformly distributed to ensure that the self-lubricating layer is formed evenly on the surface of the alloy. Achieving a uniform distribution can be challenging due to the tendency of nanoparticles to agglomerate.
2. Compatibility of nanoparticles: Another challenge is ensuring the compatibility of the nanoparticles with the aluminum-silicon alloy matrix. Some nanoparticles may react with the alloy matrix, leading to changes in the alloy's mechanical properties or reduced adhesion of the self-lubricating layer.

### 3.1. Microstructure

An optical microscope was used to examine the microstructure of the sintered sample at magnification 100x, as shown in the picture in Figure 4. It is observed uniform distribution with different sizes of the Si particles (grey color) in Al-matrix (white color) with fine eutectic phase (Al+Si). These results are similar to many researchers [22,23 ].

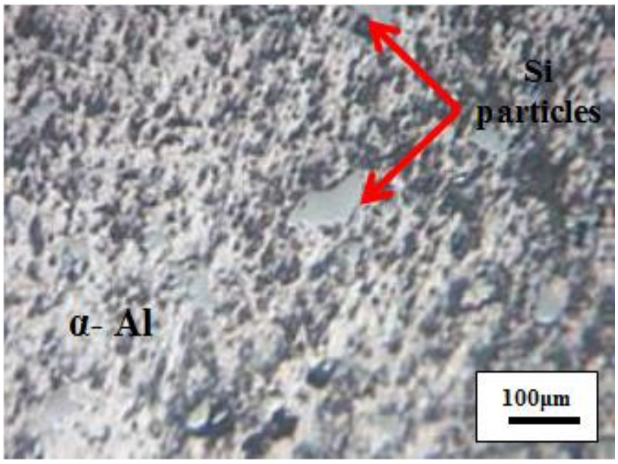



**Fig. 4.** Microstructure of sintered alloy(Al-12%Si).

### 3.2. XRD Results

The X-ray diffraction (XRD) examination showed the highest peaks for Al, followed by Si for the mixture prepared from the powders of the two metals, proving the efficiency of the mechanical mixing used. The vertical axis represents the intensity and the horizontal axis represents 2Θ. Figure (5) shows XRD analysis of the base alloy Al-12%Si. It becomes evident that distinct phases of pure aluminium are present at specific 2θ angles. These angles are measured at 38.50, 44.74, and 65.13 degrees. The presence of these phases indicates the crystalline structure of pure Al and Si within the sample.

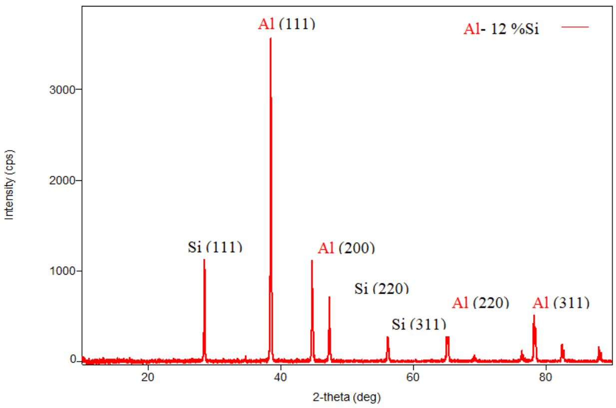
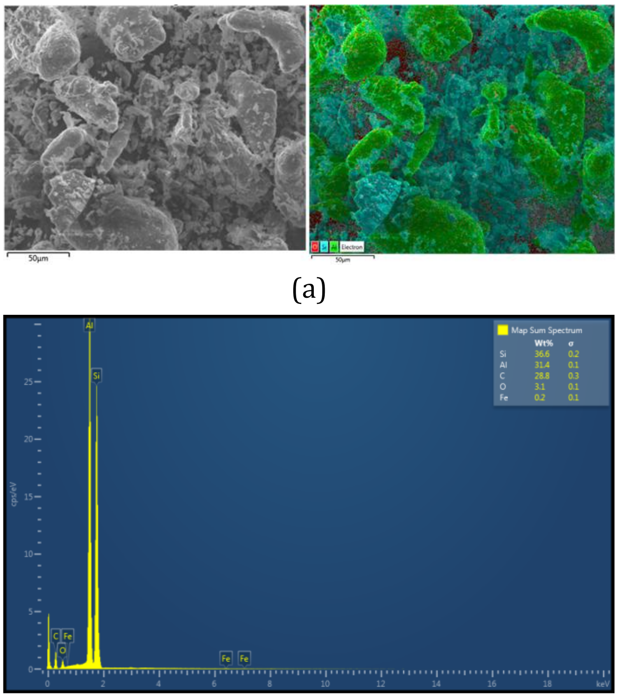



**Fig. 5.** XRD analysis of the base alloy (Al-12% Si).

### 3.3. SEM-EDS results

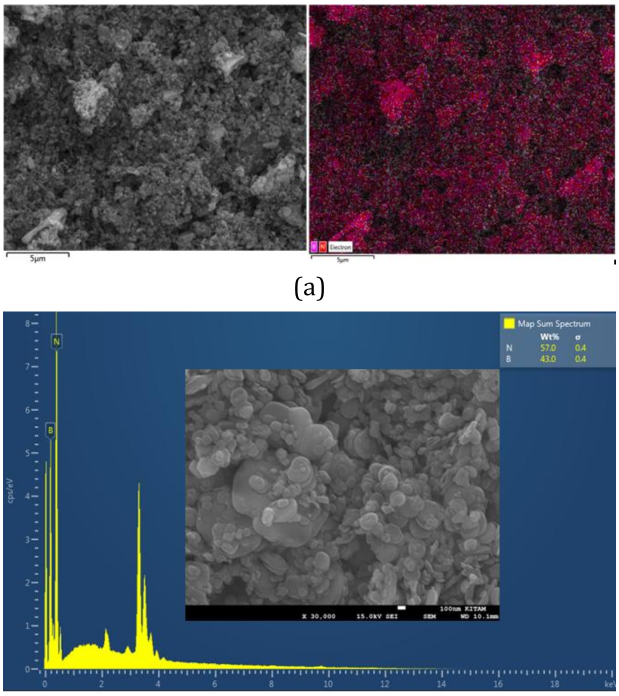
EDS showed us the results of the analysis of various elements of powders; most of them with peaks, as expected, are Al and then Si because it is an essential alloy with mixing ratios that almost obscure the rest of the elements, as shown in figure (6). From the first image which is taken with an SEM microscope at a scale of 50 µm, the grain size of Al appears clearly and Si powder distributed homogeneously with Al powder, as well as the following images of Si overlay, forming Al-12wt % Si powder. Elemental analysis shows the clarity of the higher peaks of the Al and Si elements after preparing the basic alloy by mixing balls.


(a)

(b)

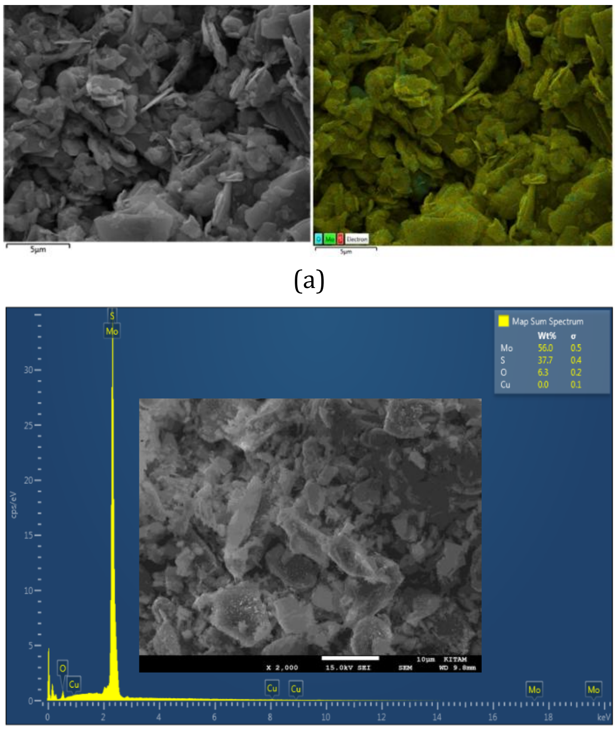
**Fig. 6.** SEM- EDS analysis for Al-Si powders showing SEM picture of Al-12%Si at 50 µm (a) and EDS of elemental analysis (b).

However, when adding nanoscale particles, the peaks do not appear clearly, but with a slight difference from the previous diagram without adding because the X-rays do not feel sensitive to the small proportions and sizes of the nanoscale. SEM confirmed powders of BN and $MoS_2$ as particle size at the nano level. Elemental analysis by spectroscopy showed the highest peaks of Mo, B, N, and S clearly, as shown in figure (7). Where B and N appeared as a result of the analysis of Boron nitride powder by analysis by EDS, the following figures showed the highest peaks and ratios of the elements. Figure (8) shows the SEM-EDX of $MoS_2$ nanoparticles.


(a)

(b)

**Fig. 7.** SEM-EDS analysis for BN powder at 5µm (a) and EDS of elemental analysis (b) with BN nanoparticles at 100nm.


(a)

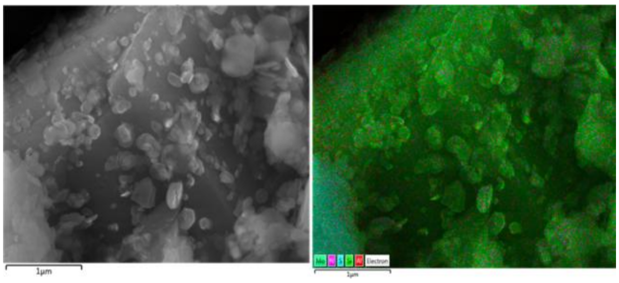
(b)

**Fig. 8.** SEM-EDS analysis for $MoS_2$ powder at 5µm (a) and EDS of elemental analysis (b) with $MoS_2$ nanoparticles at 100nm.

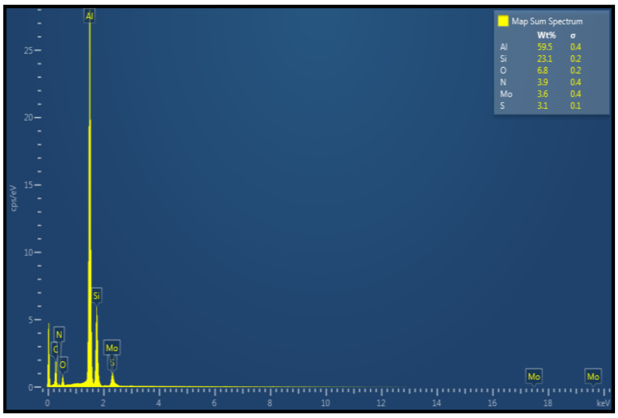
As for the $MoS_2$ analysis, it showed the presence of the highest percentage of

Molybdenum Mo, and then Sulfur S, which appeared on the highest peaks. In this examination, we noticed the presence of some oxygen, and it may be due to interaction with the atmosphere.

Figure (9) shows with this part of the powder the highest percentage of Boron element, followed by Silicon Si, and then Nitrogen N, but the most obvious peaks are for silicon and aluminum because they are the base alloy. From the analysis of the image obtained from the scanning electron microscope and using the spectral electron analysis feature of the elements in the Al-12%Si mixture (2% BN + 2% $MoS_2$), it showed the presence of aluminum Al, Silicon Si, Sulfur (S), Nitrogen( N), and Molybdenum( Mo).



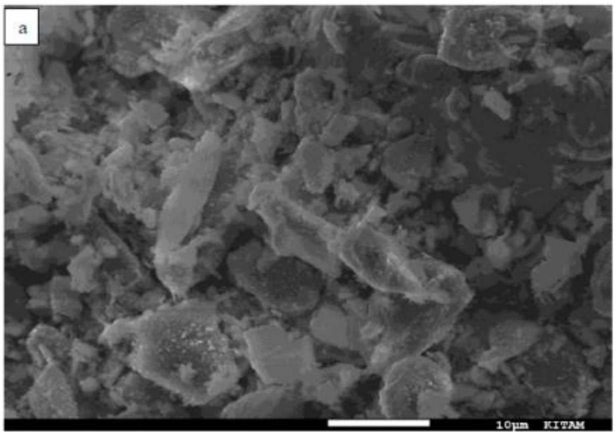
(a)



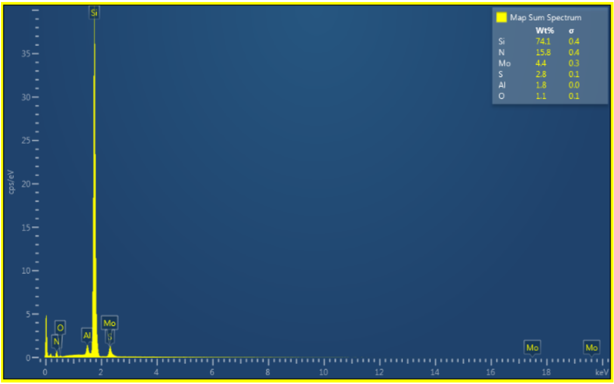

(b)

**Fig. 9.** SEM-EDS analysis for Al-12%Si (2% BN + 2% $MoS_2$) powder at 1 µm (a) and EDS of elemental analysis (b).

Figure (10) shows a part of the powder after mixing for Al-12%Si mixture (3%BN + 3% $MoS_2$), in which a high percentage of Si is indicated at the top, and then comes the rest of the elements, respectively, N, M, O, S, and Al, and part of the O that may be the result of interaction with air in the atmosphere.

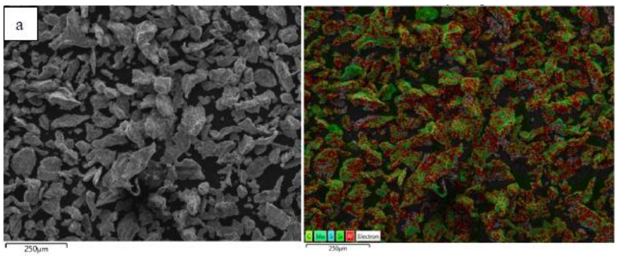



(a)

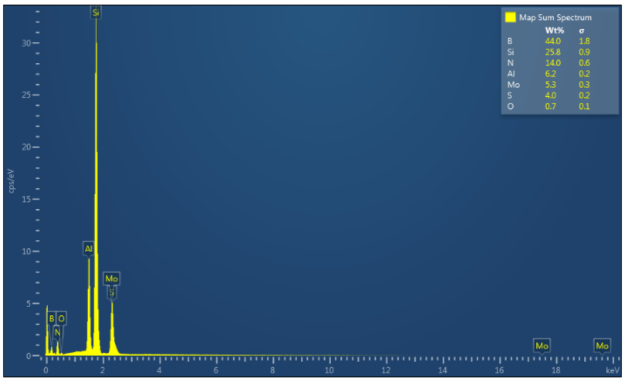



(b)

**Fig. 10.** SEM-EDS analysis of Al-12%Si (3% BN +3% MoS2) powder at 10 µm (a) and EDS of elemental analysis (b).



(a)




(b)

**Fig. 11.** SEM-EDS analysis of Al-12%Si (1% BN +1% MoS2) powder at 250 µm (a) and EDS of elemental analysis (b).

Figure (11) Represents the examined part of the mixed powder for Al-12%Si mixture (1%BN + 1% $MoS_2$). It had a high percentage of B, and then the percentage of Si came after it, and the percentages of other elements, namely N, Mo, S, and Al, followed.

### 3.4. Density and porosity measurement results

Density and porosity measurement results of (Al-12 wt % Si) and nanocomposites (MMNCs) samples sintered at 550 ∘ C for 180 min are presented in Table 2. It shows that when $MoS_2$+ BN hybrid nanoparticles are added to the base Aluminum-Silicon composite, the porosity ratio decreases, i.e., the gaps inside the new structure, and the density increases in an increased inverse and direct relationship with the increase of the added nanoparticles. Table 2 shows the density and porosity results.

**Table 2.** Density and porosity calculation for Al-12%Si alloy nanocomposites.

| No. | Sample | Reinforcement Content wt% | Density gm/cm³ | Porosity % |
|---|---|---|---|---|
| 1 | Al-12wt%Si (base alloy) | 0 | 2.580 | 0.1260 |
| 2 | Base+ 2% ($MoS_2$+BN) | 2wt% ($MoS_2$+BN) | 2.601 | 0.0988 |
| 3 | Base+ 4% ($MoS_2$+BN) | 4wt% ($MoS_2$+BN) | 2.648 | 0.0975 |
| 4 | Base+ 6% ($MoS_2$+BN) | 6wt% ($MoS_2$+BN) | 2.781 | 0.0865 |

### 3.5. Hardness results

All alloys with one or two types of nanoparticles added to them are called MMNCs. As for the base alloy of Al and Si, it can be called either metal matrix composite (MMC) or Al matrix composite (AMC). After the hardness test, the results were high for alloys with nanoparticles added, especially in the form (hybrid) $MoS_2$ + BN. The following Table (3) shows the resulting hardness values for all samples prepared after sintering them.

**Table 3.** Hardness results for base alloy and Nano composites samples.

| Sample no. | Sample | HV (Kg/mm²) |
|---|---|---|
| **1** | Base alloy (Al-12wt%Si) | 87 |
| **2** | Base+2wt% (MoS2+BN) | 112 |
| **3** | Base+4wt% (MoS2+BN) | 124 |
| **4** | Base+6wt% (MoS2+BN) | 134 |

As shown in Table 3 and Figure 12 the (MMNCs) samples have significantly higher hardness than that of base alloy (Al-12wt%Si). Also, the hardness of hybrid (MMNCs) increases with increasing the percentage of both nanopowders ($MoS_2$+ BN) in Al-matrix. This is due to effect of nanoparticles which act as filling agent to microporosty that produced from compaction and sintering processes, and then lead to increase the density and hardness. Also the porosity decreases with increasing hybrid addition of (BN+$Mo_2S$) nanoparticles to Al-12%Si alloy.

These results are in agreement with researchers Muna et al. [16,24,25], they fabricated metal matrix nanocomposites reinforced with Nano$Al_2O_3$, Nano $TiO_2$ and Nano $SiO_2$ ) by powder metallurgy route.

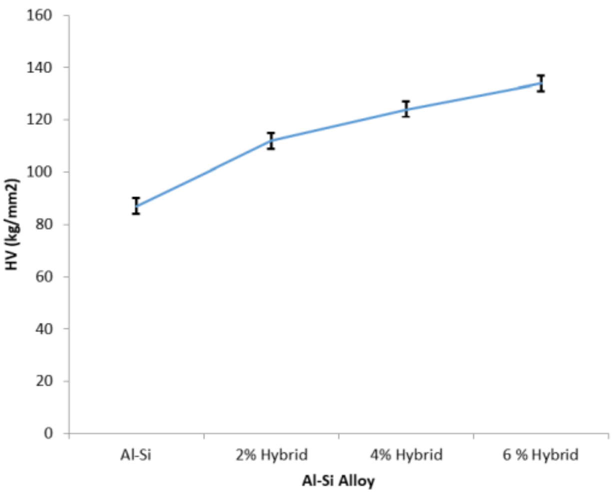
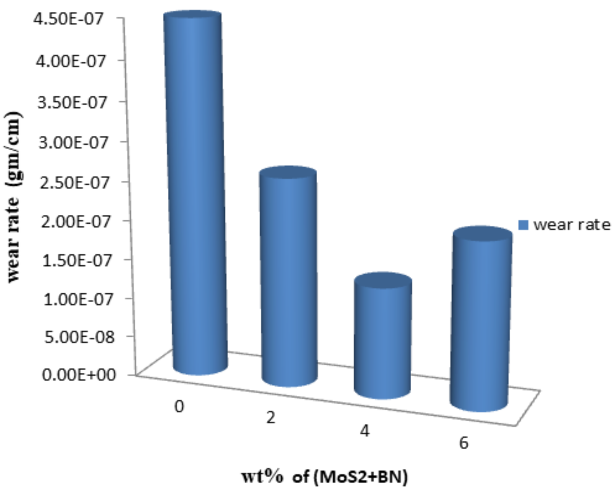


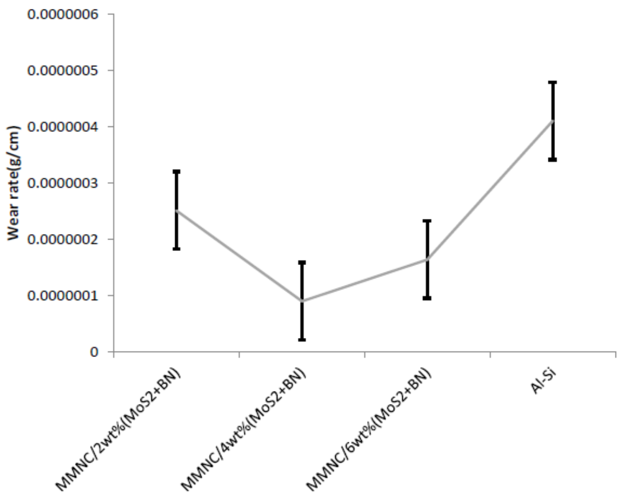

**Fig. 12.** Effect of wt. % ($MoS_2$+ BN) nano powders hybrid addition on the hardness.

### 3.6. Wear results

The results of the wear test type (pin-on-disc) test showed an improvement in the wear resistance after adding the nano-particles or elements. It was observed accurately from the co-addition of 2wt % and 4 wt%, and its decrease again when adding 6wt %. The increase in wear resistance or frictional resistance is caused by the effect of self-lubrication of the added ($MoS_2$+ BN) nano powders or nano-elements and its effect in general on improving the product, but increasing it in the composite led to an excessive increase in its fragility and fracture. Weight loss is at a combined ratio of 2wt%, and the best is at a combined ratio of 4wt %, which leads to the effect distinguished by self-lubrication, but at a combined ratio of 6 wt%, it had the opposite effect and a significant loss of weight during the examination. Therefore, we do not recommend this percentage when increasing. The effect of adding hybrid nanoparticles of ($MoS_2$+ BN) to the base alloy is shown in Figure (13 a&b) on the wear rate of MMNCs samples at a specific load (2.5 N) and a test time of (15 min).




(a)




(b)

**Fig. 13** (a, b) Effect of the weight ratios of the added hybrid nanoparticles and their effect on the wear rate at a load (2.5 N) and a test time of (15 min).

The effect of the hybrid addition of nanoparticles ($MoS_2$+ BN) to Al-12%Si alloy is evident by reducing the wear rate and weight loss, which means that the nanoparticles act as self-lubricating agent and improve the microstructure of the manufactured nanocomposite. But 6wt% hybrid addition of nanoparticles it was seen that wear rate and weight loss are higher than that with 4wt% hybrid addition of ($MoS_2$+BN). This may be due to increasing of agglomeration of BN nanoparticles and microporosity in alloy which is caused the increscent in the brittleness in the whole structure.

As for the only percentages added at a rate of 4wt%, it was better than the alloy without adding it, but if we compared with it, it was find that the BN has the advantage of high hardness, but in terms of mechanical wear resistance, the best was $MoS_2$ because it is a stable compound in the long run, as shown in Figure (14).

From the above figure,it was seen that the wear rate of all tested specimens increases with an increase in sliding time at fixed applied load (2.5N), and speed under dry sliding conditions. The wear rate of the base alloy (Al-12%Si alloy) was higher than that of the nanocomposites at all period times (10-40) min. These results are in agreement with Muna et al. [26,27].

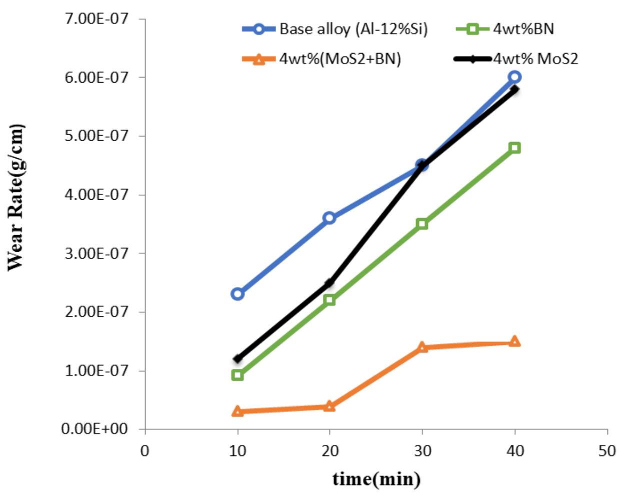



**Fig. 14.** The relationship between test time and wear rate at fixed load (2.5N).

## 3.7. Study of worn surfaces by optical microscope

The worn surfaces studied by optical microscope for all samples No.1,2,3,&4 of base alloy and three hybrid nanocomposites respectively after wear test at fixed load (2.5N) and test time (15min) as shown in Figures [15,16] as summarized in Table 3.


**Fig. 15.** Macrographs of worn surfaces for samples (1,2,3,&4) as summarized in Table 3.

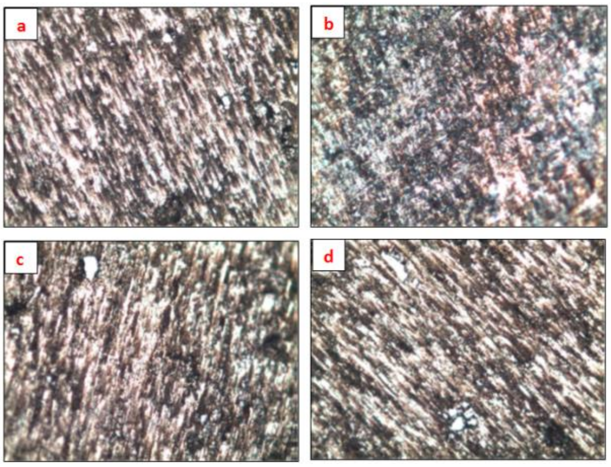
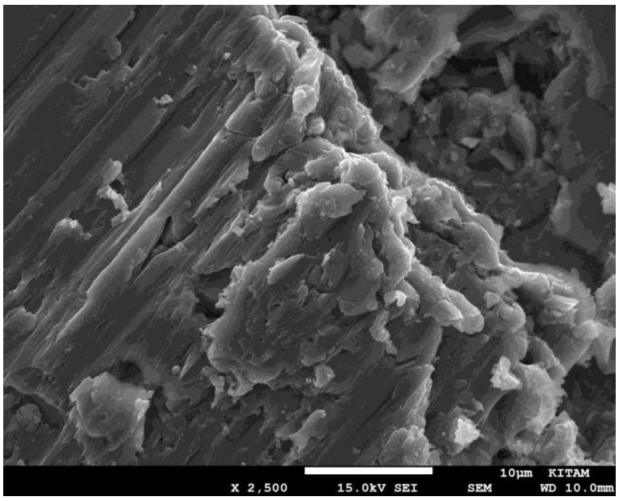



**Fig. 16.** (a, b, c & d) Microstructure of the worn surfaces for samples (1,2,3,&4) respectively after wear test at fixed load (2.5N) and test time (15min) at 100μm.

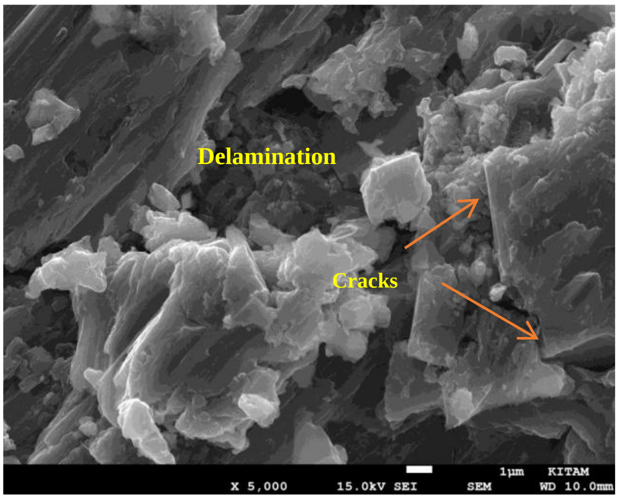
### 3.8. Study of worn surfaces by SEM

The type of wear was studied by SEM,the imaging of surfaces after the wear procedure to identify the resulting topography and analyse the type of fracture that indicates the nature of the friction occurring and what is the effect of the additives or the manufacturing method, the method of examination. Different mechanisms of wear may be produced by one sample, including adhesive or abrasive type, which may differ according to the composition if it is brittle or ductile. SEM images show the effects of the powder resulting from friction, as different sizes break them from one element or compound, and they are sometimes in the form of lumps or single particles.

Figure 17(a&b) shows the type of wear of the base alloy of Al-12wt%Si without additives, where plastic deformation and adhesion between the particles result from friction with the opposite surface of the sample. The fragments break into an elongated shape and form large lumps, which leads to a high weight loss of the sample during the wear test. Also the worn surface shows plastic deformation and grooves parallel to the sliding direction as in Figure (17a). This due to ploughing and cutting actions at the wear surface. Figure (17b ) is shown the SEM micrograph of the worn surface and debris, which reveals some features of the delamination mechanism and cracks. These results are in coincidence of researchers [28-30].




(a)



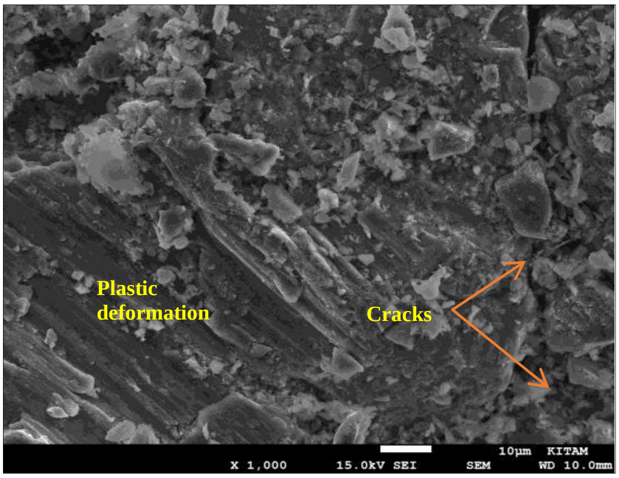

(b)

**Fig. 17.** (a, b). SEM image of the worn surfaces of the base alloy after the wear test and friction process through applying a force of 2.5 N; (a) at 10 µm, (b) at 1 µm.

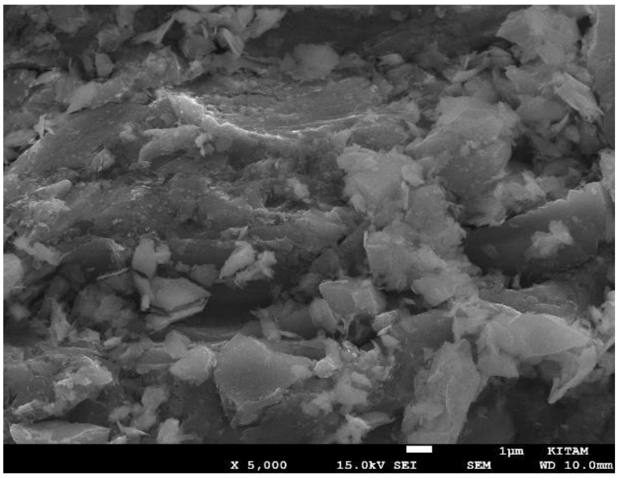
Figure 18 (a & b) shows the SEM after wear test for the second alloy containing 4 % equal to 2 % $MoS_2$ with 2 % BN. With a maximum magnification of 5kX times, it was found that the fineness in the remaining grains on the surface of the sample that was subjected to the wear test, and this is a clear difference and an improvement in structure from the addition before it.

As we mentioned earlier from, the mixing images of this alloy showed smoothness and homogeneity between the different powders, and the latter led to positive results in terms of improving the wear results. Also the wear mechanism was type of fracture or cracking with deformation resulting from friction between the specimen and abrasive paper.

From figure (18a), fine cracks may appear on the deformed surface, but some grains stop the crack from continuing, or the failure of the specimen develops. Through the examination of wear test, it was found that there is an overlap of two types of wear on the surface between some brittleness and ductile bonding, which stops the effect of friction and makes a protective layer on the surface (see figure 18b). So the self-lubricating effect of a hybrid addition with the highest possible effect is the addition of a nano-hybrid by 4wt%, and the strengthening function of the nanocomposite is added to it acceptably. These results are in agreement with researchers [31,32].




(a)




(b)

**Fig. 18.** (a, b) SEM image of the worn surface after wear test of the 4 wt. % (MoS2+BN) hybrid nanocomposite at two magnifications; (a) at 10 µm, (b) at 1 µm.

## 3. CONCLUSION

Mixing Al-12%Si powder with hybrid addition ($MoS_2$ + BN ) nanoparticles can result in a nanocomposite with self-lubricating properties, depending on the material proportions and the resulting microstructure of the mixture. $MoS_2$ and BN are known for their low friction and wear properties, and their incorporation into an Al-12%Si matrix can enhance these properties, the hardness and wear resistance increased with increasing the nanoparticles content in the aluminum-silicon alloy. The self-lubricating property was improved depending on the results of wear resistance of the alloy manufactured by powder technology, to which joint hybrid nanoparticles were added to the base alloy of Al-Si.

The best results appeared with a combined or hybrid addition of 4wt%, as it had a longer life compared to the lower or higher percentage of additives. The effect of the hybrid addition of ($MoS_2$+BN) is evident by reducing the wear rate and friction, which means that the nanoparticles act as self-lubricating and improve the microstructure of the Al-Si matrix and manufactured hybrid nanocomposite at applied loads 2.5 N. But 6% addition of hybrid reinforcements($MoS_2$+BN) provide higher wear rate than that of 4%, this is due to an increasing in weight loss in the alloy with 6 wt. % of hybrid addition of nanoparticles, and it may be because of the increased agglomeration of nanoparticles as hybrid addition increased which lead to the brittleness in the whole structure.

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