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Influence of Process Parameters on Wear Behaviour of AlSi – CNT - SiCp Nano composite Materials

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Abstract

The primary objective of this study was to investigate the wear performance of a hybrid composite, specifically the AlSi–2wt%CNTs–5wt%SiCp composite. To establish a benchmark, a comparative assessment encompassing the unreinforced AlSi alloy, AlSi–2wt%CNTs, and AlSi–5wt%SiCp composites was conducted. The fabrication process adopted was powder metallurgy, employed to produce both the unreinforced AlSi alloy and the AlSi composites. Through dry reciprocating pin-on-plate wear tests, the outcomes elucidated that wear behavior exhibited enhancement across all produced composites in contrast to the unreinforced AlSi alloy. Notably, the apex of wear performance was observed within the AlSi hybrid composite. This elevated wear resilience can be attributed to the synergistic effects arising from the amalgamation of the constituent reinforcements. Scanning electron microscopy, coupled with X-Ray Energy Dispersive Spectrometry analysis, was employed to discern and characterize the predominant wear mechanisms underpinning these findings.

Keywords:- CNT's; AlSi-hybrid Composites; SiCp; Sliding Wear

1. Introduction

The wear behavior of materials plays a crucial role in determining their suitability for various applications, especially in industries such as automotive, aerospace, and manufacturing. One class of materials that has gained significant attention in recent years is metal matrix composites (MMCs), which exhibit improved mechanical and tribological properties compared to conventional materials [1-2]. Among MMCs, aluminum-based composites reinforced with silicon carbide (SiC) particles is a better choice for automobile components due to their good wear and mechanical properties. The various reinforcement materials are incorporated in aluminum alloys are used to improve desired properties, it shows that very attractive for particular applications. Few reinforced particles are used in aluminium alloys are SiC [3-6] Al₂O₃ [7], TiC [8], TiAl [9], B₄C [10], TiB₂ [11], CNTs [12–15], graphite [16], etc. and carbon nanotubes (CNTs) have shown great potential for enhancing wear resistance. The processing route significantly influences the distribution of particles within the material. Powder metallurgy (PM) has been widely recognized as an effective method to achieve a highly uniform dispersion

of particles. Additionally, it is worth noting that hot pressing is a favorable technique for promoting efficient densification during the fabrication process [17]. As far as the authors are aware, there is limited research focusing on the wear behavior of aluminum (Al) alloys reinforced with carbon nanotubes (CNTs) [12-15, 17-20]. Nevertheless, the existing studies have shown promising results, indicating that CNTs serve as effective reinforcements to enhance the wear properties of Al-based composites [12-15].

The wear behavior of the material can be attributed to several key factors, including the dispersion of carbon nanotubes (CNTs), the size and fraction of CNT agglomerations, and the formation of carbides [12]. Previous studies have reported that the coefficient of friction (COF) decreases with an increase in CNT content, which can be attributed to the self-lubricating effect of carbon content [12-15, 17-20]. Additionally, it has been observed that the formation of agglomerations actually contributes to a reduction in COF, leading to improved wear resistance. These agglomerations act as effective lubricants between the contacting surfaces, further enhancing the material's tribological performance [12].

According to previous research by the same authors, a critical concentration of carbon nanotube (CNT) agglomerations has been reported, beyond which a well-known detrimental effect occurs. In another study investigating the effect of CNT content (ranging from 2 wt% to 6 wt%) on the mechanical and wear behavior of AlSi-CNT composites, it was concluded that at 2 wt% CNTs, an equilibrium is achieved, resulting in an improvement in mechanical properties across various tests, including tensile, fatigue, and wear [21-22]. The authors found that 2 wt% CNTs was the optimal content, specifically for enhancing tensile properties.

Consequently, to enhance the wear properties while preserving the tensile strength, the inclusion of an additional reinforcement becomes essential. This reinforcement should introduce a distinct strengthening mechanism or the same mechanism but at a different scale. In the current study, silicon carbide particles (SiCp) were chosen as the secondary reinforcement. The utilization of SiCp as a reinforcement in aluminum alloys has been extensively investigated by various researchers in previous works [4-6, 23]. According to Mondal et al. [23] have identified several factors that contribute to the improvement in wear resistance. These include: (a) The presence of hard silicon carbide particles (SiCp) that protrude on the material's surface, resulting in a rougher surface texture. This roughness can provide enhanced wear resistance by reducing direct contact and minimizing material loss during frictional interactions. (b) The accumulation of debris around the silicon carbide particles. This accumulation can act as a protective layer, shielding the surface from further wear and reducing the overall wear rate. These factors play a crucial role in enhancing the wear resistance of the material, as observed and reported by Mondal et al. [23]. Consequently, the incorporation of SiC particles into the AlSi-2%wtCNTs composite opens the possibility of creating innovative hybrid metal matrix composites (HMMC) [16, 24-26]. Numerous studies have highlighted the notable enhancement in wear resistance achieved with hybrid composites [16, 25, 26]. Specifically, the addition of graphite to an AlSi-SiCp [23] composite as a secondary reinforcement has been demonstrated to significantly reduce wear rates compared to the SiCp-reinforced composite alone. This promising outcome highlights the potential of hybrid composites as advanced materials with superior wear properties, offering exciting prospects for various industrial applications.

Aruri et al. [26] observed that the increase in wear resistance for both studied hybrid composites (Al-SiCp/Al₂O₃ and Al-SiCp/graphite) can be attributed to the synergistic effects of both reinforcements. The SiC particles function as load-bearing elements, effectively enhancing the composite's mechanical strength and durability. Meanwhile, the addition of graphite acts as a

solid lubricant, significantly reducing friction and wear during sliding interactions. This combination of reinforcements results in a material with superior wear properties, demonstrating the potential for these hybrid composites to outperform traditional single-reinforcement composites in demanding tribological applications. In their study, Ames et al. [16] demonstrated a notable enhancement in the wear behavior of an aluminum alloy (A356) when two reinforcements, graphite (3%) and SiC particles (20%), were added. The improved wear resistance was mainly attributed to the load-bearing effect of SiC particles, which effectively strengthened the composite and reduced wear. However, it was also noted that SiC particles can serve as abrasives during sliding interactions, contributing to the machining of the counterface surface. This dual role of SiC particles as both load-bearing elements and abrasives provides valuable insights into the wear mechanisms of the composite and highlights the complex interplay of reinforcement materials in influencing the overall wear behavior of the material.

This study explores the wear characteristics of an AlSi alloy containing Multi-Wall Carbon Nanotubes (MWCNT) and SiC particles as reinforcements. The primary objective was to investigate the synergistic effects of both reinforcement types (CNTs and SiCp) on wear behavior under dry reciprocating sliding conditions. The aim was to determine whether the combination of these constituents could yield enhanced advantages, pushing the composite's properties beyond the limits achieved by individual reinforcements, without adversely affecting other essential properties.

By systematically analyzing the wear behavior of the composite material, this research aimed to shed light on the point at which each reinforcement demonstrated its optimal beneficial impact. Additionally, it sought to ascertain whether introducing another reinforcement could further amplify the composite's properties while maintaining the integrity of other relevant material properties. The study focused on identifying the optimal balance between the constituents, striving to create a composite material that exhibited exceptional wear resistance and mechanical properties.

2. Experimental Methodology

2.1 Development of AlSi Composites

An AlSi alloy with a powder size of $\phi 325$ mesh ($\phi 44$ μm) and a chemical composition listed in Table 1 served as the matrix material. The AlSi powder was acquired from Triveni Chemical— Mumbai. For reinforcement, Ni-coated Multi-Wall Carbon Nanotubes (MWCNTs) were used, with an outer diameter of 450 nm and a length ranging from 0.5 to 2.0 μm . The purity of MWCNTs before coating was 495 wt%, with an ash content of $\phi 1.5$ wt%. Additionally, SiC particles, measuring 13 μm in size, were utilized as reinforcements. The Ni-coated MWCNTs were purchased from Triveni chemicals — Mumbai.

To fabricate the AlSi-matrix composites, the traditional hot isostatic pressing (HIP) technique was employed. The process involved applying a pressure of 35×10^6 Pa for 10 minutes at a temperature of 550°C under vacuum conditions (1 Pa). Prior to this, the AlSi powders were mixed inside a sealed stainless steel jar, along with 12 steel milling balls (10 mm in diameter). The ball powder ratio was maintained at 10:1. The mixture was subjected to low-energy ball milling, where the bottle rotated at a constant speed of 40 rpm for a duration of 6 days. This milling process ensured uniform distribution and effective integration of the reinforcing components within the AlSi matrix.

2.2 Microstructural and chemical characterization of AlSi composites

SEM was employed to investigate the microstructure and morphology of the AlSi composites, providing detailed imaging at high resolution. This technique allowed researchers to visualize the distribution and arrangement of the reinforcement materials within the AlSi matrix and gain insights into their interactions and bonding.

EDS was used in conjunction with SEM to analyze the elemental composition of the composites and the worn surfaces. By detecting the characteristic X-rays emitted from the sample when bombarded with an electron beam, EDS facilitated the identification and quantification of the elements present in the materials. This analysis helped to determine the elemental distribution and any compositional variations resulting from wear processes.

The combination of SEM and EDS characterization provided valuable data on the structural integrity, interfacial bonding, and elemental changes occurring in the AlSi composites during wear. Through these techniques, the researchers could gain a deeper understanding of the wear mechanisms, contributing to a comprehensive assessment of the composites' performance and wear resistance.

2.3 Hardens Test

During the hardness tests, a consistent load of 200 gf (gram-force) was applied for a duration of 15 seconds. This standard testing procedure allowed for precise assessment of the materials' hardness properties. The obtained hardness data offered valuable insights into the AlSi composites' mechanical strength and resistance to indentation, crucial for evaluating their suitability for various applications.

2.4 Details of Reciprocating wear test

To assess the wear behavior of AlSi composites when in contact with Graphite Cast Iron (GCI) sliding pairs, a reciprocating pin-on-plate tribometer model PLINT-TE67/R was employed. For this purpose, pins were carefully machined from both the unreinforced AlSi alloy and three different AlSi matrix composites, namely AlSi–2wt%CNTs, AlSi–5wt%SiCp, and AlSi–2wt%CNTs–5wt%SiCp.

The reciprocating pin-on-plate tribometer provided a controlled and reproducible environment to simulate the sliding interactions between the pins and the GCI plate. By utilizing pins made from various AlSi composite formulations, the wear characteristics of each composite type could be systematically investigated and compared against the unreinforced AlSi alloy.

This experimental setup allowed for a comprehensive evaluation of the tribological properties of the AlSi composites when subjected to sliding conditions against the GCI material, providing valuable insights into their potential as robust and wear-resistant materials for specific engineering applications.

Table 1. Chemical composition of AlSi alloy (wt.%)

Al	Si	Fe	Others
87.3	11	0.20	1.5

Table 2. Chemical Composition of GCI.

Fe	C	Mn	Si	P	Cr	Ni	Cu	S	Mo	Others
90.4	3.59	0.392	2.37	0.624	0.249	1.52	0.28	0.023	0.007	0.545

The pins used in the study possess specific dimensions, with a radius of curvature measuring 40 mm, a thickness of 3.5 mm, and an arc length of 20 mm. These carefully defined dimensions were essential to ensure standardized testing conditions and accurate wear assessment.

The AlSi composite material under investigation shows promising potential for practical applications in engine pistons or compression piston rings. The composite's favorable wear characteristics and mechanical properties make it a viable candidate for these critical engine components, where durability and performance are paramount. Its successful application in such engine components could lead to improved engine efficiency, reduced friction, and enhanced overall reliability.

The counterpart utilized in the study comprised plates measuring 40×18×5 mm in dimensions, which were carefully machined from grey cast iron (GCI) possessing a hardness value of 338 HV. The GCI material offered a robust and durable surface for the tribological tests, simulating real-world conditions. Table 2 provides an overview of the chemical composition of the grey cast iron (GCI)

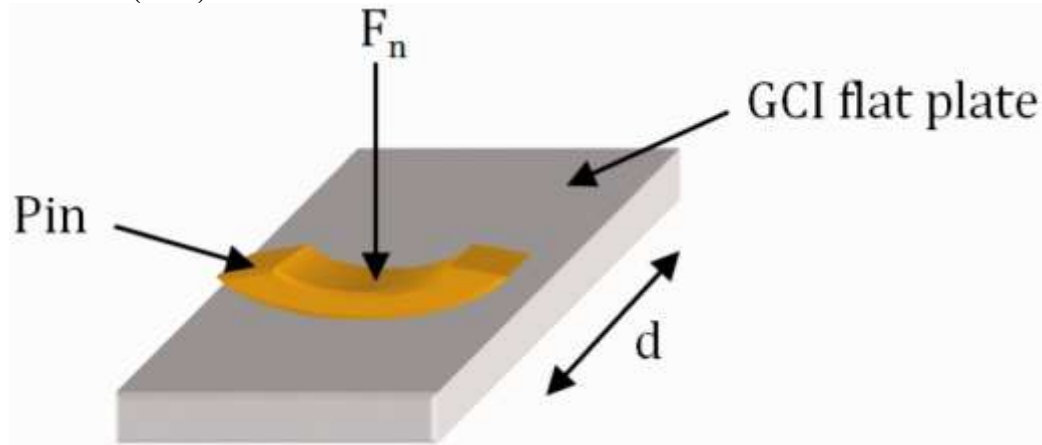


Figure 1. Schematic Test Setup: F_n represents the applied normal load; d corresponds to the amplitude of alternating displacement.

Figure 1. depicts a schematic representation of the test setup used in this study. The tests involved applying a normal load (F_n) on the pin, while the GCI plate underwent alternative displacement (d). A series of experiments were conducted with a consistent normal load of 10 N and a relative displacement amplitude of 10 mm. The sliding distance for each test was 148 meters, with a total duration of 2 hours, and a sliding speed of approximately 0.02 m/s.

To maintain consistent conditions, compressed air was directed to the contact zone throughout the tests, effectively removing loose wear debris. The reciprocating motion frequency for all tests was set at 1 Hz. All wear tests were conducted under identical conditions, with the only variable being the material of the pins, which included different reinforcements: CNTs,

SiCp, or a combination of CNTs-SiCp. Additionally, an unreinforced AlSi alloy was employed for comparison purposes.

To ensure accurate and reliable results, all tests were conducted at the ambient temperature of $20 \pm 2^\circ\text{C}$. By controlling these parameters, researchers could systematically investigate and evaluate the wear characteristics of the various AlSi composites in comparison to the unreinforced AlSi alloy under controlled and consistent experimental conditions.

The tribometer used in this study was equipped with a data acquisition system, which meticulously recorded various testing variables, such as the coefficient of friction and sliding distance. To ensure accuracy and reliability, both the pin and GCI plate underwent thorough ultrasonic cleaning in alcohol before and after each test. The amount of wear experienced by the materials was determined by measuring the weight loss resulting from the tribological interactions.

To gain further insights into the wear mechanisms at play, detailed characterization was performed using Scanning Electron Microscopy (SEM) in conjunction with Energy Dispersive Spectrometry (EDS) analysis. This analysis allowed to identify and understand the dominant wear mechanisms, providing crucial information about the material's performance and potential failure modes. By meticulously recording and analyzing the testing data, along with comprehensive SEM/EDS analysis, this study aimed to unravel the underlying wear phenomena and contribute to a better understanding of the tribological behavior of the AlSi composites in contact with the GCI material.

3. Results And Discussion

3.1 Microstructural characterization

Figure 2 displays the microstructures of both the unreinforced AlSi alloy and all AlSi matrix composites after etching. Detailed SEM images unveiled the arrangement of Carbon Nanotubes (CNTs) at the grain interfaces, as anticipated, and revealed the presence of certain CNT agglomerates (Fig. 2b). It is noteworthy that a previous study by the same authors [21] demonstrated that over 93% of these agglomerates possess an area less than $1 \mu\text{m}^2$. In the micrographs, the CNTs are represented by the white dots or areas, highlighting their distribution within the AlSi matrix. The average grain size of the AlSi alloy was observed to be approximately $6 \mu\text{m}$.

These microstructural insights offer valuable information about the distribution and dispersion of CNTs within the AlSi matrix composites. Understanding the spatial arrangement of the reinforcements and their interactions with the AlSi grains is essential for interpreting the subsequent tribological behavior and wear mechanisms exhibited by the composites during the experimental tests.

Figure 2c displays the microstructure of AlSi with 5wt% SiCp, revealing the presence of black SiC particles distributed within the AlSi matrix. These SiC particles are observed at the grain interfaces, a finding consistent with the research conducted by Balani et al. [27] Notably, no distinct interface was formed between the SiC particles and the AlSi matrix in this particular microstructure. However, Walczak et al. [28] reported that under certain processing routes, such as squeeze casting, there is a possibility of an interface being formed between the SiC particles and the AlSi matrix. This suggests that the manufacturing technique, specifically the hot isostatic pressing (HIP) technique, can influence the formation of such interfaces in the AlSi/SiC

composite [29]. The microstructure of AlSi with 5wt% SiCp demonstrates the dispersion of SiC particles in the AlSi matrix, visibly present at grain interfaces, and the absence of an interface with the AlSi matrix. Nonetheless, it is important to consider the processing route, as alternative techniques like squeeze casting may lead to the formation of interfaces between the SiC particles and AlSi matrix.

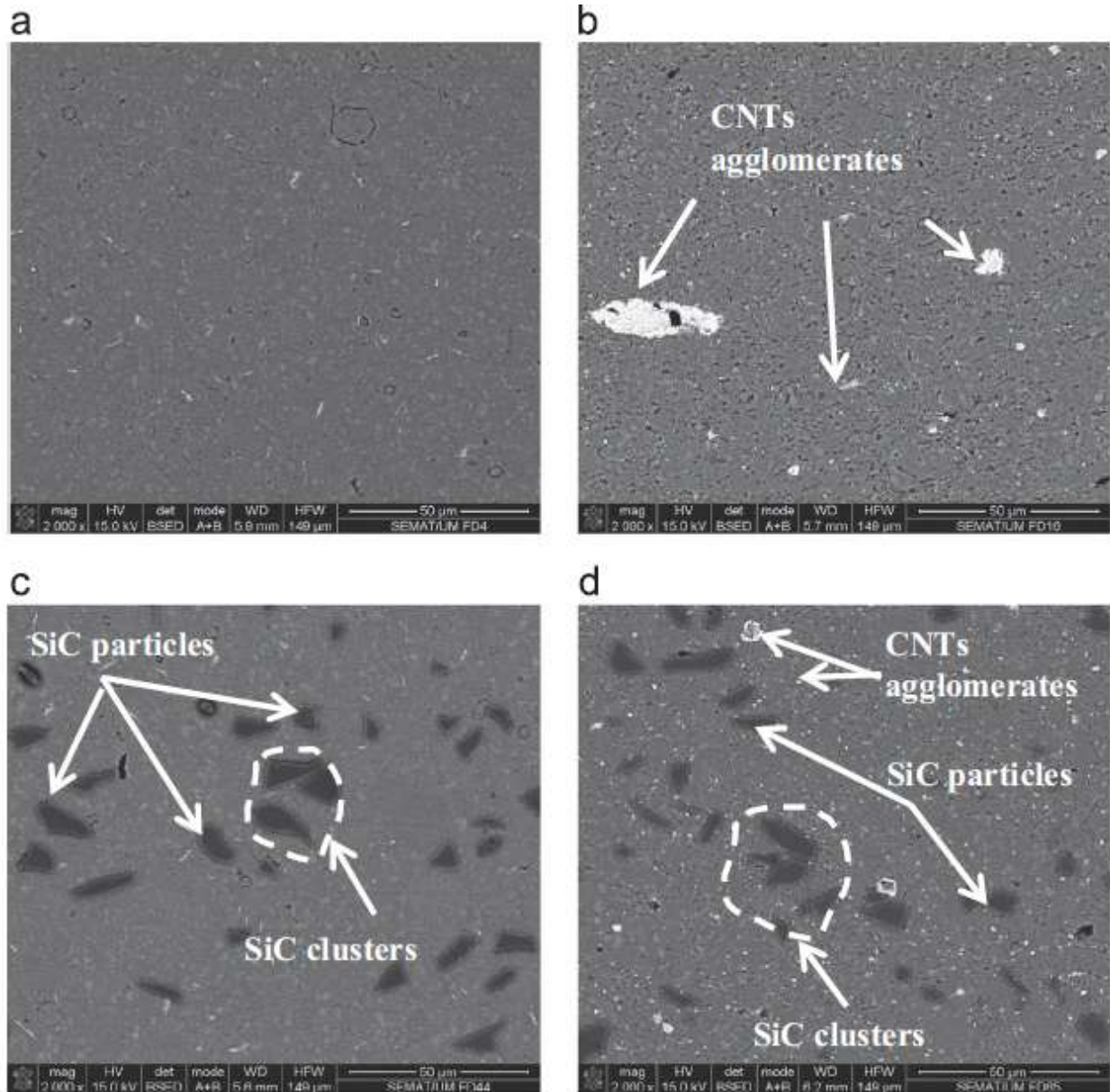


Figure 2. Scanning Electron Microscopy (SEM) Images of Composite Microstructures: (a) Unreinforced AlSi Alloy, (b) AlSi-2%wtCNTs, (c) AlSi-5wt%SiCp, and (d) AlSi-2%wtCNTs-5%wtSiCp.

Figure 2d illustrates the microstructure of the hybrid composite (Al-2wt%CNTs-5wt%SiCp), showcasing the presence of composite reinforcements, namely the black SiC particles and the Carbon Nanotubes (CNTs). Some agglomerates of CNTs can be observed

within the microstructure. Interestingly, the addition of SiCp does not appear to influence the distribution of the CNTs in the hybrid composite. Similar to the AlSi–5wt%SiCp composite (Fig. 2c), both composites, Al–2wt%CNTs–5wt%SiCp, and AlSi–5wt%SiCp exhibit the formation of SiC particle clusters. These clusters may act as stress concentrations, potentially inducing micro plasticity, which has been pointed out by other researchers. In summary, the microstructure of the hybrid composite (Al–2wt%CNTs–5wt%SiCp) reveals the presence of CNTs and SiC particles as reinforcement. The addition of SiCp does not appear to affect the distribution of CNTs. Furthermore, both composites show the formation of SiC particle clusters that could potentially influence micro plasticity, as indicated by previous studies [30,31].

3.2 Hardness

Figure 3 illustrates the hardness outcomes for both the unreinforced AlSi alloy and the AlSi composites.

Consistent with expectations, the inclusion of reinforcements (CNTs or SiCp) leads to a rise in hardness. In comparison to the unreinforced AlSi alloy, the AlSi–2%wtCNT composite displays an approximately 25% hardness increase, as documented in another research by the same authors [22]. Similarly, the AlSi–5%wtSiC composite exhibits a hardness enhancement of roughly 27%. Notably, the hybrid composite registers a more pronounced increase in hardness, reaching around 36%.

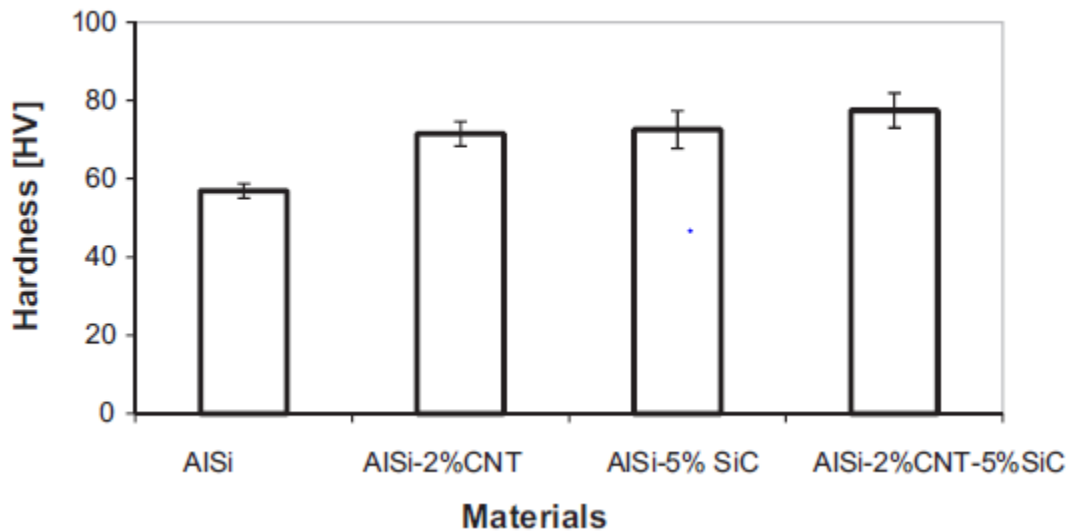


Figure 3. Hardness measurements were conducted on both the unreinforced AlSi alloy and all variants of the AlSi composites.

The hardness results obtained in our study are consistent with findings from previous research [32–34]. It appears that the primary factor influencing the increase in hardness in both cases is the volume fraction of the reinforcement. As the volume fraction of the reinforcement materials increases, the hardness of the composite material also tends to rise accordingly. This correlation aligns with the observations made in other related studies, emphasizing the significant role played by the volume fraction of the reinforcements in determining the hardness of the composites under investigation.

The enhancement in hardness resulting from the addition of CNTs can be attributed to the presence of CNTs at the grain interfaces, which act as barriers to dislocations. This phenomenon leads to an increase in strain hardening during plastic deformation, as previously reported by Mondal et al. [33]. The CNTs' ability to impede the movement of dislocations within the material contributes to the overall increase in hardness, making it a crucial factor in understanding the mechanical properties of the composite.

The observed increase in hardness in the AlSi–5wt%SiCp composite compared to the unreinforced AlSi alloy aligns with findings from previous research [32, 35]. This hardness enhancement has been attributed to two main factors in the literature. Firstly, the thermal mismatch between the matrix and the reinforcement induces a high dislocation density in the matrix, contributing to the overall increase in hardness [27]. Secondly, the presence of harder reinforcements impedes the movement of dislocations within the material, further reinforcing the hardness of the composite [24]. These combined effects play a crucial role in understanding the improved mechanical properties of the AlSi–5wt%SiCp composite compared to its unreinforced counterpart.

The hybrid composites exhibited an increase in hardness compared to both the unreinforced AlSi alloy and the studied AlSi composites, as shown in Figure 3. These findings are consistent with results from other research studies [24, 26, 36]. The rise in hardness can be attributed to the strengthening effects of both reinforcements, namely SiCp and CNTs, which act synergistically to enhance the material's mechanical properties. Multiple strengthening mechanisms contribute to the increase in hardness. The presence of SiCp and CNTs induces strengthening effects such as shear lag [37], thermal mismatch [25, 27], and Orowan looping [38, 39]. As both reinforcements possess distinct properties, shapes, and sizes, they are expected to contribute differently to the mentioned models of strengthening. The behavior of hybrid composites reflects a combination of the inherent advantages and disadvantages of both SiCp and CNT reinforcements. Numerous studies have already demonstrated the additional effects of these reinforcements on the mechanical properties of composites [24, 27]. Therefore, the observed increase in hardness in our hybrid composites can be attributed to the cumulative benefits of SiCp and CNTs, showcasing their potential to significantly enhance the material's overall mechanical performance.

3.3. Wear Loss

Figure 4 illustrates the volume losses of the AlSi pins, including both the unreinforced AlSi alloy and the AlSi-composites, along with the mating GCI (Graphite Cast Iron) plates. A noticeable trend emerges when comparing all the AlSi composites with the unreinforced AlSi alloy: the wear in all the studied composites is notably lower than that of the unreinforced alloy.

As the study progresses from the unreinforced AlSi alloy to the AlSi composites, it becomes evident that the wear volume steadily decreases with the addition of either CNTs or SiCp reinforcements. Moreover, this wear reduction is further enhanced with the incorporation of both reinforcements (CNTs and SiCp) simultaneously. The combined effect of CNTs and SiCp demonstrates a significant improvement in reducing wear, highlighting the potential benefits of hybrid composites in wear resistance applications. Overall, these findings emphasize the positive

impact of reinforcement materials in mitigating wear and enhancing the tribological performance of the AlSi-based composites.

In the case of the AlSi–2wt%CNTs/GCI tribopair, a notable reduction in volume loss was observed, with approximately 8% less wear for the AlSi–2wt%CNTs composite (pin) and 29% less wear for the GCI plate, compared to the contact involving the unreinforced AlSi alloy/GCI [21]. These findings align with the outcomes of various other studies [12–15, 18, 40], which have consistently shown that CNTs, when used as a reinforcement in Al-matrix composites, effectively enhance wear characteristics. The improvement in wear behavior can be attributed to several factors. Firstly, the dispersion of CNTs within the matrix plays a crucial role in reducing wear, as indicated by previous research [15]. Secondly, the size and fraction of CNT agglomerations also contribute to the wear reduction effect [19]. Lastly, the self-lubricating property of the carbon content in CNTs provides an additional benefit in improving wear resistance [13]. These combined effects of CNTs in the AlSi–2wt%CNTs composite have demonstrated its efficacy as an effective reinforcement for enhancing wear resistance, making it a promising material in tribological applications.

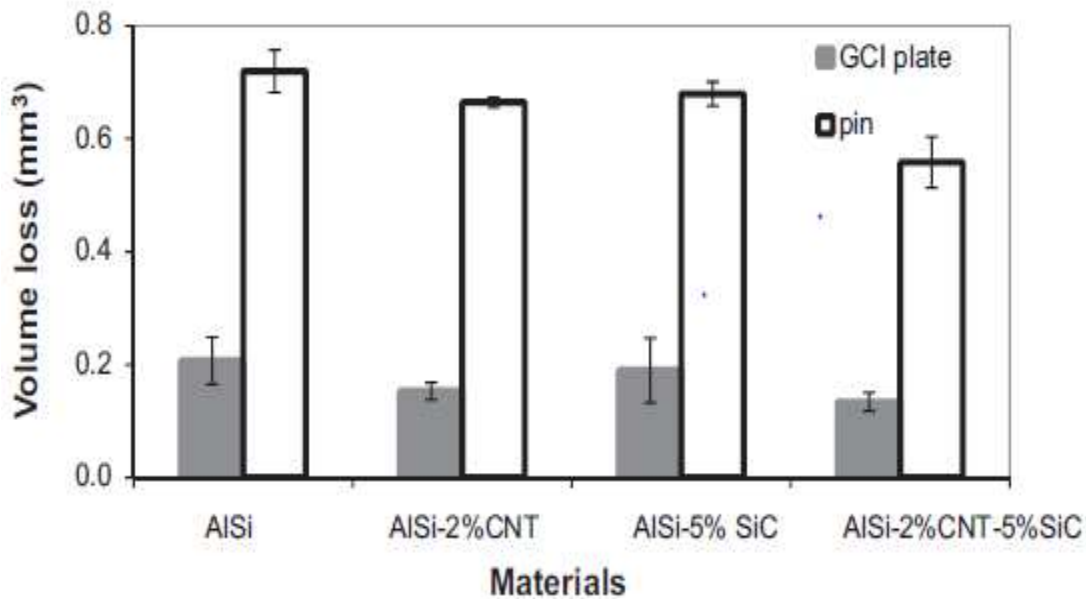


Figure 4. Alterations in volume loss were tracked for both the unreinforced AlSi and the AlSi composites.

In the context of the AlSi–5wt%SiCp/GCI tribopair, a noticeable reduction in volume loss was observed, with approximately 6% less wear for the AlSi–5wt%SiCp composite (pin) and 10% less wear for the GCI plate, compared to the contact involving the unreinforced AlSi alloy/GCI. This wear reduction trend aligns with the findings of several other studies [4–6, 23], which have also demonstrated the improved wear behavior resulting from the incorporation of SiCp into the AlSi alloy. The addition of SiCp to the AlSi alloy has been consistently associated with enhanced wear resistance in prior research. The reinforcement's presence effectively mitigates wear in the tribological system, offering improved material durability and performance.

These positive outcomes further affirm the valuable role played by SiCp in AlSi-based composites, highlighting their potential benefits in various wear-critical applications.

In the case of the AlSi–2wt%CNTs–5wt%SiCp/GCI tribopair, a significant decrease in volume loss was observed, with approximately 22% less wear for the AlSi–2wt%CNTs–5wt%SiCp composite (pin) and 38% less wear for the GCI plate, compared to the contact involving the unreinforced AlSi alloy/GCI. This reduction in wear volume showcases the combined beneficial effect of both reinforcements, CNTs and SiCp, within the AlSi matrix.

The presence of both CNTs and SiCp in the AlSi matrix plays a crucial role in reducing wear for both the pin and the GCI counterface material. The synergistic combination of these reinforcements contributes to the remarkable wear resistance observed in the tribological system. Notably, both the pin and the GCI counterface exhibited lower wear volume in comparison to the unreinforced AlSi/GCI tribopair and even the individual AlSi composites/GCI tribopairs. These results highlight the promising potential of hybrid composites incorporating both CNTs and SiCp as reinforcements in AlSi matrices, showcasing their significant positive impact on reducing wear and improving the overall tribological performance of the materials in the specific tribopair configuration.

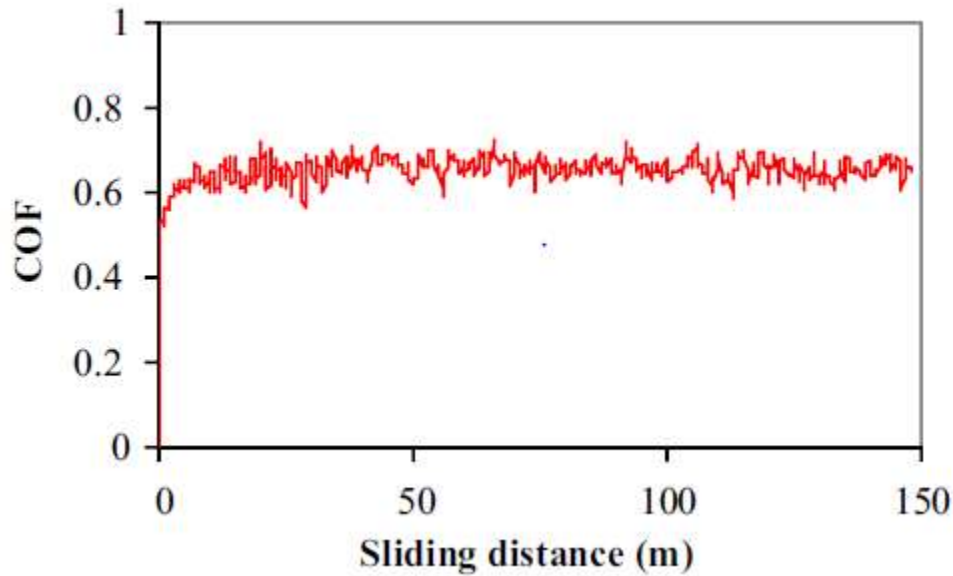


Figure 5. The progression of the Coefficient of Friction (COF) with respect to sliding distance in the AlSi–2wt%CNTs–5wt%SiCp hybrid composite was observed.

In this study, the SiCp functions as a load-bearing element, while the CNTs exhibit a self-lubrication effect. These specific roles of the reinforcements will be discussed in more detail later in the paper. Both SiCp and CNTs have a strengthening effect on the AlSi matrix, contributing to an overall improvement in wear behavior. The SiCp reinforcement enhances the structural integrity of the composite by acting as a load-bearing element, effectively distributing external forces and reducing wear-inducing stresses. On the other hand, the CNTs provide a self-lubricating effect due to their inherent properties, reducing friction and wear during sliding contact. Moreover, the presence of both SiCp and CNTs reinforces the AlSi matrix, leading to

enhanced mechanical properties and wear resistance. These combined effects of the reinforcements in the AlSi matrix contribute to a significantly improved wear behavior, making the hybrid composite a promising material for wear-critical applications. The subsequent sections of the paper will delve into the mechanisms and experimental findings that elucidate these effects in more detail.

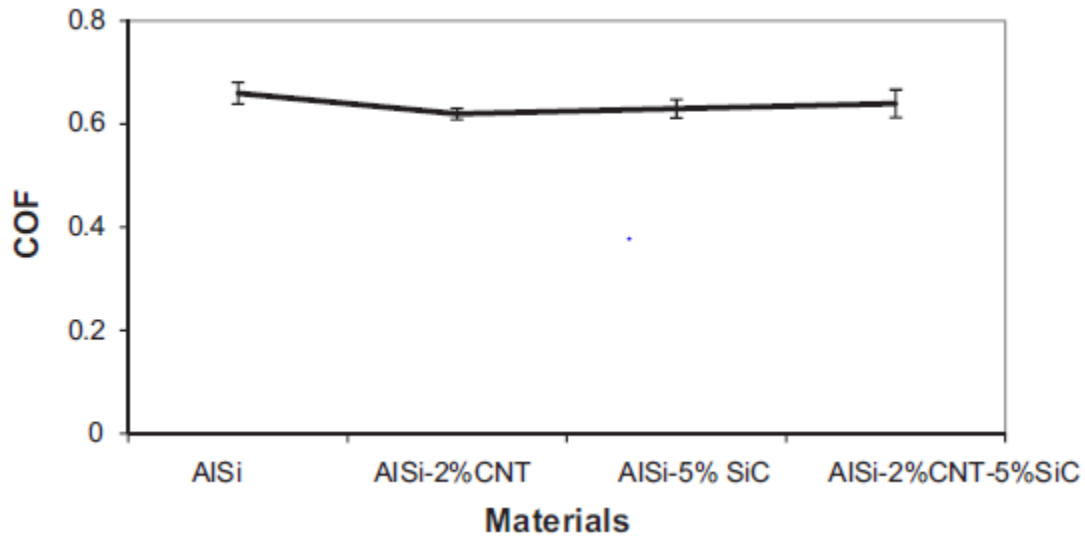


Figure 6. The mean Coefficient of Friction (COF) was calculated for both the unreinforced AlSi alloy and the Al–Si composites.

An important observation from this study is that the enhancement in wear resistance of all the studied AlSi composites (pins) also led to an improvement in the wear resistance of the opposing component in the sliding contact, namely the GCI plate. This practical benefit of improving wear performance for both parts involved in the tribological system is significant. Achieving an optimal operating condition of the entire system, referred to as tribosystem optimization, is highly desirable in practice. When the wear resistance of the pin and the GCI plate is improved simultaneously, it leads to reduced material loss, longer component lifespan, and decreased maintenance requirements, ultimately resulting in more efficient and cost-effective operations. By focusing on improving the wear characteristics of the AlSi composites, this study has successfully demonstrated the potential for enhancing the overall tribological performance of the tribosystem. This knowledge contributes to the pursuit of tribosystem optimization, where comprehensive improvements in wear behavior benefit both the individual components and the overall system, ensuring better functionality and longevity in real-world applications.

3.4. Coefficient of friction

Figure 5 illustrates the variation of the coefficient of friction (COF) with sliding distance in the case of the AlSi–2wt%CNTs–5wt%SiCp hybrid composite against GCI during a reciprocating sliding wear test. The COF evolution exhibits a typical pattern observed in such tests. Initially, there is a running-in regime where the surfaces of the materials adapt to each other, leading to significant changes in the COF over the initial sliding distance. During this phase, the COF increases as the sliding distance progresses. Following the running-in period, the COF reaches a steady-state condition where it remains relatively constant for the remainder of the test. In this phase, the tribological system has stabilized, and the COF maintains a consistent value as the sliding distance continues to increase.

This behavior in the evolution of the COF during the reciprocating sliding wear test provides valuable insights into the tribological performance of the AlSi–2wt%CNTs–5wt%SiCp hybrid composite against GCI. Understanding the running-in phase and the subsequent establishment of steady-state conditions is essential in assessing the composite material's wear behavior and its suitability for practical applications.

Figure 6 exhibits the average coefficient of friction (COF) for both the unreinforced AlSi alloy and the AlSi-composites. Notably, the COF values of the AlSi-composites demonstrate a slight decrease in comparison to the unreinforced AlSi alloy. Throughout this study, the COF values obtained for the AlSi-composites remain relatively consistent, with minimal variation among them. The decrease in COF for the AlSi-composites indicates improved frictional behavior and reduced resistance during sliding contact. This positive effect is attributed to the reinforcing action of the composites, whether they contain CNTs, SiCp, or both. The incorporation of these reinforcements appears to be beneficial, resulting in a more favorable tribological performance when compared to the unreinforced AlSi alloy. Importantly, the COF values obtained for the AlSi-composites remain stable and consistent, regardless of the variation in reinforcement type and content. This finding underscores the overall effectiveness of the reinforcement materials in enhancing the tribological characteristics of the AlSi matrix. As a result, these AlSi-composites show great promise for applications requiring improved wear resistance and reduced friction in practical engineering scenarios.

In the context of the slight decrease in the coefficient of friction (COF) observed with the addition of CNTs, a related study by the same authors [22] suggests that this behavior can be attributed to the presence of GCI as the counterpart material. The GCI contains a significant amount of free carbon, which may outweigh the potential contribution of carbon from the CNTs content in the composite. The CNTs in the composite play two significant roles in its tribological behavior. Firstly, they exhibit a self-lubrication effect, reducing friction during sliding contact. Secondly, they contribute to strengthening the Al matrix, enhancing the bonding between grains, as also confirmed by the mechanical properties results from another study by the same authors [21]. The CNTs' strong bonding with the Al matrix makes their removal more challenging, resulting in their resilience within the composite during wear tests.

Due to their specific shape and size, particularly CNTs that come from agglomerates, they have the potential to roll between the mating surfaces [41]. The presence of agglomerates may have a more pronounced effect on tribological properties if released into the contact. However, the shear forces acting during sliding can lead to the disaggregation of these agglomerations, allowing individual CNTs to roll into the sliding contact [41]. Once the CNTs are released into the sliding contact, they may act as a third body, contributing to the wear process. Despite the slight decrease in COF, the complex interplay between the self-lubrication and strengthening effects of CNTs and their potential role as a third body highlights the intricate nature of the tribological behavior of the AlSi–2wt%CNTs–5wt%SiCp hybrid composite against GCI. Further investigations are necessary to fully understand and optimize the tribological performance of the composite in practical applications.

The slight decrease in the coefficient of friction (COF) value observed in the case of AlSi alloy reinforced with SiCp, as compared to the unreinforced AlSi alloy, can be explained by considering two main mechanisms: adhesion and abrasion. In relation to adhesion, two factors contribute to the reduction of COF values. Firstly, the presence of hard SiCp increases the hardness of the matrix, resulting in less adhesion between the pin composites and the GCI plate. This effect arises due to the reduced tendency of the composite to stick or adhere to the GCI surface during sliding contact. Secondly, SiCp acts as load-bearing elements, providing protection to the matrix from wear during the tribological process. The presence of SiCp as load-bearing elements has been demonstrated in previous studies [26, 42], supporting its role in reducing adhesive wear.

As for the abrasion mechanism, it is expected that the COF values might be slightly higher due to the harder SiCp potentially penetrating the counter surface, as suggested in [23]. The increased hardness of the composite, attributed to the presence of SiCp, makes it more resistant to the cutting action of roughness peaks during sliding contact. Consequently, there may be more abrasion of the SiCp and the harder matrix, as stated in [15] by Zhou et al. Therefore, the combination of reduced adhesion and increased abrasion results in only a slight decrease in the COF value for the AlSi alloy reinforced with SiCp. Further analysis and morphological examination of the contact pairs will be presented later in the paper to better explain these mechanisms and their impact on the tribological behavior of the composite.

3.5. Wear mechanism—SEM and EDS analysis

3.5.1. GCI plates

Figure 7 presents scanning electron microscope (SEM) images of the worn surfaces of GCI plates after sliding against both the unreinforced AlSi alloy and the AlSi composites. These images provide a visual depiction of the wear patterns and surface changes that occurred during the sliding contact between the GCI plates and the different AlSi materials.

Figure 8 exhibits backscattered scanning electron microscope (SEM) images of the worn surface of GCI plates after sliding against the AlSi–2wt%CNTs–5wt%SiCp hybrid composite. Additionally, the image includes an energy-dispersive X-ray spectroscopy (EDS) spectrum

representative of the dark zones observed in the micrograph. The backscattered SEM images provide a detailed view of the worn surface, revealing the patterns and features resulting from the sliding contact between the GCI plates and the hybrid composite. The EDS spectrum, on the other hand, offers valuable information about the composition of the dark zones observed in the micrograph, aiding in the analysis of the chemical elements present on the worn surface.

Observing the worn surface morphology of GCI plates across the various materials studied in this investigation (as shown in Fig. 7), it becomes evident that although the dominant wear mechanisms appear to be similar, some notable differences can be highlighted.

Common wear mechanisms observed include the presence of abrasion grooves, which are attributed to the presence of reinforcement particles in the composites, and delamination marks resulting from the sliding contact. These features are indicative of the material removal and deformation processes during the tribological interaction. However, despite the shared wear mechanisms, the specific characteristics and patterns of abrasion grooves and delamination marks may differ among the different materials. These distinctions could arise from variations in the composition, microstructure, and mechanical properties of the composites. Additionally, the presence and behavior of reinforcement particles, such as CNTs and SiCp, may also influence the wear patterns observed on the GCI plates.

The presence of CNTs or/and SiCp at the mating surface leads to a noticeable reduction in GCI surface damage, as indicated by the increased extension of smooth plateaus observed in Fig. 7(a)–(d). The smooth plateaus on the GCI worn surface indicate areas where the damage has been mitigated due to the interaction with the composites. This reduction in surface damage can be attributed to the beneficial effects of the reinforcements present in the composites. The CNTs and SiCp act as protective elements, forming barriers and absorbing some of the wear-induced stresses during the sliding contact. As a result, the wear on the GCI surface is minimized, and the extent of smooth plateaus on the worn surface increases.

In the case of the hybrid composite (Fig. 7d), notable changes are observed in the worn surface morphology. The groove size appears to decrease in width, indicating a reduction in plastic deformation (abrasion) and delamination (adhesion) compared to the other materials (Fig. 7a-c). These observations align with the trends observed in the volume wear loss data of the GCI plates (Fig. 4), where there is a decreasing tendency in the volume wear loss when sliding against the unreinforced AlSi alloy and AlSi composites. The decrease in groove size and plastic deformation suggests that the presence of the hybrid composite has a protective effect on the mating GCI surface during sliding contact.

The combination of CNTs and SiCp in the hybrid composite seems to provide a synergistic effect, reducing wear-induced damages on the GCI surface. This finding is consistent with the overall improvement in tribological performance demonstrated by the hybrid composite, as evidenced by the reduced volume wear loss compared to other materials.

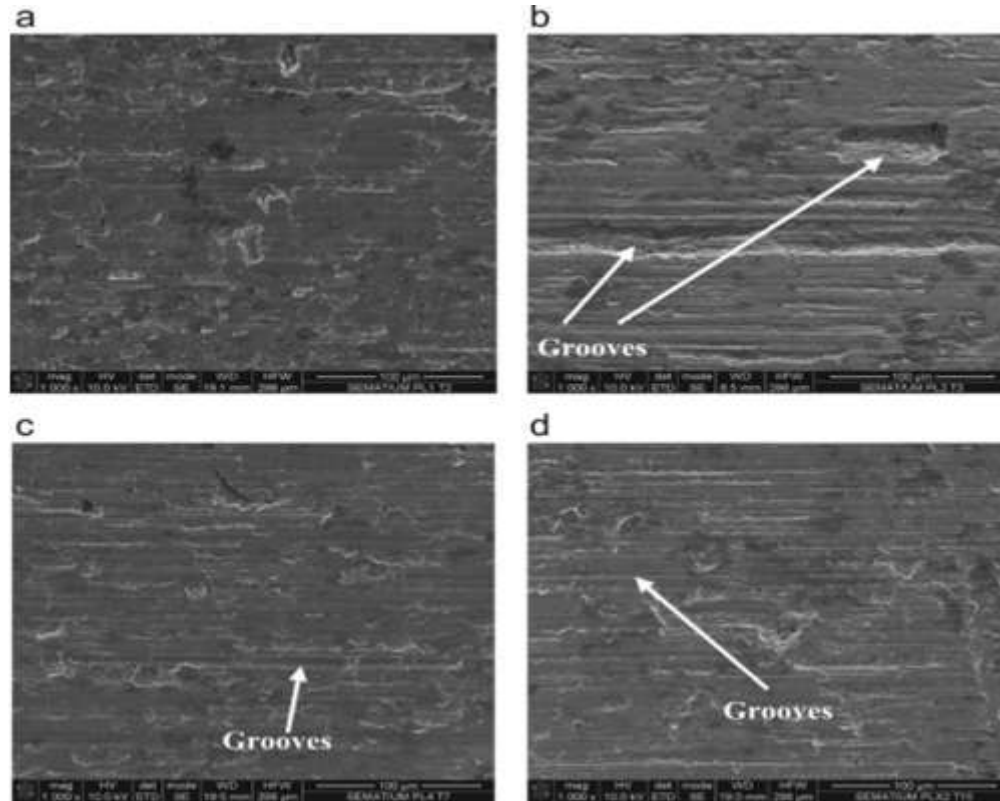


Figure 7. Scanning Electron Microscopy (SEM) images portraying the worn surfaces of Graphite Cast Iron (GCI) plates subsequent to sliding against AlSi-based pins: (a) Unreinforced AlSi Alloy; (b) AlSi–2wt%CNT; (c) AlSi–5wt%SiC; and (d) AlSi–2wt%CNT–5wt%SiC.

These results highlight the significant potential of the hybrid composite in enhancing wear resistance and reducing the adverse effects of sliding contact on the mating surface. The observed changes in the worn surface morphology provide valuable insights into the mechanisms and effectiveness of the reinforcement materials, supporting the feasibility of using the hybrid composite in wear-critical applications.

EDS analysis conducted on the dark zones (Z1) depicted in Fig. 8 provided valuable insights into the material transfer occurring between the pin counterface and the GCI plate. The analysis in zone Z1 revealed the presence of several elements: 19% oxygen (O), 59% aluminum (Al), 2% silicon (Si), and 20% iron (Fe).

The presence of oxygen indicates the likely presence of aluminum oxides on the worn surface. The transfer of Al and Si from the pin to the GCI plate suggests that the wear mechanisms of the GCI also involve adhesion, as evidenced by material transfer between the two surfaces during sliding contact.

In addition to Al, Si (originating from the matrix alloy), and O, the EDS analysis also detected the presence of Fe and C (from the GCI). The detection of Fe and C confirms the contribution of the GCI material to the wear process, as the counterface undergoes wear and interacts with the composite pin. The combined EDS analysis results highlight the complex

nature of the tribological interaction between the AlSi–2wt%CNTs–5wt%SiCp hybrid composite and the GCI plate. The transfer of materials between the pin and the GCI indicates the involvement of both adhesive and abrasive wear mechanisms during sliding contact. These findings further contribute to our understanding of the wear behavior of the hybrid composite and its interactions with the GCI plate, providing valuable information for optimizing tribological performance in practical applications. EDS analysis conducted on the dark zones (Z1) depicted in Fig. 8 provided valuable insights into the material transfer occurring between the pin counterface and the GCI plate. The analysis in zone Z1 revealed the presence of several elements: 19% oxygen (O), 59% aluminum (Al), 2% silicon (Si), and 20% iron (Fe).

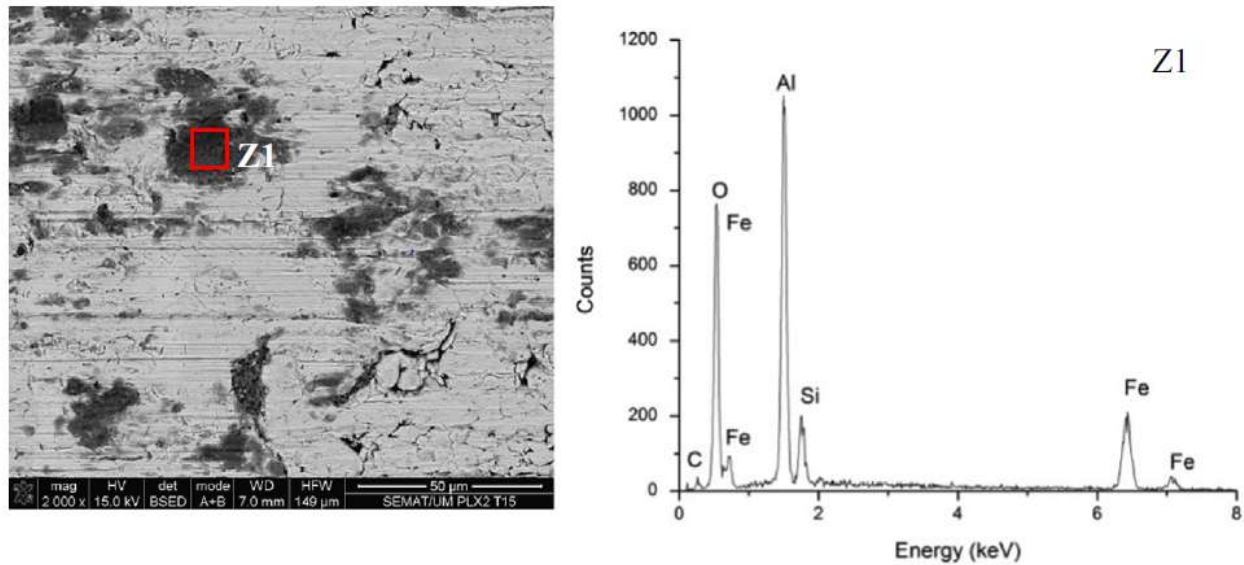


Figure 8. Backscattered SEM image depicting the worn surface of the Graphite Cast Iron (GCI) plate, accompanied by the Energy Dispersive Spectroscopy (EDS) spectrum, subsequent to sliding against the AlSi–2wt%CNTs–5wt%SiCp hybrid composite. This image is illustrative of the dark/grey zones observed within the micrograph.

The presence of oxygen indicates the likely presence of aluminum oxides on the worn surface. The transfer of Al and Si from the pin to the GCI plate suggests that the wear mechanisms of the GCI also involve adhesion, as evidenced by material transfer between the two surfaces during sliding contact. In addition to Al, Si (originating from the matrix alloy), and O, the EDS analysis also detected the presence of Fe and C (from the GCI). The detection of Fe and C confirms the contribution of the GCI material to the wear process, as the counterface undergoes wear and interacts with the composite pin.

The combined EDS analysis results highlight the complex nature of the tribological interaction between the AlSi–2wt%CNTs–5wt%SiCp hybrid composite and the GCI plate. The transfer of materials between the pin and the GCI indicates the involvement of both adhesive and abrasive wear mechanisms during sliding contact. These findings further contribute to our understanding of the wear behavior of the hybrid composite and its interactions with the GCI plate, providing valuable information for optimizing tribological performance in practical

applications. Based on the observed wear behavior and material transfer between the pin and the GCI plate, it can be concluded that the main wear mechanisms governing the wear of the plates are abrasion and adhesion.

The presence of hard reinforcement particles, such as CNTs and SiCp, in the AlSi composite leads to abrasion. These hard particles create abrasion grooves on the GCI plate during sliding contact, resulting in material removal and deformation on its surface. Additionally, the difference in hardness between the AlSi matrix and the GCI plate contributes to adhesion. The softer AlSi matrix is prone to adhere and transfer material to the GCI plate during sliding contact, further contributing to wear. The combination of both abrasion and adhesion mechanisms highlights the complex nature of the tribological interaction between the hybrid composite and the GCI plate.

3.5.2. AlSi composites (pins)

The SEM images in Fig. 9 display the wear surfaces of different materials: unreinforced AlSi alloy, AlSi-composites pins (Fig. 9 a1-d1), and the mating Graphite Cast Iron (GCI) pins (Fig. 9 a2, b2, c2, d2). The magnification used for these images is 130x

Fig. 10 presents higher magnification SEM images (1000x and 5000x) of the worn surface of an AlSi–2wt% CNTs–5wt%SiCp hybrid composite, enabling a detailed analysis of its microstructure and wear characteristics. Fig. 11 complements this by displaying the EDS analysis of distinct zones on the worn surface, revealing material composition and transfer from the mating GCI plate. These findings contribute to a better understanding of the hybrid composite's wear behavior and its interactions with the GCI mating plate in practical applications.

The analysis of scanning electron microscope (SEM) images of the worn surfaces (Fig. 9, magnification 130) illustrates a distinct contrast in the topography between unreinforced AlSi alloy and AlSi composites (Fig. 9 a1, b1, c1, d1). Notably, the worn surface topography of the unreinforced AlSi alloy (Fig. 9a1) exhibits a more uniform pattern when compared to the AlSi composite reinforced with carbon nanotubes (CNTs) (Fig. 9b1).

The analysis of scanning electron microscope (SEM) images of the worn surfaces (Fig. 9, magnification 130) illustrates a distinct contrast in the topography between unreinforced AlSi alloy and AlSi composites (Fig. 9 a1, b1, c1, d1). It observed variation in plateaus can be attributed to the incorporation of CNTs within the composite material, which introduces alterations in the surface topography during wear. Further insights and comprehensive information regarding the worn surface characteristics of both the unreinforced AlSi alloy and AlSi–CNTs composite can be found in the detailed study provided elsewhere [23]. This additional reference likely contains in-depth analysis and discussions on the specific mechanisms underlying the observed surface differences, offering a more comprehensive understanding of the effects of CNT reinforcement on the wear behavior of the composite.

The enhancement mechanism attributed to the presence of Carbon Nanotubes (CNTs) within sintered AlSi components operates by reinforcing the material, thereby leading to an augmentation in its strength [33,34,43,44]. This strengthening effect primarily manifests in regions where CNTs are uniformly distributed, particularly on the smoother plateaus of the surface.

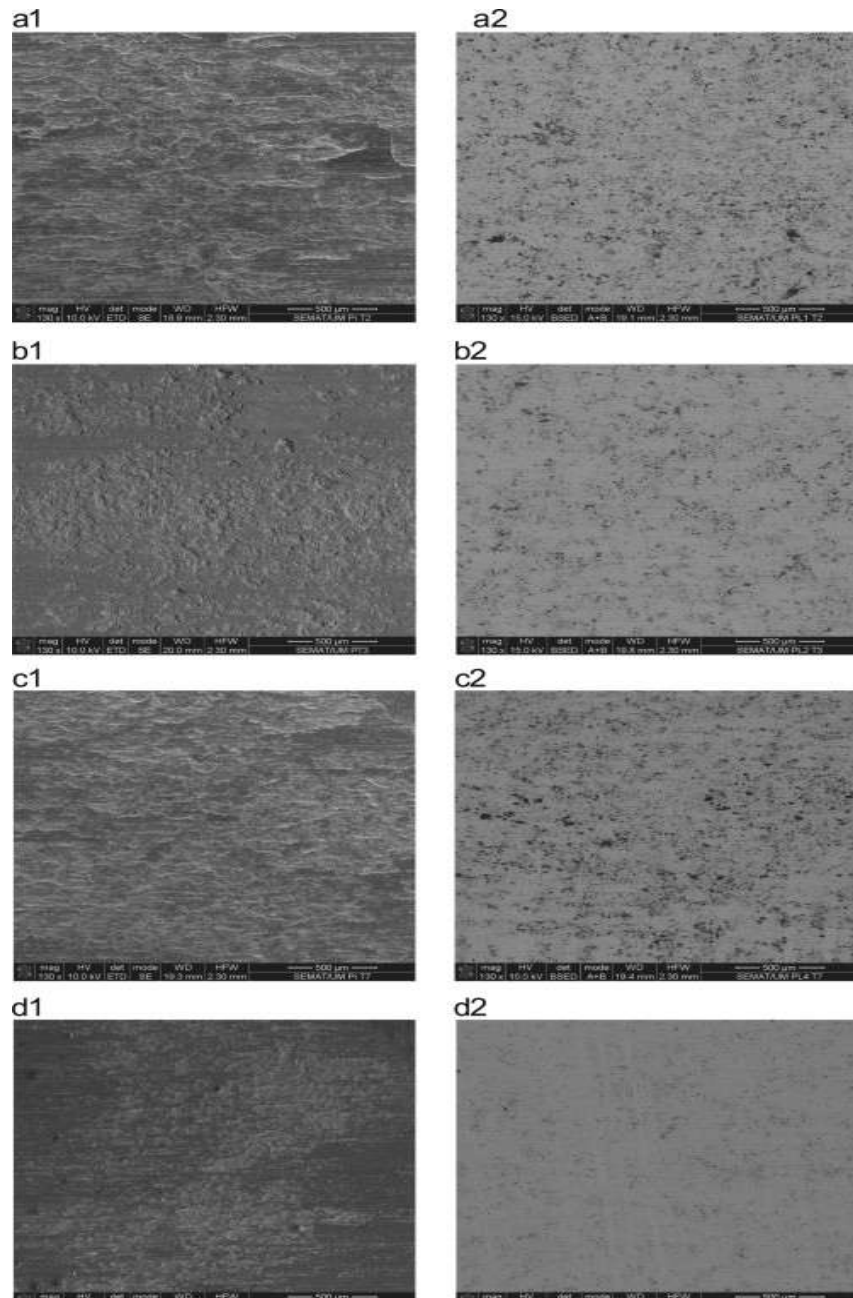


Figure 9. Scanning Electron Microscopy (SEM) images of the worn surfaces of AlSi-based pins (magnified at 130x) and the corresponding mating Graphite Cast Iron (GCI) plates (visualized using backscattered imaging): (a1/a2)—Unreinforced AlSi Alloy/GCI Plate; (b1/b2)—AlSi–2wt%CNTs/GCI Plate; (c1/c2)—AlSi–5wt%SiCp/GCI Plate; (d1/d2)—AlSi–2wt%CNTs–5wt%SiCp/GCI Plate.

Concerning the worn surface analysis of the AlSi–5wtSiCp composite (depicted in Fig. 9c1), it becomes evident that it bears a remarkable resemblance to the worn surface of the unalloyed AlSi alloy (illustrated in Fig. 9a1). The worn surface of the composite displays a substantial degree of plastic deformation; however, this deformation is comparatively lower when juxtaposed with the unreinforced AlSi alloy. Additionally, it is noticeably less pronounced than the plastic deformation observed in the AlSi–2wt%CNTs composite (as depicted in Fig. 9b1).

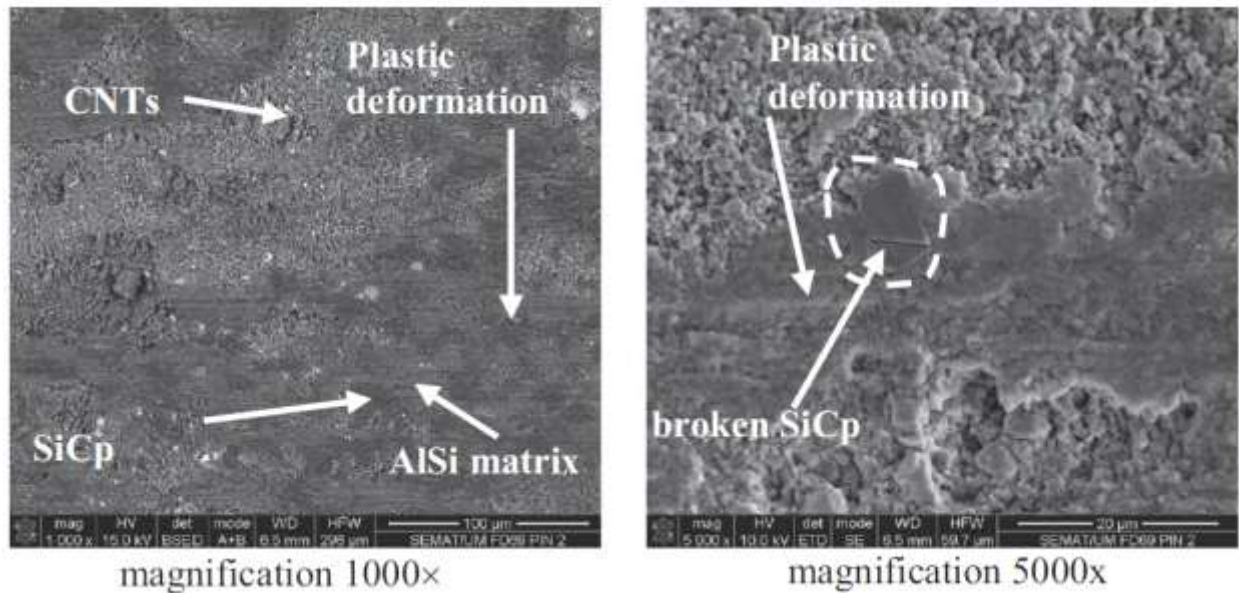


Figure 10. SEM images of the worn surface of AlSi–2wt%CNTs–5wt%SiCp hybrid composite.

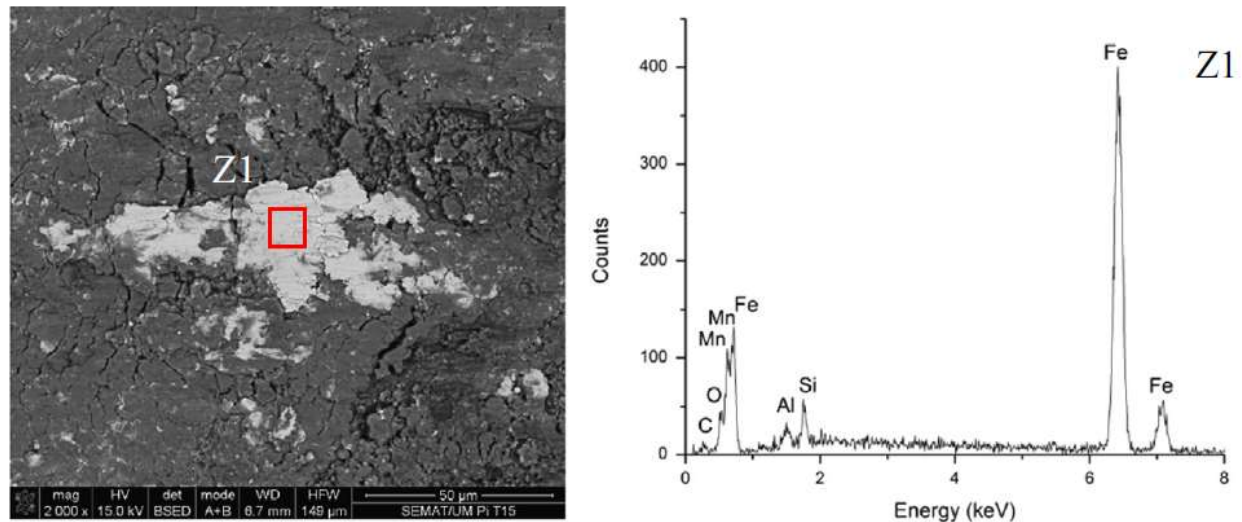


Figure 11. SEM image (backscattered view) and EDS spectra (corresponding to Z1) of 2wt%CNTs–5wt%SiCp hybrid composite.

Figure 2c underscores the presence of a SiCp cluster formation, which is identified as a potential weak point due to its diminished bonding strength. Consequently, this characteristic

renders the SiC particles more susceptible to detachment. While the detachment of particles, as a phenomenon known as the third body effect [5,25], can potentially elevate the abrasive wear in composite materials, our study reveals a distinct situation. This is because the detached SiC particles were effectively expelled from the sliding region by a consistent flow of air. Consequently, their impact on the wear behavior of the AlSi composite-based pins is anticipated to be inconsequential. This observation aligns with previous research [45], which has postulated that the mechanism of particle detachment amplifies the abrasive wear mechanism, consequently leading to heightened wear losses. In contrast to this notion, our findings indicate that the expulsion of detached particles from the sliding interface mitigates their influence on the wear performance of AlSi composite-based pins.

Observation of the worn surface of the hybrid composite AlSi–2wt%CNTs–5wt%SiCp (as depicted in Fig. 9d1) reveals the presence of plateaus resembling those observed in the context of the unreinforced AlSi alloy. These plateaus can be categorized into two distinct types: one characterized by smooth surfaces indicative of adhesive wear, and the other displaying a greater number of voids, characteristic of abrasive wear.

Evidently, a dynamic interplay unfolds between these two mechanisms—abrasive and adhesive wear—during the sliding process, as discernible from the competition apparent in Fig. 9d1. Notably, the region characterized by smoother plateaus corresponds to areas within the composite where the CNTs and SiCp are evenly dispersed throughout the AlSi matrix. Conversely, the rougher regions, while seemingly less prevalent, exhibit signs of material removal in the form of surface debris. Furthermore, the relatively more extensive presence of smoother plateaus in the AlSi–2wt%CNTs–5wt%SiCp hybrid composite might be attributed to the higher volume fraction of constituents in comparison to the AlSi–2wt%CNTs composite. This suggests that the hybrid composite benefits from a greater proportion of reinforcing components, contributing to the augmentation of these smoother plateaus.

It's noteworthy to acknowledge that the quantity of material transfer from the pin to the plate exhibits a reduction in the scenario of the AlSi–2wt%CNTs–5wt%SiCp hybrid composite, evident through the diminished presence of darker zones in the backscatter images (as depicted in Fig. 9d2). This contrasts with the situations observed in both the unreinforced AlSi alloy and the AlSi composites (as illustrated in Fig. 9a2, b2, and c2).

The hybrid composite exhibits a distinct absence of any observable pull-out mechanism, as evident from the observations in Fig. 10. Within Fig. 10, a debonded SiC particle is conspicuous, displaying signs of fracture as well. In comparison to the unreinforced AlSi alloy and AlSi composites, the level of plastic deformation discernible in the AlSi hybrid composite is notably lower. Simultaneously, an enhancement in wear resistance is observed in the AlSi hybrid composite (as depicted in Fig. 4) in comparison to the unreinforced AlSi alloy. Consequently, it is feasible to infer that the wear-induced damage in both the unreinforced AlSi alloy and the AlSi composites-based pins is primarily influenced by two fundamental mechanisms: abrasive wear, characterized by the delamination and pull-out of grains or particles, alongside adhesive wear that involves plastic deformation and the exchange of material between mating surfaces. In the

context of the AlSi hybrid composite, these mechanisms persist, albeit with the distinguishing factor of wear predominantly involving plastic deformation and material transfer between the mating surfaces.

The incorporation of dual reinforcements (Carbon Nanotubes and SiC particles) into the AlSi matrix appears to yield advantageous outcomes. In the AlSi-hybrid composite versus the unreinforced AlSi alloy and the AlSi alloy composites, a notable enhancement in wear resistance is evident within the AlSi-hybrid composite/GCI tribopair. As previously mentioned, the primary contributions of these reinforcements are as follows:

- **Strengthening effect of CNTs:-** The reinforcement offered by Carbon Nanotubes (CNTs) is primarily attributed to the strengthened bonding observed between the interfaces of AlSi grains. This phenomenon aligns well with several proposed mechanisms put forth in the literature. Notably, the work by George et al. [41] introduces concepts like thermal mismatch, Orowan looping, and shear lag theory, all of which seem to resonate with the observed strengthening effect. Similarly, the findings by Zang and colleagues [42] and Bustamante et al. [45] are also in concordance with this notion. However, it's important to note that the formation of CNT agglomerations can counteract this strengthening effect, leading to adverse consequences. These agglomerations are implicated in the initiation of voids within the material.
- **The self-lubricating attribute facilitated by Carbon Nanotubes (CNTs) is notable:-** During operation, both the individual CNTs and clusters of CNTs are released into the contact area. As shear forces come into play, these agglomerations undergo disintegration, resulting in the emergence of distinct, individual CNTs. These individual CNTs are then capable of assuming a rolling motion within the sliding contact, contributing to the self-lubrication mechanism.
- **The reinforcement effect brought about by Silicon Carbide particles (SiCp):** manifests in the matrix strengthening. The introduction of SiCp results in an augmentation of the composite's hardness, thereby contributing to its overall mechanical enhancement.
- **(Supporting load-bearing role: SiC particles serve as load-bearing elements, assuming a role in bearing the load during sliding. These particles effectively shield the AlSi matrix from direct contact with the GCI plate, preventing direct surface interaction.)**

Lastly, it's crucial to underscore the effectiveness of the approach centered on dual reinforcements, each operating through distinct mechanisms or functioning at varied scales (nano or micro). An illustrative instance pertains to the tensile strength enhancement through Carbon Nanotubes (CNTs) as reinforcement, where optimal strength was achieved at a 2% CNT concentration, as documented in a preceding study [21]. Similarly, the utilization of Silicon Carbide particles (SiCp) as reinforcement demonstrated a saturation point for tensile strength at a 5% reinforcement content. Consequently, elevating the reinforcement content in both scenarios could potentially bolster wear resistance; however, this elevation would correspondingly lead to a significant reduction in tensile strength. Moreover, it was observed that attaining the peak

tensile strength through one type of reinforcement (such as CNTs) opened up the possibility of further enhancing tensile strength by introducing an additional reinforcement type (like SiCp). This strategic combination of reinforcements presented an avenue for maximizing the material's mechanical properties.

In conclusion, it can be deduced that employing a dual reinforcement strategy, either through the convergence of distinct reinforcement mechanisms or through the integration of mechanisms operating at differing scales, offers the potential to yield superior comprehensive properties in comparison to relying solely on a single reinforcement approach. Therefore, the utilization of hybrid composites, as presented in this study, stands out as a promising avenue for achieving enhanced overall material properties.

CONCLUSIONS

Based on the comprehensive analysis conducted on the sliding wear characteristics of AlSi composites/GCI tribopairs, the following key conclusions can be ascertained:

- AlSi-2wt%CNTs, AlSi-5wt%SiCp, and AlSi-2wt%CNTs-5wt%SiCp reinforced composites were effectively fabricated using the hot pressing technique.
- The hardness of all the generated AlSi composites exhibited a noticeable enhancement, with the hybrid composite displaying the highest hardness compared to both the unreinforced material and the other composites. This heightened hardness within the hybrid composite was attributed to the combined reinforcing effects of both CNTs and SiCp.
- Both the AlSi-2wt%CNTs and AlSi-5wt%SiCp composites demonstrated an enhancement in wear resistance in contrast to the unreinforced AlSi alloy. The wear performance of these AlSi composites is fundamentally influenced by abrasive wear mechanisms involving the delamination and pull-out of grains or particles, as well as adhesive wear characterized by plastic deformation and material transfer between mating surfaces.
- Incorporating both reinforcements, Carbon Nanotubes (CNTs) and Silicon Carbide particles (SiCp), into the AlSi matrix led to an enhanced wear resistance in the AlSi-2wt%CNTs-5wt%SiCp hybrid composite, surpassing the performance of individual AlSi composites. Within the AlSi hybrid composite, the wear dynamics are predominantly influenced by two fundamental mechanisms: abrasive wear and adhesive wear.
- The investigation demonstrates that through the dual reinforcement of AlSi alloy, the wear performance of the tribopair (consisting of AlSi-hybrid composite/GCI) is markedly enhanced in comparison to the unreinforced AlSi/GCI and AlSi alloy-composites/GCI tribopairs. This improvement can be attributed to a series of reinforcing mechanisms, including the strengthening effect of Carbon Nanotubes (CNTs), the self-lubrication impact of both individual CNTs and CNT clusters, the reinforcement role of Silicon Carbide particles (SiCp), and the load-bearing function of SiC particles.

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