The Effect of Different Fly Ash and Vanadium Carbide Contents on the Various Properties of Hypereutectic Al-Si Alloys-Based Hybrid Nanocomposites

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Abstract
In the current work, a hybrid nanocomposite Al-Si matrix was fabricated using the powder metallurgy method. Due to their superior mechanical strength, formability, and durability, aluminum composite matrices have considered attractive materials for structural and advanced applications. The incorporation of fly ash (FA) as one of the cheapest and lowest density reinforcement available during the combustion process with high-density ceramic particles such as vanadium carbide (VC) has significant benefits in the production process of such composites. The hybridization of VC and FA nanoparticles with different weight percentages were used to reinforce the Al-Si matrix under various sintering conditions. A scanning electron microscopy (SEM) and diffraction particle size analyzer were utilized to examine the microstructure of the prepared powder and particle size. In addition to the mechanical and physical properties, the wear and corrosion resistance were investigated for the fabricated samples. The results revealed that the addition of 10 wt.% VC and 10 wt.% FA nanoparticles caused a decrease in the Al-Si alloy particle sizes up to 47.8 nm and act as a barrier for dislocation movement. Also, the microhardness, yield strength, and ultimate compressive strength were enhanced by 75, 42 and 38%, respectively. Moreover, there was an increase of about 25% in the ultrasonic longitudinal and shear velocities, thus showing a significant improvement in the elastic moduli group of about 50%. Finally, the addition of VC and FA particles significantly affected the wear and corrosion resistance; hence, they increased by 40 and 67%, respectively.

Keywords Al matrix · Hybrid nanocomposites · Powder metallurgy · Strength · Wear rate · Younge’s modulus · Corrosion

1 Introduction
Aluminum composite materials (ACM) are increasingly being used in various applications, including airplanes, spacecraft, cars, and other sectors. Aluminum oxide, boron carbide, silicon carbide, and other fine ceramics particulates are commonly used to reinforce the aluminum matrix to improve the different properties of the resultant composites. Hence, the high elasticity modulus, durability, wear resistance, and low linear thermal expansion coefficient of ceramic particle reinforced ACM distinguishes it from other ACM materials [1–7]. When two or more reinforcements are added to this alloy, the resulting hybrid nanocomposite achieves superior properties such as outstanding mechanical properties, wear behavior, and thermal expansion coefficients [8, 9]. Hypereutectic Al-Si alloy is the preferred material as production matrix (ASMCs) reinforced with ceramic particles. The reasons behind Al-Si alloy being considered the best choice as a matrix for such desirable nanocomposites are its low ductility coupled with high strength compared to pure Al and fair resistance to corrosion in air [9, 10]. To further improve the corrosion resistance of Al-Si alloy, some corrosion inhibitors can be added to modify the neighboring environment. Notably, these corrosion inhibitors include alloying elements, anodizing the surface, and painting their surfaces with a protective coating layer [11, 12].
Several studies have investigated the properties of Al and Al alloy matrix nanocomposites. For example, Rohatgi et al. [13] found a slight increase in hardness, tensile strength and wear resistance of Al based composites reinforced by FA. Raju and Kumar [14] investigated the mechanical properties of Al/FA composites prepared by stir casting method. The hardness of the composite was increased by about 15% after adding 25 wt.% FA. Soy et al. [15] used the pressure infiltration method to produce Al-SiC-B₄C composites and studied the influence of both SiC and B₄C on the mechanical and tribological properties of Al matrix hybrid composites. The results showed the hardness increases about 83% after addition of 17 wt% SiC and B₄C. Moreover the wear rate reduced to about 79% compared to the pure Al. Shanmughasundaram et al. [16] studied the mechanical behaviour of Al-Si Alloy–Al₂O₃-graphite hybrid composites. The results showed a clear improvement in hardness about 44% with adding 5 wt.% Al₂O₃ and 7.5 wt.% graphite. Baradeswaran et al. [17] used the liquid casting method to produce Al matrix hybrid nanocomposites reinforced with boron carbide and graphite particles. The results showed a clear improvement in nanocomposite hardness and wear rate with increasing reinforcement contents. Ashrafi et al. [18] studied the effect of Fe₃O₄ and SiC reinforcements on the microstructure, tribology, and corrosion properties of the Al matrix. They observed a clear improvement in the coefficient of friction and the corrosion rate with reinforcements.

According to the authors’ knowledge, this study is possibly the first attempt to improve the different properties of Al-Si alloy using the combination of vanadium carbide (VC) and fly ash (FA) as reinforcements particles to produce Al matrix hybrid composites using the powder metallurgy technique. Regarding the previous literature, which confirms that FA has tremendous potential to strengthen aluminum matrix composite (AMC) with a maximum volume fraction that not exceeds 12%, but the other properties may be affected when the volume fraction increased. In the same vein, the carbides ceramic particles tend to increase the hardness and wear resistance behavior, while the density of the fabricated composite will increase. From this point, the hybridization of low and high-density reinforcement particles enhances the mechanical properties and the corrosion and wear resistance of the resultant composite. By incorporating hybrid reinforcing particles with different properties and morphology, it achieves the balance between the variation in their properties and their reflection on the outcome characteristics of the nanocomposite matrix.

2 Materials and Experimental Setup

In this work, the Al356 alloy was chosen as the matrix, while VC (< 75 nm) and FA (< 80 nm) particles were used as reinforcements with various weight percentages. The composition of Al-Si alloy and FA were listed in Tables 1 and 2, respectively, while the batch compositions designed for the nanocomposites with the Al-Si alloy matrix, along with their abbreviations, were tabulated in Table 3. The nanocomposites powders were subjected to the milling process for 20 h with rotation speed = 550 rpm and BPR = 20:1 having in mind that the milling process was done in a cycle of 2 h and paused for 2 h. To investigate the morphology of the mechanically alloyed powders, they were characterized using scanning electron microscopy (SEM; Philips XL30). Moreover, particle size was measured using a diffraction particle size analyzer to get the average distribution pattern for each powder. Then, the milled powders were pressed and sintered at 500 and 575 °C in an argon atmosphere for 1 h. Notably, the rule of the mixture was carried out to calculate the theoretical densities of samples taking into account the density of the Al-Si alloy, VC and FA = 2.67, 5.77 and 2.34 g/cm³, respectively. On the other hand, Archimedes method was carried out to measure both bulk density and apparent porosity. The microstructure of the sintered samples was examined by scanning electron microscopy. Vickers microhardness (HV) was measured with a Shimadzu-HMV (Japan) according to ASTM: B933–09 as described in Ref. [19]. Furthermore, the compressive tests of the sintered nanocomposites were performed according to ASTM E9–19 standard. The ultimate strength, yield strength, and elongation were calculated from the stress-strain curve; hence, the ultimate strength and elongation are the maximum stress-strain values and strain on the stress-strain curve. On the other hand, yield strength was calculated using the 0.2% offset principle. Using the pulse-echo technique, longitudinal (Vₐ) and ultrasonic shear velocities (Vₛ) were measured. On the opposite side, constants of Lamé’s (i.e. λ and μ) were calculated according to the formula present in Refs. [20, 21]:

\[
\lambda = \rho (V_a^2 - 2V_s^2) \tag{1}
\]

\[
\mu = \rho V_s^2 \tag{2}
\]

The elastic modulus (L), Young’s modulus (E), shear modulus (G), bulk modulus (B) and Poisson’s ratio (ν) of the nanocomposites were calculated by equations [22, 23]:

\[
L = \lambda + 2\mu \tag{3}
\]

\[
G = \mu \tag{4}
\]

| Table 1 Chemical composition of A356 alloy (wt%) |
|---------|---------|-------|-------|-------|-------|-------|-------|
| Si      | Mg      | Fe    | Zn    | Cu    | Mn    | Al    |
| 6.9     | 0.32    | 0.2   | 0.1   | 0.08  | 0.09  | balance |
The wear test was performed using a pin-on-disk tester machine; the specimens were weighed and measured by a digital balance of accuracy of 0.0001 g. All samples were prepared with the same dimensions and polished well using grinding papers with different grades (600 to 4000). The test was carried out using four different loads. The wear rate due to the weight loss was calculated from the following equations (Eq. 8 and 9) [24]:

Net weight = weight before wear−weight after wear (8)
Wear rate = net weight/time (9)

The sintered samples’ corrosion rate was determined using the static immersion weight loss method at room temperature, where each sample was weighed before its immersion in 0.1 M HNO3 solution and later taken out after 24, 48, 72, 96, 120 and 144 h. After drying thoroughly, the specimens were weighed again. The weight loss was measured and converted into corrosion rate expressed in mm penetration per year (mm/year).

### 3 Results and Discussion

#### 3.1 Milled Powders

Figure 1 (a-e) illustrates a considerable difference between the microstructure of Al-Si alloy and the powders of its nanocomposites with different VC and FA contents after milling for 20 h. The most likely explanation for such observations is that during mechanical milling, the Al-Si alloy matrix particles are subjected to deformation (flattening), while both VC and FA particles undergo fragmentation. When the particles of Al-Si alloy matrix (ductile particles) start to weld, the reinforcement particles come between two or more matrix particles at the moment of ball collision. As a result, the reinforcement particles reside at the interfacial boundaries of the particles of the welded matrix, and the result is the formation of true nanocomposite powders [25]. Interestingly, these decreases in particle sizes due to increased local plastic deformation in VC and FA particles. Moreover, the ceramics particles act as milling balls and can cause a higher energy transfer to the Al-Si alloy matrix.

The particle size distribution of the milled powders samples as shown in Fig. 2. As the VC and FA content increased, the particle size decreased and the distribution shifted to smaller sizes. The mean particle sizes of the Al0, Al5, Al10, A15, and Al20 samples were 94.8, 87.7, 74.3, 61.2, and 47.8 nm, respectively.

#### 3.2 Physical Properties

It is well-known that pressing milled nanocomposites powders is an important step for obtaining bulk materials after the mechanical alloying process. Therefore, this step controls the porosity and the shape of the final sintered nanocomposites [26]. The bar graph that explains the relative density and apparent porosity of the sintered samples for 1 h at 500 and 575 °C as a function of VC and FA weight percentages is represented in Fig. 3. By considering the theoretical densities of Al0, Al5, Al10, A15, and Al20 samples = 2.67, 2.697, 2.724, 2.752, and 2.775 g/cm3, respectively, the values of the relative densities of A10 and Al20 after sintering at 500 °C are 93.69 and 86.11%, respectively. On the opposite side, the apparent porosity is 5.18 and 9.460%, respectively, for the same samples. This result may be because increasing the weight percentages of reinforcement in the Al-Si alloy matrix leads to a decrease in the pressing capacity of the sintered samples because of the higher hardness of the reinforcement particles. Moreover, the melting point of the VC and FA reinforcement (= 2810 & 1710 °C, respectively) is much more than that of the Al matrix, and hence, the contents of the increased reinforcement have an inhibitor effect of the

| Table 2 Chemical composition of fly ash (wt.%) |
|-----------------------------------------------|
| Element | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | MgO | SO₃ | K₂O | Na₂O | TiO₂ | L.O.i |
| wt.%    | 60.85 | 20.84 | 6.69 | 3.87 | 1.34 | 0.98 | 1.17 | 0.74 | 0.58 | 2.94 |

| Table 3 Batch design of the investigated Al356/VC/fly ash nanocomposites |
|--------------------------------------------------|
| Sample  | Al356 | VC  | Fly ash |
|---------|-------|-----|---------|
| A10     | 100   | 0   | 0       |
| A15     | 95    | 2.5 | 2.5     |
| A110    | 90    | 5   | 5       |
| A115    | 85    | 7.5 | 7.5     |
| A120    | 80    | 10  | 10      |

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Fig. 1 SEM micrographs of the milled powders (a) Al0, (b) Al5, (c) Al10, (d) Al15 and (e) Al20 samples

Fig. 2 Particle size distribution of the milled powders in various VC and FA contents
sintering process and consequently act as a barrier against diffusion steps during this process [27].

On the contrary, increasing the sintering temperature from 500 to 575 °C has an effective role in improving the relative density due to the formation of necks between particles and increasing bonding between particles [28]. Moreover, the increased sintering temperatures lead to an acceleration of solid-state diffusion and, consequently, better densification behavior [29]; when the sintering temperature = 575 °C, the relative density of the samples decreases from 97.48 to 92.21% by increasing the reinforcement contents from 0 to 20 wt.%.

3.3 Microstructure

Figures 4 illustrated the SEM images of nanocomposites with different VC and FA contents and sintered at 570 °C in an argon atmosphere. Generally, VC and FA particles are found at the matrix’s grain borders, considering the sample has the lowest reinforcements content (Al5) exhibits somewhat homogeneous distribution for FA and VC particles noting that this distribution decreases with increased reinforcements contents (Al20). Notably, it was also observed that the porosity increased by increasing reinforcement particles in the studied specimens. However, the elevation of sintering temperature to 575 °C causes promotion for diffusion process during the heating process, resulting in better densification behavior, i.e., nearly reaching full density. The contact border between particles seems to be growing and indicates the achievement of strong reinforcements matrix interfacial bonding during sintering of the nanocomposites samples and the absence of pores in the area of reinforcements particles.

3.4 Elastic and Mechanical Properties

The longitudinal ($V_L$) and shear ultrasonic velocities ($V_S$) results were measured using a non-destructive test, i.e. ultrasonic technique for samples sintered at 575 °C as shown in Fig. 5. It is interesting to see that ultrasonic velocities increase by increasing VC and FA contents. The figures indicate that as the reinforcement contents increased from 0 to 20 wt.%, the $V_L$ and $V_S$ values of the samples range from 5503.32 to 6885.29 and 2871.08 to 3501.04 ms$^{-1}$, respectively. As can be seen from Fig. 6, the elastic moduli exhibit the same trend for ultrasonic velocities. For example, in the Al0 sample (i.e.,

![Image 1](attachment:image1.png)

**Fig. 4** SEM micrographs of a) Al0, b) Al5 and c) Al20 samples sintered at 575 °C.
the free content of CV and FA particles), the elastic modulus and Poisson’s ratio are 80.87 GPa and 0.3130, respectively. Interestingly, they increase to 131.45 GPa and 0.3256, respectively, when VC and FA refinement increases to 20 wt.% (Al20). This marked improvement of ultrasonic velocities and elastic moduli due to the addition of highly hard nano-reinforcement particles as reinforcement and fully corresponds to the precise results of microhardness and compressive strength.

The average microhardness values of the Al-Si alloy and nanocomposite samples sintered at 575 °C are presented in Fig. 7. It is noted from the results that pronounced increase in the values of microhardness with increasing the different contents of VC and FA particles. The microhardness of the Al-Si alloy matrix increases from 68.17 to 119.21 Hv as a result of the addition of 10 wt.% VC and 10 wt.% FA particles. Generally, the increase in nanocomposites samples’ microhardness can be attributed to various reasons, including homogenous distribution of reinforcement in the matrix, decreased grain sizes of the matrix with successive increases in reinforcement contents, and the existence of hard ceramic particles (i.e., VC & FA) [13]. This enhancement can be better understood by noting the following Eqns. (10) [30].

\[ H_c = H_{Al}F_{Al} + H_VF_V + H_FF_F \]  

where \( H_c \), \( H_{Al} \), \( H_V \), and \( H_F \) are microhardness of the nanocomposite, Al-Si matrix, VC and FA, respectively. On the other hand, \( F_{Al} \), \( F_V \), and \( F_F \) are the volume fractions of matrix VC and FA. Figure 8 shows the compressive stress-strain curves of samples. It can be observed that, for the same sintering temperature, Al-Si alloy (Al0) has a lower yield strength (\( \sigma_y \)) and ultimate compressive strength (\( \sigma_{ucs} \)), and higher elongation (\( \varepsilon \)) than the other nanocomposite samples. From the graphs obtained from the compression tests of the sintered samples, the values of \( \sigma_{ucs} \), \( \sigma_y \), and \( \varepsilon \) were calculated and shown in Fig. 9. According to the results, both \( \sigma_{ucs} \) and \( \sigma_y \) of all nanocomposites samples gradually increase, while elongation reduces with increasing VC and FA contents, which agree with the observed trend in their microhardness results as shown in Fig. 7. The \( \sigma_{ucs}, \sigma_y, \varepsilon \) are 278.72 MPa, 119.54 MPa, 11.1% for Al0, respectively, and for Al20 were 384.46 MPa, 170.61 MPa, 6.02%, respectively. Generally, many factors are responsible for the increases in ultimate and yield strength, while the decreases in the elongation of Al alloy matrix reinforced with different reinforcement content is influenced by the following factors:

(i) Thermal-mismatch strengthening

Thermal mismatch strengthening is related to the large difference between the CTE of Al-Si alloy matrix, VC, and FA particles, contributing to producing thermally induced residual stresses [31]. Even with small temperature changes, the thermal stresses generated in the Al-Si alloy matrix significantly contribute to high dislocation density in the vicinity of the interface and, therefore, strengthen the nanonanocomposite.

(ii) Orowan strengthening

The Orowan strengthening effect plays a vital role in enhancing Al-Si matrix nanocomposites’ mechanical properties, resulting from homogenous dispersion of hard VC and FA phase into Al alloy matrix, which acts as a barrier for dislocation movement. Consequently, dislocation loops are created around reinforcement particles, causing an increase in the stress required for more deformation.

(iii) Load transfer from the Al alloy to the VC and FA nanoparticles

During compressive testing, the load transfer, \( \sigma_{load} \), between the hard ceramics particles and Al-Si alloy, especially if the connection between reinforcement particles and Al-Si alloy matrix is good enough, as explained by Eq. (11) [32]:

\[ \sigma_{load} = 0.5V_f\sigma_Y \]  

where \( \sigma_Y \) is the yield strength of the matrix.

It can be concluded that the work hardening capacity (\( H_c \)) of samples is reduced by adding various reinforcement contents, as shown in Fig. 9(b). The \( H_c \) of nanocomposites samples can be calculated using the value of \( \sigma_{ucs} \) and \( \sigma_Y \) according to Eq. (12):

\[ H_c = \frac{\sigma_{ucs} - \sigma_Y}{\sigma_Y} \]  

It is interesting to observe that \( H_c \) of pressed nanocomposites decreases with the increase in the ceramics particle
content. The nanocomposites’ Hc depends on its yield strength, which is further correlated to grain sizes based on the Hall–Petch Equ. If the grain sizes decrease, the difference in the flow resistance between the grain boundaries is also reduced, leading to increased yield strength, leading to decreased work hardening [33].

Several authors have previously studied the effect of the content of hybrid reinforcement on the mechanical properties of Al or Al alloy matrix composites. For example, Shaikh et al. [34] have studied the effect of SiC and FA particles with different contents on the hardness of Al and they found that the maximum value obtained was 62 GPa. Kumar et al. [35] studied the effect of different contents of SiC and graphene on the hardness of Al-Si alloys. They found that the maximum value obtained was about 100 Hv.

3.5 Wear Analysis

Figure 10 represents the variations in weight loss and wear rate of Al0, Al5, Al10, Al15, and Al20 samples with different applied loads of test (10, 20, 30, and 40 N). The results point out that nanocomposites samples’ wear resistance tends to increase with an increase in VC and FA contents, while it is decreased with increasing of the load. The weight loss of an
The weight loss of the un-reinforced sample (i.e. Al0) at applied loads, i.e. 10, 20, 30, and 40 N, is 12.78, 13.48, 13.89, and 14.51 mg, respectively. For the sample containing 20 wt.% of reinforcement (i.e., Al20) at the same applied loads, the weight loss is 7.15, 7.78, 8.39, and 8.73 mg, respectively. Furthermore, the wear rate of Al0, Al5, Al10, Al15 and Al20 samples when the applied load equals to 40 N is 0.0242, 0.0211, 0.0183, 0.0166, and 0.0145 mg/s, respectively. Undoubtedly, the addition of ceramics particles (i.e., VC and FA) has a positive outcome in the synthesized nanocomposites in which wear resistance is found to be effectively improved [36]. To explain the enhancement of wear resistance of nanocomposites, it is important to highlight that the addition of VC and FA particles to Al alloy results in an enhancement in nanocomposites’ microhardness and strength samples as previously discussed, and therefore, the wear rate decreases according to Archad Eq. (13) [37]:

\[ W = \frac{kP}{H} \]  

(13)

W is wear rate, K is a wear coefficient (constant value), P is the load, and H is the specimen’s Vickers hardness.

Furthermore, the increase of microhardness is consistent with a decrease in a real area of contact. It is well-accepted that real area of contact can be expressed in terms of the ratio of the normal load to the hardness of the pin material, and accordingly, decreased real area of contact leads to considerable decreases in wear rate [38]. On the other hand, increases in weight loss and wear rate with increases in the applied load and the surface temperature encourage surface softening, causing more surface and subsurface damage, resulting in decreased wear resistance [39]. One can say that both wear and loss of metals are highly dependent on an increase in the load as the initial friction period works to fracture the surface layers, leading to cleaning the surfaces and increasing the strength of connections between surfaces. This process increases the tillage effect between surfaces, which increases the temperature between them, resulting in adhesion and deformation at the surface layers, driving more loss for metals [40].

In this work, we also made sure to compare the results obtained with similar work by other researchers. Reddy et al. [41] revealed that the addition of B₄C and FA was effective to improve the wear rate of Al alloy by 33.33%. Celik and
Kilickap [42] investigated the effect of B₄C and SiC, up to 16 wt.%, on the wear behavior of Al. They revealed that this addition was very helpful in reducing weight loss to 40%.

### 3.6 Corrosion Analysis

The weight-loss method was used to evaluate Al-Si or nano-composites specimens’ corrosion behavior in an acidic medium. Generally, many factors affect the studied nanocomposites’ corrosion behavior, such as compaction, density, sintering, and weight percentages of VC and FA. In this sense, the weight loss and corrosion rate of Al0, Al5, Al10, Al15, and Al20 sintered samples were immersed in a 0.1 N HNO₃ at room temperature (30 °C), as a function of exposure time were examined and represented in Fig. 11. It is interesting to observe that Al alloy matrix nanocomposites’ weight loss increases with increasing exposure time, and therefore, the corrosion rate decreases. The weight loss of the sample increases with increases in exposure time because increasing contact period with acidic medium decreases in corrosion rate [43]. The weight loss of Al0 sample immersed for 24, 96, and 168 h are 12.24, 22.78, and 31 mg, respectively, and for sample Al20, at the same immersion times, is 8.08, 14.40, and 18.52 mg, respectively. It could also be observed that both weight loss and corrosion rate decrease by increasing VC and FA contents. Generally, the particles of ceramic reinforcements remain the same, i.e. without a noticeable corrosion behavior, and consequently, the existence of ceramics particles in the surface of the nanocomposite samples that will protect the surface layer in the acidic medium [44]. The Al0 sample shows that the corrosion rate is higher compared to the Al20 nanocomposite samples. This result is that VC and FA are a ceramic material that possesses high corrosion resistance, i.e. it remains inert and unaffected by the acidic medium throughout the corrosion tests. The corrosion rate of Al0, Al5, Al10, Al15, and Al20 samples submerged for 168 h are 1.27, 1.18, 1.06, 0.90, and 0.77 mmpy, respectively. Unfortunately, the corrosion behavior of Al hybrid nanocomposites has not been studied before. Therefore, in comparison with the literature [43], adding 12% Si and 10% ZrC to Al was effective to reduce the corrosion rate by 21%.

### 4 Conclusions

In the current study, the VC and FA enhanced Al-Si hybrid nanocomposites were prepared using powder metallurgy. The following conclusions were drawn:

- It was observed that the nanocomposites prepared by the method of mechanical alloying had a good distribution of VC and FA particles in a matrix with noticeable agglomerations.
- The particle sizes decreased with increasing the weight percentages of VC and FA particles until they reached 47.8 nm for the higher contents of the reinforcement (Al20 sample).
- The relative density of the nanocomposite decreased with increasing the contents of reinforcements, while the apparent porosity had an opposite trend.
- The ultrasonic velocities of the sintered samples increased with the increase in FA and VC contents, which led to an increase in the value of the elastic moduli. The elastic and bulk moduli were enhanced to 61 and 66%, respectively, after adding 20 wt.% of reinforcements (Al20).
- Microhardness, ultimate, and yield strength were improved, while elongation and work hardening were reduced by increasing the reinforcement weight percentages. The maximum values of the microhardness and ultimate strength of the Al20 sample were recorded, i.e., ~1.7 and 1.4 times, respectively, higher than those of the Al0 sample.
- The wear rates of specimens decreased as the contents of the reinforcements increased with an increase in the

![Fig. 11](https://example.com/fig11.png)

**Fig. 11** a) Weight loss and b) corrosion rate of specimens sintered at 575 °C for different exposure time
application. For the applied load of 10 N, the wear rate of the Al-Si alloy decreased by about 44.1% for the sample Al20.

- The wear rate of nanocomposites is reduced by increasing the exposure time and weight percentages of ceramic reinforcements.

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