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Evaluation of Mechanical Properties of Al -7005/Red Mud and Phosphogypsum Hybrid Composites

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Keywords:

Al-7005 alloy; Composite materials; Mechanical properties; Phosphogypsum; Red-mud; Stir casting.

Highlights:

- *Stir casting was an effective technique for creating aluminum-based MMCs.*
- *Red mud (5%) and phosphogypsum (5%) were used as reinforcing agents.*
- *Tensile strength, hardness, and impact resistance were all enhanced by reinforcement, and the composite's wear rate was considerably reduced.*
- *Combined phosphogypsum and red mud provided better performance than using them individually.*

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Abstract: In this work, an aluminum-based metal matrix composite has been manufactured. Then, its microstructure and mechanical properties, such as tensile strength, hardness, impact strength, and wear rate, have been studied. Additionally, a modest attempt has been made in the present work to create aluminum-based metal matrix composites (MMCs) with a reinforcing material to develop a traditional, low-cost technique for creating MMCs and achieving uniform dispersion of the reinforced material. The stir casting method has been utilized to accomplish this goal. Phosphogypsum with red mud and aluminum alloy (7005) have been selected as the matrix and reinforcing materials, respectively. The experiment was conducted using constant weight fractions of phosphogypsum (5%) and red mud (5%). The results showed that the addition of phosphogypsum and Red mud particles increased the hardness, tensile strength, and impact strength resistance of the specimen while decreasing the wear rate. On the other hand, combining the two materials (phosphgypsum and red mud) yielded better flexible results than adding each material separately.

تقييم الخواص الميكانيكية لمواد مركبة هجينة من سبيكة الالمنيوم (Al- 7005) المقواة بالفوسفوجبسوم والطين الاحمر

وليد تركي راشد
كلية هندسة الإنتاج والمعادن/ الجامعة التكنولوجية / بغداد - العراق.

الخلاصة
في هذا العمل، تم تصنيع مركب معدني ذو أساس من الألومنيوم، ومن ثم تمت دراسة بنيته المجهرية وخواصه الميكانيكية، مثل قوة الشد، الصلابة، قوة الصدمة، ومعدل التآكل. تم تصنيع المواد المركبة ذات اساس الألومنيوم مع مادة تقوية، لإنشاء طريقة تقليدية منخفضة التكلفة لإنتاج مادة مركبة والحصول على تشتت متجانس للمواد المقوية. ولتحقيق هذا الهدف، تم اعتماد تقنية السباكة بالخلط. تم اختيار سبائك الألومنيوم (7005) كسبيكة اساس والفوسفوجبسوم مع الطين الأحمر كمواد تقوية. أجريت الدراسة باستخدام أجزاء وزنية ثابتة من مادة الفوسفوجبسوم (٥٪) والطين الأحمر (٥٪). أظهرت النتيجة أن إضافة الفوسفوجبسوم والطين الأحمر أدت إلى زيادة قوة الشد والصلابة ومقاومة الصدمة للعينة وانخفاض معدل التآكل. ومن ناحية أخرى فإن إضافة المادتين معاً (الفوسفوجبسوم والطين الأحمر) أعطى نتائج مرنة أفضل من إضافة كل مادة على حده.

الكلمات الدالة: سبيكة الالمنيوم ٧٠٠٥، المواد المركبة، الخواص الميكانيكية، الفوسفوجبسوم، الطين الاحمر، السباكة بالخلط.

1.INTRODUCTION

Aluminum alloys are utilized in various industries; however, airplanes, in particular, are prone to poor resistance from use, which modifies their mechanical properties, especially when subjected to overload and high-temperature operating conditions [1]. As a result, many researchers have focused their attention on the potential application of aluminum alloys in producing composite materials with an aluminum matrix reinforced by fiber and ceramic particles. Since these materials are less expensive and offer more benefits than non-composite materials, they are significantly more important. They also offer superior resilience and good wear strength [2]. A composite material is a "material system" made up of two or more micro or macro elements that are largely insoluble in one another and differ in form and chemical makeup [3]. The reinforcing phase is one component, and the matrix phase is the other. To produce the required feature, the reinforcing phase is integrated into the matrix [4]. It is commonly recognized that the qualities of the metal matrix composite are significantly influenced by the microstructural features of the reinforcement, including form, size, orientation, distribution, and volume or weight percentage [3, 5]. The primary difficulties in producing metallic material composites (MMCs) are choosing the appropriate matrix and reinforcing materials. [6]. Researchers are currently paying close attention to strengthening AMMCs utilizing ceramic materials, such as zirconium oxide, boron carbide, and silicon carbide [7]. Numerous studies have investigated the advantages of employing using minerals like bauxite particles to create composites and have shown how effective they are as affordable reinforcing agents when making high-performance composites [8]. When strengthened with ceramic particles, these composites are also more suited for applications that need high temperatures. Although many people are unaware that these applications involve composite materials, metal matrix composite materials have found use in many aspects of daily life [9]. Stir casting is one of the most practical since it allows for the most effective control of process variables and improves MMC properties. The process factors, including stirring rate, stirring temperature, and pouring temperature, must be maintained. Investigations of the tribological characteristics and other mechanical property assessments of MMCs are also possible [10]. During the Bayer's process, which produces alumina from bauxite, red mud becomes the primary waste product. Along with certain other minor components, it contains iron, titanium, aluminum, and silica oxides. It results from the digestion of bauxite with sodium hydroxide at high pressures and temperatures [9]. Phosphogypsum (PG) is a fine-grained, powdery, wet material with a gray color; its maximum particle size ranges from 0.5 to 1.0 millimeters. Rhombic and hexagonal crystal structures of phosphogypsum are well known. The grade of the phosphogypsum produced depends on the phosphate rock and the method used to produce phosphoric acid [11]. A byproduct of phosphate rock processing is phosphogypsum. In the western part of Iraq, waste byproducts from the Al-Qaim Fertilizers Co. contained more than 12 million tons of phosphogypsum [12]. The goal of this study is to use stir casting to create hybrid composites of Al-7005/PG/Red Mud. Additionally, it ensures how PG and red mud interact to affect the mechanical and tribological characteristics of Al-7005 MMCs.

2.METHODOLOGY

2.1.Materials

Hybrid metal matrix composites, including three weight percentages of red mud and phosphugypsum particles, were made using the stir casting technique. Al-7005 alloy was employed as the matrix material, while red mud and phosphugypsum particles, with an average size of (≤51 µm), were used as the reinforcements to make the hybrid MMCs. The densities were 3.26 and 1.32 g/cm^3 for red mud and phosphogypsum, respectively. Table 1 displays the chemical composition of the Al-

7005 alloy. In Tables 2 and 3, the chemical composition of red mud and PG is tabulated, respectively. In Fig. 1, the red mud and PG are depicted.

Table 1 Chemical Composition of the Matrix Alloy (Al-7005).

Elements	Si	Cr	Mg	Mn	Zn	Fe	Al
Concentration %	0.05	0.1	1.8	0.52	4.2	0.13	BAL

Table 2 Chemical Composition of Phosphogypsum Sample as Received.

Elements	SO_3	CaO	P_2O3	SiO2	MgO	SrO	K_2O
Concentration %	46.42	36.91	2.006	2.152	0.37	0.6326	0.0875

Table 3 Chemical Composition of Red Mud Sample as Received.

Elements	Al_2O_3	Fe_2O_3	CaO	TiO_2	SiO_2	Na_2O
Concentration %	20.1	53.3	7.3	4.1	5.9	9.1

Fig. 1 Phosphogypsum and Red Mud Powders.

2.2.Stir Casting Process

The matrix reinforcement ratios used to create the AMMC specimens for the present study are listed in Table 4. The Al alloy was incorporated into a graphite crucible and placed into a handmade electrical furnace for the stir-casting method of creating AMMC composites. To melt the aluminum alloy, the furnace temperature was gradually raised above the liquidus temperature, and then maintained at 700°C. The aluminum foil-covered, weighted reinforcements of particles were gently packed to isolate them from the air and then heated at 250°C for 10 minutes to remove any moisture. Slowly, the temperature was lowered until it was below the liquidus temperature of the matrix material. To achieve a homogeneous distribution of ceramic particles and increase the wetting and permeability of the reinforcements in the liquid matrix, the semisolid molten was stirred for 10 minutes at a speed of 900 rpm. To make the molten metal more fluid, the temperature was then gradually raised back above the liquidus temperature of 900°C. Finally, a hot casting mold was filled with the melt. Following casting, the casts were processed to create the test specimens. Figure 2 elucidates that the basic alloy and hybrid composite were created. Figure 3 illustrates the stir-casting technique.

Fig. 2 Base Alloy and Composite Casting.

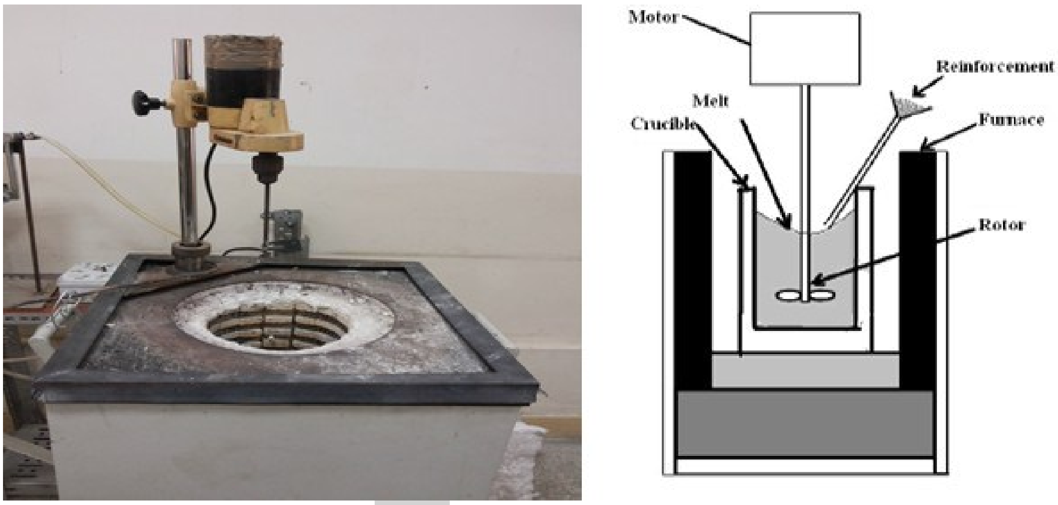


Fig. 3 Stir Casting Method.

Table 4 Hybrid Composite Compositions.

Samples	Al-7005(%)	Red Mud (%)	PG (%)
A1	100	0	0
A2	95	5	0
A3	95	0	5
A4	90	5	5

2.3.Composite and Base Alloy Tests

The mechanical behavior of the composite testing was investigated using hardness, compressive tensile strength, impact strength, and wear rate tests. All specimens created for this investigation underwent a tensile test in accordance with ASTM E-8 criteria [13]. The stress-strain curves obtained from the tension tests, which covered the ultimate tensile strength, yield strength, and elongation, were utilized to evaluate the tensile properties. Figure 4 depicts the tensile specimen test. Brinell hardness ratings were determined on the polished samples using a diamond cone indenter with a weight of 100 kg and a holding duration of 15 seconds. Readings taken at various zones on the polished specimen yielded an average hardness value of 500 HB and a load application duration of 30 seconds. To obtain an exact average value based on the test's results for hardness, the test was repeated three times. Figure 5 exhibits the hardness tested specimens, which had a diameter of 20 mm and a length of 20 mm. A compression test was conducted similarly to a tension test. On a universal testing machine, the tensile test was performed. Given a load interval of 2 tons, until breaking, the corresponding change of length for each load interval was measured and recorded. The compressive stress-strain curve was plotted, and the behavior of the test specimen under compression can be inferred from this curve. The test specimen's compressive characteristics, such as its compressive strength, were determined from the graph. To investigate the dry sliding wear characteristics of Al-7005 and its composites, a pin-on-disc device was employed. Wear samples of 20 mm and 10 mm were prepared. The hardness of the carbon steel disc was (45 HRc). The wear rate was evaluated by the wear test using a weight of (20 N) and a sliding time of (30 min). All tests were conducted at room temperature. A pin-on-disc wear test rig with a single-pan electronic weighing system, having an accuracy of 0.0001 g, was used to determine the original weight of the specimens. Figure 6 shows the wear test device. All experiments were conducted in the testing laboratories of the Department of Production Engineering and Metallurgy at the University of Technology. The following relation was used to compute the wear rates of each sample [14]:

$$\boldsymbol{Wear\ rate\ (Wr)\ = Vr/SD} \quad (1)$$

where:

Vr = Volume of the removed material (mm^3) = $\Delta w/\rho$.

SD = Sliding distance of the material removal (mm) = πDnt.

And:

$$\boldsymbol{Wr\ =\ \Delta w/\rho\pi Dnt\ (mm^3/mm)} \quad (2)$$

where:

Δw = Lost weight after the test.

ρ = Density of the material.

D = Distance from the center of the specimen to the center of the disc (mm).

n = Average disc speed (510 r.p.m).

t = Time of test (min).

Fig. 4 Tensile Strength Specimen Test.

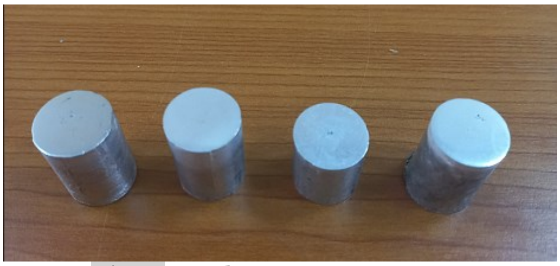


Fig. 5 Hardness Specimen Test.

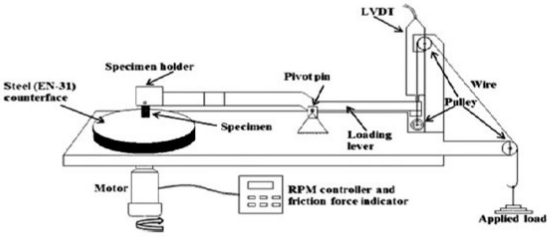


Fig. 6 Pin on Disc Machine.

3.RESULTS AND DISCUSSION

3.1.SEM Micrographs of The MMc

The FESEM micrographs of the red mud and PG composites are displayed in Fig. 7. Particulate composites' sizes, densities, types of reinforcing particles, and distribution all significantly affect their properties. Particle dispersion is affected by several factors, including the inclusion technique, type of reinforcement, fluidity, and solidification rate. Even dispersion of the particles during the casting is crucial for producing particulate composites. The first goal is to distribute the particles uniformly in the liquid melt; the second goal is to prevent the particles from segregating or clumping together during the pouring and solidification process. Wettability is an important condition for the uniform dispersion of particles in the melt. This type of hybrid AMC is primarily designed for performance enhancement, with minimal consideration given to manufacturing costs. The microstructure of composites can be used as an indicator of composite quality and as a measure of the success of the composite manufacturing process. Figure 7 demonstrates the FESEM photomicrographs of the composites, which reveal that the reinforcements are evenly distributed in the matrix material and clearly illustrate the dispersed reinforcement content within the composite.

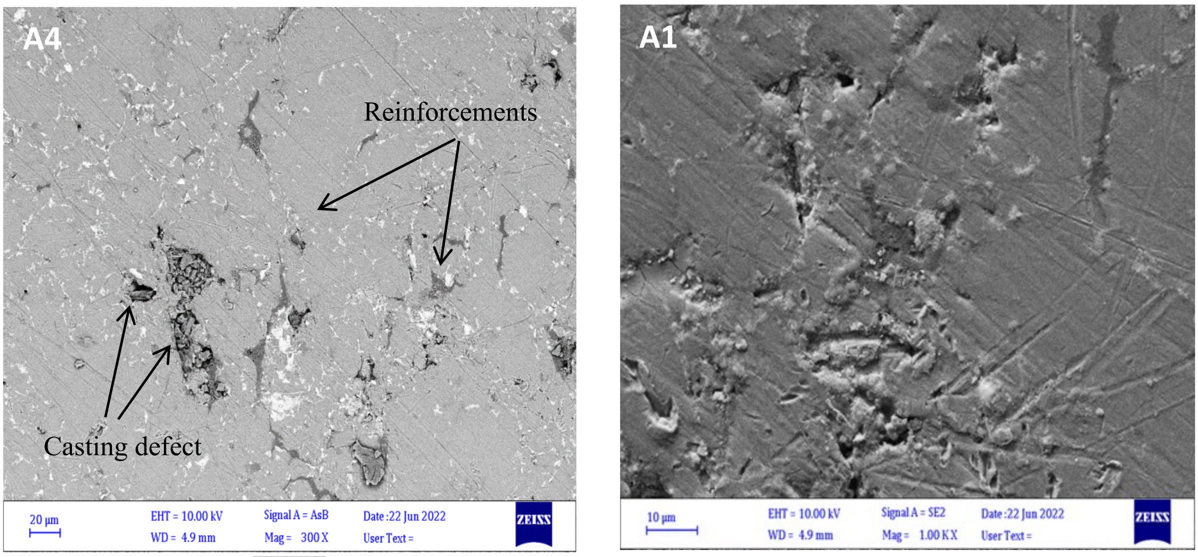


Fig. 7 SEM Images of the Al-7005(A1) and Composite (A4).

3.2.Hardness Test

Figure 8 portrays the measured hardness of the Al-7005 alloy and composite. The casting's hardness should be constant, which is right if the reinforcement particles are distributed evenly throughout the casting. Other variables, like cooling rate, gravity effect, and non-uniform particle dispersion in the casting, will result in varying hardness levels. Figure 8 indicates that the addition of PG and red mud particles to the aluminum matrix resulted in a reasonable improvement in hardness. The composite can be strengthened by the dispersion of reinforcement particles [15]. As a result, using PG and red mud as fillers in the Al-7005 casting increased the material's hardness. Brinell's microhardness of the composite with more reinforcing material exhibited greater hardness. The introduction of hard reinforcing particles (PG and red mud) enhanced the composite material's load-bearing capability while limiting the matrix deformation by constraining dislocation movement. The mechanical parameters of the metal matrix composite reinforced with phosphogypsum were marginally superior to those of the red mud-reinforced metal matrix composite. Compared to the unreinforced Al 7005 alloy, Fig. 9 illustrates an increase in hardness, accompanied by an increase in the percentage of red mud and phosphogypsum particles. For an 8% PG, the hardness was determined to be

83.7 BHN, which is 42.3% higher than that of the base alloy. The addition of red mud and phosphogypsum particles significantly increased the hardness of the alloy matrix, which was determined to be 80.4 BHN for 8% red mud (an increase of 30.9% over the base alloy). A hardness reading revealed a greater value, consistent with [16], suggesting that the presence of particles in the matrix increased the composites' overall hardness. This behavior is attributed to the reinforcing particle, especially the ceramic material, which contributes positively to the composites' hardness despite aluminum's inherently soft nature. The limitation to plastic deformation of the matrix during the hardness test increased in the presence of stiffer and harder red mud and phosphogypsum reinforcement. Consequently, the comparatively high hardness of red mud and phosphogypsum itself may be the cause of the composites' increased hardness [16].

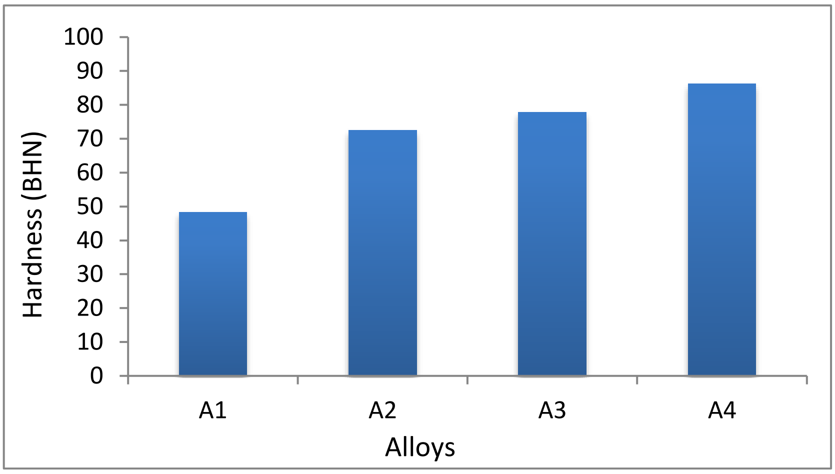


Fig. 8 Micro Hardness Values of PG and Red Mud Reinforced Aluminum 7005 Composites.

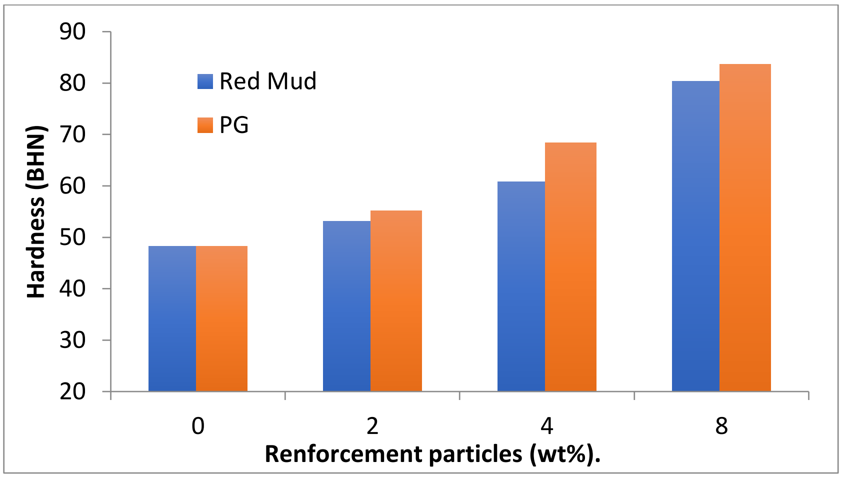


Fig. 9 Effect of Percentage PG and Red Mud on Microhardness Aluminum 7005 Composites.

3.3.Impact Test (Charpy Test)

The Charpy v-notched impact tester was used to evaluate the impact of all samples. The findings are presented in Fig. 10. According to Fig. 10, it can be observed that the mechanical properties of the alloy improve with the addition of red mud and phosphogypsum, exhibiting excellent hardness, impact, tensile strength, and wear resistance compared to the base alloy.

3.4.Tensile Test

Figure 11 displays the tensile strength values of the Al-7005 hybrid metal matrix composites reinforced with PG and red mud. Al-7005 hybrid composites had higher tensile strength than the base metal. The incorporation of hard reinforcing particles into the composites produces a strengthening effect. The particles (red mud and PG) in the aluminum alloy composite are dispersed homogeneously, acting as a barrier to the matrix alloy dislocation motion, thereby decreasing the fracture. The inclusion of ceramic particles primarily enhanced the composite fracture and tensile strength by transferring stress from the (ductile) aluminum matrix to the reinforced (brittle) particles [17]. This behavior is attributed to the Rowan mechanism, whereby a dislocation bypasses the obstacles that restrict its movement around a particle [18, 19], resulting in increased tensile strength. Sample A4 had a maximum strength of 230 MPa compared to the base alloy's strength of 168 MPa.

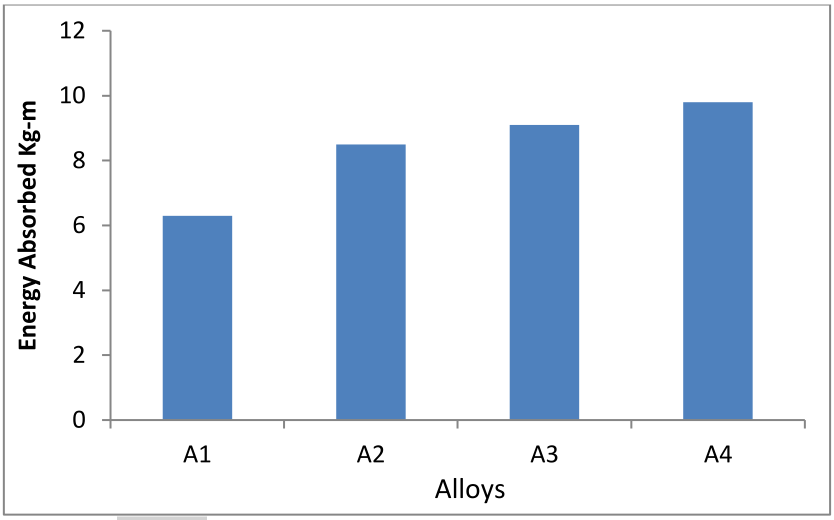


Fig. 10 Impact Test for 7005 Alloy and Composite.

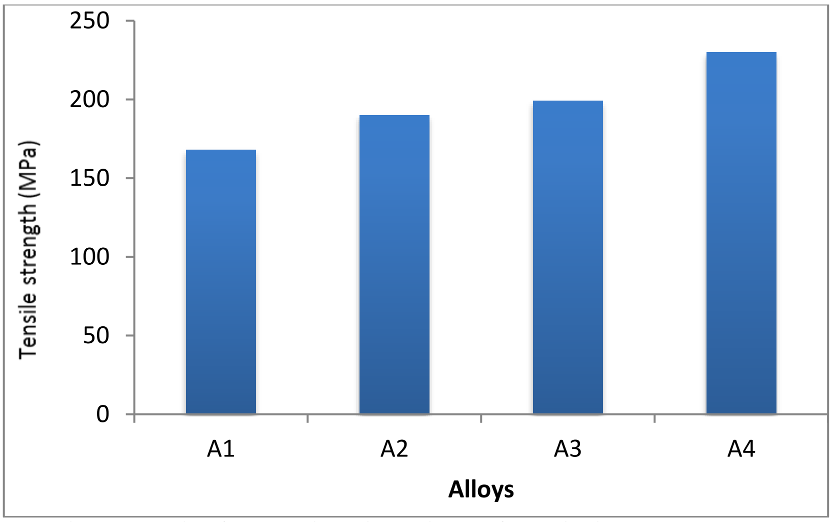


Fig. 11 Tensile Strength of PG and Red Mud Reinforced Aluminum 7005 Composites.

Figure 12 compares the effects of adding red mud and phosphogypsum particles on tensile strength, where the addition ratios were 0, 2, 4, and 8 wt%. Tensile strength increment was proportional to reinforcement quantity up to 8 wt.% red mud and phosphogypsum. It is evident from the figure that the composites' tensile strength was greater than that of their underlying matrix. Additionally, it can be shown that adding more filler increased the composite's tensile strength; this finding is consistent with [20]. With an 8% PG reinforcement, a maximum tensile strength of 219 MPa was achieved, which is 23.3% greater than the strength of the unreinforced cast 7005 aluminum alloy (168 MPa). The maximum tensile strength of 200 MPa was observed for 8 wt.% PG reinforcement, which is 16% more than the strength (168 MPa) of unreinforced cast 7005 aluminum alloy. This increase is due to the thermal mismatch phenomenon that occurred between the molten Al7005 and the reinforcement particles, resulting in a decrease in the strength of the composites (Al7005, red mud, and phosphogypsum). The strength also improved due to the grain refinement and the particle-strengthening effect [21].

3.5. Wear Test

Figure 13 depicts the change in wear rate. The addition of PG and red mud reduced the wear rate of the composite. Compared to an unreinforced aluminum matrix, the addition of reinforcement particles reduced the wear rate of the composites. The presence of reinforced particles, which reduced the rate of wear of the composites by producing a thin protective barrier between the disc and pin during sliding, can be the reason for the improvement in the wear resistance of the Al-7005 PG/red mud composites compared to aluminum. Additionally, the increase in wear resistance can be attributed to the strengthening of the matrix material due to the dispersion of hard particles, which is associated with an increase in dislocation density upon the addition of reinforcement [22].

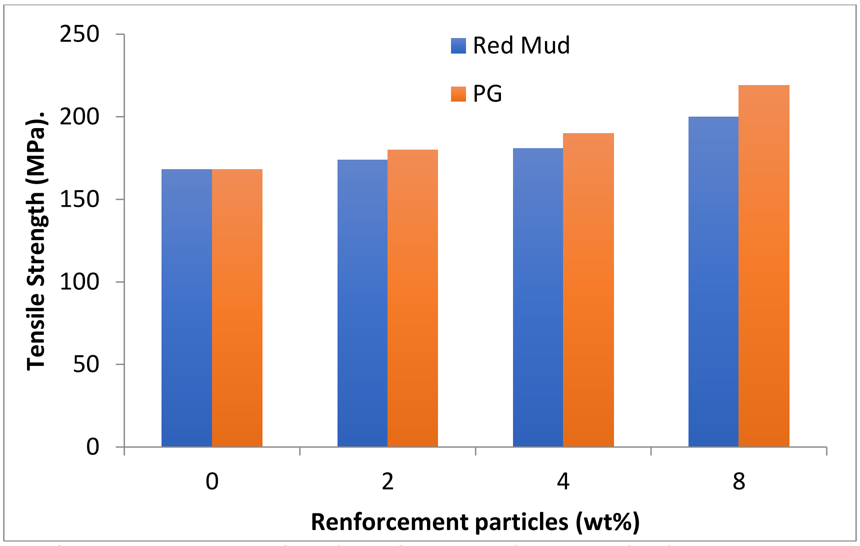


Fig. 12 Effect of Percentage PG and Red Mud on Tensile Strength Aluminum 7005 Composites.

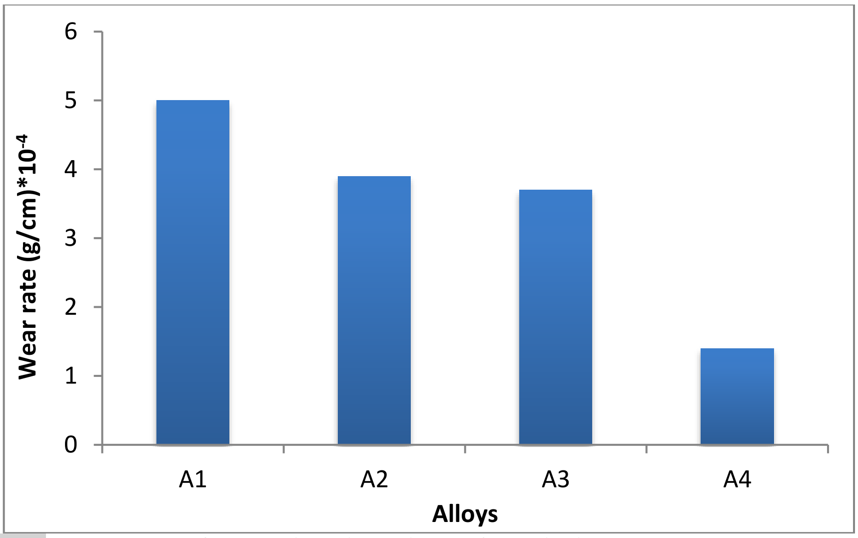
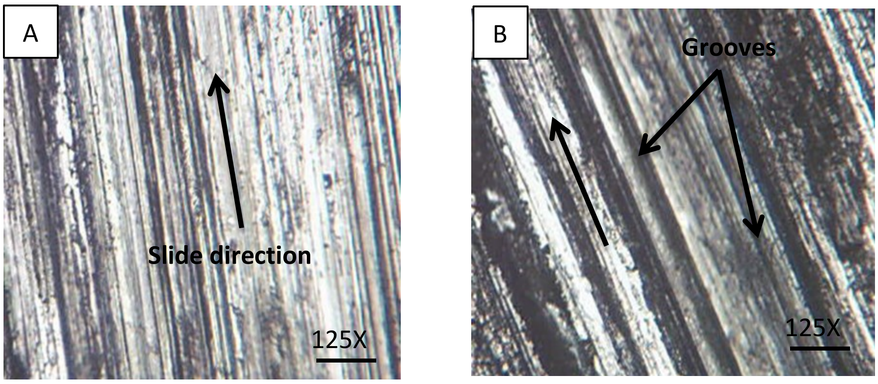


Fig. 13 Wear Rate of PG and Red Mud Reinforced Aluminum 7005 Composites.

3.6.Study of Worn Surfaces by Optical Microscope

Using an optical microscope, the effects of applied load on the topography of the worn surfaces of samples were examined for A1 and A2 alloys at low loads of 10 N and high loads of 20 N. With the same settings, Fig. 14 (a) and (b) reveal the effect of different loads in the dry case. It was found that with a higher load, due to the formation of deep wear tracks, grooves, and prominent wear lines, the surface undergoes significant wear. Additionally, the aluminum alloy's surface may exhibit minor fissures and abrasive wear, and a few pieces of wear debris may be separated from it, reducing its resistance to wear [23]. Lesser loads, however, cause less severe wear to be visible on the surface, and shallow wear lines are more apparent than deep ones.



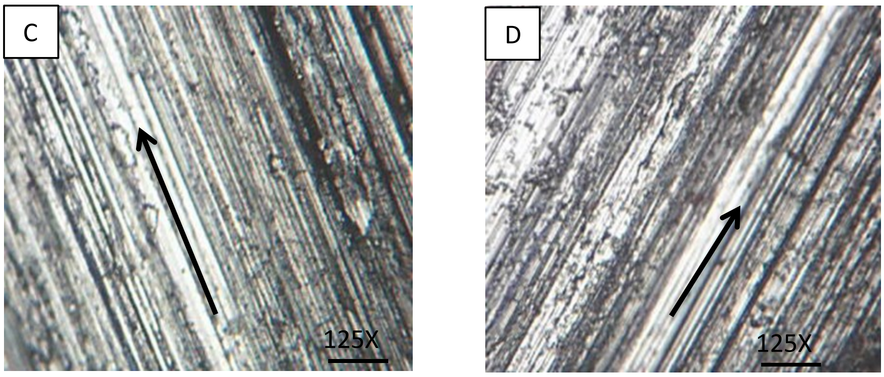


Fig. 14 Optical Micrographs of the Surface Topography of Different Worn Surfaces Under Loads of (20N). (A) Al and (B) A4. And under Loads of (10N). (C) Al and (D) A4. Pictures with Magnification of (125×).

4.CONCLUSION

From the results of the present study, the following conclusions can be drawn:

1- The mechanical testing results showed improvements in tensile strength (by 23.3%), hardness (by 42.3%), tensile strength (by 16%), and hardness (by 30.9%) compared to cast unreinforced Al7005, using each of the PG and red mud, respectively.

2- Both phosphogypsum and red mud particles were distributed throughout the matrix alloy, enhancing its mechanical characteristics and resulting in improved values of hardness, tensile strength, and compression compared to the base alloy.

3- The mechanical parameters of a metal matrix composite reinforced with phosphogypsum were slightly superior to those of a metal matrix composite reinforced with red mud.

4- The prepared composite (with the addition of phosphogypsum and red mud particles) exhibited a decrease in the wear rate (by 72%), as compared with the base alloy.

5- The average wear rate increased gradually with the applied load, reaching (5×10^{-4}). In contrast, the wear rate decreased by adding PG and red mud (5 wt%) to (1.4×10^{-4}). However, the wear rate with the red mud was higher than that of the PG state.

6- Examined the effects of varying loads and found that at higher loads, the surface experienced significant wear as a result of the creation of deep wear tracks, grooves, and distinct wear lines. However, when less force was applied, it was found that the surface exhibited less severe wear, with shallow rather than deep wear lines.

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