Peer-reviewed version available at *Materials* **2018**, *11*, 2524; doi:10.3390/ma11122524

Article

Investigations on the Tribological Performance of A390 Alloy Hybrid Aluminum Matrix Composite

Abhilash Edacherian[1*], Ali Algahtani[2], Vineet Tirth[1]

[1] Mechanical Engineering Department, College of Engineering, King Khalid University, Abha-61413, Asir - Kingdom of Saudi Arabia. ; edalheriad@kku.edu.sa.; vtirth@kku.edu.sa

[2] Research Center for Advanced Materials Science (RCAMS), PO Box 9004, King Khalid University, Abha-61413, Asir, Kingdom of Saudi Arabia.; alialgahtani@kku.edu.sa

* Correspondence: edalheriad@kku.edu.sa; Tel.: +966 56 0466543

Abstract: Several challenges stand in the way of production of Metal Matrix Composites (MMCs) such as higher processing temperatures, particulate mixing, particulate-matrix interface bonding issues and ability to process into desired geometrical shapes. Although there are many literatures showing composites with single particulate reinforcements, the studies on composites with multiple reinforcing agents (hybrid composites) are found to be limited. Development of a hybrid particulate composite with optimized mechanical and tribological properties is very significant to suit modern engineering applications. In this study, Al-Si hypereutectic alloy (A390) is used as the matrix and Silicon Carbide (SiC) and Graphite (Gr) and Molybdenum di-Sulphide (MoS_2) are used as particulates. Particulate volume (wt%) is varied and sample test castings are made using squeeze casting process through stir casting processing route. The evaluation of mechanical properties indicates that presence of both the hard phase (SiC) and the soft phase has distinct effect on the properties of Hybrid Composite. Composite samples were characterized to understand the performance and to meet the tribological applications. Fractography study indicated an intra-granular brittle fracture for hybrid composites. Wear study shows that Hybrid MMCs has better tribological performance compared to that of A390 alloy.

Keywords: Aluminum Matrix Composites, Hybrid, A390, SiC, Gr, MoS_2, Tribological Properties

---

1. Introduction

Aluminum matrix composites (AMCs) have received great attention in the market of modern engineering materials which mainly focus on cost, quality and durability, styling and performance, emission and fuel economy, and recyclability [1]. AMCs with appropriate reinforcements offers several advantages such as high specific strength, hardness, stiffness, high thermal and electrical conductivity, low coefficient of thermal expansion, good corrosion and wear resistance etc. [2]. The reinforcement in AMCs may be monofilaments, continuous or discontinuous fibers, short fibers or whiskers, fiber preforms and particulates [3, 4]. Literature review indicate the dominance of particulate reinforced AMCs due to their ease of manufacturing and process competiveness. This type of composites is generally produced by (i) solid state processing such as powder metallurgy techniques, physical vapor deposition, diffusion bonding etc [5] (ii) liquid state processing such as stir casting, squeeze casting, melt-infiltration, spray deposition etc [6], and (iii) in situ processing such as directional solidification of eutectics and formation of intermetallic phases [7]. Hard ceramic particulates such as carbides, oxides, nitrides and borides have been widely used as reinforcements in AMCs. Generally used reinforcement constituent in aluminum alloy matrix may be non-metallic phases such as SiC, Al_2O_3, MgO, TiC, TiB_2, B_4C, BN, AlN, or dissimilar metallic phases (Pb, Be, Mo, Ti, W etc.) [8, 9]. The addition of these particulates have found to improve the properties of commonly used matrix alloys of series 2xxx, 5xxx, 6xxx and 7xxx (wrought alloys) through various strengthening mechanisms. However, to improve the tribological performance of the AMCs, researchers have used soft phase solid lubricating agents such as Graphite and MoS2 [10-12]. A few of the proven applications of the AMCs include pistons, connecting rods, brake drums and rotors, braking systems of trains and cars, recreational products such as golf club shaft and head, skating shoe, baseball shafts, horseshoes and bicycle frames etc [13-15]. Also, particulate reinforced composites have been successfully used in fan exit guide vane in the gas turbine engine as ventral fins and fuel access cover doors, flight control hydraulic manifolds in military aircrafts, and as rotating blade sleeves in helicopters [16-18]. Growing engineering and technology demands newer materials of superior performance. Hybrid composite materials, another class of composite materials which uses multiple reinforcements, have recently received attention of the scientific world. Hybrid Aluminum Matrix Composite (HAMCs) materials are promising solution for future material requirements to replace heavier materials and to suit a wide range of engineering components. However, making these components of exact shape and size from the bulk of composite materials has been a challenge over these years. Other challenges in the development of HAMCs include inferior ductility, low fracture toughness and precise control of the distribution of the different micro constituents during processing. Many of the traditional metallurgical methods can be conveniently used to produce HAMCs by various methods mainly through stir casting process, which may be followed by cost effective casting methods such as Gravity Die casting (GDC) or Permanent Mold Casting (PMC) or Squeeze Die Casting (SDC). In the present work, HAMCs of A390 alloy as matrix and silicon carbide, graphite (Gr) and molybdenum di sulphide (MoS_2) as particulate constituents are developed by using a stir casting technique followed by squeeze casting technique.

Mostly, monolithic materials are either incapable of satisfying the desired design requirements or are too expensive to meet superior tribological performance. Tribological products are finding increasing use in industries and provide means to conserve energy and materials. An understanding of various friction and wear properties is necessary for to make the right selection of materials and operating conditions for a given engineering application. Friction is a serious cause of energy dissipation, and wear is the main cause of material wastage in any system with mating bodies. Considerable savings can be achieved by reducing the friction and controlling the wear. Appropriate selection of materials for mating bodies and solid/liquid lubrication is used to control friction and wear to an acceptable level. Newly developed HAMCs has its potential to meet this desired performance.

This investigation is limited to the study of MMC of A390 aluminum cast alloy, as this alloy has wide acceptance in tribological applications such as cylinder blocks, transmission pump and air compressor housings, small engine crankcase, air conditioner pistons [19]. The main aim of this work is to understand the tribological performance of the hybrid composite made using this matrix alloy. The work include design of a composite materials systems (by varying both hard and soft particulate constituents wt%) and processing conditions. There is no doubt that for the development of an appropriate HAMC, a number of experiments which quantifies the various properties such as mechanical and wear properties are required. Characterization studies mainly include metallurgical analysis to understand different phases and measurements of important properties such as tensile, compressive, impact strength and hardness. In additions to this, the experimental observations in the production and characterization of HAMC can serve as a qualitative and quantitative guide to understand the effect of particulates which has a potentially important role in determining the properties.

2. Materials and Methods

Among the various alloys of Al, Mg, Cu, Ni, Ti, Fe, the Al alloys are the most popular matrix for MMCs. AMCs offer a range of mechanical properties depending on the chemical composition of the Al-alloy. Mostly used matrix alloys are wrought alloys such as 2xxx or 6xxx alloys or cast alloys such as 2xx (Al-Cu) and 3xx (Al-Si-Cu) system. They are usually reinforced by cost effect particulates such as SiC, Al_2O_3 and TiC.. Being a hyper-eutectic alloy of the aluminum-silicon system, (A390

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 2 November 2018 doi:10.20944/preprints201811.0034.v1
Peer-reviewed version available at Materials 2018, 11, 2524; doi:10.3390/ma11122524

alloy designated as per ASM standards) is commercially important as its high strength-to-weight ratio and wear resistance makes it suitable for applications where reduction of weight is a design consideration such as in automobile engine block, gear boxes, engine pistons, cylinder heads, manifolds. This alloy designated as LM 30 as per UK standards has lower coefficient of thermal expansion than LM 13 and LM 28 alloy. The work during nineties has shed light on many aspects of aluminum alloys and has classified Al-Si alloys as wrought alloys (0%-1.65% Si) and foundry alloys (5% -18% Si). Considering A390 alloy as a "quasi-binary alloy" (with Si as major alloy content), it belongs to hyper-eutectic group of Al-Si alloy system. Table 1 shows the chemical composition of A390 alloy used in this study.

Table 1. Chemical composition of A390 alloy.

Al	Si	Cu	Mg	Fe	Mn	Zn	Ti
75.3-79.5	16.0-18.0	4.0-5.0	0.50-0.65	0.40	0.10	0.20	-

The particulate reinforcements in HAMCs may be either hard ceramic particulate or soft self-lubricating non- metals. Ceramics such as oxides, carbides, nitrides, borides and silicide of mostly refractive metals have very high melting points and are ideal for wear resistant materials in a variety of tribological applications. These particulates are chemically inert and are chemically and thermally stable in ambient conditions up to their melting points, and they retain their properties at high temperature. The inorganic soft non-metals generally used in HAMCs include MoS_2, Gr, talc and other salts. MoS_2 and graphite have lubricating abilities because of their layered lattice structure. Table 2 shows a few properties of materials used in this investigation. Through adequate control of particulate distribution within the bulk of the component, HAMCs can achieve tailored properties like wear resistance and solid lubrication, preserving other relevant properties of the matrix alloy. Among the various liquid state processing of composites, HAMC components can be made conveniently by using liquid metal stir casting followed by squeeze casting. In stir casting, the reinforcement particle phase is dispersed in the melt by following a vortex method (manual or ultrasonic) and is allowed to solidify in a metal mold under pressure (direct squeeze casting). As an economical and effective processing route, many researchers have used this method to produce HAMCs.

Table 2. Properties of matrix alloy and constituent agents of HAMC.

Property	Unit	A390	SiC	Graphite	MoS_2
Density (at 20°C)	g/cm^3	2.73	3.22	2.09-2.23	5.06
Melting point	°C	650	2973	3915	1185
Coefficient of thermal expansion	μm/m °C	18	4	2-6	1-4
Thermal conductivity	W/mK	170	126	85	40
Young's Modulus	GPa	82	410	10	330

In this investigation, a commercial aluminum (A390 alloy) ingot was melted using an induction furnace by following standard melting practice [20]. In each experiment, desired quantity of preheated particulates (300°C) are purged into the furnace and the molten alloy was stirred (of a rotation speed of 100 rpm) and poured under gravity at a temperature of 800°C into the steel molds of cylindrical cavity to solidify under pressure (5-10 MPa) in order to obtain the test castings. Figure 1 shows the casting set up used for the present study. Two processing methods, Gravity Die Casting (GDC) and Squeeze Die Casting (SDC), are used to understand the influence of processing in the development of composites. To obtain squeeze cast samples, an additional set up was made for pouring the melt into the steel mold and forge it and solidify under hydraulic pressure. In order to properly mix the preheated particulates both motorized stirring and ultrasonic stirring have been used. No refiner or modifier was added to the melt and the melt preparation was done with great attention to obtain defect fee samples by avoiding slag and oxide layers.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 2 November 2018 doi:10.20944/preprints201811.0034.v1

Peer-reviewed version available at *Materials* **2018**, *11*, 2524; doi:10.3390/ma11122524

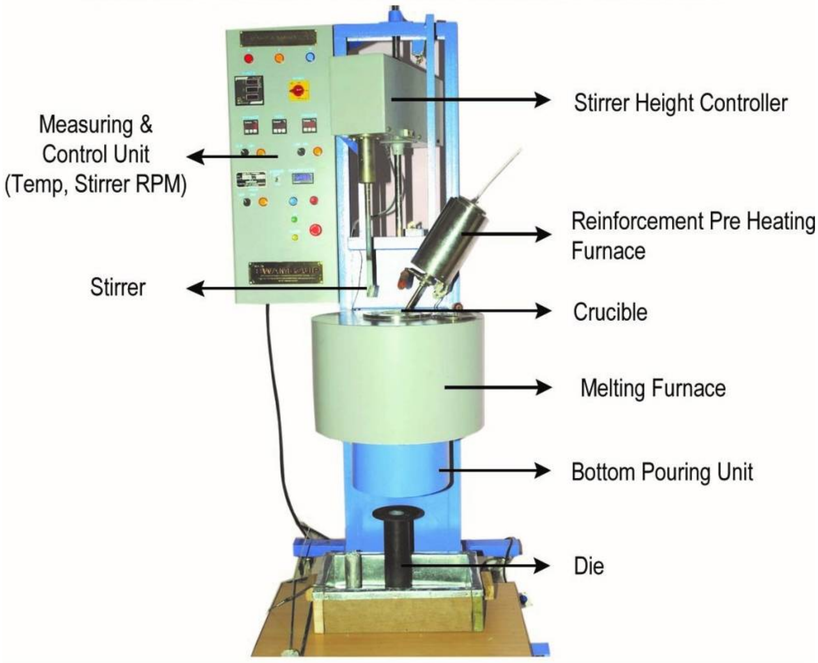


Figure 1. Stir casting set-up used for manufacturing HAMCs [Courtesy: www.swamequip.in].

HAMCs samples developed under this study followed the addition of particulates by varying its wt% according to the melt volume required for the mold. Two additional AMCs are developed to understand the effect of hard and soft phase on the properties of HAMCs. Table 3 shows various material samples designed in this work to effectively assess the properties of HAMCs. Higher percentage of the reinforcing agents in the matrix generally deteriorates the properties of the composites by forming oxide inclusions and porosity within the samples. Hence, a lower wt% of the constituents in the composite design was conceptualized in order to achieve the best performance of Graphite and MoS_2 in the presence of SiC [10, 11].

Table 3. Material samples developed for this investigation.

Sample No	Sample Code	SiC%	Gr%	MoS_2%	Process
1	A390-GDC	0	0	0	GDC
2	A390-SDC	0	0	0	SDC
3	HAMC-2-2-2	2	2	2	SDC
4	HAMC-3-1-1	3	1	1	SDC
5	HAMC-4-1-1	4	1	1	SDC
6	HAMC-1-1-1	1	1	1	SDC
7	AMC-0-1-1	0	1	1	SDC
8	AMC-2-0-0	2	0	0	SDC

3. Characterization Studies

3.1. Surface Characterization

The art and science of making the matrix surface suitable for the analysis include sectioning, mounting, grinding, polishing, and etching of the specimens to reveal the microstructural features. All the above procedures are followed as per ASTM-E3 standards. Etching of aluminum alloys is usually done by immersing the polished surface in the etching reagent for 10-40 seconds. In this work, diluted hydrofluoric acid (HF (48%) + H_2O) was used. After etching, each specimen was washed

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 2 November 2018 doi:10.20944/preprints201811.0034.v1

Peer-reviewed version available at *Materials* **2018**, *11*, 2524; doi:10.3390/ma11122524

thoroughly with distilled water and then moped with pure cotton wetted with acetone to remove the water content and was subsequently dried using hot air blower. Microstructures of the etched samples were observed under an optical microscope and the photomicrographs were obtained using high resolution CCD camera attachments. In addition to optical microscopy, wear samples were also examined with a high resolution SEM (Hitachi SU6600, Japan) to obtain photomicrographs so as to analyze the wear surface. SEM studies also include fractography to provide a comprehensive description on fracture mechanisms and its morphologies on tensile fractured specimens.

3.2. Mechanical Properties

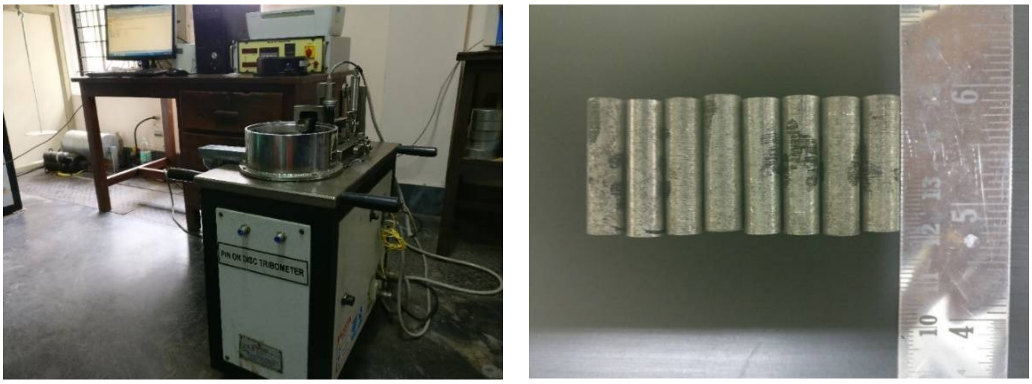
Each metallurgical sample prepared as per ASTM-E3 standards was subjected to Vickers hardness measurements following ASTM-E92 standards. The hardness test with diamond indenter (with angle between opposite faces, $\theta = 136^{o}$) was made at different of the composite specimens using a test load (P) of 1 kgf and 10 second dwell time. The tensile and compression test properties (ultimate tensile strength and compressive strength) at room temperature were measured by performing tests at a constant strain rate of 1mm/min using specimens prepared as per ASTM E8 standards on a computerized tensile testing machine (INSTRON, UK) of 150 kN capacity. The Charpy v-notch test, is a standardized high strain-rate test which determines the amount of energy absorbed by a material during fracture. This absorbed energy is a measure of the toughness and acts as a tool to study temperature-dependent brittle-ductile transition. Charpy impact tests were carried out for all the samples on an Armstrong impact testing machine at a room temperature of 29^{o}C.

3.3. Tribological Properties (Dry Sliding Wear Testing)

Cylindrical wear pins were prepared from three different sections of the composite castings to conduct wear test under dry sliding test condition in accordance with ASTM G-99 standard using a pin-on-disc tribometer (shown in Figure 2). Figure 3 shows a set of wear pins as per the standards (8 mm diameter and 27 mm length) made from each samples. Figure 4 shows a graph indicating the variation of height removed due to wear with respect to the sliding distance at a normal load of 10 N for a few as-cast samples. Since the computer generated data was very sensitive, wear tests were conducted at various loads i.e., 10 N, 20 N, 30 N and 40 N for a constant sliding distance of 1000 m and a constant sliding speed of 2.5 m/s to obtain wear properties based on the weight loss method. The selection of these testing parameters for the wear analysis was made based on the erstwhile studies [11, 12]. Before each experiment, the specimens were preheated and cooled to room temperature and the steel disc was ensured clean and dry. The track radius and time of the test was set according to the experiment and the K-type thermocouple was used to measure the temperature at 5 mm above the wear surface, for each testing load, just before the preset time elapses. The wear volume loss can be obtained from the displacement values given by LVDT (Linear Variable Differential Transformer) attached with tribometer. The SiC paper of 800 grid size was used to grind the face of each wear pin to match the average roughness (CLA 0.1 μm) of rotating disc made of EN24 steel of hardness 57 Rc.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 2 November 2018 doi:10.20944/preprints201811.0034.v1

Peer-reviewed version available at *Materials* **2018**, *11*, 2524; doi:10.3390/ma11122524



(a) (b)

Figure 2. (a) Pin-on-disc tribometer used in this study (b) a set of wear test specimens prepared as per ASTM G-99 standards.

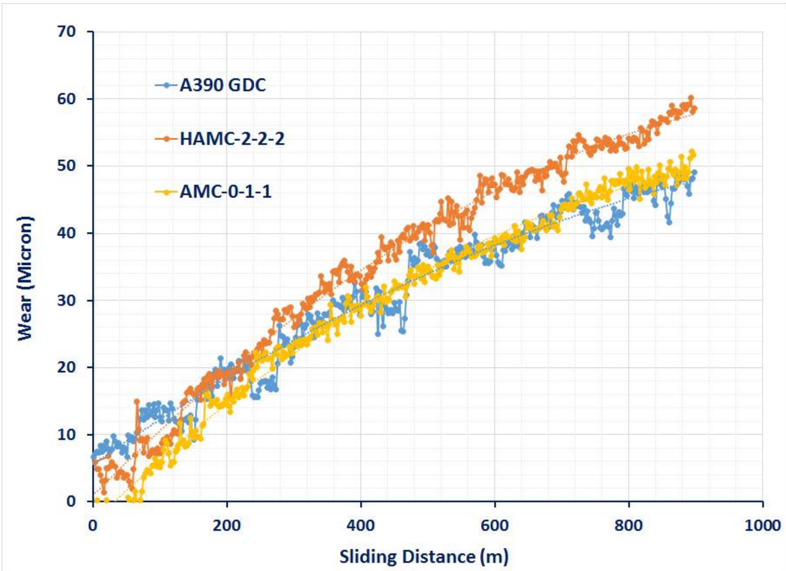


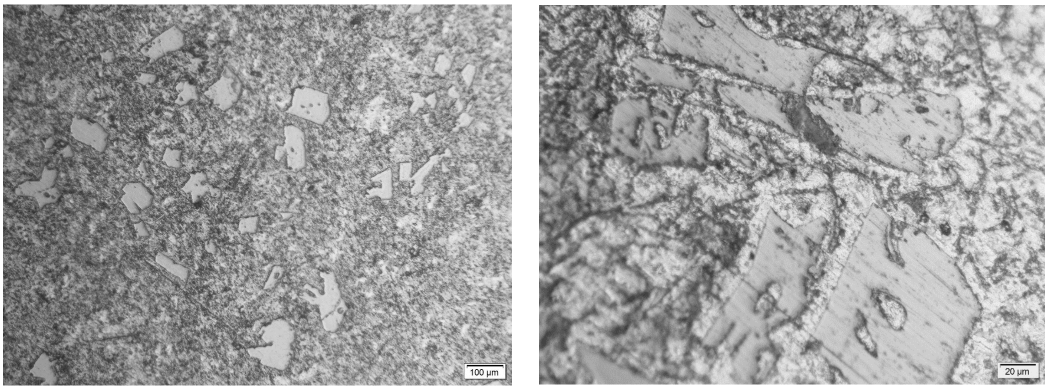
Figure 4. Wear behavior (computer generated) of a few samples.

4. Results and Discussions

In the initial experiments, there were a few defects such as cold shut due to decreased fluidity of melt added with SiC particles and raining due to improper melt pouring. Melt biting due to the oxidation of the constituents were also noticed. Ultrasonic stirring was done to prevent agglomeration and ensure effective mixing of soft constituents. It was noticed that ultrasonic stirring (using waves of frequency 18 to 20 kHz) is limited to a lower melt volume and temperature. The stirring time depends on the capability of the sonotrode horn to withstand the melt temperature. However, with the effective use of this new stir casting set up, it has been demonstrated that HAMCs and AMCs may conveniently be fabricated from SiC, Gr, MoS_2 and aluminum alloys using this advantageous casting route. Further, squeeze casting (melt forging) is a potential manufacturing process for producing defect-less casting parts. With proper operating parameters, quality HAMCs and AMCs with good dimensional accuracy can be produced using this process through stir casting processing route.

Peer-reviewed version available at *Materials* **2018**, *11*, 2524; doi:10.3390/ma11122524

From the metallurgical samples, very fine optical micrographs were obtained. Initially, the micrographs indicating an over etching using Kellers reagent. This may be due to the presence of soft phase at the grain boundaries. However, the use of Dix-Keller's reagent (2 ml hydrofluoric acid, 3 ml hydrochloric acid, 5 ml nitric acid and 190 ml distilled water) helped to obtain typical microstructure as shown in Figure 5. The micrograph of MMC with 2% SiC (220 mesh size) indicated banding of SiC (the white shiny particles) within the casting. A fine grading of faceted particulates was observed from the micrographs (refer Figure 5 (a) and (b). The presence black Gr and MoS_2 can also be observed at the grain boundaries, which is not that distinct. Micrographs indicated the absence of porosity and an apparently uniform distribution of SiC in the A390 matrix. The absence of porosity within the HAMC samples indicate the efficiency of squeeze casting process to manufacture defect less composite products even without using any wetting agents. The XRD of A390 as-cast sample is shown in Figure 6. This indicated the absence of intermetallic phases which may form during the processing of castings.



(a) (b)

Figure 5. Photomicrograph showing the particulate morphology of SiC in A390 alloy matrix.

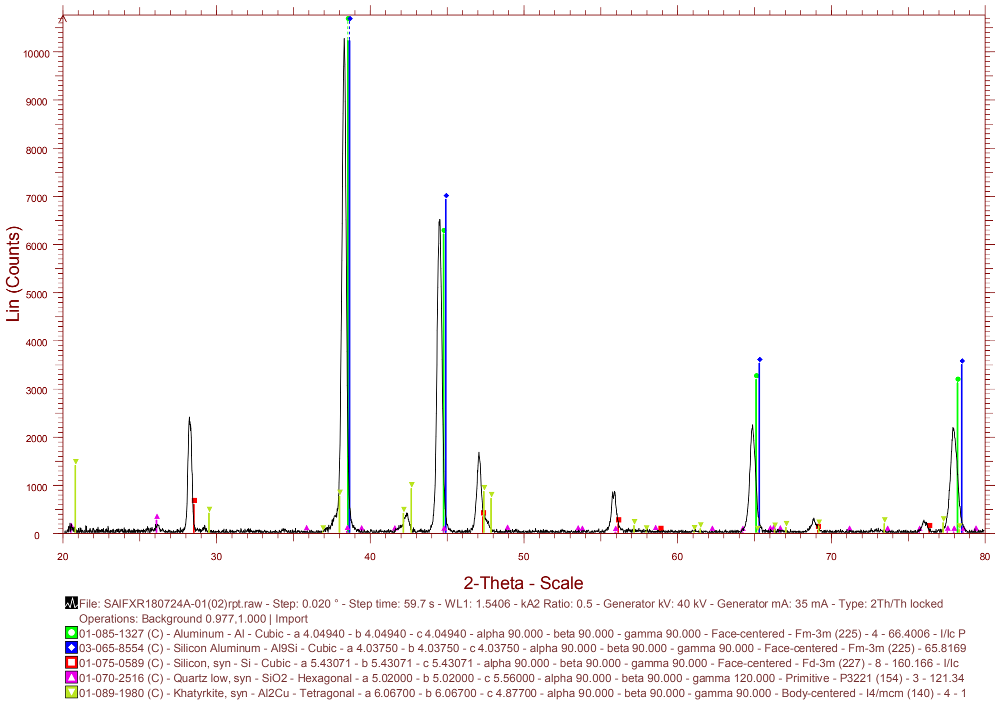


Figure 6. XRD pattern of as-cast A390 cast sample.

Peer-reviewed version available at Materials 2018, 11, 2524; doi:10.3390/ma11122524

4. 1. Hardness Test Studies

The average VHN values for a set of samples is shown in Table 4. It can be seen that hybrid AMC is harder than other samples. Also, it is noted that the hardness value increased with increase in SiC particulate. However, only a little variation is noted in the AMCs having the presence of soft phase particulates Gr and MoS_2. An average VHN value of 123 is observed for HAMCs showing improvement over AMC with soft particulate constituent and A390 cast samples.

Table 4. Average values of VHN and Impact energy.

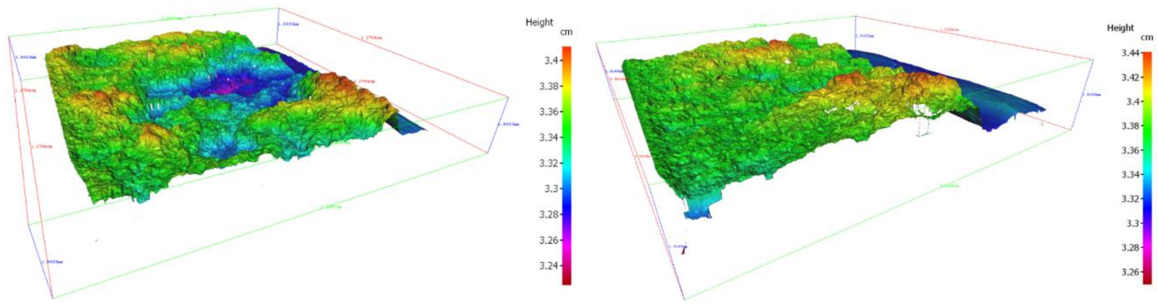
Sample Code	VHN Values	Impact Energy (N-m)
A390-GDC	107.3	49.03
A390-SDC	122.6	48.01
HAMC-2-2-2	117.8	47.07
HAMC-3-1-1	117.9	45.11
HAMC-4-1-1	127.9	52.95
HAMC-1-1-1	126.4	43.64
AMC-0-1-1	124.6	43.14
AMC-2-0-0	152.5	46.06

Hardness values obtained from Vickers hardness test varied from 107 VHN-155 VHN. A variation of tensile strength values from 134 MPa to 160 MPa and hardness values VHN 70 to VHN 138 for Al-Si (4 to 20 wt%) system was noted from previous studies to compare the respective values obtained from the experimental studies. The higher values of VHN for A390 alloy is observed in the case of squeeze cast samples compared to that of gravity die cast samples. This indicates the process capability of squeeze casting process in producing defect-less HAMCs.

4. 2. Impact Test Studies

Charpy impact tests were carried out for all material samples (as-cast A390 GDC and SDC samples, AMCs, HAMCs) on an Armstrong impact testing machine at a room temperature of 29^{o}C. As indicated by the Table 4, the as-cast A390 (both GDC and SDC) samples showed higher impact energy than the AMC and HAMC samples. This also indicated decrease of impact strength with the increase of wt% SiC in the matrix. Only a little variation in impact energy was observed among the samples. However, it is noted that the presence of soft phase particulates decreases the impact strength. The average impact energy of HAMCs is found to be 47.6 joules. This may be due to the ability of propagating the crack by the particles. Impact strength of HAMCs is found to vary according to the wt% of the constituents and validates the rule of mixtures in the case of composites. Also, from the analysis of the fracture surface of the Charpy test samples it is found that the fracture was a mixed brittle ductile fracture indicating dull and little shining dots with lot of dimples in the case of base alloy cast samples, whereas that in HAMCs is brittle fracture. 3D profilometry (Alicona) of these samples are shown in the Figure 7. This indicate that matrix alloy (A390 alloy) samples have more ductility compared to the HAMCs.

Peer-reviewed version available at *Materials* **2018**, *11*, 2524; doi:10.3390/ma11122524



(a) (b)

Figure 7. 3D profilometry of Charpy test sample A390SDC and HAMC 4-1-1.

4. 3. Tensile and Compression Test Studies

According to the compositional variation introduced by the melt-treatment, ultimate tensile strength (UTS) of material samples varied from 190 MPa to 250 MPa (refer Figure 8). The microstructure containing small cells and Si particles develop damage at a lower rate whilst the microstructure with large cell sizes and large or elongated Si flakes tend to crack at low strains, indicating a poor ductility. Accordingly, superior tensile test values were obtained for HAMCs samples compared to other samples, especially as-cast A390 GDC and SDC samples, which may be due to the heterogeneous nucleation phenomena in composite samples. Similarly, UTS obtained from the compression test of the material samples varied from 450 MPa to 680 MPa (refer Figure 8). Least compressive strength is observed in the case of the sample AMC-0-1-1 indicating the incapability of soft phase to resist the compressive strength. HAMCs showed better compressive strength compared to base alloy cast samples and AMC samples.

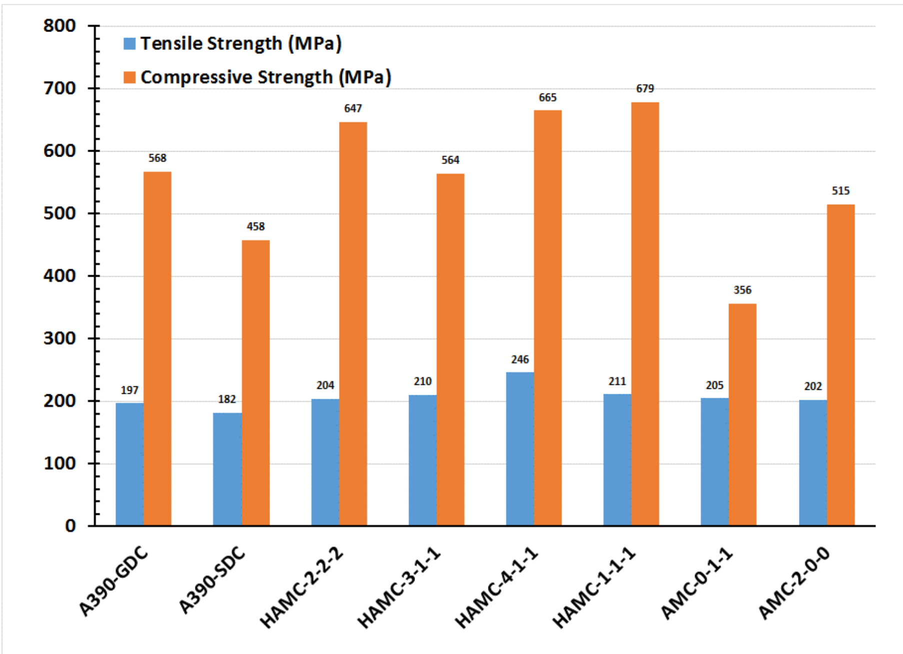


Figure 8. Average values of tensile and compressive strength of material samples.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 2 November 2018 doi:10.20944/preprints201811.0034.v1

Peer-reviewed version available at *Materials* **2018**, *11*, 2524; doi:10.3390/ma11122524

4. 4. Dry Sliding Wear Studies

The results obtained from computerized wear test, ie wear (in micron) to sliding distance were very sensitive to do the analysis and resume the inference. Hence, to appropriately evaluate the wear property based on computer generated wear data, weight loss method was devised. It is evident from the figure that for all the cast samples, the wear increases as the normal load is increased. Among all samples, wear rate is found to be less for HAMCs for which the average weight loss is 0.0035 gm for a sliding distance of 1000 m at sliding speed of 2.5 m/s.

Addition of reinforcement has been reported to enhance the wear properties of A390 alloys. The processing method, distribution of reinforcements and reinforcement morphology is important in the determination of the wear mechanism. Wettability of particulates is an important parameter often discussed when dealing with particulate reinforced metal matrix composite. Better the wettability of particulate, better the particulate matrix interface strength, which is a key factor in the effective transmission of load from the matrix to the particulate. In addition to the sliding conditions, properties of reinforcements & matrix like chemical affinity, work hardening ability, fracture toughness and hardness also influences the wear mechanism of the composites. More analysis with XRD and SEM of wear debris and MML are desirable to understand the composition and iron particle transfer to the pin surface contributing to the wear mechanisms of these materials. Table A1 to Table A3 shows the wear loss of material samples at a load of 20N, 30N, and 40 N respectively for sliding distance of 1000 m at a sliding speed of 2.5 m/s.

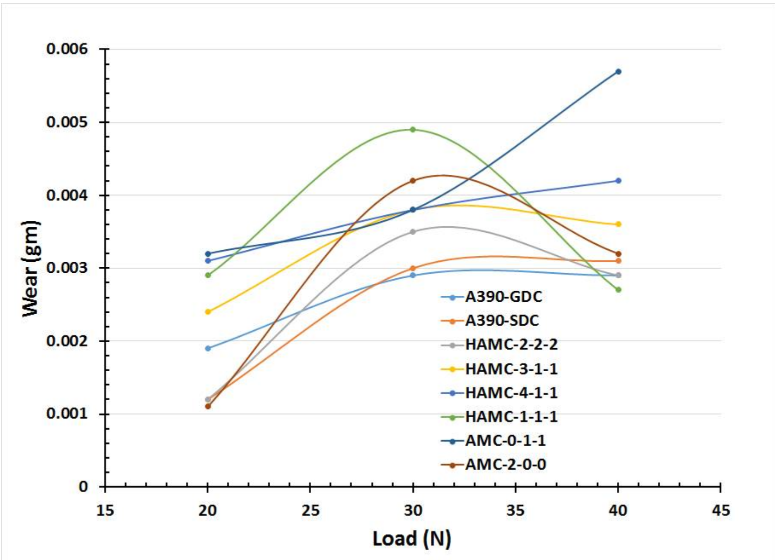


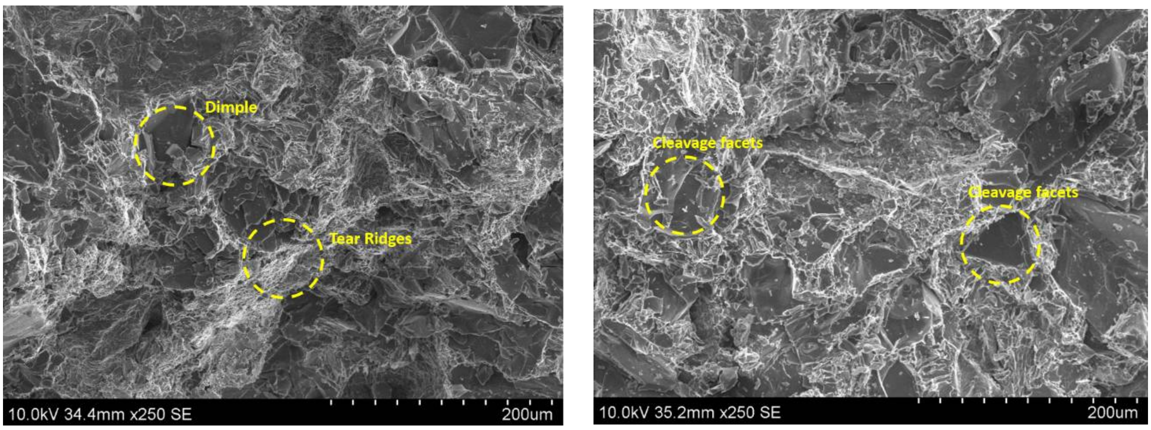
Figure 9. Plot showing the average wear loss of material samples at different wear loads.

The volume loss due to the wear of the samples is plotted against different loads for a constant sliding speed and distance, as shown in Figure 9. It is evident from the figure that the wear increases as the normal load is increased for all the materials up to a load of 30 N. However, at higher loads, the volumetric wear loss of HAMCs is found to be less than that of matrix alloy (A390 aluminum alloy). Also, SiC reinforced AMC showed a lower wear rate than that of Gr & MoS_2 reinforced AMC which showed a steeper wear volume loss as the test load increases. The volumetric wear loss of HAMCs is found to vary between that of AMC samples of soft and hard phase reinforcements. At a higher applied test load of 30 N and at constant sliding speed of 2.5 m/s, it can be considered that wear occurred in as-cast A390 samples is severe or plastically dominated and that in HAMCs and AMC is mild wear. However, these composites are susceptible to a two-body or three-body abrasive wear.

Peer-reviewed version available at Materials 2018, 11, 2524; doi:10.3390/ma11122524

4. 5. Fractography and Worn Surface Characterization

As understood from the literature the most likely factor causing fracture initiation in A390 alloy casting is the silicon particle cracking causing initiation of micro cracks. The brittle nature of silicon needles and their sharp tips create zones of localized stress that are expected to contribute to deterioration of the tensile properties. The fracture of the A390 alloy is governed by the silicon phase itself. Usually, micro-cracks are initiated in the silicon phase and which then grow and link until the complete fracture occurs. SEM photomicrograph of gravity die cast A390 alloy showing many cleavage surfaces and tear ridges is shown Figure 10 (a). The presence of tear ridges (white lines) is an indication of higher deformation energy absorbed during the tensile fracture by the specimen. This fracto-micrograph also shows many regions of cleavage facets besides displaying small dimples of grains, small microstructure discontinuities (gas pores or pores by particulates) showing a ductile-brittle nature of failure. The silicon phase forms a continuous network and the crack propagates on the silicon cleavage planes or other brittle microstructure components (intermetallic phase). The sharp edges of Si precipitates or ends of brittle SiC particles are preferred crack initiation sites generating cleavage facets. Figure 10 (a) shows cleavage facets due to Si flakes the SDC samples whereas Figure 10 (b) shows cleavage facets due to SiC particulates. Figure 10 (b) indicated a lesser tear ridges compared to that in Figure 10 (a) indicating the poor ductility of squeeze cast samples. Many micro dimples due to the presence of Gr or MoS_2 can also be seen in the figure. Similarly, the micro cracks on the cleavage facets shows the brittleness of the Si flakes in HAMCs. The visible secondary cracks and cleavage steps in the fracto-micrographs (Figure 11 (a) and (b)) confirms the trans-crystalline brittle fracture in both squeeze die casted A390 alloy and HAMCs. This also indicates that the decohesion mechanism and crack paths are strongly influenced by the volume fraction and morphology of particulates.

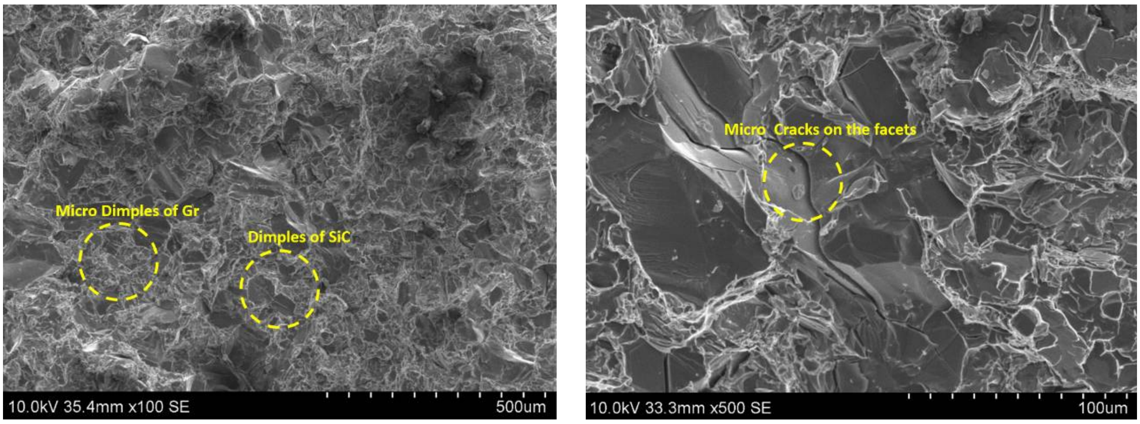


(a) (b)

Figure 10. SEM photomicrographs (a) Gravity die cast A390 alloy showing many dimples and tear ridges (b) Squeeze die cast A390 alloy showing many cleavage surfaces and fewer tear ridges.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 2 November 2018 doi:10.20944/preprints201811.0034.v1

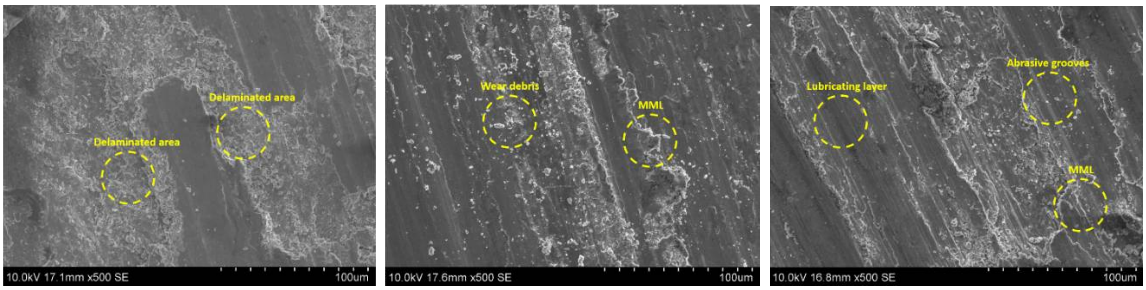
Peer-reviewed version available at Materials 2018, 11, 2524; doi:10.3390/ma11122524



(a) (b)

Figure 11. SEM photomicrograph of HAMCs (a) showing many dimples of particulates and a fewer tear ridges (b) cleavage facets and micro cracks.

The worn surface topography and the morphology of wear debris formed on it during pin-on-disc test are studied using SEM. Figure 12(a) shows SEM photomicrographs of the worn surface of A390-GDC Sample at a normal load of 40 N. It shows the subsurface deformation of the sample showing micro-cracks and craters formed on the surface. On the other hand, the samples HAMC-4-1-1 (refer Figure 12 (b)) and HAMC 1-1-1 (refer Figure 12(c)) indicated the formation of mechanically mixed layer (MML) on the pin surface. The fine wear debris of soft particles reattach to the worn surfaces due to the Van der Waals force as well as electrostatic force leading to the formation MML. The presence of MML in HAMC samples contribute to have a lower wear rate at higher loads compared to that of other samples. The presence of dark lubricating layer on the pin surface indicates the efficiency of Gr or MoS_2 soft phase agents in reducing the wear in HAMCs which occurs mainly due to the abrasive grooves due to SiC debris. It can be inferred that the predominant wear mechanisms in HAMCs are brittle fracture due to two & three body abrasion of dislodged SiC, Gr & MoS_2 particulates, and the resulting fatigue and micro-cracking of MML.



(a) (b) (c)

Figure 12. SEM photomicrograph of the worn surface of the sample (a) A390-GDC (b) HAMC-4-1-1 and (c) HAMC-1-1-1.

5. Conclusions

Designing a suitable composite for tribological applications requires keen observation of a real materials system. Many variables such as matrix material, particulate reinforcements, distribution of hard and soft phase constituents within the matrix, pouring temperature, squeeze pressure, stirring speed, stirring methods and processing conditions have a significant impact on the performance of the composite material. This study considered A390 alloy as the matrix and SiC, Gr and MoS_2 as

Peer-reviewed version available at Materials 2018, 11, 2524; doi:10.3390/ma11122524

particulate constituents to develop a hybrid composite to suit tribological applications. Wear tests, tensile tests, compression tests, impact tests (Charpy), hardness tests, are a few main characterization test to evaluate the overall performance of the hybrid composite system designed as per this investigation. In addition to this, optical microscopy, fractography and wear surface study using scanning electron microscopy (SEM) and 3D optical profilometer are a few other characterization methods used in this study. The main conclusion and recommendations of this work are detailed hereunder.

Major conclusions from this study are:

- Defect-less hybrid metal matrix composites may conveniently be fabricated through stir casting process followed by squeeze casting technique. Micrographs showed uniform dispersion of the reinforcement particles SiC, Gr and MoS_2 in A390 alloy without any porosity.
- Hardness of the AMCs are found to be better than that of the A390 alloy, and is found increasing with % of SiC and the 3D profilometry of fracture surface showed poor ductility for HAMCs.
- Presence of SiC in AMCs reduces the impact energy and it is further reduced with the addition of soft phase constituents like Gr and MoS_2.
- Fractography of the tensile test specimens indicated intra-granular brittle fracture of AMCs and HAMCs.
- The wear study proposes that predominant wear mechanisms in Hybrid AMCs are brittle fracture due to two & three body abrasion of dislodged SiC, Gr & MoS_2 particulates, and the resulting fatigue and micro-cracking of MML. Hybrid Aluminum Matrix Composites exhibited better dry sliding wear behavior than die cast A390 matrix alloy, indicating enhanced tribological characteristics HAMCs with soft phase constituents such as Gr & MoS_2 in the presence of hard phase reinforcements like SiC.

The study revealed the formation of dross and melt biting if the SiC addition is more and especially when it is added without purging. The limitation of ultrasonic stirring is assessed and study suggests that it is feasible only for a small quantity of the melt at a lower range of temperature. Major recommendations include appropriate preheating and stirring to ensure proper mixing of particulate in the matrix and corrosion study to understand the oxidation behavior of hybrid composite during tribological applications.

Author Contributions: Conceptualization, Abhilash Edacherian; Formal analysis, Abhilash Edacherian; Investigation, Abhilash Edacherian, Ali Algahtani and Vineet Tirth; Methodology, Abhilash Edacherian; Project administration, Ali Algahtani; Supervision, Ali Algahtani; Writing – original draft, Abhilash Edacherian; Writing – review & editing, Vineet Tirth.

Acknowledgments: The authors extend their appreciation to the Deanship of Scientific Research at King Khalid University for funding this work through General Research Project under grant number (G.R.P- 421-1438).

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Wear loss of Samples (Sliding Velocity: 2.5 m/s, Load: 20 N, Sliding Distance: 1000 m).

Sample No.	Initial weight (gm)	Final weight (gm)	Track diameter (mm)	Test speed (RPM)	Time (MM:SS)
1	3.7131	3.7112	60	795	06:40
2	3.6852	3.6840	70	682	06:40
3	3.5425	3.5413	80	596	06:40
4	3.6051	3.6027	90	530	06:40
5	3.7072	3.7041	100	497	06:40
6	3.8174	3.8145	110	434	06:40
7	3.6756	3.6724	120	397	06:40
8	3.6857	3.6846	90	530	06:40

Table A2. Wear loss of Samples (Sliding Velocity: 2.5 m/s, Load: 30 N, Sliding Distance: 1000 m).

Sample No.	Initial weight (gm)	Final weight (gm)	Track diameter (mm)	Test speed (RPM)	Time (MM:SS)
1	3.6829	3.6800	60	795	06:40
2	3.6055	3.6025	70	682	06:40
3	3.5117	3.5082	80	596	06:40
4	3.5459	3.5421	90	530	06:40
5	3.5661	3.5623	100	497	06:40
6	3.7483	3.7434	110	434	06:40
7	3.5956	3.5918	120	397	06:40
8	3.6362	3.6320	90	530	06:40

Table A3. Wear loss of Samples (Sliding Velocity: 2.5 m/s, Load: 40 N, Sliding Distance: 1000 m).

Sample No.	Initial weight (gm)	Final weight (gm)	Track diameter (mm)	Test speed (RPM)	Time (MM:SS)
1	3.6804	3.6775	60	795	06:40
2	3.6033	3.6002	70	682	06:40
3	3.5087	3.5058	80	596	06:40
4	3.5426	3.5390	90	530	06:40
5	3.5634	3.5592	100	497	06:40
6	3.7441	3.7414	110	434	06:40
7	3.5924	3.5867	120	397	06:40
8	3.6325	3.6293	90	530	06:40

References

1. Allison, J. E.; Cole, G. S. Metal-matrix composites in the automotive industry: Opportunities and challenges. *JOM* **1993**, 45, 19–24. DOI:10.1007/bf03223361.
2. Miracle, D. B. Metal matrix composites – From science to technological significance. *Compos. Sci. Technol.***2005**, 65, 2526–2540. DOI:10.1016/j.compscitech.2005.05.027.
3. Srivatsan, T. S.; Ibrahim, I. A.; Mohamed, F. A.; Lavernia, E. J. Processing techniques for particulate-reinforced metal aluminium matrix composites. *J. Mater. Sci* **1991**, 26, 5965–5978. DOI:10.1007/bf01113872.
4. Shalu, T.; Abhilash, E.; & Joseph, M. A. Development and characterization of liquid carbon fibre reinforced aluminium matrix composite. *J. Mater. Process. Technol.* **2008**, 209, 4809–4813. DOI:10.1016/j.jmatprotec.2008.12.012.
5. A Schmidt; S Siebeck; U Götze; G Wagner; D Nestler Particle-Reinforced Aluminum Matrix Composites (AMCs)—Selected Results of an Integrated Technology, User, and Market Analysis and Forecast, *Metals* **2018**, 8, DOI:10.3390/met8020143.
6. Sijo, M. T.; Jayadevan, K. R. Analysis of Stir Cast Aluminium Silicon Carbide Metal Matrix Composite: A Comprehensive Review, *Procedia Technology* **2016**, 24, 379–385. DOI:10.1016/j.protcy.2016.05.052.
7. Tash, M.; Mahmoud, E. Development of in-Situ Al-Si/CuAl2 Metal Matrix Composites: Microstructure, Hardness, and Wear Behavior. *Materials* **2016**, 442-449, DOI: 10.3390/ma9060442.
8. Bodunrin, M. O.; Alaneme, K. K.; Chown, L. H. Aluminium matrix hybrid composites: a review of reinforcement philosophies; mechanical, corrosion and tribological characteristics. *J. Mater. Res. Technol* **2015**, 4, 434–445, DOI:10.1016/j.jmrt.2015.05.003.
9. Kainer, K.U. Basics of metal matrix composite. In *Metal Matrix Composite: Custom-Made Materials for Automotive and Aerospace Engineering*, Kainer, K.U., Ed.; K.U, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, 2006, pp. 1–54, ISBN: 3-527-31360-5
10. Suresha, S.; Sridhara, B. K. Friction characteristics of aluminium silicon carbide graphite hybrid composites. *Mate. Des.* **2012**, 34, 576–583. DOI:10.1016/j.matdes.2011.05.010.
11. Monikandan, V. V.; Joseph, M. A.; Rajendrakumar, P. K. Dry sliding wear studies of aluminum matrix hybrid composites. *Resource-Efficient Technologies* **2016**, 2, S12–S24. DOI:10.1016/j.reffit.2016.10.002.
12. Pitchayyapillai, G.; Seenikannan, P.; Raja, K.; Chandrasekaran, K. Al6061 Hybrid Metal Matrix Composite Reinforced with Alumina and Molybdenum Disulphide. *Adv. Mater. Sci. Eng.*, **2016**, 1–9. DOI:10.1155/2016/6127624.
13. Prasad, S. V.; Asthana, R. Aluminum Metal–Matrix Composites for Automotive Applications: Tribological Considerations, *Tribol. Lett.* **2004**, 17(3), 445–453. DOI:10.1023/b:tril.0000044492.91991.f3.
14. G.S. Cole, A.M. Sherman, Lightweight materials for automotive applications, *Mater. Charact.* **1995**, 35, 3-9
15. A. Vencl, A. Rac, I. Bobic, Tribological Behaviour of Al-Based Mmcs and Their Application in Automotive Industry, *Tribology in industry* **2004**, 26, 31-38
16. Koli, D. K., Agnihotri, G., & Purohit, R. (2015). Advanced Aluminium Matrix Composites: The Critical Need of Automotive and Aerospace Engineering Fields. *Mater.Today: Proceedings* **2015,** 2(4-5), 3032–3041. DOI:10.1016/j.matpr.2015.07.290.
17. Singh, J., & Chauhan, A. Characterization of hybrid aluminum matrix composites for advanced applications – A review *J. Mater. Res. Technol* **2016**, 5, 159–169, DOI:10.1016/j.jmrt.2015.05.004
18. Meysam Toozandehjani, Nuruldiyanah Kamarudin, Zahra Dashtizadeh, E. Yee Lim, Ashen Gomes, Chandima Gomes, Conventional and Advanced Composites in Aerospace Industry: Technologies Revisited, *American Journal of Aerospace Engineering* **2018**; 5, 9-15
19. Barrie S. S.; Douglas A. G; William G. T.; Alcoa Technical Center, Friction and Wear of Aluminum-Silicon Alloys. In *ASM Handbook, Volume 18: Friction, Lubrication, and Wear Technology*, Blau, P.J., Ed; ASM International, Metals Park, OH, 1992, pp 785-794, ISBN: 978-1-62708-141-2.
20. The Foseco Foundryman's Handbook: Facts, Figures and Formulae, Burns T.A, Ed; Pergamon Press, New York, 9th Ed, 1986, ISBN: 008-032549