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EXPERIMENTAL INVESTIGATION AND CHARACTERIZATION OF ALUMINIUM ALLOY (AA6063) – SILICON NITRIDE (Si_3N_4) COMPOSITE

EKSPERIMENTALNA RAZISKAVA IN KARAKTERIZACIJA KOMPOZITA NA OSNOVI MATRICE IZ Al ZLITINE (AA6063) IN OJAČITVE S SILICIJEVIM NITRIDOM (Si_3N_4)

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To obtain a homogeneous material, the aluminum (AA6063)-Si_3N_4 composite was processed for microstructural characterization using the powder metallurgy technique. Powder particles were cold welded and fractured repeatedly in a high-intensity ball mill. In this work, aluminum alloy (AA6063) matrix composites of various weight percentages of silicon nitride (Si_3N_4) were produced using mechanical alloying. Among the synthetic compositions were composites of: aluminum alloy (AA6063) with 0 weight percent Si_3N_4, aluminum alloy (AA6063) with 4 weight percent Si_3N_4, aluminum alloy (AA6063) with 8 weight percent Si_3N_4 and aluminum alloy (AA6063) with 12 weight percent Si_3N_4. By looking at the milled composite powders, the properties of the aluminum alloy (AA6063), Si_3N_4 composite were investigated with an SEM. The SEM analysis confirmed the homogenous distribution of Si_3N_4 in the AA6063 matrix and no pores. The introduction of Si3N4 into the AA6063 matrix led to the enhanced mechanical properties and low porosity in the composites.

Keywords: aluminium, silicon nitride, powder metallurgy

V članku avtorji opisujejo izdelavo homogenega kovinskega kompozita na osnovi matrice iz aluminijeve zlitine tipa AA6063 in silicijevega nitrida (Si_3N_4) s postopkom metalurgije prahov. Med visokoenergijskim mletjem so se v krogličnem mlinu delci prahu ponavljajoče hladno varili in lomili. Tako so avtorji s tako imenovanim postopkom mehanskega legiranja izdelali različne kompozite z Al matrico AA6063 in različnimi masnimi deleži Si_3N_4. Izdelali so kompozite s 4, 8 in z 12 mas. % Si_3N_4 in jih nato primerjali s čisto (brez dodatka Si_3N_4) Al zlitino AA6063. Sledila je karakterizacija mehansko legiranih kompozitov s pomočjo vrstične elektronske mikroskopije (SEM). Analiza SEM je potrdila homogeno neporozno porazdelitev Si_3N_4 v kovinski matrici AA6063. Vnos Si_3N_4 v matrico AA6063 je omogočil izdelavo kompozitov z izboljšanimi mehanskimi lastnostmi z majhno poroznostjo.

Ključne besede: aluminijeva zlitina vrste AA6063, silicijev nitrid, metalurgija prahov, mehansko legiranje

1 INTRODUCTION

Metal matrix composites (MMCs) have become advanced engineering materials thanks to their improved combination of mechanical, thermal and tribological characteristics. Among the various MMC systems, composites based on aluminium and reinforced with ceramic particulates like silicon nitride (Si_3N_4) have attracted huge interest. Aluminium-silicon nitride composites are designed to have superior wear resistance, greater hardness, and superior temperature stability over conventional monolithic alloys. These composite materials are intended to provide the best characteristics in terms of lightness of aluminium and strength and thermal stability of the ceramic reinforcements. The composites offer excellent dimensional stability, high wear resistance, enhanced load-bearing capacity and resistance to thermal fluctuations, thus making them suitable for demanding engineering applications. The idea of composite materials is that two or more different phases will be combined to create a material with properties better than those of the constituents. In MMCs, the metallic matrix, which is in most cases aluminium, represents the continuous phase, and the ceramic reinforcements such as Al_2O_3, SiC, TiC, TiB_2, Si_3N_4, and B4C are the dispersed phase.[1–6] These reinforcements are used to improve the hardness, stiffness and strength of the base alloy with a relatively low density. Aluminium is especially favoured as a matrix material because of its low weight, its good corrosion resistance, high thermal and electrical conductivity and good formability. The addition of ceramic reinforcements leads to a very substantial improvement in the mechanical performance of aluminium without a sig-

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nificant increase in its weight. The rising demand for fuel-efficient and environmentally sustainable transportation systems has also seen the interest in composites made out of aluminium increase. Lightweight materials are directly linked to lightweight vehicles and thus improved fuel economy and reduced nitrogen oxide (NOx) emissions. Consequently modern automotive design trends including carbon-credit initiatives and emission-control regulations have spurred research aimed at the development of advanced aluminium matrix composites (AMCs).[7–10] By replacing heavier steel components with aluminium composites, manufacturers can realise weight reductions, without affecting structural integrity or performance. Aluminium has a high ductility, is tough and has a moderate strength. However, its wear resistance and hardness are rather low for high load applications. In order to overcome these limitations, ceramic reinforcements like silicon nitride are used. Silicon nitride particles are effective strengthening agents because they are hard, thermally stable and chemically inert. They contribute to better load transfer between matrix and reinforcement and thus strengthened the tensile strength, yield strength and modulus of elasticity.[11-13] Furthermore, a uniform dispersion of reinforcement particles in the matrix is very important in determining the final composite properties. Proper particle distribution prevents an inconsistent mechanical behavior and eliminates the occurrence of localized stress concentration. Tribological performance is another important matter of aluminiu, Si_3N_4 composites. Under dry-sliding wear conditions, reinforced composites have much lower wear rates than unreinforced alloys. Studies show that the frictional behavior improves with increasing reinforcement content because of the formation of protective tribolayers and the reduction of the direct metal-metal contact.[14–16] At different loads and sliding speeds these composites show stable wear performance, so they are useful for brake rotors, pistons, cylinder liners and other automotive applications which are exposed to frictional forces. In MMC systems, the matrix material can be aluminium, copper, magnesium, titanium or alloys, according to the application requirements. Aluminium, however, is the most widely used matrix material due to its availability, recyclability and cost-effectiveness. Additionally, aluminium-matrix composites provide very good resistance to moisture, radiation and high temperatures. They also have good thermal and electrical conductivity with enhanced mechanical strength.[17] These attributes make AMCs suitable for aerospace structures, satellite components and high-performance automotive parts. Reinforcing materials are chosen according to their compatibility with the aluminium matrix, and their capacity to improve the general performance of the composite. Some common reinforcements are TiC, SiC, B4C, TiO_2, ZrO_2, BN and Si_3N_4.[18–20] Carbide reinforcements usually have superior wettability and bonding properties with molten aluminium when compared to nitrides. Wettability is an important factor affecting the interfacial bonding between the matrix and the reinforcement. Good wettability ensures good load transfer and reduces the tendency of interfacial debonding during the mechanical loading. Although the contact angle of silicon nitride particles with the molten aluminium is relatively higher than that of silicon carbide, the use of suitable processing techniques such as stir casting, powder metallurgy, surface treatments, etc. can enhance the interfacial bonding.[21] The aerospace, automotive, and defense industries use aluminium matrix composites extensively because they have a better strength-to-weight ratio. Reduced density adds to reduced structural mass, which improves fuel efficiency and payload-carrying capacity of aircraft and satellites. In addition, AMCs have good creep resistance, vibration-damping performance, corrosion resistance and thermal conductivity.[22] These properties are especially advantageous in high-temperature environments as well as cyclic loading conditions. Manufacturing techniques for aluminium- Si_3N_4 composite include stir casting, squeeze casting, powder metallurgy, and advanced additive manufacturing routes. Each method has an effect on the microstructure, particle distribution, porosity levels and overall mechanical performance.[23–25] Among these methods, powder metallurgy is more controllable in terms of particle dispersion and a lower porosity, which resulted in improved mechanical properties. Meanwhile, stir casting is still cost-effective and can be used in large-scale industrial production.

To sum up, aluminium, silicon-nitride metal-matrix composites are a major breakthrough in materials engineering. By combining lightweight aluminium and high-performance ceramic reinforcements, these composites have excellent mechanical strength, wear resistance, thermal stability and corrosion resistance. Their ability to decrease the weight of components with high structural performance is consistent with modern industrial requirements for sustainability and energy savings. Based on findings reported in journals, aluminium based MMCs have continued to feature in aerospace, automotive and structural applications because of their multifunctional performance and economic feasibility

2 EXPERIMENTAL PART

In order to prepare the aluminium, silicon-nitride (Si_3N_4) composites to ensure accurate composition, proper mixing effect and effective composite consolidation, a systematic powder metallurgy route was selected. The first step in the fabrication process was accurate weighing of the raw materials. Aluminium powder and silicon nitride powder were precisely measured with a calibrated electronic weighing balance according to the manufacturer's material proportions set out in **Table 1**. Accurate weighing is extremely important in the fabrication of composites because even minor variations in percentage composition of reinforcement can have a major impact on the microstructure and mechanical properties of the final product. The compositions used to prepare in this study were pure aluminium (0 *w*/% Si_3N_4), aluminium reinforced with 4 *w*/% Si_3N_4, 8 *w*/% Si_3N_4 and 12 *w*/% Si_3N_4. These different reinforcement levels were chosen to assess the effect of ceramic particles content on the structural and mechanical behaviour of the composite.

Once the powders are weighed to the required compositions, the process of blending was performed by a high-energy planetary ball milling machine. Ball milling is a very important process in powder metallurgy due to its ability to ensure homogeneous mixing, reduce particle size and increase the contact surface between the matrix and reinforcement materials. In this process the aluminium and silicon nitride powders were placed inside a cylindrical milling jar together with hardened milling balls. The milling operation was carried out under dry conditions to prevent any possible contamination or unwanted chemical reactions that could occur if the operation were performed in wet milling environments.

The milling time was 5 h, which was found to be sufficient to achieve homogeneous mixing without excessive cold welding and damage to the structure of the powders. The powder-to-ball ratio was kept at 1:3, i.e., for each unit mass of powder, 3 units of ball mass were used. This ratio allows for the transfer of impact energy to be effective in milling thus ensuring that mill particles

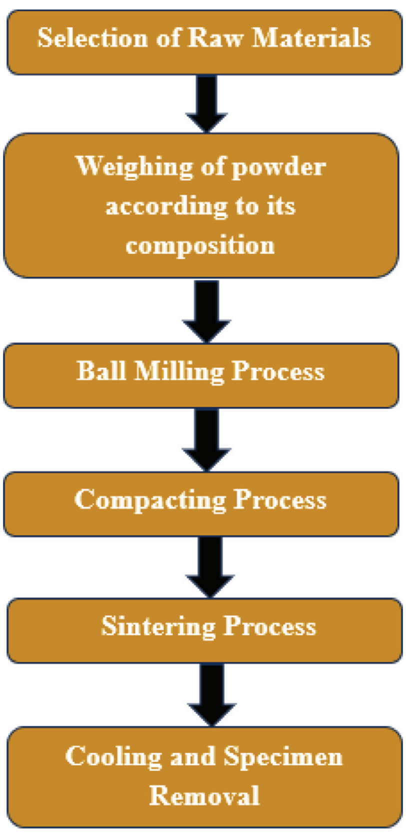

Figure 1: Representation of Powder Metallurgy Processing Composite

are efficiently refined and Si_3N_4 is dispersed throughout the aluminium matrix. Rotational speed of milling drum was fixed at 350 min^{-1}. This speed gave sufficient centrifugal force to high-energy collisions between the balls and powder particles as a result of mechanical alloying and intimate mixing of the powder and balls. to minimize wear and contamination during milling, the inner surface of the cylindrical milling chamber was coated with tungsten carbide. Tungsten carbide lining helps increase the durability and reduce the excessive abrasion of the chamber walls when they can mix any impurities into the powder mixture. The repeated fracturing and cold welding events that occur during the milling process helped contribute to the reduction in particle size and the improvement in homogeneity. As a result of this, silicon nitride particles were evenly distributed in the aluminium matrix powder resulting in a well-blended composite mixture.

After completion of the ball milling process, the mixed powder was subjected to compaction. The blended powder was carefully filled into a hardened steel die cavity. Compaction is a very important step in powder metallurgy as it converts loose powder into a coherent shape that is known as green compact. The die with the powder in it was put in a hydraulic press, and was pushed with large compressive pressure. In this study compaction pressures from 10 t/in^2 to 50 t/in^2 (from about 150 MPa to 700 MPa) were used. The application of high pressure makes the particles of powder rearrange with plastic deformation and establishes interparticle contact, thereby increasing the density of the compact. When high pressure was applied, the powder mixture took the desired shape of the die cavity. After the compaction, the formed green compact was carefully ejected from the compact die chamber. At this point, the compact had sufficient strength for handling but did not have a full metallurgical bonding. The green compact still had interconnected pores, and needed further processing to improve the mechanical integrity.

The next stage was sintering, which is a thermal treatment process that is carried out to strengthen the compacted material. The green compacts were put into an electric muffle furnace and sintered under a controlled argon atmosphere for three hours. The use of an inert argon environment is necessary so as to avoid oxidation of aluminium during exposure to high temperatures. Oxidation can hinder bonding and decrease mechanical performance, therefore keeping the atmosphere clean in terms of particles and effective diffusion is important. During the sintering process the temperature was increase-d to below the melting point of aluminium but was sufficiently high to allow diffusion of atoms between particles. Under these elevated temperatures strong metallurgical bonds formed between adjacent powder particles. The pores that were present in the green compact were also found to become smaller with diffusion and neck growing at the particle contact points. The long holding

Figure 2: Sintered Samples of AA6063 – Si_3N_4

time of three hours provided for adequate bonding and densification. After sintering, the furnace was allowed to cool down slowly and allowed to solidify the composite into a rigid and structurally stable component.

Through this controlled sequence of weighing, milling, compaction and sintering the aluminium-Si_3N_4 composites with varying reinforcement percentages were successfully fabricated. The optimized powder metallurgy route resulted in a uniform distribution of reinforcements, good interface bonding, and good mechanical properties of the final composite specimens.

Table 1: Composition of AA6063 – Si_3N_4

Sample	Aluminium %	Silicon nitride (Si_3N_4) %
1	100	0
2	96	4
3	92	8
4	88	12

3 RESULTS

3.1 Analysis using a scanning electron microscope

The microstructural features of the prepared aluminium, silicon-nitride (Si_3N_4) composites were analyzed by the scanning electron microscope (SEM) and the corresponding images are shown in **Figures 3** to **6**. These micrographs give detailed information on particle distribution, interfacial bonding and the general morphological characteristics of the composite at various reinforcement levels. The compositions analysed are unreinforced aluminium (0 *w*/% of Si_3N_4) and aluminium reinforced with 4 *w*/%, 8 *w*/% and 12 *w*/% Si_3N_4. By comparing these microstructures carefully, it is possible to understand the influence of reinforcement content on the bonding quality, particle dispersion and mechanical behavior. **Figures 3a** to **3c**) is the SEM images of the unreinforced aluminium matrix with 0 *w*/% Si_3N_4. In this condition, aluminum particles with compaction and sintering microstructure are predominant in the microstructure. The particles are apparently well fused, which is an indicator of good consolidation during processing. The boundaries between the aluminium particles are visible but have good metallurgical bonding. The lack of reinforcement is what makes it possible to have uniform plastic deformation during compaction, resulting in increased contact between the particles. As a result, the matrix structure has a relatively homogeneous structure, with little voids and a continuous metallic phase. The quality of bonding in case of unreinforced sample can be explained to the optimized ball milling parameters before compaction. A controlled ball-milling process ensures that the aluminium particles are well enough activated without excessive cold welding and particle fracture. In this study it was found that a duration of five hours of ball milling was effective in producing a fine and consistent mixture. Proper milling will provide a better particle contact area and help create a more uniform densification in sintering. Although there are no reinforcement

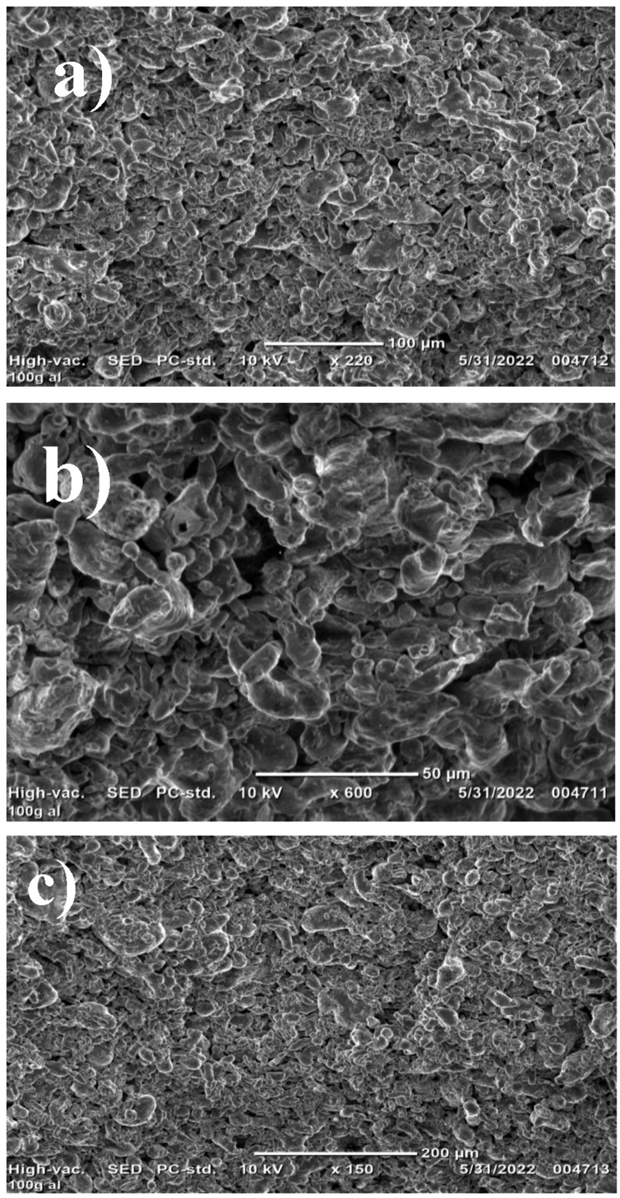

Figure 3: Sem images Aluminium + 0 *w*/% Silicon Nitride

particles present in this composition, the processing route provides a reference microstructure to compare with the samples that contain reinforcements.

Figure 4 shows the microstructure of aluminium as reinforced with 4 *w*/% Si_3N_4. At this reinforcement level, the silicon nitride particles are observed to be distributed in the aluminium matrix. The SEM images show a more or less homogeneous dispersion of ceramic particles, with very little clumping. The interface between the aluminium matrix and Si_3N_4 particles seems to be clean and well bonded. This means that the high-energy ball milling process managed to mix the ceramic and metallic powders. The mechanical interlocking and intimate contact that is obtained during the milling process better the interfacial adhesion during sintering.

The homogeneous dispersion of 4 *w*/% reinforcement has particular significance as it contributes to the excellent transfer of the load. When an external stress is used, the ceramic particles help in bearing a portion of the stress applied thus enhancing the strength and hardness of the composite. The lack of apparent agglomeration indicates that the reinforcement percentage is at an optimum level in which particle distribution can be well controlled. Furthermore, the microstructure does not show significant porosity or interfacial gaps which shows successful densification.

Figure 5 shows the microstructure of the composite with 8 *w*/% Si_3N_4 reinforcement. At this intermediate level, the reinforcement effect goes stronger. The number of ceramic particles embedded in the aluminium matrix is shown in the SEM images. The dispersion is relatively uniform, although the particle density is visibly increased relative to the dispersion of the 4 *w*/% sample. The interfacial bonding between aluminium and Si_3N_4 appears to remain strong suggesting that the ball milling

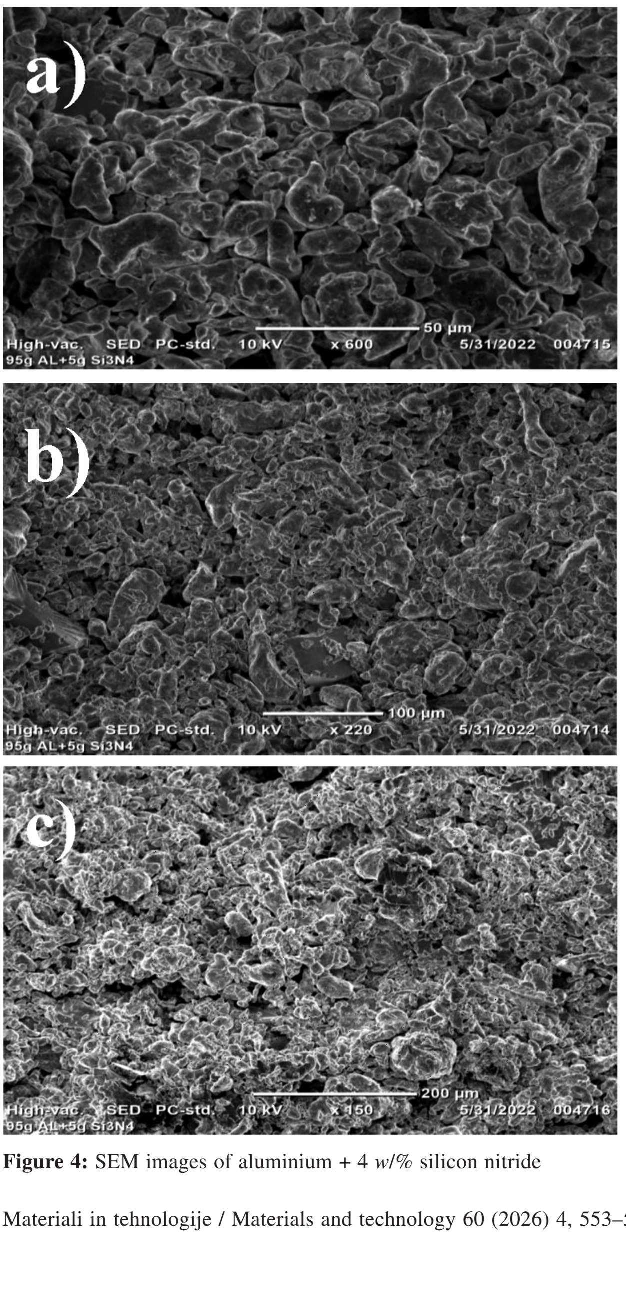

Figure 4: SEM images of aluminium + 4 *w*/% silicon nitride

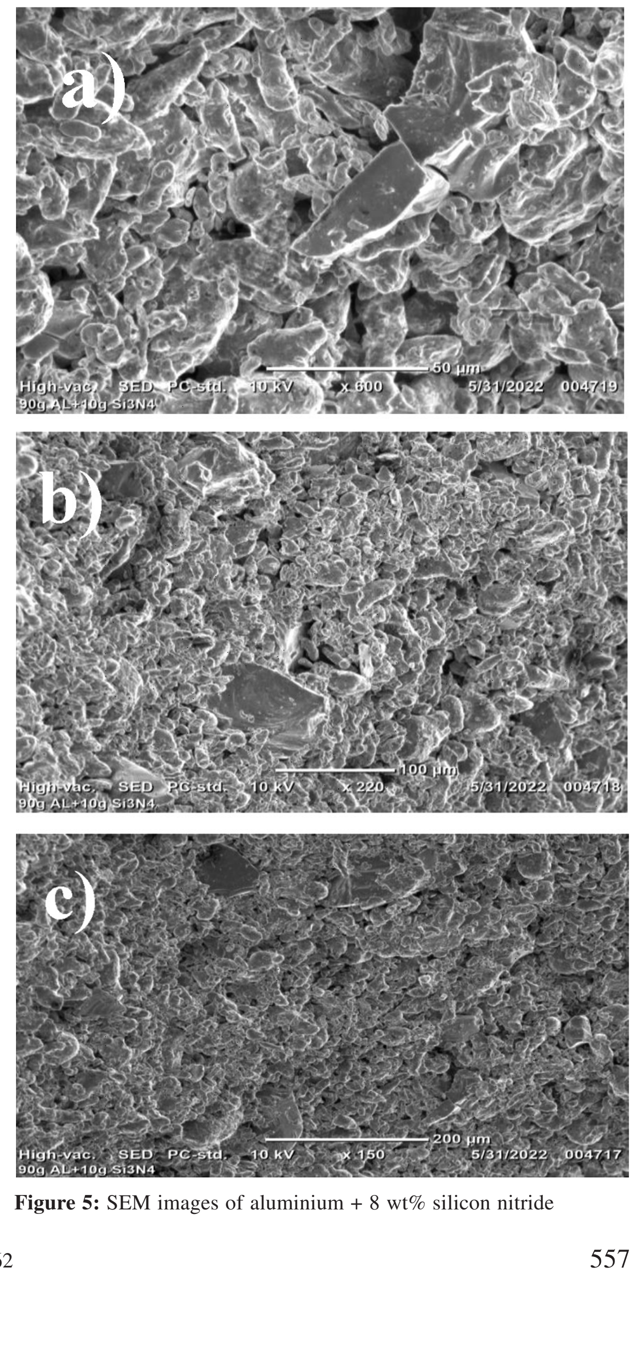

Figure 5: SEM images of aluminium + 8 wt% silicon nitride

and sintering parameters selected are sufficient for good compatibility between the two phases.

The presence of increased reinforcement results in improved strengthening mechanisms. Silicon nitride particles are barriers for dislocation motion and limit plastic deformation of the aluminium matrix. Consequently, composite strength coefficient increases with an increase in the content of the reinforcement (up to 8 *w*/%). The microstructure shows the good distribution of effective stress and no significant particle pull-out or debonding. The uniformity seen at this stage is due to the success of the powder metallurgy method of having obtained a homogeneous mixing.

However, if the addition of the reinforcement is increased to a level of 12 *w*/% Si_3N_4 as shown in **Figure 6** certain challenges begin to present themselves. Although the images still show a visible bond between reinforcement and matrix, the higher concentration of ceramic particles leads to more interaction and the likelihood of clustering of particles. At higher reinforcement percentages it becomes more difficult to keep dispersion 100 %.

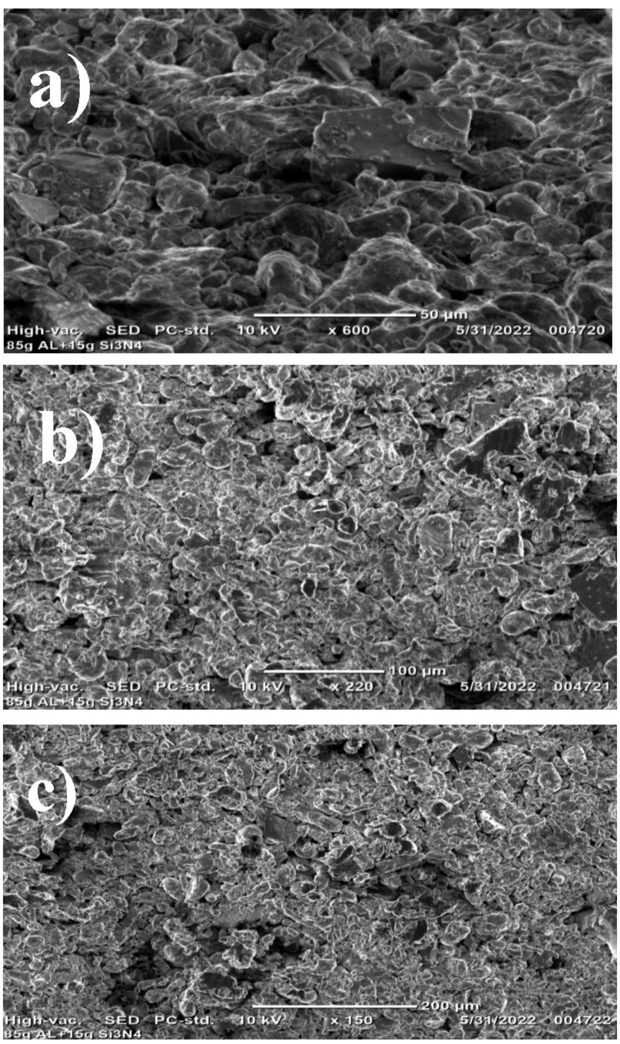

Figure 6: SEM images of aluminium + 12 *w*/% silicon nitride

Agglomeration can result from the particles not being separated evenly when they are mixed. Such clustering can generate a localised region of stress concentration and potentially have an adverse effect on the mechanical behaviour.

Despite the potential of the agglomeration at 12 *w*/%, the SEM images show the relatively intact state of the reinforcement-matrix interface, in which there is no major evidence of particle debonding. The absence of large scale agglomerates suggest that the ball milling process was well enough controlled. However, the excessive amount of ceramic can cause a loss in the composite's overall ductility. While the hardness and strength may increase, the brittleness may also increase if the reinforcement is over an optimum value.

The microstructural observations on all the compositions confirm that the powder metallurgy technique used in this study was effective in the production of aluminium, Si_3N_4 composites with good interfacial bonding and controlled particle distribution. High-energy ball milling was extremely important for establishing intimate contact between the aluminium and silicon nitride particles. By optimizing the milling time and processing parameters, it was possible to obtain a clean and consistent bond between the two phases. Proper sintering also further increased densification and kept porosity to a minimum.

Overall, the SEM analysis successfully shows the effect of reinforcement percentage on the microstructural aspects. At lower levels of reinforcement (4 *w*/% and 8 *w*/% of reinforcement) particle distribution is uniform and bonding is good resulting in better mechanical performance. At higher reinforcement (12 *w*/%), despite satisfactory bonding, the risk of particle clumping rises, which can have an impact on the mechanical properties if not properly controlled. The study confirms that optimized reinforcement range and controlled powder metallurgy processing are important factors for increasing the structural integrity and mechanical behavior of aluminium, Si_3N_4 composites.

3.2 Porosity analysis

Producing composite materials that have absolutely no pores or voids is an extremely difficult task. In practice, it is very difficult to approach a completely pore-free structure due to many factors involved in the processing and solidification that lead to the formation of tiny cavities. Porosity is a typical characteristic of metal-matrix composites, particularly if they are made using process methods such as powder metallurgy, stir casting or other liquid and solid-state processing methods. The presence of pores can result from entrapped gases, incomplete densification, improper wetting between the matrix and the reinforcement, particle agglomeration, shrinkage during solidification or insufficient compaction pressure. Therefore, rather than focusing on the complete elimination of porosity, much research effort is aimed at keeping porosity at the lowest possible level without compromising the desirable mechanical and physical properties.

In the present study an aluminium matrix composite reinforced with silicon nitride (Si_3N_4) particles was developed. Aluminium is a popular matrix material because of its low density, good corrosion resistance, high thermal conductivity, and good formability. Silicon nitride is a ceramic material, on the other hand, which is known for its highest hardness, thermal stability, wear resistance and strength at elevated temperatures. When these two materials are combined, the resulting composite is intended to combine the ductility and light weight of aluminium, and the stiffness and hardness of silicon nitride. However, adding ceramic particles into the metallic matrix also presents some other challenges, especially in regard to the uniform distribution and strong bonding between the interface, without causing too much porosity.

Figure 7 shows the porosity percentage variation with the increase of the quantity of silicon nitride reinforcement of the aluminium- Si_3N_4 composite. From the plotted data, it is clear that porosity decreases with increasing percentage of Si_3N_4, i.e., from 0 g to 15 g of Si_3N_4. The value of the porosity is found to be a maximum for the sample with 100 g aluminium without reinforcement and it gradually decreases with increase in the amount of reinforcement as 5 g, 10 g and 15 g respectively. For unreinforced aluminium sample (100 g Al + 0 g Si_3N_4), the porosity is about 89 %. When 5 g Si_3N_4 is added (95 g Al and 5 g Si_3N_4), the porosity falls to about 87 %. With the addition of more 10 g Si_3N_4 (90 g Al + 10 g Si_3N_4) porosity goes down to nearly 86 %. Finally, at 15 g Si_3N_4 reinforcement content (85 g Al + 15 g Si_3N_4) the porosity is approximately 85 %, which is the lowest of all the compositions tested. The error bars displayed in the graph represent slight variations in the experiment but the general trend of decreasing is consistent and clear.

This decrease in porosity with the increase in Si_3N_4 content is suggestive of better packing efficiency in the composite structure. The fine ceramic particles probably fill micro-voids that exist between aluminium particles during the compaction. In powder metallurgy processing, porosity may come from incomplete rearrangement of process particles, insufficient compaction pressure and

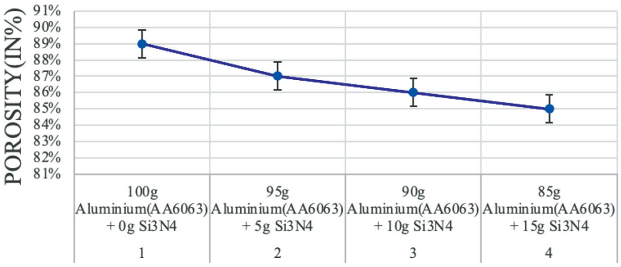

Figure 7: Porosity analysis

trapped air. When reinforcement particles are added in suitable proportions they can occupy interstitial gaps between larger aluminium particles thus resulting in improved densification during sintering. Another significant factor in the decreased porosity is good particle distribution. If the Si_3N_4 particles are evenly dispersed in the aluminium matrix, they facilitate the better transfer of loads, and reduce the possibility of the formation of voids. Proper mixing and blending before the compaction will help in minimizing particle clustering which can otherwise form localized pores. The gradual decrease that was noted in the graph shows that the reinforcement was well distributed and that the processing parameters were well controlled.

From a mechanical point of view, decreased porosity is a good thing, since pores are a stress concentration and crack initiation sites. Lower porosity usually leads to better tensile strength, compressive strength and fatigue resistance. Therefore, the composition with a dosage of 15 g Si_3N_4 is expected to have a good mechanical performance as compared to the non-reinforced aluminium sample, provided that other factors remain constant. Thermally, reduced porosity improves the thermal conduction as voids are usually low thermal conductivity materials. A more dense structure will result in better heat transfer through the solid matrix. In tribological applications, a lower porosity may help increase the load-bearing capacity, although some controlled porosity may be beneficial in helping to retain lubrication. As the reinforcement content is increased from 0 % to higher weight fractions, there is a steady decrease in the porosity. This trend is an indication of successful densification and effective composite fabrication. The results confirm the enhancement of the addition of silicon nitride particles with correct processing conditions to identify void content and structural compactness of the aluminium-based composites.

3.3 Density analysis

The variation with the density (kg/m^3) of the AA6063 aluminium alloy reinforced with different weight percentages of silicon nitride (Si_3N_4) is presented graphically. The compositions that have been considered are 100 g Al without reinforcement, then 95 g Al + 5 g Si_3N_4, 90 g Al + 10 g Si_3N_4, and 85 g Al + 15 g Si_3N_4. From the above results of the plotted graph as shown in figure 8, it is clear that the density of the composite increases progressively with the addition of silicon nitride particles.

For the unreinforced AA6063 sample (100 g Al), the density is about 1900 kg/m^3. When 5 g of Si_3N_4 is added to the matrix (95 g Al + 5 g Si_3N_4) there is a slight increase in the density to about 1920 kg/m^3. With a further increase in reinforcement to 10 g Si_3N_4 (90 g Al + 10 g Si_3N_4) the density increases to a more significant value of almost 2000 kg/m^3. Finally at the highest reinforcement level of 15 g Si_3N_4 (85 g Al + 15 g Si_3N_4) the density is around 2080–2100 kg/m^3. The error bars indicated in the graph represent small deviations of the experimental measurements, but the general trend upward is consistent and well defined.

The increase in density with reinforcement content can be explained if the intrinsic material properties of the constituents are taken into account. The ceramic material that has a relatively high density and stiffness as compared to aluminium is silicon nitride. When these ceramic particles are introduced into the aluminium matrix they add to an overall increase in mass per unit volume. As the weight fraction of Si_3N_4 increases, the contribution of the denser reinforcement phase becomes more dominant and therefore the density of the composite increases. Another important factor in density is the decreased porosity. In the case of composite fabrication processes like powder metallurgy, the density is highly influenced by the degree of voids that are present within the structure. If the addition of Si_3N_4 helps to improve the particle packing and reduces the internal pores, the effective density will increase. A denser microstructure implies that there are less air gaps and a better consolidation occurs during the compaction and sintering process. Therefore, the observed improvement in density may not result from only the higher intrinsic density of silicon nitride, but may also be the result of enhanced densification of the composite.

The uniform increase in density indicates good interfacial bonding between the matrix of aluminium and the particles of silicon nitride. Strong interfacial adhesion results in an effective integration of the reinforcement with the matrix without having large interfacial voids. Proper mixing and uniform dispersion of reinforcement particles is critical to achieve this result. If clustering or agglomeration occurs, localized porosity can be formed, which has a detrimental effect on the density. However, the steady increase in the graph is a good indicator that the fabrication process was able to control the dispersion of Si_3N_4 particles very uniformly.

The rising trend in density also represents good control over the processing parameters such as compaction pressure, sintering temperature and holding time. These parameters directly affect the bonding of particle and microstructural evolution. Proper optimization allows a maximum densification and minimum shrinkage defects. The error bars in the graph reflect slight variations in the

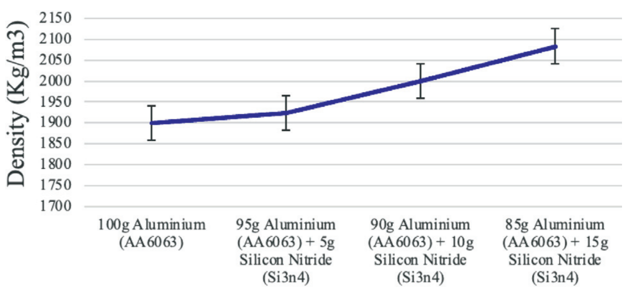

Figure 8: Density analysis

experiments which is to be expected in the fabrication of composites, but this does not change the general pattern of increasing density with the addition of reinforcement.

The improvement is due to both the increase in intrinsic density of the reinforcement and the increase in densification that is obtained during processing. The composition with 15 g Si_3N_4 shows the highest density of the tested samples showing better structure compactness. These results prove the positive function of reinforcement addition on physical properties (physical characteristics) of the aluminium matrix composite to achieve the enhanced mechanical and thermal properties for advanced engineering applications.

3.4 Hardness analysis

Figure 9 illustrates the variation in hardness (BHN) of the AA6063 aluminium alloy reinforced with different weight fractions of silicon nitride (Si_3N_4). The compositions analyzed include unreinforced aluminium (100 g AA6063), followed by 95 g Al + 5 g Si_3N_4, 90 g Al + 10 g Si_3N_4, and 85 g Al + 15 g Si_3N_4. From the plotted results, a clear and consistent increase in hardness is observed as the reinforcement content increases. This upward trend demonstrates the strengthening effect of silicon nitride particles within the aluminium matrix.

For the base alloy without reinforcement, the hardness value is approximately 190 BHN. With the addition of 5 g Si_3N_4, the hardness increases slightly to around 192–193 BHN. When the reinforcement content is increased to 10 g, the hardness rises more noticeably to approximately 200 BHN. At the highest reinforcement level of 15 g Si_3N_4, the hardness reaches nearly 208–210 BHN, which represents the maximum value among all tested compositions. Although minor experimental variations are indicated by the error bars in the graph, the overall increasing trend remains distinct and consistent. The increase in hardness with reinforcement addition can be attributed primarily to the intrinsic properties of silicon nitride. Si_3N_4 is a ceramic material known for its high hardness, wear resistance, and thermal stability. When these hard ceramic particles are incorporated into the relatively softer aluminium matrix, they act as obstacles to localized plastic deformation. During indentation testing, the applied load is resisted not only by the aluminium matrix but also by the embedded silicon nitride particles, thereby increasing the composite's resistance to indentation.

The presence of reinforcement particles also restricts dislocation movement within the aluminium matrix. In metallic materials, plastic deformation primarily occurs through the motion of dislocations. The introduction of hard ceramic particles creates barriers that impede dislocation motion. This phenomenon, often referred to as dislocation pinning or strengthening by dispersion, results in improved hardness and strength. With a higher Si_3N_4 content, the spacing between particles decreases,

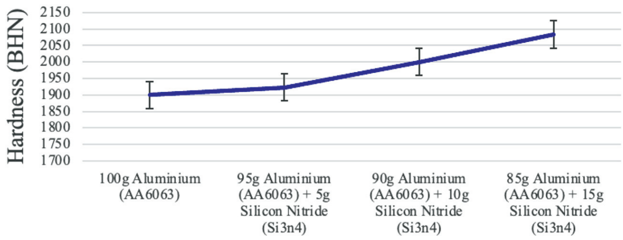

Figure 9: Hardness analysis

increasing the probability of dislocation obstruction and thereby enhancing hardness further.

The uniform distribution of silicon nitride particles within the matrix is crucial for achieving consistent hardness improvement. If the reinforcement is evenly dispersed, the strengthening effect is uniformly distributed throughout the composite. However, if particle agglomeration occurs, localized variations in hardness may result. The smooth and steady increase shown in the graph suggests that the fabrication process ensured good mixing and homogeneous particle distribution. Hardness is closely related to wear resistance and surface durability. An increase in BHN generally indicates improved resistance to abrasion and surface damage. Therefore, the composite containing 15 g Si_3N_4 is expected to exhibit superior wear performance compared to the unreinforced alloy. This makes the material suitable for applications involving sliding contact, frictional forces, or high surface stress conditions..

It is also important to consider that while the hardness increases with reinforcement, excessive addition of ceramic particles may lead to brittleness. Although hardness improvement is desirable, a balance between hardness and ductility must be maintained to ensure structural reliability. Within the tested range, the increase appears gradual and controlled, indicating an optimal reinforcement range for enhancing surface properties without severely compromising toughness.

The increase in BHN from 190 to over 208 with rising Si_3N_4 content confirms the strong reinforcing effect of the ceramic phase. The improvement can be attributed to load transfer, dislocation restriction, grain refinement, and the inherent hardness of silicon nitride. These results validate the effectiveness of reinforcement addition in improving the mechanical performance of aluminium matrix composites for advanced engineering applications.

4 CONCLUSIONS

Following the successful completion of the porosity and microstructure analyses, the following conclusions were drawn:

- The scanning electron microscope (SEM) analysis showed a homogeneous dispersion of particles of silicon nitride (Si_3N_4) in the aluminium matrix. The reinforcement particles were embedded well without much agglomeration. This uniform distribution helps to contribute to better interfacial bonding properties and uniform mechanical properties.
- The aluminium composite with 4 weight per cent Si_3N_4 had a stable and even particle distribution. No major clustering or segregation of reinforcement particles in the microstructure was observed. This is an indication of good processing and good mixing during the fabrication of the composite.
- The introduction of particles of silicon nitride Si_3N_4 improved the overall mechanical strength of the aluminium matrix composite. An increase in hardness was observed because of the presence of hard ceramic reinforcement. The strengthening effect is attributed to load transfer mechanism and resistance to plastic deformation.
- The addition of Si_3N_4 particles led to an increase in the density of the composite. This is because the ceramic reinforcement has a higher intrinsic density than that of aluminium. Denser particle packing and less micro-voids also helped boost density.
- The porosity degree in the composite decreased by increasing the Si_3N_4 content. The reinforcement particles helped fill up micro-voids in the aluminium matrix. Reduced porosity increases the structural integrity and mechanical reliability.

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No research data were generated or analysed in this article, as the work was conducted theoretically.

The author(s) declare(s) that no generative AI tools were used in the preparation of this manuscript.

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