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Effect of Heat Treatment on Mechanical Properties and Wear Behavior of Al7075 Alloy Reinforced with Beryl and Graphene Hybrid Metal Matrix Composites

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Abstract**—**In the recent years, aluminum metal matrix composites were most widely used, which are finding wide applications in various field such as automobile, aerospace defense etc., due to their outstanding mechanical properties like low density, light weight, exceptional high levels of strength, stiffness, wear resistance, high temperature resistance, low coefficient of thermal expansion and good formability. In the present work, an effort is made to study the effect of heat treatment on mechanical properties of aluminum 7075 alloy reinforced with constant weight percentage of naturally occurring mineral beryl and varying weight percentage of graphene. The hybrid composites are developed with 0.5 wt. %, 1wt.%, 1.5 wt.% and 2 wt.% of graphene and 6 wt.% of beryl by stir casting liquid metallurgy route. The cast specimens of unreinforced aluminum alloy and hybrid composite samples were prepared for heat treatment process and subjected to solutionizing treatment (T6) at a temperature of 490±5 °C for 8 hours in a muffle furnace followed by quenching in boiling water. The microstructure analysis of as cast and heat treated hybrid composite specimens are examined by scanning electron microscope (SEM). The tensile test and hardness test of unreinforced aluminum alloy and hybrid composites are examined. The wear behavior is examined by pin-on disc apparatus. The results of as cast specimens and heat treated specimens were compared. The heat treated Al7075-Beryl-Graphene hybrid composite had better properties and significantly improved the ultimate tensile strength, hardness and reduced wear loss when compared to aluminum alloy and as cast hybrid composites.

Keywords**—**Beryl, graphene, heat treatment, mechanical properties.

I. INTRODUCTION

COMPOSITE materials are made with the combination of two or more materials with different properties to produce advanced new material. A composite material can provide superior and outstanding unique physical and enhanced desirable mechanical properties which find applications in structural, automobiles, aerospace, space, defense, marine and medical. Metal matrix composites (MMCs) basically consist of one or more non-metallic reinforcements as either in continuous phase or discontinuous phase [1]. The aluminum alloys and its composites are most widely used in automobiles and aerospace due to their light weight and high strength [2]-[4]. Many engineering applications in the field of aerospace engineering, automobiles, electronic equipment etc., require very light material with good mechanical properties. Aluminum based metal matrix composites with graphene reinforcement can be a solution for such applications. The Al MMCs satisfy many engineering application and also provide convenient processing because of enough melting point of aluminum. Al 7075 alloy is most widely used in the aerospace because of its high strength and low density [5]-[11]. Recently the incorporation of particulate reinforced ceramic hard particles like silicon carbide, boron carbide, aluminum oxides, silicates such as beryllium aluminium silicates ($Be_3Al_2(SiO_3)_6$), nickel silicide (Si_3N4), magnesium silicide (Mg_2Si) etc. into the Al matrix enhance its mechanical and physical properties of the composites and make them a low cost, inherent isotropic and better candidate material for various engineering applications [12]-[16]. Aluminium and its alloys are generally reinforced with ceramic materials which are in the form of particulates, fibers, or whiskers with micron size range. But in the recent years nanomaterials were used as reinforcement in Al MMCs, due to their higher area to volume ratio, excellent and unique properties with respect to mechanical and physical properties which are capable of meeting design expectations [17]-[18].

Carbon based nanomaterials like graphene, nano-diamonds and carbon nanotubes exhibit outstanding mechanical, tribological, electro-chemical and thermal properties due to their well-organized structures. Graphene has emerged as important class of advanced and unique reinforcement material in aluminium alloys due to its high strength, large aspect ratio, improved thermal properties and high elastic modulus [19]. From the literature review it has been found that very little work has been accomplished by using beryllium aluminium silicate and graphene as reinforcement in aluminium metal matrix composite. Beryl is naturally occurring material and incorporation of beryl in metal matrix composite exhibits wear resistance and increase in hardness [20]-[24]. Speer et al. [25] have described the applications of aluminum-beryllium metal matrix composites (AlBeMet). The AlBeMet composites are most widely used in aerospace and structural applications. The AlBeMet material has excellent light weight, high strength to weight ratio and thermal properties are outstanding which perfect match for the high temperature applications. AlBeMet material has a low

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coefficient of thermal expansion, high melting point, high specific heat and high thermal conductivity these properties are favorable for variety space and aerospace application. Many researchers [24]-[31] revealed that, liquid metallurgy route (stir casting) is one of the most widely used and economical processing techniques for the fabrication of particulate MMCs. In the present study, Al 7075 as matrix and Al7075/Beryl/Graphene MMCs were fabricated by liquid metallurgy route with varying percentage of graphene from 0.5wt% to 2wt% in steps of 0.5 and fixed percentage (6wt%) of beryl. The present study aimed to investigate the effects of heat treatment on the mechanical and wear behavior of aluminium composites containing graphene and beryl reinforcement particles. The microstructural characterization of hybrid nanocomposites as cast and worn out surface is studied using SEM.

II. MATERIALS AND METHODS

A. Matrix Material

In the present work, Al7075 alloy is used as a matrix material, the alloying elements like zinc, magnesium and copper lead to corrosion resistance, high strength and hardness. Al7075 alloy has outstanding properties which leads to wide usage in many engineering sector, typically used in aircraft structural parts and other highly stressed structural application. Al7075 alloys were procured from M/s Fenfe Metallurgical, Bangalore. The chemical composition of matrix alloy is shown in Table I.

TABLE I
CHEMICAL COMPOSITION OF AL 7075 MATRIX ALLOY

Chemical Composition	Weight Percentage
Zinc (Zn)	5.602
Magnesium (Mg)	2.506
Copper (Cu)	1.598
Chromium (Cr)	0.253
Titanium (Ti)	0.18
Iron (Fe)	0.106
Manganese (Mn)	0.0014
Silicon (Si)	0.052
Aluminium (Al)	Balance

B. Reinforcement Material

TABLE II
CHEMICAL COMPOSITION OF BERYL

Chemical Composition	Weight Percentage
Silicon Oxide (SiO_2)	62.12
Aluminium Oxide (Al_2O_3)	18.05
Beryllium Oxide (BeO)	8.24
Ferric Oxide (Fe_2O3)	4.054
Calcium Oxide (CaO)	1.34
Magnesium Oxide (MgO)	0.48
Sodium Oxide (Na_2O)	0.55
Potassium Oxide (K_2O)	0.004
Manganese Oxide (MnO)	0.05

Beryl and graphene are used as reinforcing materials. Beryl, commonly known as beryllium aluminum silicate and having chemical formula (Be_3Al_2 $(SiO_3)_6$) is a naturally available mineral. The density of the mineral beryl is 2700-2800 kg/m^3 which is quite similar to the aluminum alloy, having hardness of 7.5-8.5 on Mho's scale and hexagonal crystal structure was used as the reinforcement. The particle size of reinforcement beryl used here is 60 to 70 microns (µm). The chemical composition of beryl is shown in Table II.

Fig. 1 represents the SEM image of beryl and Fig. 2 shows the XRD analysis of beryl. The presence of beryl and its hexagonal crystal structure was found in XRD analysis.

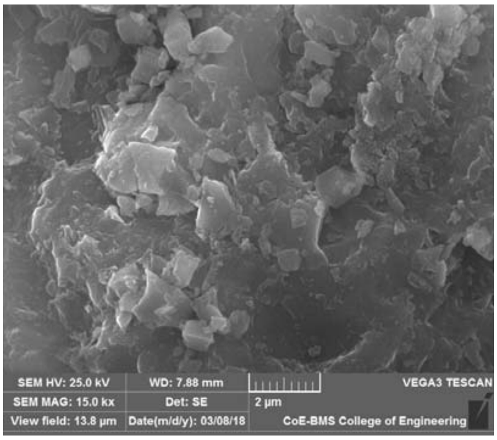

Fig. 1 SEM image of beryl particles

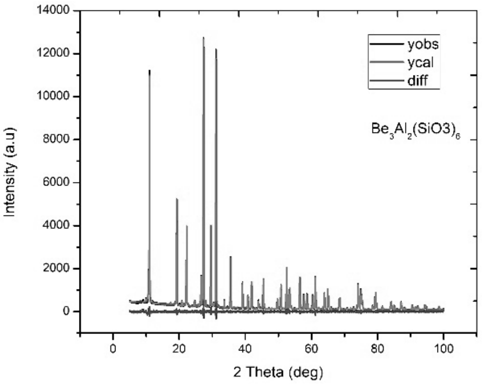

Fig. 2 XRD image of beryl particles

Graphene is a building block of graphitic materials which has two-dimensional, crystalline allotrope of carbon. In the present investigation, graphene is used as reinforcement. The particle size of graphene is 5-10 nano meter. The graphene particles have density of 480 kg/m^3 and anorthic (triclinic) crystal system was used as reinforcement. The SEM image of graphene is shown in Fig. 3.

C. Methods

Al 7075, fixed 6wt% of beryl particles and varying weight percentage of graphene reinforcement were fabricated by liquid metallurgy route (stir casting method) by using 6 kW, 5 kg melting capacity, PID temperature controlled electrical furnace. Aluminum 7075 alloy is firstly melted in furnace at 800 ºC. The preheated graphene and beryl particulates were poured slowly into vortex of molten metal. The vortex was created by using remi made mechanical stirrer for the duration of 10 minutes and the stirring speed maintained was 300 rpm. The melt is degassed by using commercially available tablets of hexachloroehtane (C_2Cl_6). Finally the molten metal is poured into the preheated cast iron molds. Heat treatment (solutionizing heat treatment T6) was carried out in an electric furnace. The specimens were heat treated for a solutionizing temperature of 490±5 ºC for 8 hours and then quenched in boiling water medium. Table III shows the list of composites prepared.

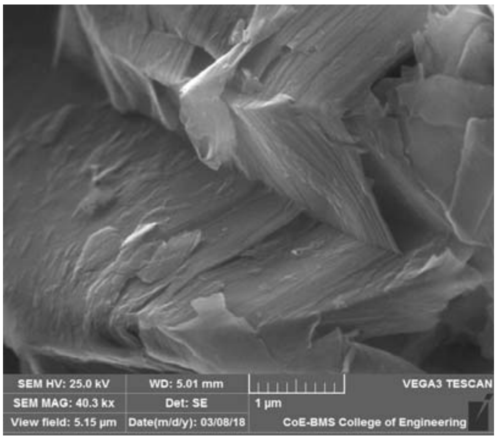

Fig. 3 SEM image of graphene

TABLE III
LIST OF PREPARED COMPOSITES

Sample	Al 7075 (wt %)	Beryl (wt %)	Graphene (wt %)
A	100	0	0
B	93.5	6	0.5
C	93	6	1
D	92.5	6	1.5
E	92	6	2

The prepared Al7075, beryl and graphene (AlBeGr) of both as cast and heat treated hybrid nanocomposite were subjected for machining to obtain tensile, hardness and wear test specimens. The tensile test was carried out on as cast and heat treated hybrid composite and matrix materials as per ASTM-E8 standard. The Brinell hardness tests were carried out as per ASTME-E10 standard. The hardness tests were conducted on three different places of the hybrid composite and matrix test specimens to stand the chance of indenter resting on reinforcement, which may result in desired expected value. A pin-on disc apparatus was used to study the dry sliding wear behavior of the as cast and heat treated Al7075 alloy and hybrid composites. The wear specimens were machined to a pin size of 8 mm diameter and 25 mm height and then polished. The counterpart disc is made of EN32 steel disc of hardness 60 HRC. The wear test of both as cast and T6-heat treated Al7075 alloy and its hybrid composites were characterized for various sliding distance, sliding speed and load.

III. RESULTS AND DISCUSSION

A. Microstructure Study

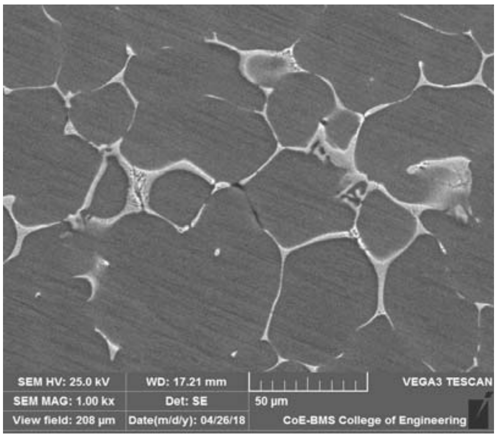

Fig. 4 (a) SEM image of Al7075 alloy

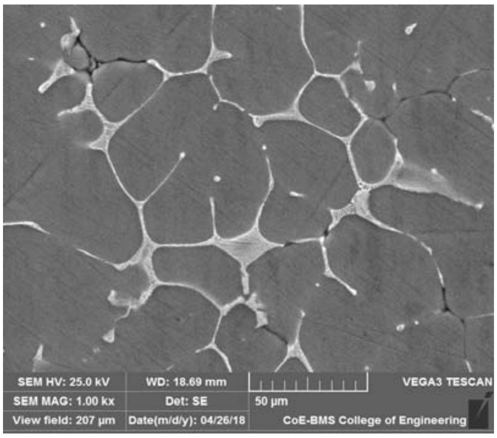

Fig. 4 (b) SEM image of Al7075/6 wt.% of beryl-0.5 wt. % of graphene

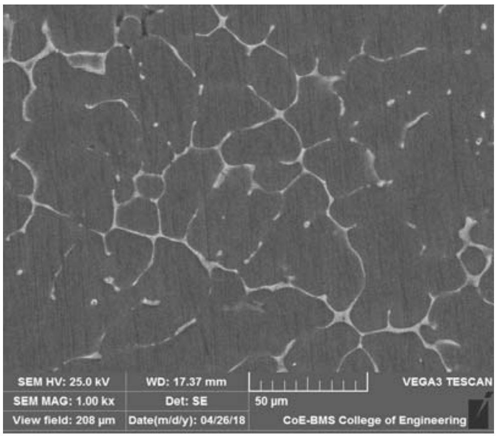

Fig. 4 (c) SEM image of Al7075/6 wt.% of beryl-1 wt. % of graphene

The microstructure study of as cast and heat treated of Al7075 and hybrid nanocomposite clearly reveals that, distribution of graphene and beryl particles in the matrix are fairly uniform along with increased filler contents with minimal porosity in the hybrid composite. Further, from tests results an excellent bonding between both the Al7075 alloy and reinforcement is inferred. Fig. 4 shows the optical micrograph of the Al7075 alloy, Al7075/6wt. % beryl 0.5 wt.% of graphene and Al7075/6wt.% beryl and 1 wt.% of graphene particulate composites.

B. Hardness

It is inferred from the test results that, the hardness of hybrid MMC increases with increasing weight percentage of reinforcement. The hybrid composites attain peak hardness on addition of 6wt. % of beryl particles and 1% of graphene (sample 3). The hybrid composites having 6wt. % of beryl particles and 1% of graphene showed enhancement of 14.66% as compared to Al7075 matrix material. However the hardness begins to drop when the graphene exceeds 1%, it may be due to poor wettability. The hardness for 6wt. % of beryl particles and 2wt. % of graphene showed enhancement of 3.52% as compared to matrix material. This occurs due to increases in surface area of the matrix and the reduced grain size and beryl particles are harder than Al7075.

The hardness of the solutionized Al7075 alloy increases around 19.07%, while the solutionized Al7075-6 wt.% beryl and 1 wt.% of graphene show an improvement in the hardness around 10.18% compared to the as-cast matrix alloy. The relationship between Brinell hardness number of the as cast and solutionized with different weight fractions of graphene and beryl particles are shown in Fig. 5.

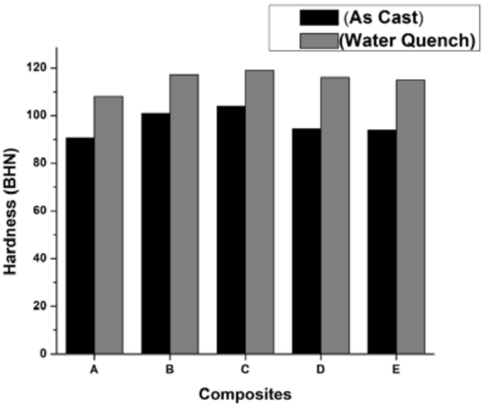

Fig. 5 Effect of heat treatment on Brinell hardness of Al7075 alloy and its composites in as-cast and solutionized conditions

C. Tensile Strength

The tensile strengths of specimen of Al7075 and developed MMC were determined by using UTM. It is inferred from the test results that, the tensile strength of hybrid MMC increases with increasing percentage of reinforcement and optimum tensile strength is achieved for 1% of graphene. This is because, the graphene and beryl particles act as barriers to the dislocations when the external load is applied. In addition, the incorporation of hard brittle materials in ductile matrix leads to increase in strength [2]. The hybrid composites attain peak strength on addition of 6wt. % of beryl particles and 1% of graphene (sample 3). The hybrid composites having 6wt. % of beryl particles and 1% of graphene showed enhancement of 76.84% **as** compared to Al7075 matrix material. The bonding, closer packing and smaller inter-particle spacing of reinforcement into the Al 7075 matrix alloy lead to increase in strength. However the tensile strength begins to drop when the graphene exceeds 1%, it may be due to poor wettability and agglomeration which is unwanted lumping of particulate reinforcement. The tensile strength for 6wt. % of beryl particles and 2wt. % of graphene showed enhancement of 60.93% as compared matrix material.

The tensile strength of the solutionized Al7075 alloy increases around 37.51%, while the solutionized Al7075-6 wt.% beryl and 1 wt.% of graphene shows an improvement in the hardness of around 81.62% compared to the as-cast matrix alloy. The relationship between ultimate tensile strength of the as cast and solutionized with different weight fractions of graphene and beryl particles are shown in Fig. 6.

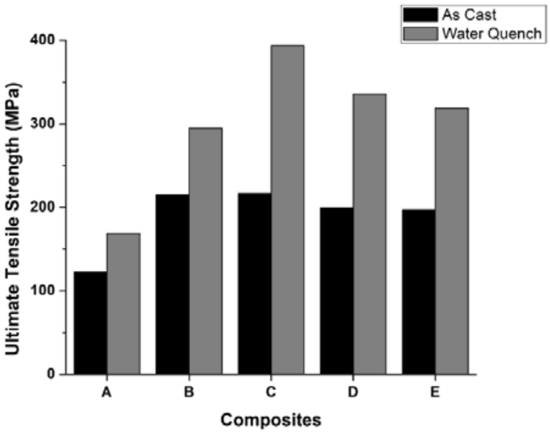

Fig. 6 Effect of heat treatment on ultimate tensile strength of Al7075 alloy and its composites in as-cast and solutionized conditions

D. Wear Behavior

Fig. 7 indicates the dependency of weight loss on the different applied load (10 N, 20 N & 30 N) for a constant sliding velocity of 3.5 m/s and sliding distance of 2000 m. The weight loss observed at a 10 N applied load is the minimum and as the load increases further the wear rate of the alloy and its composites increases for both the as-cast and solutionized conditions. The solutionizing treatment significantly minimizes the wear rate of the as-cast alloy and its composites. Due to the solutionizing treatment, precipitation is formed in the alloy and its composites which in turn reduces the weight loss and also the hard reinforcement particles protect the matrix alloy against wear, thus the wear resistance increases.

The weight loss is decreased as the increase in the weight percentage of graphene up to 1 wt.% of graphene for as cast and as well as for solutionized hybrid composite. The weight loss for heat treated Al7075 alloy and its composites are much lower than their corresponding cast alloy and its composites.

From the test results, it is inferred that about 34.52% reduction of wear is observed in heat treated Al7075 alloy/6wt. % of beryl and 1 wt. % of graphene.

Figs. 9 and 10 show the worn surfaces of the as-cast and solutionized Al7075 alloy. The scratches, cracks and plastic deformation were found at surface of Al 7075 due to debris detached and adhered. During the wear test, sliding environment leads to generation of heat due to friction which results in extensive plastic deformation on Al 7075 alloy surface and leading to high wear loss when compared to developed aluminum hybrid composites. The incorporation of hard beryl particles and graphene reduces the progress of delamination mechanism which results in high wear resistance. However, further addition of beryl particles and graphene in the composites leads development of layer of loose oxide of aluminium and iron along with fragmented reinforcement particles. The developed layer is called as mechanically mixed layer which acts as lubricating agent and offers wear resistance of hybrid composite as reported in previous literatures [32]

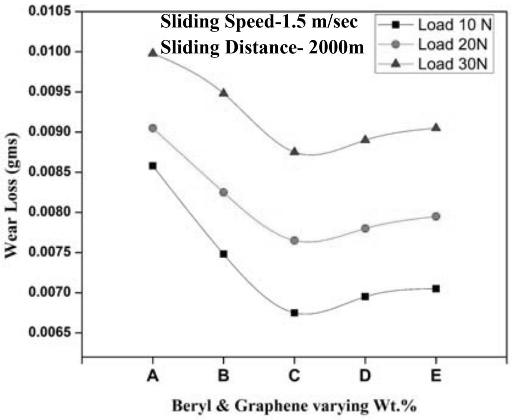

Fig. 7 Effect of load on as cast composites

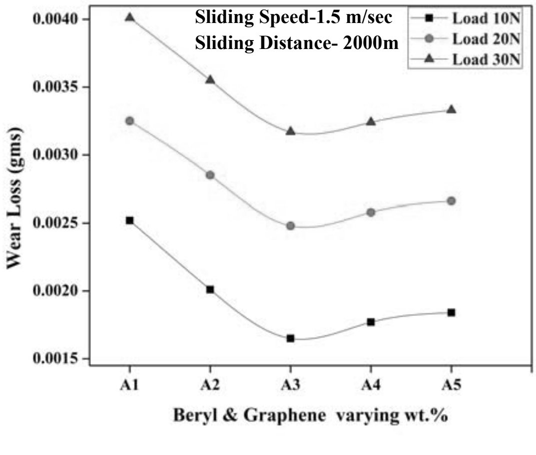

Fig. 8 Effect of load on heat treated composites

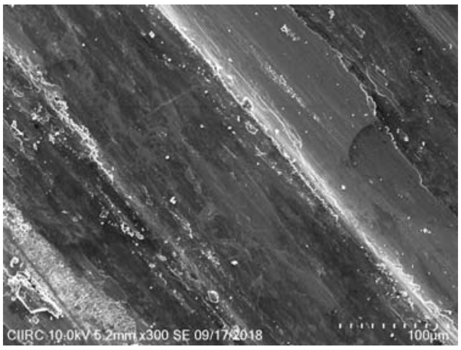

Fig. 9 (a) SEM image of as cast Al7075 alloy at 20 N Load

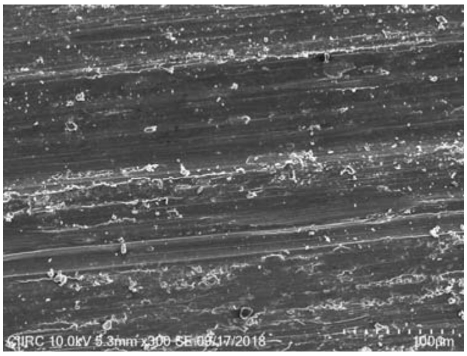

Fig. 9 (b) SEM image of as cast Al7075/6wt.% of beryl and 0.5 wt.% of graphene alloy at 20 N Load

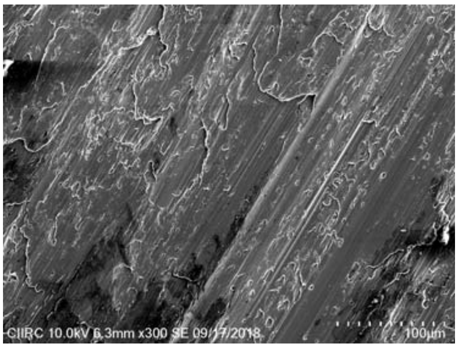

Fig. 9 (c) SEM image of as cast Al7075/6wt. % of beryl and 1wt.% of graphene alloy at 20 N Load

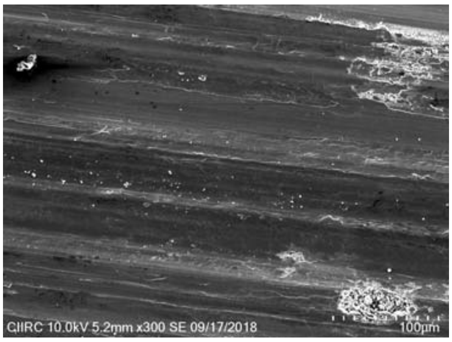

Fig. 9 (d) SEM image of as cast Al7075/6wt. % of beryl and 1.5wt.% of graphene alloy at 20 N Load

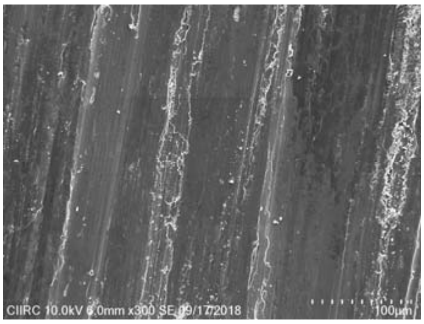

Fig. 9 (e) SEM image of as cast Al7075/6wt. % of beryl and 2wt. % of graphene alloy at 20 N Load

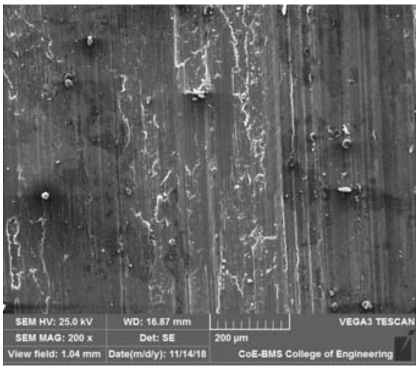

Fig. 10 (a) SEM image of solutionized Al7075 alloy

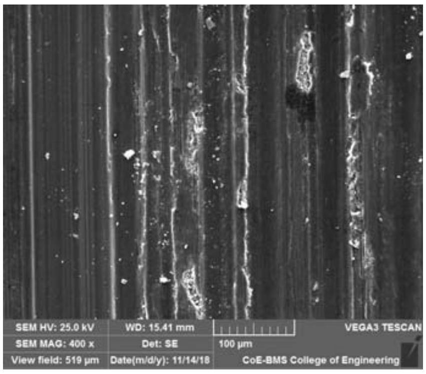

Fig. 10 (b) SEM image of solutionized Al7075/6wt. % of beryl and 0.5 wt.% of graphene alloy at 20 N load

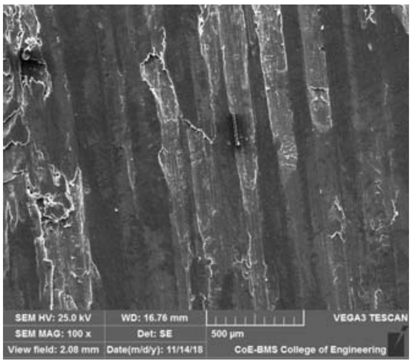

Fig. 10 (c) SEM image of solutionized Al7075/6wt. % of beryl and 1wt.% of graphene alloy at 20 N load

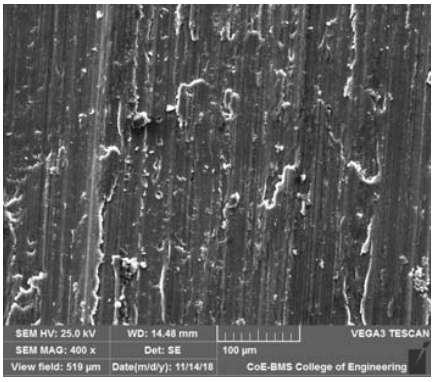

Fig. 10 (d) SEM image of solutionized Al7075/6wt. % of beryl and 1.5 wt.% of graphene alloy at 20 N Load

Fig. 11 (a) shows spot EDAX of intermetallic precipitates after solutionizing and quenching in water media. It confirms the presence of elements like graphene, Mg, Cu, Zn and Fe. The detailed elemental analysis is shown in the Table IV

TABLE IV
CHEMICAL COMPOSITION AT DIFFERENT PEAKS

Element	Weight %	Atomic %
C K	11.29	23.95
MgK	1.48	1.55
AlK	72.02	68.00
SiK	0.28	0.26
TiK	0.49	0.26
CrK	0.67	0.33
MnK	0.69	0.32
FeK	2.60	1.19
CuK	6.11	2.45
ZnK	4.37	1.70

IV. CONCLUSION

Al7075-Beryl-Graphene hybrid composite specimens are successfully prepared with fairly uniform distribution of beryl and graphene particulates using stir casing technique. The tensile strength, hardness and wear properties have been investigated for both the as cast and solutionized Al7075 and AlBeGr hybrid MMC.

The microstructure through SEM observation of the hybrid composites reveals the fairly uniform distributions of beryl and graphene into the base matrix material.

The tensile strength of as cast hybrid composites having 6wt. % of beryl particles and 1% of graphene showed enhancement of **76.84%** as compared to Al7075 matrix material. The tensile strength of the solutionized Al7075 alloy increases around 37.51%, while the solutionized Al7075-6 wt.% beryl and 1 wt.% of graphene shows an improvement in the hardness of around **81.62%** compared to the as-cast matrix alloy.

The hardness of Al7075-beryl-graphene composites show a maximum hardness of **104 BHN** at 6 wt.% of beryl and 1 wt.% of graphene particulate showing improvement of **14.66%** when compared to Al7075 matrix material without addition of reinforcement.

The hardness of the solutionized Al7075 alloy increases around 19.07%, while the solutionized Al7075-6 wt.% beryl and 1 wt.% of graphene shows an improvement in the hardness of around 10.18% compared to the as-cast matrix alloy.

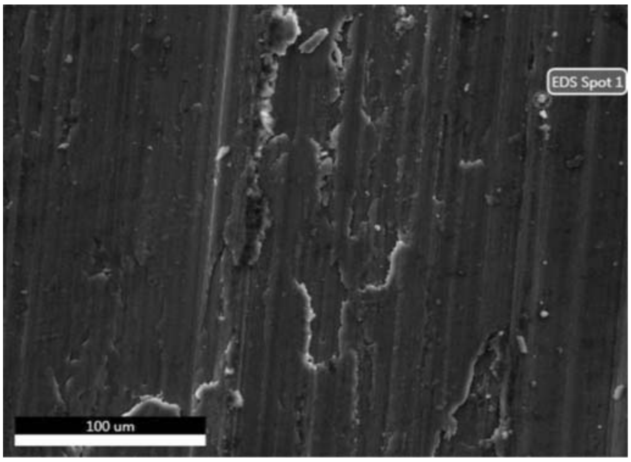

Fig. 11 (a) Spot EDAX image of solutionized Al7075/6wt. % of beryl and 1.5 wt.% of graphene alloy at 20 N Load

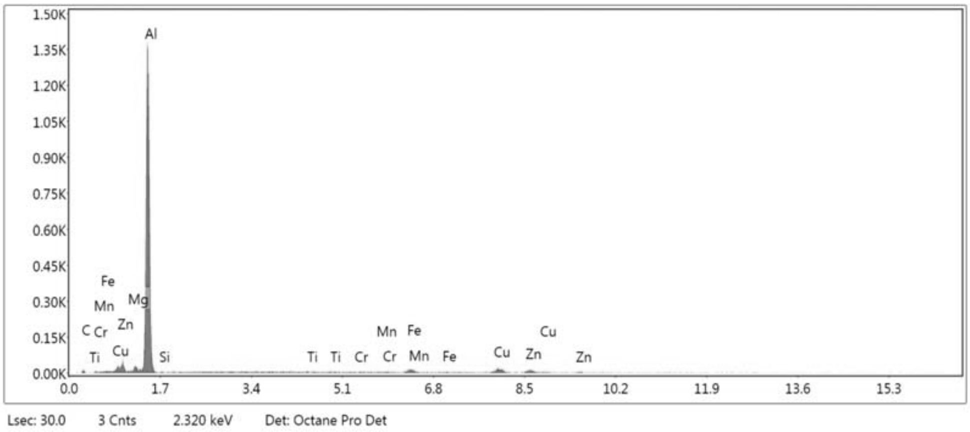

Fig. 11 (b) Peaks EDAX image of solutionized Al7075/6wt. % of beryl and 1.5 wt.% of graphene alloy at 20 N Load

The weight loss is decreased as the increase in the weight percentage of graphene up to 1 wt.% of graphene for as cast and weight loss decreased up to 1 wt. % for heat treated composites. The weight loss for heat treated Al7075 alloy and its composites are much lower than their corresponding cast alloy and its composites. A maximum of 34.52% reduction of wear observed in heat treated Al7075 alloy/6wt. % of beryl and 1 wt.% of graphene.

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