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Investigation on impact and wear behavior of Al6061 ($SiC + Al_2O_3$) and Al7075 ($SiC + Al_2O_3$) hybrid composites

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Abstract
The current study focuses on the properties of dry sliding characteristics and impact strength of two different aluminum alloys that were reinforced with 100 nm sized Silicon carbide (SiC) and Aluminum oxide (Al_2O_3) ceramic particles, for improving the mechanical properties of the final alloy with the mixing materials characteristics. Stir casting method is adopted for fabricating the composites, matrix being Al6061 and Al7075, utilizing three distinct reinforcement ratios. In order to improve the mechanical properties and increase resistance to wear, tear, and shear, SiC and Al_2O_3 are utilized as reinforcing elements. Following the creation of the composite matrices, their physical and mechanical behaviors are examined in accordance with ASTM standards, and a comparison between the hybrid composites made of Al6061 and Al7075 is then completed. Comparison of the obtained samples showed that the Al7075 (12 % SiC + 6 % Al_2O_3) alloy exhibits characteristics with exceptional tribological and mechanical characteristics. The studied alloy can be used in the automotive industry, for example, in the production of pistons, connecting rods, due to the minimum degree of wear and variable thermal expansion coefficient.

Keywords
hybrid composite, Al6061, Al7075, impact strength, wear resistivity, optical microscope analysis

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УДК 621.763

Исследование ударных свойств и износостойкости гибридных композитов Al6061 ($SiC + Al_2O_3$) и Al7075 ($SiC + Al_2O_3$)

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Аннотация
Исследованы характеристики сухого скольжения и ударной вязкости двух алюминиевых сплавов, армированных керамическими частицами карбида кремния (SiC) и оксида алюминия (Al_2O_3) размером 100 нм. Сплавы

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применены для улучшения механических свойств и повышения сопротивления износу, разрыву и сдвигу конечного сплава с характеристиками смешиваемых материалов. Для изготовления композитов использован метод литья с перемешиванием. Матрица композитов представляет собой сплавы Al6061 и Al7075 с использованием трех способов армирования. Физические и механические свойства композитных матриц проверены в соответствии со стандартами Американского общества по материалам и их испытаниям. Приведено сравнение гибридных композитов, изготовленных из Al6061 и Al7075. Сравнение полученных образцов показало, что сплав Al7075 (12 % SiC + 6 % Al_2O_3) обладает исключительными трибологическими и механическими характеристиками. Изученный сплав может найти применение в автомобильной промышленности, например, в производстве поршней, шатунов, благодаря минимальной степени износа и варьируемому коэффициенту теплового расширения.

Ключевые слова
гибридный композит, Al6061, Al7075, ударная вязкость, сопротивление износу, оптический микроскопический анализ

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Introduction

The alloys of aluminum perform a vital function in numerous programs and in particular in car programs due to their awesome mechanical attributes, resistivity in opposition to corrosion, extremely good ductility, low density and outstanding thermal conductivity. But those alloys do now no longer exhibit honest tribological behavior which limits their programs in numerous engineering disciplines. Increasing call for much less dense and determined fabric brought about the improvement of recent substances known as composites. The engineering of blending or extra substances to attain the behavioral houses of all of the blended substances is called as composite substances. These composites are proved to have ameliorated mechanical and materialistic attributes which incorporates resistivity in opposition to wear, tear and hardness, reduced thermal growth with stepped forward fatigue strength [1–5]. Low-cost production techniques with extemporaneous behavioral attributes also make matrix composites the choice of researchers for applications in many fields, including automotive, aerospace, and others [6].

Combined reinforcement plays an important role in improving behavioral attributes. Aluminum is known to be obtained from bauxite, which is much less dense and ductile than steel, making it easier to cast and machine. Formation of a thin Al_2O_3 (Aluminum Oxide) layer makes it very resistant to corrosion and prevents oxidation. Uniform distribution of the reinforcement throughout the alloy significantly increases the stiffness and strength of the alloy [7]. Carbides, oxides, borides, and nitrides are commonly used as reinforcements [8]. Basically, SiC (Silicon Carbide) is seen as a compelling reinforced material due to its novel properties such as very high melting point, excellent thermal conductivity, and extreme machinability. SiC is also chemically compatible with Al alloys, avoiding intermetallic steps and forming strong bonds [9, 10].

According to the works of Alpas [11], reduced particulate size reinforcements will ensure only the protection of the alloy but whereas the efficient and effective of Al matrix is provided only with the increased particle size. Thus, for low speed applications, Al matrix with minimized reinforcement is opted [12]. To investigate and determine the dry sliding attributes of the Al matrix, this article involves the study of Al alloy reinforced with the SiC and Al_2O_3 with particle size of 100 nm. To further enhance the experimental investigation, comparison between the attributes of the Al6061 (SiC + Al_2O_3) and Al7075 (SiC + Al_2O_3) hybrid composite was done and concluded; to make the comparison more effective, three different reinforcement ratios were considered in the experimental procedures explained as in later sections.

The three samples of two mixtures taken for comparison in this study, wearing behavior of the alloys were concluded from the POD test simulated using WINDUCOM software. From the results it is clear the Al7075 reinforced with 12 % SiC and 6 % Al_2O_3 has good resistivity in comparison with the other composites. Also, it exhibits improvised hardness and good strength. In additional the alloy study under optical microscope also reveals the same.

Materials and method

Chemical composition of Al6061 & Al7075 alloys

For the comparative analysis of different composite matrix, the alloys considered for the current investigation were Al6061 and Al7075. The reinforcing materials selected for the effective and efficient performance of the alloys were SiC [13, 14] and Al_2O_3 with the average thickness ranging for about 100 nm [15]. The chemical distribution of the selected alloys was tabulated in detail in the Table 1.

Fabrication method

A stir casting method was employed to produce Al composite alloys with three different strengthening rates. This manufacturing technology plays an important role in determining parameters such as: melting temperature, stirring speed, preheating temperature of reinforcing material, etc. [16].

The fabrication process associated with the production of the Al composite alloys is as follows. Initially the SiC reinforcement and the Al_2O_3 were pre-heated for about 40 min at the temperature of 600°C in a muffle furnace. This heating improves the equalization of the volumes

Table 1. Chemical distribution of Al6061 and Al7075 composite alloys

Material	Chemical Composition, %								
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Al6061	0.35	0.50	1.50	0.59	0.90	1.80	0.59	0.20	Bal
Al7075	0.40	0.43	1.90	0.47	1.50	0.38	1.10	0.20	Bal

Table 2. Detailed Composition of Reinforced particles in composite matrix

Material	Sample no.	wt.% of reinforcement		wt.% of base material
		SiC	Al_2O_3	
Al6061	1	0	0	100
	2	4	2	94
	3	8	4	88
	4	12	6	82
Al7075	1	0	0	100
	2	4	2	94
	3	8	4	88
	4	12	6	82

which gets added in the vertex during stirring and allows repelling out the moisture which causes cluster formations. The reinforcement of the SiC in Al_2O_3 is done to improve the characteristics attribute of the composite alloy in terms of interfacial connect and the instructive phase [17, 18]. The impeller is continuously involved on stirring at the rate of 500 rpm for about 10 min. Then the melt consisting of the reinforcing material is then casted into the mould with a radius of about 15 mm and a length of 150 mm. The mould is cylindrical in shape and ensures constant casting. The attributes of the alloys considered for comparison are tabulated and compared against each other in the Table 2. The required samples are machined as per ASTM (American Society for Testing and Materials) Standards.

Then the casted rods were immediately subjected to cooling at the optimum room temperature. Then the rods were knocked out of the casting machine after the duration of 10 min. The stir casting setup used for fabricating the composite material is shown in Fig. 1, along with the cast sample. Depending upon the filler ratio, the alloys are differentiated. The ductility level of the reinforced particles was estimated by the brittle testing. The samples fabricated with different filler ratios of each alloys were illustrated in Fig. 1, *b*, as the macrographic picture where the brittle fracture of the samples is significantly visible with normal view to the absence of expanded and fibrous appearance over the surface.

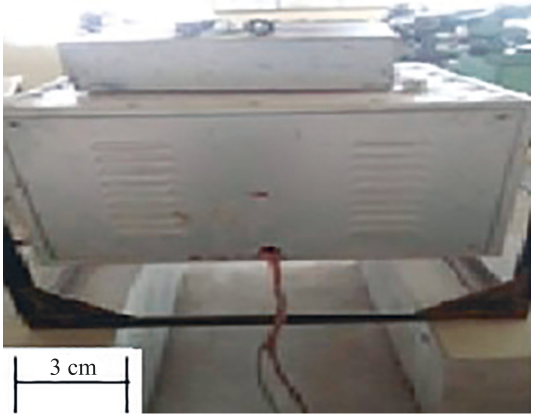
Experimental tests

The investigations for determining the hardness, resistivity against the wear and tear and the impact tests were carried out in agreement to the standards of ASTM.

Impact test

The significant of impact test is analyzed with ASTM E23 standard [19]. The impact behavior is estimated by determining the energy spent to shatter the sample then correlated with the sample cross sectional

a



b

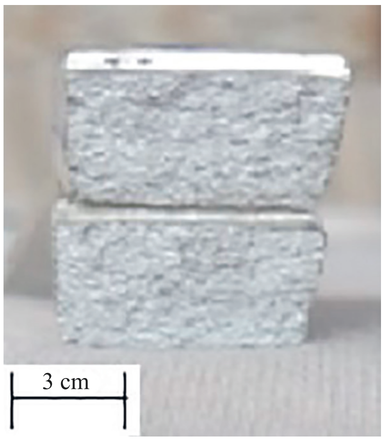


Fig. 1. Stir casting setup (*a*) and casted sample (*b*)

dimension, and the standard size adopted for the impact testing in the current investigational procedure which is 10 × 10 × 55 mm.

Hardness test

To conduct the hardness test, the samples were polished to form a smooth surface. The hardness of the samples was determined by the Brinell hardness testing method, as per ASTM E10 standard [20]. This method consists of a ball like structure with the radius of 2.5 mm. A load of 100 kg was subjected on each sample for about 10 secs, and the corresponding readings were recorded. For getting the accurate measuring, the test on each sample was carried out thrice.

Wear test

Pin-on-disc test estimated the wear rate of the composite alloys. The optimal dry laboratory environment was set up for conducting the wear test. All prepared samples were as per the standards of ASTM G99. The experimental set up and the required sample dimension were illustrated in the Fig. 2, *a*. Tribometer estimated the wear and frictional force between the sliding surfaces. The testing sample is placed on the given holder, and then a load is suspended at the sample end [21, 22]. A sliding disc with high carbon high chromium steel was connected across the holder of the Tribometer. The corresponding radius and the thickness of the disc are 100 mm and 8 mm respectively. When the motor starts running, the sliding between the disc and the sample occurs. The motor is stopped after the pre estimated time of 10 min. The same procedure is repeated for all the samples and the corresponding reading were recorded and tabulated. The required dimension of the pin samples was 6 mm diameter and 25 mm length (Fig. 2, *b*, *c*).

Results and discussion

Impact test results

The results of the instrumented impact test of all HMMC of Al6061 (SiC + Al_2O_3) and Al7075 (SiC + Al_2O_3) alloys at different composition ratio are discussed in this section. The samples before and after impact test were shown in Fig. 3.

From the results it is clearly evident that the impact of both the composite matrices depends upon the dispersion of the particles in the composite matrix [23, 24]. When the stress distribution is uniform, the increase of the impact value of all samples of Al7075 composite alloy is noted. The addition of the reinforcement nanoparticles results in the larger grain boundary with the smaller grain sizes. When the nanoparticles size added to the Al7075 alloy composite increases, the results are obtained as per the expected values with increasing ductility. Thus, the addition of reinforced nanoparticles tends to ameliorate the strength and stiffness and also significantly reduces the thermal expansion.

The comparison of the Al7075 and Al6061 composite alloys is represented in graphical form in the Fig. 4. From

a *b* *c*

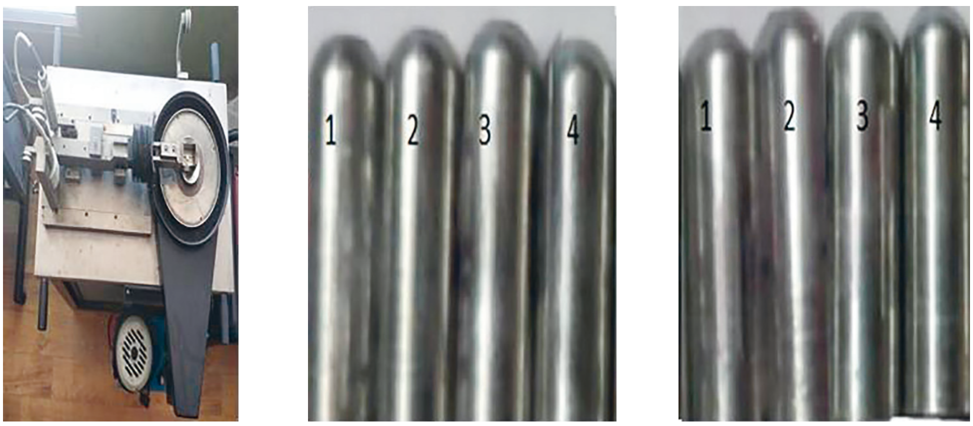


Fig. 2. Wear testing machine (*a*); pin samples: Al6061 (SiC + Al_2O_3) (*b*) and Al7075 (SiC + Al_2O_3) (*c*)

a *b* *c* *d*

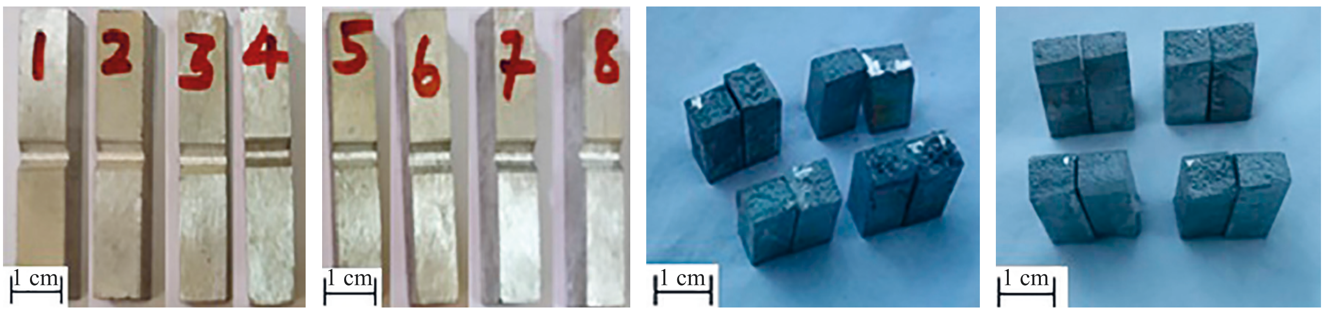


Fig. 3. Samples before test: Al6061 (SiC + Al_2O_3) (*a*); Al7075 (SiC + Al_2O_3) (*b*). Samples after test: Al6061 (SiC + Al_2O_3) (*c*); Al7075 (SiC + Al_2O_3) (*d*)

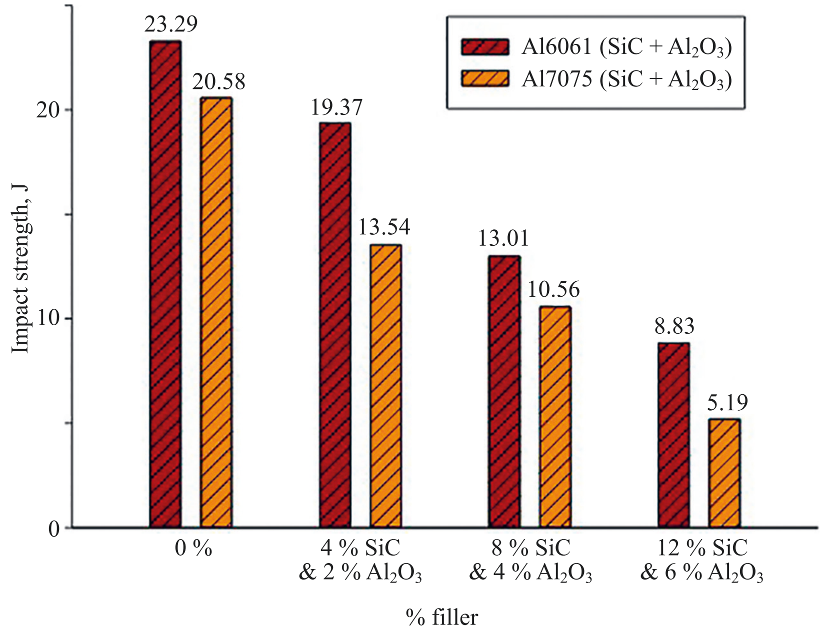


Fig. 4. Graphical representation of the comparative analysis of impact strength

the graph it is observed that the impact strength decreases by increasing the addition of nanoparticles in the alloy matrix. Additionally, for both alloys, the impact strength tends to decline as volume percent. However, it is evident from the results and graph that the alloy Al7075 has lesser impact strength than the other. An additional amazing fact is that the impact strength does not vary with different temperatures [25]. The reducing impact strength in the reinforced alloy composites led to the precipitation of the brittleness in the composite matrix which agrees with the previous studies [26, 27].

Hardness test results

The picture below displays the outcomes of Brinell testing using ASTM E10 standards. A steel ball is squeezed during this test, after which the ball is taken out. A microscope is used to measure the intended sample diameter.

A graphic illustration of the comparison analysis of the Brinell hardness test data is shown in Fig. 5 where the graphical depiction clearly displays the testing findings for both composite alloys with various filler percentages. The study reveals that the enhanced component ratio is bigger as a result modified mechanical qualities such as toughness and hardness. Upon analyzing the graph, it is evident that the hardness of the Al7075 (12 % SiC+6 % Al_2O_3) is higher to the value of 123 BHN. This clearly signifies that the Al7075 (12 % SiC+6 % Al_2O_3) has better performance characteristics in terms of hardness when compared with

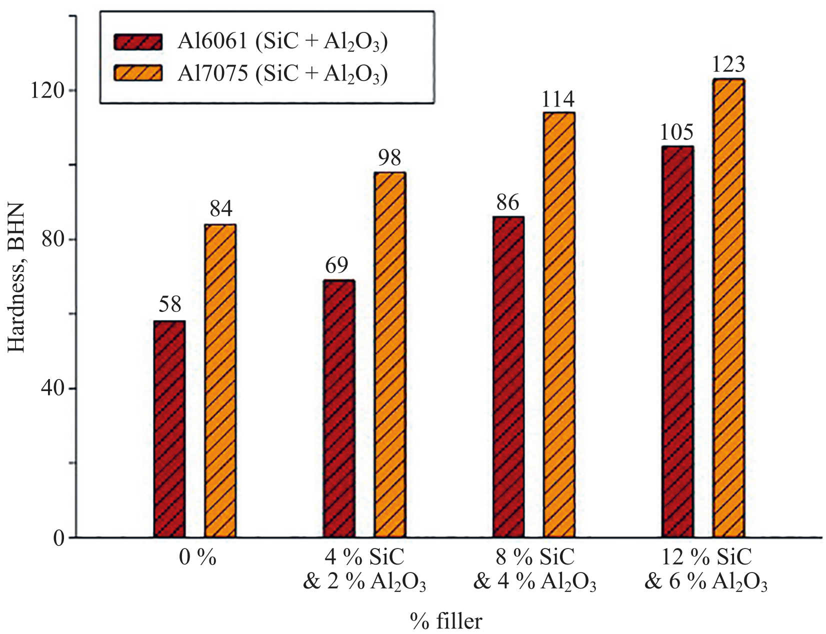


Fig. 5. Comparative analysis of Brinell hardness test

the other alloys. The reinforced material SiC has higher hardness when compared to that of the Al_2O_3, thus by increasing the composite alloy hardness.

Wear test results

On all three samples of each alloy, the rotary wear test was conducted for approximately 10 min with a load of 30 N spinning at a speed of 500 rpm to evaluate the alloys resistance to wearing. Sample wear rate is identified by weight loss method. Weight is divided for known distance to identify the sliding distance. Different sliding speeds with different normal load were used for wear test. To find out the wear loss, the weights are measured before and after testing the sample. While sliding, friction force of the sample is used to obtain the coefficient of friction of sample and it was plotted against sliding distance.

The ratio of different compositions is kept constant throughout the test procedure.The experimental setup is connected to a DAC that calculates friction forces, and the corresponding coefficients of WINDUCOM software are used to generate graphic data for the results compared the coefficient of friction force load and rotational speed for both alloy composites tabulated in Table 3.

Wear loss

From the investigation, it was found that with time increasing, the losses due to wear increase indicating an increase in wear loss. With the increasing wear loss, deformation of the Al matrix occurs which could end up in the surface cracking of the alloys. These effects result in the removal of higher material from the substrate as wear loss. The reinforced NPs of SiC and Al_2O_3 also wear out of the surface causing the formation of grooves on the matrix alloy surfaces. From the research it is concluded that the alloy resistivity increased due to SiC nanoparticle reinforcement, as shown in Fig. 6.

Coefficient of friction

The frictional coefficient investigated for the SiC and Al_2O_3 in Al6061 and Al7075 is shown in the Fig. 7. The coefficient of friction tends to decline with the sliding rate and load. The frictional coefficient value of the Al composite matrix is always higher when compared with the

Table 3. Wear test results of Al7075 and Al6061

Material	Reinforcement volume, %		Matrix volume, %	Sliding speed, m/s	Time, min	Wear loss, g	Friction force, N	Coefficient of friction
	SiC	Al_2O_3						
Al6061	0	0	100	1.32	10	0.038	15.53	0.398
	4	2	94	1.32	10	0.027	26.22	0.415
	8	4	88	1.83	10	0.020	32.45	0.456
	12	6	82	2.62	10	0.015	41.37	0.487
Al7075	0	0	100	2.83	10	0.034	13.43	0.343
	4	2	94	2.83	10	0.022	22.51	0.356
	8	4	88	1.62	10	0.016	28.15	0.387
	12	6	82	1.62	10	0.010	34.56	0.405

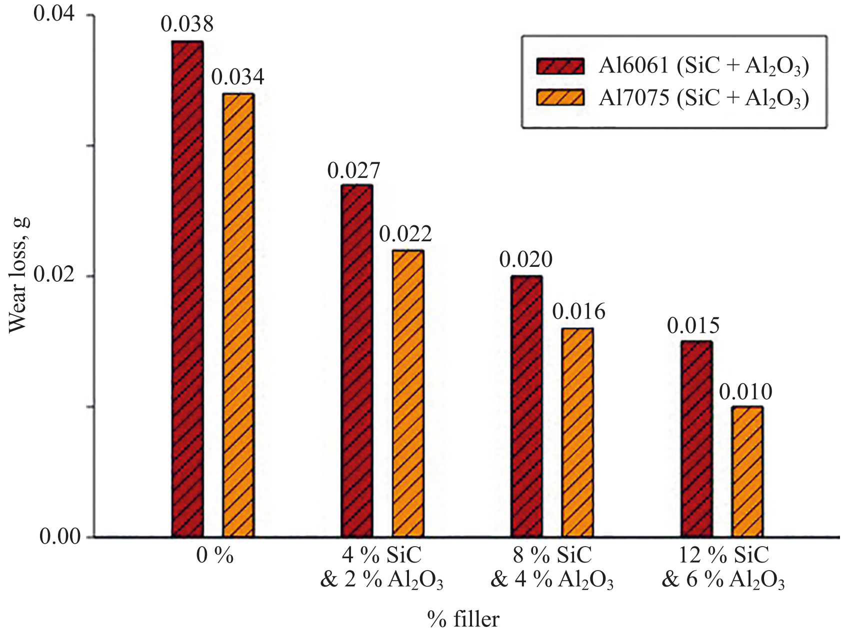


Fig. 6. Wear loss for Al6061 ($SiC + Al_2O_3$) and Al7075 ($SiC + Al_2O_3$)

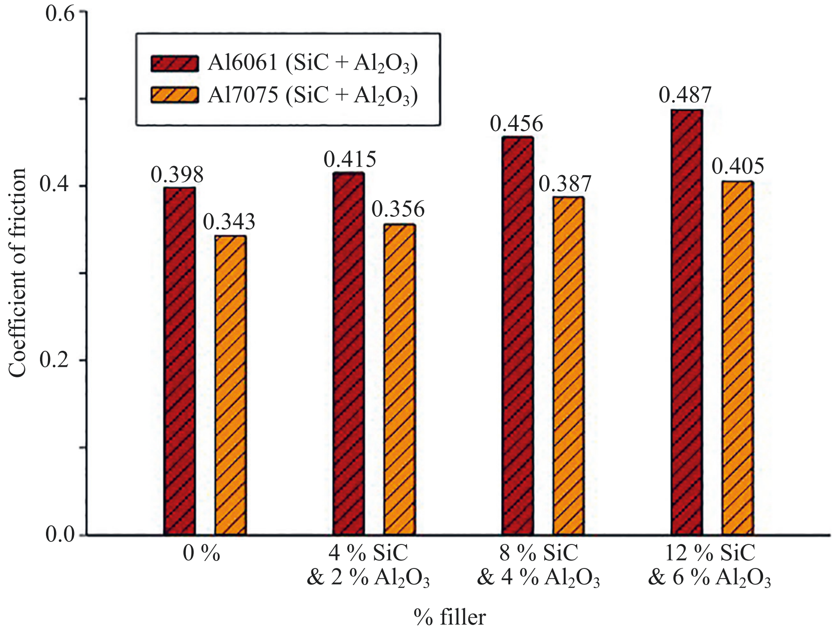


Fig. 7. Coefficient of friction for Al6061 (SiC + Al_2O_3) and Al7075 (SiC + Al_2O_3)

original Al alloy. With the value of the frictional coefficient increase, the wear loss also decreases and, hence, there is less wear loss in the Al composite matrices. This agrees with the conclusions made by other researches. From the graphs it is concluded that the increasing in the frictional coefficient occurs when the reinforcement particles SiC and Al_2O_3 are uniformly dispersed in the Al composite matrix.

Frictional force

From the graphs it is clear that the value of the frictional force depends upon the ratio of the reinforcement materials in the composite matrix. Similar to the results of the frictional coefficient, frictional force also tends to increase with the increasing ratio of the SiC and Al_2O_3, as shown in Fig. 8.

Microstructural analysis of wear test samples

The metallographic process which includes the selection of sample, mounting, grinding, polishing and etching was done in order to subject the samples to the micro structural analysis. Then the constructional architecture of the samples was then microscopically characterized after etching with the NaOH solution. The microscopic studies of the Al7075 and Al6061 with scope ratio of $100^{\times}$ and $500^{\times}$ were illustrated in the Fig. 9.

The microphotographs of the Al7075 (4 % SiC + 2 % Al_2O_3) were shown in the Fig. 9, *a*, *b* where the distribution of the nanoparticles along the grain margin of the primary solid solution of Al can be seen. The microscopic analysis of the Al7075 (8 % SiC + 4 % Al_2O_3) is illustrated in the

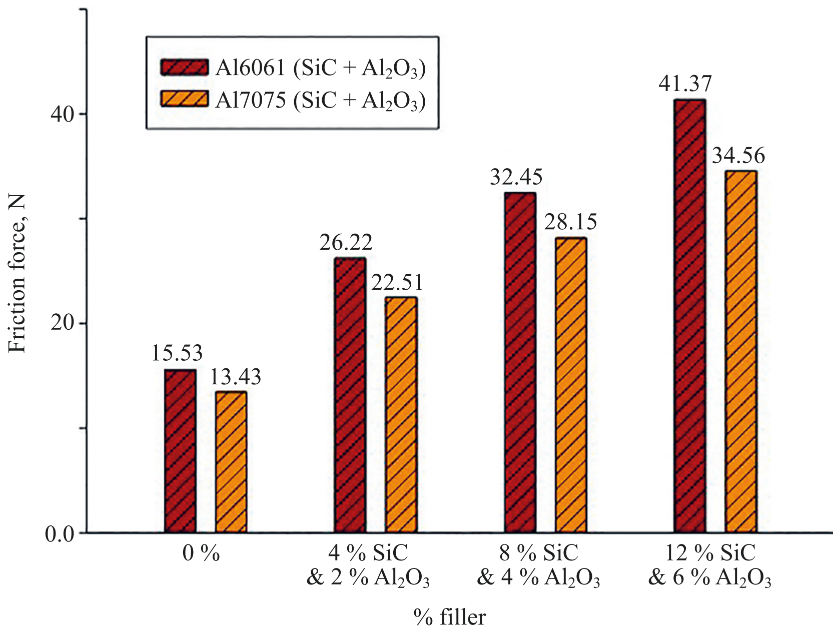


Fig. 8. Frictional force for Al6061 (SiC + Al_2O_3) and Al7075 (SiC + Al_2O_3)

Fig. 9, *c*, *d*. On these figures the significant feature is the even dispersion of the nanoparticles along the margins. In the Fig. 9, *e*, *f* the microscopic analysis of Al7075 (12 % SiC + 6 % Al_2O_3) is given. This picture also clearly depicts the even distribution of the SiC and Al_2O_3 throughout the alloy matrices.

Fig. 9, *g*, *h* illustrates the microphotographs of the alloy Al6061 (4 % SiC + 2 % Al_2O_3). On the pictures the significant distribution of the SiC and Al_2O_3 is clearly observed. The particles are viewed as the clusters. Fig. 9, *g* presents the isolated distribution of the reinforced nanoparticles along the grain margins. The microscopic illustration of the alloy Al6061 (8 % SiC + 4 % Al_2O_3) was given in the Fig. 9, *i*, *j* for different magnification. Upon keen observation the fair distribution of the reinforced nanoparticles was clearly evident. The microphotographs

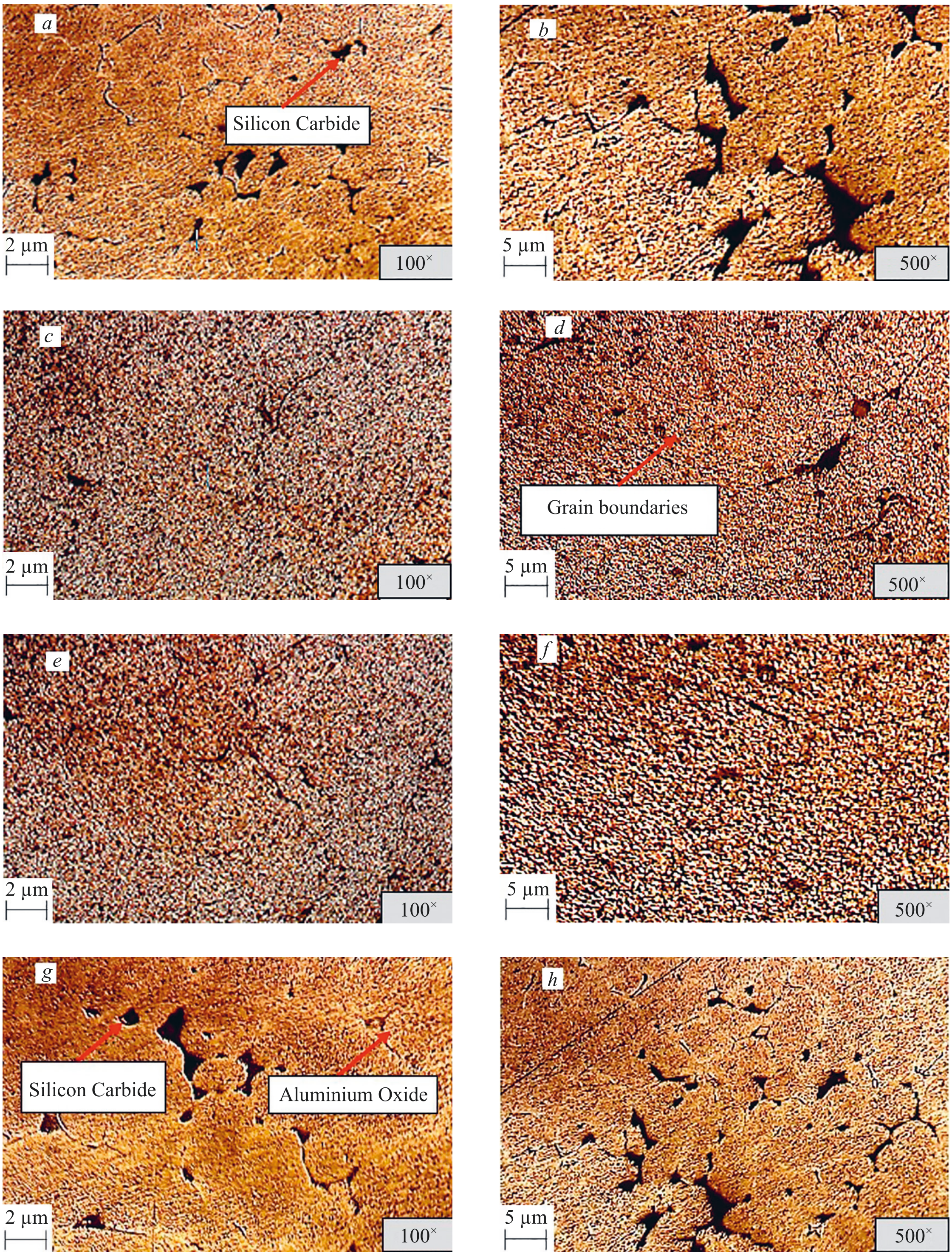


Fig. 9. Microstructure illustration composite alloys with scope ratio of 100× and 500×: Al7075 (4 % SiC + 2 % Al_2O_3) – 100× (*a*) and 500× (*b*); Al7075 (8 % SiC + 4 % Al_2O_3) –100× (*c*) and 500× (*d*); Al7075 (12 % SiC + 6 % Al_2O_3) – 100× (*e*) and 500× (*f*); Al6061 (4 % SiC + 2 % Al_2O_3) – 100× (*g*) and 500× (*h*); Al6061 (8 % SiC + 4 % Al_2O_3) – 100× (*i*) and 500× (*j*); Al6061 (12 % SiC + 6 % Al_2O_3) – 100× (*k*) and 500× (*l*)

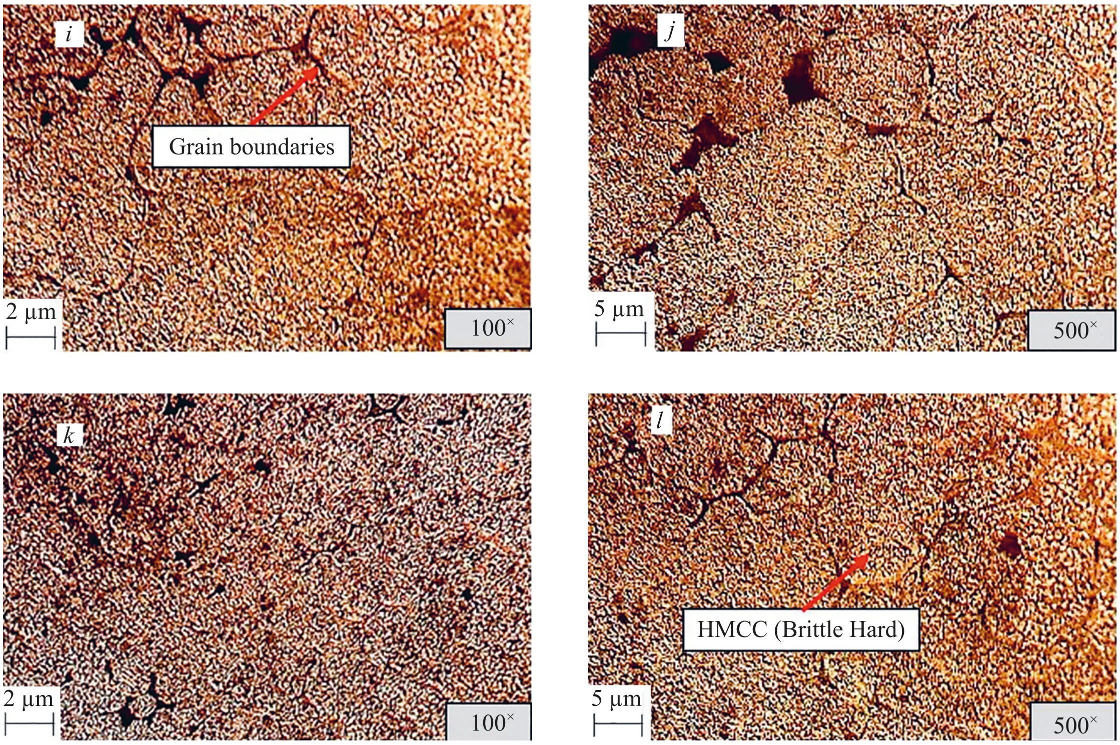


Fig. 9. Continuation

of the alloy Al6061 (12 % SiC + 6 % Al_2O_3) were given in the Fig. 9, *k*, *l*. In these figures the increased concentration of the nanoparticles in the composite matrices can be observed.

Upon investigation of all the samples, it is found that Al7075 (12 % SiC + 6 % Al_2O_3) composite has the minimal wearing rate when compared with the other samples. From the study it was proven that the distribution of the reinforcement materials SiC and Al_2O_3 was uniform throughout the matrix. Thus, it is concluded that with the increase in the filler composition the mechanical attributes and the hardness and wear rate of the matrix is also improved. Also, the thermal expansion was significantly reduced. The fusion of the reinforced particles to the Al alloy progresses the hardness, reduces the impact strength and ameliorates the wear resistance against sliding as concluded in the previous studies.

Conclusion

The considerable conclusions of the current investigation involving the comparison of the Al6061 and Al7075 matrix composite alloys were presented as follows.

The fabrication process (involving the liquid metallurgy methods) is advantageous to produce the composite of Al6061 and Al7075 alloys reinforced with SiC and Al_2O_3 with the filler ratio of about 18 %.

The particulates were dispersed evenly throughout the composite matrix which was confirmed through the microstructural analysis.

Increase in the hardness of the sample with the increasing filler ratio was observed and the corresponding hardness estimated for the Al6061 and Al7075 in the current investigation were 105 and 123 BHN respectively.

The impact test results reveal that the composite alloys have reduced impact strength when compared with that of the base alloys. Among the two alloys under consideration, Al7075 has the highest impact strength.

Generally, the samples of both alloys show improvised resistivity against wear, but Al7075 (12 % SiC + 6 % Al_2O_3), specifically, exhibits notable increase in the resistivity against wear and friction.

From the microscopy analysis of all the samples, Al7075 (12 % SiC + 6 % Al_2O_3) holds minimal wear rate with fair distribution of the reinforced nanoparticles along the grain boundary and throughout the alloy matrix. It is clearly evident that the filler composition of this sample improvises the hardness and rate of wear of the matrix with significant reduction in the thermal expansion.

Thus, if you draw a conclusion after comparing all the samples, Al7075 (12 % SiC + 6 % Al_2O_3) shows an outstanding behavioral attributes with the extraordinary tribological and mechanical specifications.

From the above conclusions, Al7075 (12 % SiC + + 6 % Al_2O_3) is considered to be a promising alloy in the applications of automobile industry, like piston manufacturing, connecting rod due to its minimized wear rate and improvised thermal expansion.

References

1. Chawla K.K. *Composite Materials. Science and Engineering*. 2nd ed. New York, Springer Verlag, 1998, 165 p.
2. Chawla N., Shen Y.L. Mechanical behavior of particle reinforced metal matrix composites. *Advanced Engineering Materials*, 2001, vol. 3, no. 6, pp. 357–370.
3. Senthilkumar N., Kalaichelvan K., Elangovan K. Mechanical behaviour of aluminum particulate epoxy composite — experimental study and numerical simulation. *International Journal of Mechanical and Materials Engineering*, 2012, vol. 7, no. 3, pp. 214–221.
4. Srivatsan T.S., Al-Hajri M., Smith C., Petraroli M. The tensile response and fracture behavior of 2009 aluminium alloy metal matrix composite. *Materials Science and Engineering: A*, 2003, vol. 346, no. 1-2, pp. 91–100. https://doi.org/10.1016/S0921-5093(02)00481-1
5. Tan M., Xin Q., Li Z., Zong B.Y. Influence of SiC and Al_2O_3 particulate reinforcements and heat treatments on mechanical properties and damage evolution of Al-2618 metal matrix composites. *Journal of Materials Science*, 2001, vol. 36, no. 8, pp. 2045–2053. https://doi.org/10.1023/A:1017591117670
6. Lloyd D.J. Particle reinforced aluminium and magnesium matrix composites. *International Materials Reviews*, 1994, vol. 39, no. 1, pp. 1–23. https://doi.org/10.1179/imr.1994.39.1.1
7. Sundaraselvan S., Senthilkumar N. Surface modification of AZ61 magnesium alloy with nano-Al_2O_3 using laser cladding technique: optimization of wear properties through hybrid GRA-PCA. *International Journal of Rapid Manufacturing*, 2019, vol. 8, no. 3, pp. 221. https://doi.org/10.1504/IJRAPIDM.2019.10020259
8. Tjong S.C., Wu S.Q., Zhu H.G. Wear behavior of in situ TiB2·Al_2O_3/Al and TiB2·Al_2O_3/Al–Cu composites. *Composites Science and Technology*, 1999, vol. 59, no. 9, pp. 1341–1347. https://doi.org/10.1016/S0266-3538(98)00172-9
9. Nair S.V., Tien J.K., Bates R.C. SiC-reinforced aluminium metal matrix composites. *International Metals Reviews*, 1985, vol. 30, no. 1, pp. 275–290. https://doi.org/10.1179/imtr.1985.30.1.275
10. Bhojan N., Senthilkumar B., Deepanraj B. Parametric influence of friction stir welding on cast Al6061/20%SiC/2%MoS_2 MMC mechanical properties. *Applied Mechanics and Materials*, 2016, vol. 852, pp. 297–303. https://doi.org/10.4028/www.scientific.net/AMM.852.297
11. Alpas A.T., Zhang J. Effect of microstructure (particulate size and volume fraction) and counter face material on the sliding wear resistance of particulate-reinforced. *Metallurgical and Materials Transactions A*, 1994, vol. 25, no. 5, pp. 969–983. https://doi.org/10.1007/BF02652272
12. Kwok J.K.M., Lim S.C. High-speed tribological properties of some Al/SiCp composites. I. Frictional and wear-rate characteristics. *Composites Science and Technology*, 1999, vol. 59, no. 1, pp. 55–63. https://doi.org/10.1016/S0266-3538(98)00055-4
13. Friend C.M. Toughness in metal matrix composites. *Materials Science and Technology*, 1989, vol. 5, no. 1, pp. 1–7. https://doi.org/10.1179/mst.1989.5.1.1
14. Nardone V.C., Strife J.R., Prewo K.M. Microstructurally toughened particulate-reinforced aluminum matrix composites. *Metallurgical Transactions A*, 1991, vol. 22, no. 1, pp. 171–182. https://doi.org/10.1007/BF03350959
15. Ozden S., Ekici R., Nair F. Investigation of impact behaviour of aluminium based SiC particle reinforced metal–matrix composites. *Composites Part A: Applied Science and Manufacturing*, 2007, vol. 38, no. 2, pp. 484–494. https://doi.org/10.1016/j.compositesa.2006.02.026
16. Ragupathy K., Velmurugan C., Senthilkumar N. Tribological and heat treatment prediction of stir cast Al 6061/SiC/MoS_2 composites using grey relational analysis. *Journal of the Balkan Tribological Association*, 2018, vol. 24, no. 2, pp. 198–217.
17. Saminathan S., Laksmipathy J. Experimental investigation and prediction analysis on Granite/SiC Reinforced Al7050 and Al7075 using hybrid deep neural network based salp swarm optimization. *Silicon*, 2022, vol. 14, no. 11, pp. 5887–5903. https://doi.org/10.1007/s12633-021-01349-0
18. Nielson L.E., Landel R.F. *Mechanical Properties of Polymers and Composites*. New York, Marcel Dekker, Inc., 1994.
19. *ASTM E23-93a. Standard test methods for notched bar impact testing of metallic materials*. 1993 Annual book of ASTM Standards, pp. 206–26.

Литература

1. Chawla K.K. Composite Materials. Science and Engineering / 2nd ed. New York: Springer Verlag, 1998. 165 p.
2. Chawla N., Shen Y.L. Mechanical behavior of particle reinforced metal matrix composites // Advanced Engineering Materials. 2001. V. 3. N 6. P. 357–370.
3. Senthilkumar N., Kalaichelvan K., Elangovan K. Mechanical behaviour of aluminum particulate epoxy composite – experimental study and numerical simulation // International Journal of Mechanical and Materials Engineering. 2012. V. 7. N 3. P. 214–221.
4. Srivatsan T.S., Al-Hajri M., Smith C., Petraroli M. The tensile response and fracture behavior of 2009 aluminium alloy metal matrix composite // Materials Science and Engineering: A. 2003. V. 346. N 1-2. P. 91–100. https://doi.org/10.1016/S0921-5093(02)00481-1
5. Tan M., Xin Q., Li Z., Zong B.Y. Influence of SiC and Al_2O_3 particulate reinforcements and heat treatments on mechanical properties and damage evolution of Al-2618 metal matrix composites // Journal of Materials Science. 2001. V. 36. N 8. P. 2045–2053. https://doi.org/10.1023/A:1017591117670
6. Lloyd D.J. Particle reinforced aluminium and magnesium matrix composites // International Materials Reviews. 1994. V. 39. N 1. P. 1–23. https://doi.org/10.1179/imr.1994.39.1.1
7. Sundaraselvan S., Senthilkumar N. Surface modification of AZ61 magnesium alloy with nano-Al_2O_3 using laser cladding technique: optimization of wear properties through hybrid GRA-PCA // International Journal of Rapid Manufacturing. 2019. V. 8. N 3. P. 221. https://doi.org/10.1504/IJRAPIDM.2019.10020259
8. Tjong S.C., Wu S.Q., Zhu H.G. Wear behavior of in situ TiB2·Al_2O_3/Al and TiB2·Al_2O_3/Al–Cu composites // Composites Science and Technology. 1999. V. 59. N 9. P. 1341–1347. https://doi.org/10.1016/S0266-3538(98)00172-9
9. Nair S.V., Tien J.K., Bates R.C. SiC-reinforced aluminium metal matrix composites // International Metals Reviews. 1985. V. 30. N 1. P. 275–290. https://doi.org/10.1179/imtr.1985.30.1.275
10. Bhojan N., Senthilkumar B., Deepanraj B. Parametric influence of friction stir welding on cast Al6061/20%SiC/2%MoS_2 MMC mechanical properties // Applied Mechanics and Materials. 2016. V. 852. P. 297–303. https://doi.org/10.4028/www.scientific.net/AMM.852.297
11. Alpas A.T., Zhang J. Effect of microstructure (particulate size and volume fraction) and counter face material on the sliding wear resistance of particulate-reinforced // Metallurgical and Materials Transactions A. 1994. V. 25. N 5. P. 969–983. https://doi.org/10.1007/BF02652272
12. Kwok J.K.M., Lim S.C. High-speed tribological properties of some Al/SiCp composites. I. Frictional and wear-rate characteristics // Composites Science and Technology. 1999. V. 59. N 1. P. 55–63. https://doi.org/10.1016/S0266-3538(98)00055-4
13. Friend C.M. Toughness in metal matrix composites // Materials Science and Technology. 1989. V. 5. N 1. P. 1–7. https://doi.org/10.1179/mst.1989.5.1.1
14. Nardone V.C., Strife J.R., Prewo K.M. Microstructurally toughened particulate-reinforced aluminum matrix composites // Metallurgical Transactions A. 1991. V. 22. N 1. P. 171–182. https://doi.org/10.1007/BF03350959
15. Ozden S., Ekici R., Nair F. Investigation of impact behaviour of aluminium based SiC particle reinforced metal–matrix composites // Composites Part A: Applied Science and Manufacturing. 2007. V. 38. N 2. P. 484–494. https://doi.org/10.1016/j.compositesa.2006.02.026
16. Ragupathy K., Velmurugan C., Senthilkumar N. Tribological and heat treatment prediction of stir cast Al 6061/SiC/MoS_2 composites using grey relational analysis // Journal of the Balkan Tribological Association. 2018. V. 24. N 2. P. 198–217.
17. Saminathan S., Laksmipathy J. Experimental investigation and prediction analysis on Granite/SiC Reinforced Al7050 and Al7075 using hybrid deep neural network based salp swarm optimization // Silicon. 2022. V. 14. N 11. P. 5887–5903. https://doi.org/10.1007/s12633-021-01349-0
18. Nielson L.E., Landel R.F. Mechanical Properties of Polymers and Composites. New York: Marcel Dekker, Inc., 1994.
19. ASTM E23-93a. Standard test methods for notched bar impact testing of metallic materials: 1993 Annual book of ASTM Standards. P. 206–26.
20. Selvakumar V., Muruganandam S., Senthilkumar N. Evaluation of mechanical and tribological behavior of Al–4 %Cu–x %SiC

20. Selvakumar V., Muruganandam S., Senthilkumar N. Evaluation of mechanical and tribological behavior of Al–4 %Cu–x %SiC composites prepared through powder metallurgy technique. *Transactions of the Indian Institute of Metals*, 2017, vol. 70, no. 5, pp. 1305–1315. https://doi.org/10.1007/s12666-016-0923-7
21. Thirumalvalavan S., Senthilkumar N. Experimental investigation and optimization of HVOF spray parameters on wear resistance behaviour of Ti-6Al-4V alloy. *Comptes rendus de l'Academie bulgare des Sciences*, 2019, vol. 72, no. 5, pp. 664–673. https://doi.org/10.7546/crabs.2019.05.15
22. Gajalakshmi K., Senthilkumar N., Prabu B. Multi-response optimization of dry sliding wear parameters of AA6026 using hybrid gray relational analysis coupled with response surface method. *Measurement and Control*, 2019, vol. 52, no. 5-6, pp. 540–553. https://doi.org/10.1177/0020294019842603
23. Bonollo F., Ceschini L., Garagnani G.L. Mechanical and Impact behaviour of (Al_2O_3)p/2014 and (Al_2O_3)p/6061 Al metal matrix composites in the 25–200°C range. *Applied Composite Materials*, 1997, vol. 4, no. 3, pp. 173–185. https://doi.org/10.1007/BF02481779
24. Surappa M.K., Sivakumar P. Fracture toughness evaluation of 2040-Al/Al_2O_3 particulate composites by instrumented impact. *Composites Science and Technology*, 1993, vol. 46, no. 3, pp. 287–292. https://doi.org/10.1016/0266-3538(93)90162-A
25. Poza P., Llorca J. Fracture toughness and fracture mechanisms of Al–Al_2O_3 composites at cryogenic and elevated temperatures. *Materials Science and Engineering: A*, 1996, vol. 206, no. 2, pp. 183–193. https://doi.org/10.1016/0921-5093(95)09999-9
26. Hasson D.F., Hoover S.M., Crowe C.R. Effect of thermal treatment on the mechanical and toughness properties of extruded SiCw/aluminium 6061 metal matrix composite. *Journal of Materials Science*, 1985, vol. 20, no. 11, pp. 4147–4154. https://doi.org/10.1007/BF00552410
27. Unsworth J.P., Bandyopadhyay S. Effect of thermal ageing on hardness, tensile and Impact properties of an alumina microsphere-reinforced aluminium metal–matrix composite. *Journal of Materials Science*, 1994, vol. 29, no. 17, pp. 4645–4650. https://doi.org/10.1007/BF00376291

composites prepared through powder metallurgy technique // Transactions of the Indian Institute of Metals. 2017. V. 70. N 5. P. 1305–1315. https://doi.org/10.1007/s12666-016-0923-7

21. Thirumalvalavan S., Senthilkumar N. Experimental investigation and optimization of HVOF spray parameters on wear resistance behaviour of Ti-6Al-4V alloy // Comptes rendus de l'Academie bulgare des Sciences. 2019. V. 72. N 5. P. 664–673. https://doi.org/10.7546/crabs.2019.05.15
22. Gajalakshmi K., Senthilkumar N., Prabu B. Multi-response optimization of dry sliding wear parameters of AA6026 using hybrid gray relational analysis coupled with response surface method // Measurement and Control. 2019. V. 52. N 5-6. P. 540–553. https://doi.org/10.1177/0020294019842603
23. Bonollo F., Ceschini L., Garagnani G.L. Mechanical and Impact behaviour of (Al_2O_3)p/2014 and (Al_2O_3)p/6061 Al metal matrix composites in the 25–200°C range // Applied Composite Materials. 1997. V. 4. N 3. P. 173–185. https://doi.org/10.1007/BF02481779
24. Surappa M.K., Sivakumar P. Fracture toughness evaluation of 2040-Al/Al_2O_3 particulate composites by instrumented impact // Composites Science and Technology. 1993. V. 46. N 3. P. 287–292. https://doi.org/10.1016/0266-3538(93)90162-A
25. Poza P., Llorca J. Fracture toughness and fracture mechanisms of Al–Al_2O_3 composites at cryogenic and elevated temperatures // Materials Science and Engineering: A. 1996. V. 206. N 2. P. 183–193. https://doi.org/10.1016/0921-5093(95)09999-9
26. Hasson D.F., Hoover S.M., Crowe C.R. Effect of thermal treatment on the mechanical and toughness properties of extruded SiCw/aluminium 6061 metal matrix composite // Journal of Materials Science. 1985. V. 20. N 11. P. 4147–4154. https://doi.org/10.1007/BF00552410
27. Unsworth J.P., Bandyopadhyay S. Effect of thermal ageing on hardness, tensile and Impact properties of an alumina microsphere-reinforced aluminium metal–matrix composite // Journal of Materials Science. 1994. V. 29. N 17. P. 4645–4650. https://doi.org/10.1007/BF00376291

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