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Fabrication of Aluminium AA7075 Reinforced by Zinc Metal Matrix Composites and Their Wear Behaviour Analysis

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In this study, we report effects of zinc on casted aluminium 7075 by using of stir casted method. The volume fraction of composites is prepared by density method. Stir casted composites are fabricated in different volume-fraction levels. Microstructure analysis of alloy and nanocomposites are performed by using SEM. Dry sliding wear is measured on pin-on-disc testing apparatus at various testing conditions for alloy and nanocomposite materials. As shown with the obtained results, the wear resistance increases with increasing the wt.% of reinforcing zinc nanoparticles. The different volume fractions of fabricated composites are shown, which leads to decreasing the wear rate from 40% to 60%. The nanoparticles' sizes, microstructure, and wear rate are approximated from high-resolution diffraction analysis.

Keywords: AA7075-T6 aluminium alloy, reinforcing zinc nanoparticles, stir casting, wear rate, SEM.

Дана робота стосується дослідження впливу цинку на литий алюміній 7075 при використанні методи лиття з перемішуванням. Об'ємну частку композитів підготовлено методою ущільнення. Перемішані литі композити виготовлено за різних рівнів об'ємної частки допанту. Мікроструктурну аналізу стопів і нанокомпозитів виконано за допомогою СЕМ. Зношування сухого ковзання для стопів і нанокомпозитних матеріялів визначали на штифт-диск-апараті за різних умов випробувань. Результати досліджень свідчать, що опір зношуванню зростає при збільшені мас.%

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зміцнювальних наночастинок цинку. Спостерігалася різна об'ємна частка виготовлених композитів, що приводило до зменшення коефіцієнту зношування з 40% до 60%. Розміри наночастинок, мікроструктура і швидкість зношування узгоджуються з даними високороздільчої дифракційної аналізи.

Ключові слова: алюмінійовий стоп AA7075-T6, зміцнювальні наночастинки цинку, лиття з перемішуванням, швидкість зношування, СЕМ.

Данная работа посвящена исследованию влияния цинка на литой алюминий 7075 при использовании метода литья с перемешиванием. Объёмная доля композитов подготовлена методом уплотнения. Перемешанные литые композиты изготовлены при различных уровнях объёмной доли допанта. Микроструктурный анализ сплавов и нанокомпозитов выполнен с помощью СЭМ. Износ из-за сухого скольжения для сплавов и нанокомпозитных материалов определяли на штифт-диск-аппарате при различных условиях испытаний. Результаты исследований свидетельствуют, что сопротивление износу растёт при увеличении масс.% упрочняющих наночастиц цинка. Наблюдалась различная объёмная доля изготовленных композитов, что приводило к уменьшению коэффициента износа с 40% до 60%. Размеры наночастиц, микроструктура и скорость износа согласуются с данными высокоразрешающего дифракционного анализа.

Ключевые слова: алюминиевый сплав AA7075-T6, упрочняющие наночастицы цинка, литьё с перемешиванием, скорость износа, СЭМ.

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1. INTRODUCTION

Composites derive their properties from their matrix and the reinforcements. The greatest advantage is that the matrix and the reinforcements, providing the material with properties which can meet specific and difficult requirements in many applications. The metal matrix composite is a material with a minimum of two constituent elements, one being a metal basically, the other material may even be a singular metal or another material, sort of a ceramic or compound. If more than two materials are present, it is referred to as a hybrid composite. Metal matrix composite has found its applications in several areas of automotive and aerospace industries [1]. Nanotechnology is spreading massively in the different demanding fields of engineering and medicine like defence, aerospace, automobiles, electronics, information, and communication technology [2]. The 7075 aluminium alloy is a primary alloy in many aerospace applications due to its specific strength and high fracture tolerance toughness [3]. Heat treatable 7xxx series Al–Zn–Mg and Al–Zn–Mg–Cu alloys have received great interest as the main materials in aviation and aerospace applications as well as automotive and marine industries [4]. Aluminium alloys are preferred due to their high strength to weight ratio, abundance in nature and corrosion resistance properties. The low density, high specific strength, ductility and thermal conductivity of aluminium alloys have provided many applications, particularly in the aerospace and automotive sectors [5–6]. However, their uses are limited due to low wear resistance. In order to improve its physical properties, metal matrix composites are widely used. Metal matrix composites covers in aerospace industry (high thrust to weight ratio for engines, high stiffness, low density, controlled thermal expansion, high wear resistance *etc.*), in automobile industry (high wear resistance, lower cost, lower density, elevated temperature strength, fatigue resistance), electronic packaging (high stiffness, high heat dissipation capacity, controlled thermal expansion, low density), sports industry (high stiffness, low density, high fatigue resistance) [7].

2. EXPERIMENTAL DETAILS

In recent years, many processing techniques have been developed to process particulate reinforced metal matrix composites. According to the type of reinforcement, the fabrication techniques can vary considerably. A wide variety of fabrication techniques have been explored for metal matrix composites. The properties of composites are strongly dependent on the properties of their constituent materials, their distribution and the interaction among them. Apart from the nature of the constituent materials, the geometry of the reinforcement (shape, size and size distribution) influences the properties of the composite to a great extent. The concentration distribution and orientation of the reinforcement also affect the properties. The matrix can be selected based on oxidation and corrosion resistance or other properties [8]. Generally Al, Ti, Mg, Ni, Cu, Pb, Fe, Ag, Zn, Sn and Si are used as the matrix material, but Al, Ti, Mg are used widely.

The chemical composition of AA7075 is represented in Table 1.

2.1. Liquid Metallurgy Route (Stir Casting)

The simplest and most commercially used technique is known as vortex technique or stir-casting technique. The stir casting process has been employed for producing discontinuous particle reinforced metal ma-

TABLE 1. Nominal composition of AA7075 alloy.

Element	Zn	Mg	Cu	Cr	Mn	Ti	Si	Fe	Al
Weight%	5.6	2.5	1.6	0.23	0.3	0.2	0.4	0.5	Rest

trix composites by many researchers [9–11]. Some modifications in the stir casting process have also been tried to improve the performance of the process. Stir casting technique is a very promising route for manufacturing near net shape hybrid metal matrix composite components at a normal cost [12].A comparative evaluation of all the liquid state processing method is listed in Table 2.

The vortex method was adopted to prepare the composite specimens and the melting was carried out in an electrical resistance furnace. The temperature of the furnace was precisely measured and controlled in order to achieve sound quality composite. Thermocouple and controllers were used for this purpose. The melt was maintained at a temperature between 1023 K and 1073 K for one hour. Nanoparticles of 50 nm size varying from 2 to 10% wt. in steps of 2% wt. were used to prepare the composites (Table 3). The vortex was created using an aluminate coated mechanical stirrer, as it is necessary in order to prevent the migration of ferrous ions from the stirrer into the matrix alloy melt. The

TABLE 2. A comparative evaluation of different techniques for the discontinuously reinforced metal matrix composite (DRMMC) fabrication [10].

Method	Range of shape and size	Metal yield	Range of volume fraction	Damage of reinforcement	Cost
Liquid metallurgy (stir casting)	Wide range of shapes, larger size up to 500 kg	Very high 90%	Up to 0.3	No damage	Least expensive
Squeeze casting	Limited by preform shape, up to 2 cm height	Low	Up to 0.45	Severe damage	Moderately expensive
Powder metallurgy	Wide range restricted size	High	–	Reinforcement fracture	Expensive
Spray casting	Limited shape, large size	Medium	0.3–0.7	–	Expensive

TABLE 3. Sample designation and reinforcement weight ratio.

Sample designation	Composition of reinforcing materials
A0	Al 7075 (100%)
A1	Al 7075 (98%) + Zinc (2%)
A2	Al 7075 (96%) + Zinc (4%)
A3	Al 7075 (94%) + Zinc (6%)
A4	Al 7075 (92%) + Zinc (8%)
A5	Al 7075 (90%) + Zinc (10%)

nanoparticles were preheated to a temperature of 800 K and then introduced into the slurry. The stirring is continued until particle and matrix wetting occurred. Chemical analysis is carried out which showed that a significant part of the particles were retained in the melt. Finally, the melt was degassed and the refined metal was poured into cylindrical mould (0.02 m diameter and 0.15 m length). After, the mould was cooled down to the room temperature; the specimens were taken out and cut in to required dimensions.

3. TRIBOLOGICAL STUDIES FOR ALUMINIUM ALLOY NANOMETAL MATRIX COMPOSITES. WEAR TEST (PIN-ON-DISC APPARATUS)

Pin on disc wear testing is a commonly used technique for investigating abrasive wear of the material (Fig. 1). The contact surface of the pin may be flat, spherical or indeed of any convenient geometry, including that of actual wear components. The coefficient of friction is continuously monitored as wear occurs and the material removed is determined by weighing and/or measuring the profile of the resulting wear track.

Changes in coefficient of friction are frequently indicative of a change in wear mechanism, although marked changes are often seen during the early stages of wear tests as equilibrium conditions become established. The tests were carried out at various applied loads (20, 40, 60, and 80 N) at a sliding velocity of 1 m/s, 2 m/s, 3 m/s and sliding distance of 2000 m. The volumetric loss was computed by multiplying the cross section of the test pin with its loss of height. Worn surfaces and wear debris of selected specimens were observed using scanning electron microscope. The wear test was carried out according to ASTM-

Fig. 1. Pin-on-disc apparatus setup.

Fig. 2. Wear test specimen details (height of 50 mm and diameter of 10 mm).

G99-05 test standards (Fig. 2).

The process parameters can be listed in four categories as follows [13]: (i) extrinsic factors—applied load, sliding speed, distance and sliding material (steel or abrasive paper glued disc); (ii) intrinsic factors—particle type, volume fraction, size and shape; (iii) manufacturing factors—processing route and heat treatment; (iv) environment factors—dry or wet.

3.1. Design of Experiments

Design of experiments (DOE) is a technique for studying any situation that involves a response that varies as a function of one or more independent variables. This approach helps to understand, how the change in the levels of application of a group of parameters affects the response (Table 4). Various techniques are available from the statistical theory of experimental design, which is well suited for engineering investigations. The main statistical based approaches that have been investigated in past work are discussed below.

The first approach, Taguchi method, offered several innovations

TABLE 4. Wear rate reading.

Run	Sliding distance, mm	Speed, rpm	Load, kg	Time, min
1	20	600	5	90
2	20	500	3	60
3	20	400	1	30
4	60	400	5	60
5	40	400	3	90
6	40	500	5	30
7	60	500	1	90
8	40	600	1	60
9	60	600	3	30

including a widely used procedure for addressing the impact of 'noise factors', which can be controlled during experimentation but not during standard operations. Yet, despite the many advantages of Taguchi methods, there are some limitations.

The total number of experimental runs using product arrays can make experimental costs substantially higher than when classical DOEs are used because the total number of runs is often higher for a given number of factors. Investigation of the experimental outcomes uses S/N to support the determination of the finest process design and has been effectively used for the study of dry sliding wear behaviour of composite materials. The identified influencing parameters on the wear rate and friction coefficient have been applied load, sliding velocity, sliding time and percentage of reinforcement.

3.2. Influences of Load on Wear Rate

The influences of load on wear rate with variation of the sliding velocity are shown in Figs. 3–5. The graphs are representing the wear rates of the composites at different applied loads at different sliding velocities.

Transition from sliding wear to severe wear occurred with increasing loads. The wear rates of particular materials increase with increasing the sliding speed and then decrease because of either surface oxidation or the effects of work hardening [14–15]:

$$\text{Wear rate} = \frac{V_w}{\pi d_t N T},$$

where V_w is wear volume, d_t is track diameter, N is disc speed, T is time.

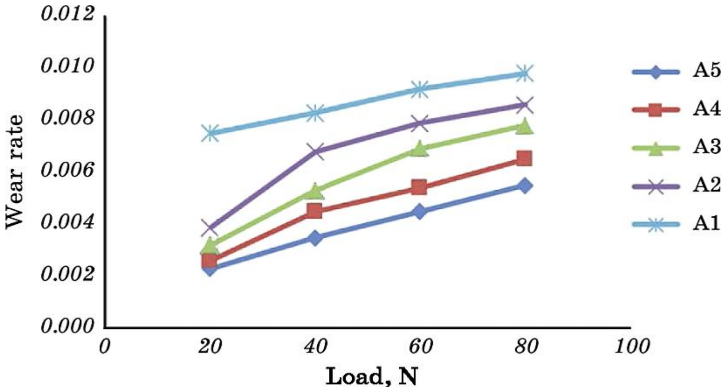

Fig. 3. Load and wear rate relation at velocity of 1 m/s.

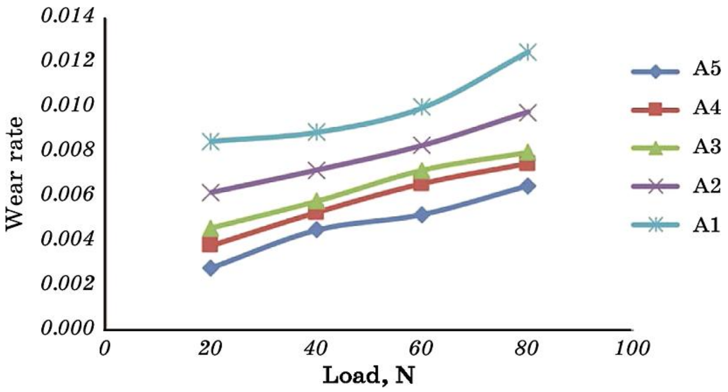

Fig. 4. Load and wear rate relation at velocity of 2 m/s.

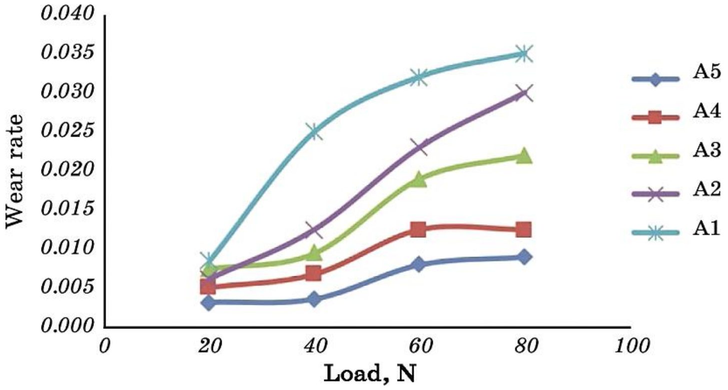

Fig. 5. Load and wear rate relation at velocity of 3 m/s.

From Figures 3–5, it is clear that wear rate increases with increase of load [N], in sample A0–A5. The addition level % wt. of composite material particle size limit based on the wear rate was increase or decrease with increase of load with increasing content of zinc component. The wear resistance of Zn-based alloy enhanced with increasing A2 content [16]. The overall wear resistance of the MMC under all control conditions can be attributed to the ceramic particles, which have the ability to restrict the deformation and to prevent hard asperities from causing abrasive wear [17].

3.3. Influences of Load and Coefficient of Friction

A detailed study of the variation of the coefficient of friction and the SEM micrographs of the worn surface of samples were undertaken to understand the wear mechanism. At the beginning of the tests, the friction coefficient of AA7075 alloy increases to a peak value (initially at a very high rate), followed by a gradual steady state value. The Zn particles could also act as a solid lubricant. These effects substantially reduced the values of coefficient of friction and increased the wear resistance of the Al matrix composites [18].

The effect of parameters on the friction coefficient is shown in Figs. 6–8. As observed, there is a gradual decrease in the friction coefficient with increase of load up to 20–60 N with varying velocity conditions (1 m/s, 2 m/s, 3 m/s). When the load is further increased, the friction coefficient value remains almost constant or decreased at all the remaining loads studied. It normally happens due the squeezing out of the reinforcement and forming a thin film, which acts as a lubricant. Hence, the friction coefficient was lowered or maintained as constant.

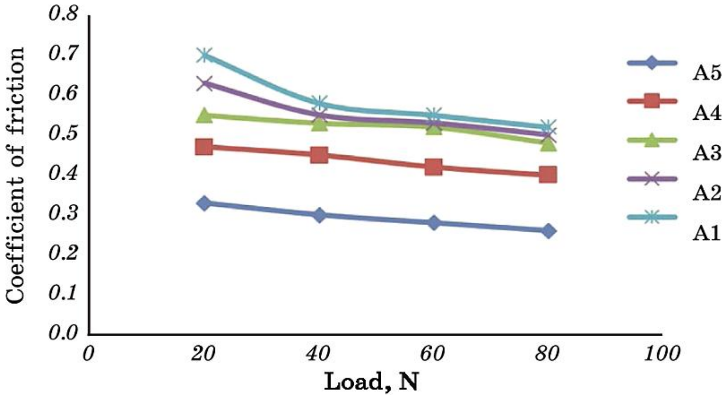

Fig. 6. Load and coefficient of friction at velocity of 1 m/s.

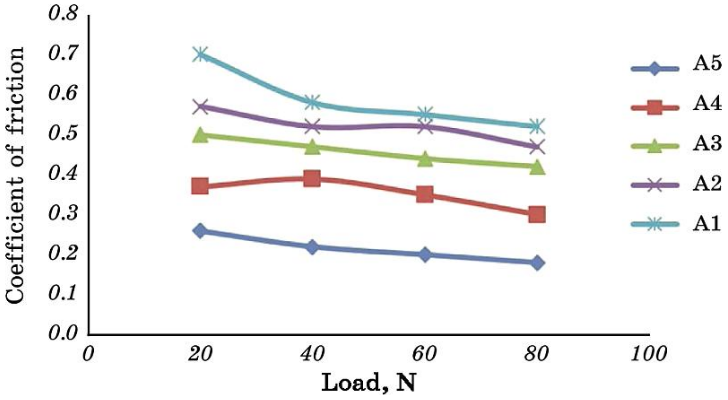

Fig. 7. Load and coefficient of friction at velocity of 2 m/s.

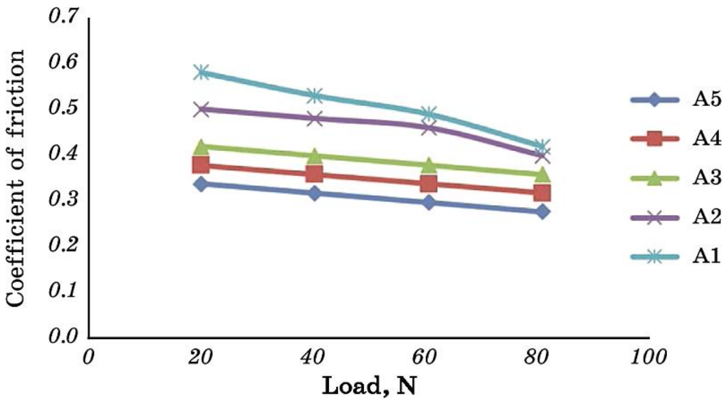

Fig. 8. Load and wear rate relation at velocity of 3 m/s.

The coefficient of friction first decreases with increase in load up to a certain value that reaches minimum and then, with further increasing load, that will result in constant coefficient of friction. From Figures 6–8, it was observed that the friction coefficient decreased with increasing load and reinforcements of nanoparticles. This is probably due to the high hardness of zinc compared to other inclusions [18].

4. RESULT AND DISCUSSION

4.1. Microstructure Analysis

The major task during the fabrication of AMCs is to obtain uniform distribution of reinforcing particles. The distribution of reinforcing particles and the morphology of composites have significant influence on the mechanical and tribological properties [19]. From Figures 9–12, it can be observed that there is a fine scale micro structural region in which the second phase particles are uniformly distributed in the matrix. Presence of uniformly distributed Zn particles in the composite layer leads to severe grain refinement. Besides, the grain refinement in stirred region can be attributed to restricted grain growth as result of grain boundary pinning by the zinc particles. The microstructure of specimen Al-composite (A1) is shown in Fig. 9. It clearly indicates that the zinc particles are uniformly distributed within the alloy matrix. Further, higher magnification of the composite has been shown in Fig. 10, which clearly shows a good bonding at the interface between zinc particle and metallic matrix. This uniform distribution of the reinforcing particles within the matrix alloy is a characteristic of the IPM method [20, 21], which, in turn, contributes to the improved mechanical and tribological properties of composites.

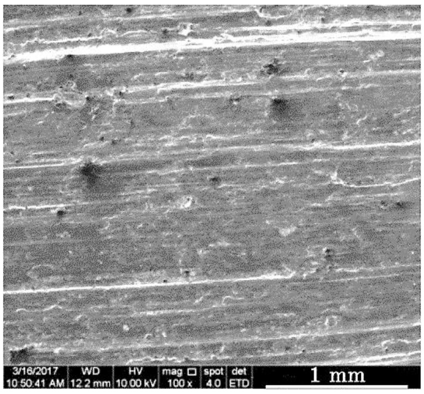

Fig. 9. SEM texture of specimen A1.

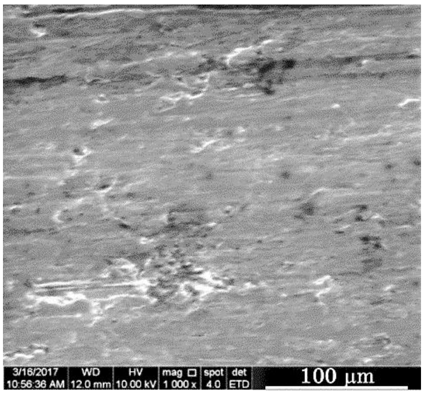

Fig. 10. SEM texture of specimen A1 with higher magnification (×1000).

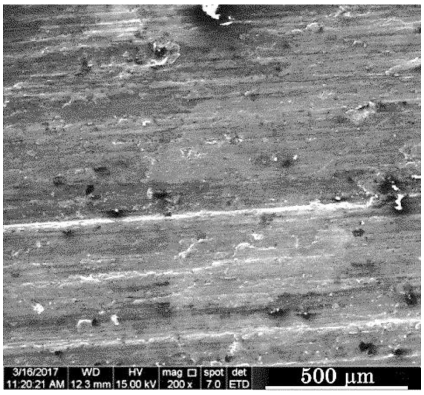

Fig. 11. SEM texture of specimen A2.

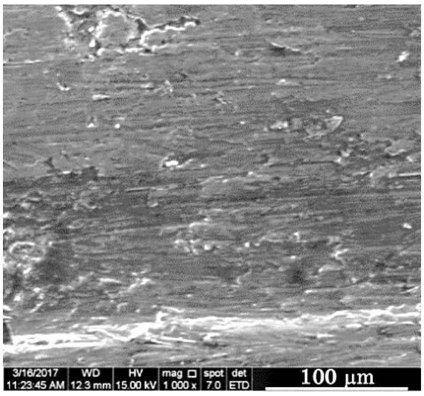

Fig. 12. SEM texture of specimen A2 with higher magnification (×1000).

The microstructure and mechanical properties of a composite is directly proportional to the amount and size of its reinforcements.

The microstructures of the composites samples A1 and A2 show that the distribution of nanoparticles was more uniform and confirms that the presence of zinc particles prevents proper densification of composites.

4.1. Wear Rate Analysis

From Table 5, it is clear that the specimen number 8 has less wear rate when compared with all other specimen. So, it shows that the specimen number 8 has the highest wear resistance. The total distance covered by this specimen is 2261 m. The value of sliding distance is 40 mm, speed—600 rpm, load—1 kg and time—60 minutes.

From the tabulated result, the mechanical parameters are con-

TABLE 5. Wear rate for sample designation A2 and specimen number 1–9 at velocity of 1m/s.

Sample designation	Specimen number	Wear rate, 10^{-6} mm^3/min
A2	1	3.53
A2	2	4.18
A2	3	3.97
A2	4	3.69
A2	5	3.90
A2	6	3.36
A2	7	4.24
A2	8	2.96
A2	9	3.96

cerned, applied load, sliding velocity, temperature, sliding distance, and hardness of counterface are the major factors influencing the wear performance of Al-composites [22, 23].

5. CONCLUSION

Aluminium AA7075 reinforced by zinc composite were prepared using stir casting. The effect of nanoparticles and its volume fraction on the micro structural features and dry sliding wear behaviour were studied.

The results can be summarized as follows: liquid metallurgy techniques were successfully adopted in the preparation of Al7075–Zn composites; stir processing of AA7075 aluminium alloy resulted in fine and uniform microstructure consisting of zinc particles in matrix therefore it is suitable method for fabrication of this kind of composites; the microstructural studies revealed the uniform distribution of the particles in the matrix system; the stir processing of AA7075 alloy and zinc significantly improved the wear resistance over that of the base metal and particle size of zinc was found to affect the wear resistance of substrate; wear rate of aluminium 7075 reinforced with zinc (A2) shows the improved wear properties when compared to other aluminium alloys; the reinforcement of zinc decreases the coefficient of friction with increasing load up to 60 N and then increasing the load the coefficient if friction get constant value.

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