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Ashwath P[1], Joel J[2], Jeyapandiarajan P[3], Anthony Xavior M[4*], Rajendran R[5]

[1,2,3,4] *School of Mechanical Engineering,*
Vellore Institute of Technology, Vellore, Tamil Nadu, India
[5] *CVRDE, Chennai, Tamil Nadu, India*

Abstract

Aluminum alloy based metal matrix composites are widely used in aerospace, military and automotive industry. The aluminium grades used in present research work are Aluminium alloy 6061, Aluminium alloy 2024, LM6. In this research, composites with Aluminum alloy as matrix with 6 weight % of nano alumina as reinforcement were fabricated using two processing technique namely, powder metallurgy technique (cold pressing and microwave sintering), and by squeeze casting technique. Thus fabricated samples were used to study the effect of processing technique on mechanical properties and wear aspects of the composite. Scanning electron microscope data and mechanical property characteristics reveals the presence of nano alumina particles and their uniform distribution in case of powder metallurgy processed samples. Mechanical and wear properties achieved on the fabricated samples were compared with the existing aerospace brake pad material. The data related to wear characteristics correlated with the number of landings for the existing brake pad material is considered as the bench mark data and the feasibility of replacing it with the developed composites were studied.

Keywords: Aluminium-alumina composites, powder metallurgy, squeeze casting, aerospace brake pads, wear

1. Introduction

In recent decades, the major efforts of materials designers are directed towards developing light weight metals which have a high strength-to-weight ratio with favourable frictional properties [1, 2]. Among these materials, aluminium-based metal matrix composites (MMCs) are appropriate materials for structural applications in the aircraft and automotive friction applications. Particulate metal matrix composites (MMCp) are engineering materials in which a hard-ceramic component is dispersed in a ductile metal matrix in order to obtain characteristics that are superior to those of conventional monolithic metallic alloys [3,4]. Metal matrix Nano composites (MMNCs) are a class of metal matrix composite in which the size of matrix or fibre is in the Nano scale (usually 1 to 100 nanometres) [5].

It should be noted that Al-Alumina composites are difficult to obtain by conventional melting-based methods due to the poor wettability between molten Al and the Alumina particulates. In addition, these methods usually lead to an undesirable ambiguity between the Alumina and molten Al, which leads to non-homogeneous distribution of the reinforcement added. Powder metallurgy (P/M) has been widely utilized to fabricate and develop metal or ceramic-based composite powders with enhanced composite properties [3,7]. There are some other benefits of composites such as the ability to control the mechanical and physical properties by appropriate selection of matrix, second phase, and volume fraction of particles. It has been observed that all processed samples exhibited better properties and evident microstructure development than the parent metal. Production of composites is a low-cost process with respect to their high performance [8, 9]. Since the ceramic particle in the Nano scale, cause increasing of strength of the matrix without significant reduction in ductility, the construction of the composites is much considered. On the other hand, the surface area of Nano particle size is much smaller than the micro matrix particle size that lead to lesser dislocation density after processing of the Nano composites. Nano alumina particles are widely used to improve the mechanical and thermal properties of metal matrix composites especially aluminium matrix composites

[5][10]. Aerospace brake pads are in need of performing at elevated temperature in the order of 400 to 500 ^{o}C for which the existing materials are made of copper-based pads or ferrous based pads. Aluminium alloy composites reinforced with Al_2O_3 are found to be a potential material in replacing the current brake pads material used in aerospace dry braking pads because of their good thermal conductivity and the wear resistance at elevated temperatures. Current research work focus on developing the MMC to evaluate for the strength characteristics and wear aspects compared with the fabrication methods used.

2. Materials and Methods

The material used to fabricate the composite is aluminium alloy 6061, 2024 and LM6 for which the Spectra xSort-XRF composition analyser is used to determine the composition of the alloys used and to detect the grade. The grades and the composition evaluated by XRF analyser is shown in table 1a. The ceramic reinforcement used to reinforce is Alumina (Al_2O_3, 99% pure, particle size 10 nm, procured from Angstron Inc. Germany). Samples are fabricated by powder metallurgy route by compacting (550 MPa Pressure) followed by microwave sintering at 500 ^{o}C at 25 ^{o}C rate of heating for 20 mins. Figure 1 shows the stir casting setup and the squeeze casted samples where as Figure 2a presents the SEM Morphology of Aluminium Alloy powder and the samples produced through powder metallurgy process. Figure 2b shows the experimental setup used for powder metallurgy fabrication. Figure 3 shows the nano alumina powder morphology at as received condition. The benchmark aerospace brake pads properties are presented in Table 1. Squeeze casting was done in a semi-automatic stir-squeeze casting setup where ingots of the matrix material are fed and heated to 700 ^{o}C for melting. Then the molten matrix is added with ultra sonication processed nano alumina and stirred for 10 mins [1, 24]. The molten mixture is poured to casting die and then squeezed using a rammer. The pressure developed in the squeeze casing stage was recorded around 475 MPa. Thus, developed composites are subjected to wire cut process to get samples for various mechanical testing. The wire cut samples are micro drilled for 2mm to conduct the high temperature wear property evaluation studies.

Rockwell hardness was measured across the surface of the developed composites at a load of 30 Kgf with dwell time of 10 seconds using 2.5 mm diameter ball equipped Rockwell hardness tester. The distance between successive indentations is 5 mm. Wear test is done on the surface of the stir zone with a 45HRC steel disc which is rotating at 400 rpm for total landing run way distance (4500 m) and calculated for the service period of 120 landings. The applied force used was around 100 Mpa dry braking force which is exactly used in aircraft dry braking. The temperature at which the pins are tested is around 300 ^{o}C for creating the exact dry braking environment as experienced in the aerospace dry braking. Data regarding coefficient of friction and frictional force is collected and it's then projected to get wear loss and frictional coefficient. Micro structural evaluation is done by using SEM and optical microscope. X-ray diffraction is used to analyze the compounds present in the composite samples after fabrication. Table 1b shows the benchmark property of the conventionally used disc pads material.

Fig 1: Stir casting setup and Squeeze Casted Samples (Scale – 10 cm)

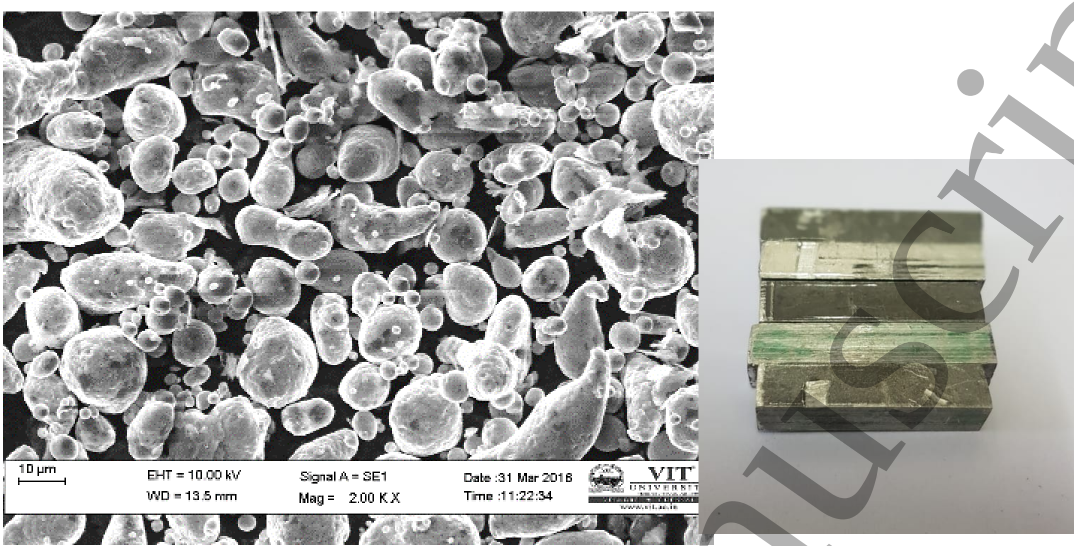

Fig 2a: SEM Morphology of Aluminium Alloy powder and Powder Metallurgy Samples (Scale – 10 cm)

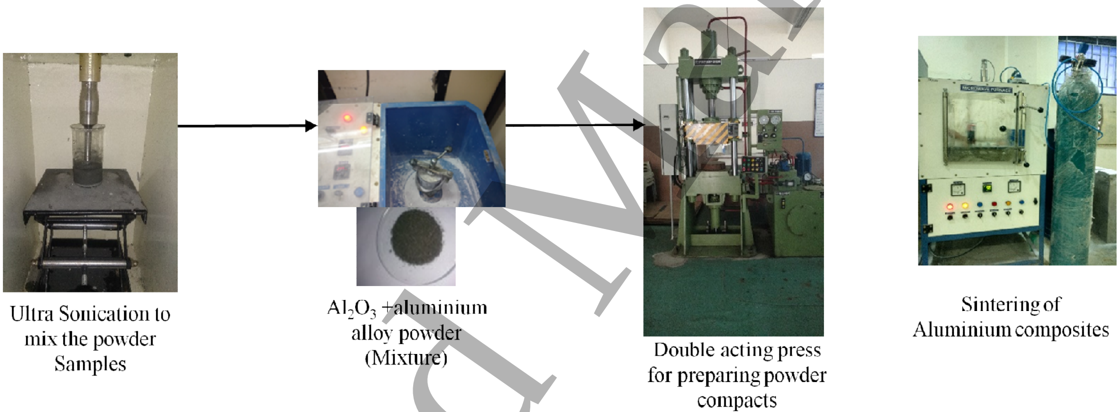

Fig 2b: Experimental setup for Powder metallurgy route

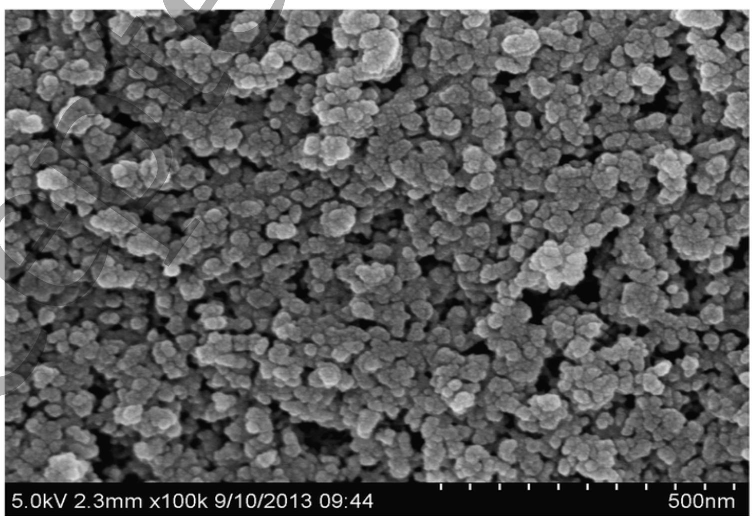

Fig 3: SEM Morphology of "as procured" Nano alumina

Table 1a: Chemical Composition of the aluminium alloy used measured from XRF

Element	Cu	Mg	Si	Fe	Sn	Al
2024	3.25	1.47	0.30	0.09	0.67	94.22
6061	0.35	1.10	0.57	0.66	-	97.32
LM6	0.10	0.05	11.2	-	0.05	88.60

Table 1b: Benchmark properties of existing brake pads used in aerospace application

Target properties of Conventional disc pads	
Compression Strength	159 MPa
Surface Hardness	67 BHN
Wear Loss	1.5 mm (max)
CoF	0.32
Impact Strength	9.5

3. Results and discussion.

Density Evaluation

Density was measured by using Archimedes principle as per ASTM Standards B-703. In general, all the parent materials such as LM6, Aluminium alloy 6061, Aluminium alloy 2024 holds an average density between 2.65 to 275 g/cm³, and the reinforcement material used is proposing a density value of 3.95 g/cm³ [11]. Observing from the Fig. 4 the powder metallurgy samples show a higher density compared to squeeze casted samples. This phenomenon is because, the powder metallurgy process rectifies the basic conventional problems like porosity and reinforcement agglomerations. Irrespective of the aluminium alloys used the density observations exhibits the closer range of density values observed in the parent alloy material. The reduction in the density is observed because of the reinforcement addition which leads to the dislocation density increased and the inter particle distance between the matrix particles are increased. Addition of Al_2O_3 particles lead to compromise in the ductility of the composites. From Fig. 4 comparing density data of squeeze casted samples with the microwave sintered samples the microwave processed samples exhibits good density [11-13]. This phenomenon is because of the good sinterability of the samples as the heat is developed from inside to outside leading to lesser porosity and the good interfacial bonding between the matrix and the reinforcement [12].

Comparing LM6, AA 6061 and AA 2024 the copper based aluminium alloy with powder metallurgy process fetched the highest density of 2.66 g/cm³. As microwave sintering technique is employed in the process along with the powder metallurgy process the density of the sintered samples are intact with and achieved closer to the parent aluminium alloys. In case of the squeeze casting the temperature gradient change at the moment of adding the reinforcement leads to the clogging and the agglomeration of the reinforcement added [12-15]. Other factor that leads to reduction in density is the addition of nano reinforcement to a molten metal during the stirring mechanism. This process leads to further chance of agglomeration leading to poor density even after squeeze casting of the samples.

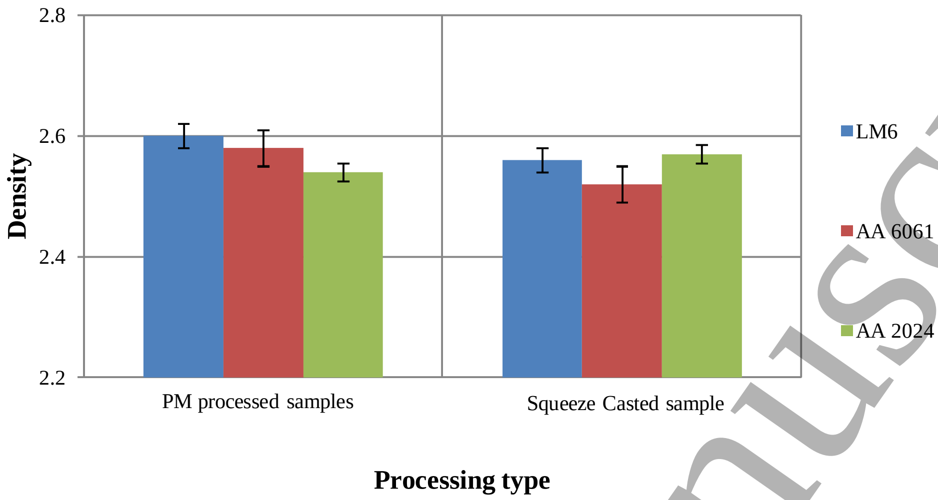

Figure 4: Comparison of density between Aluminium Alloys with 6 wt% Al_2O_3

Strength Evaluation

Average of 5 reading was taken and reported for the Rockwell hardness measured on the sample surface.

Table 2: Hardness data of Sintered and casted material with 6 wt% Al_2O_3

S.No.	Metal Matrix	Method of fabrication	Rockwell hardness B Scale
1	**LM6**	**PM**	**77**
2	**LM6**	**SC**	**73**
3	**AA 6061**	**PM**	**78**
4	**AA 6061**	**SC**	**71**
5	**AA 2024**	**PM**	**93**
6	**AA 2024**	**SC**	**87**

Experimental data reveals that, indentation hardness correlates linearly with tensile strength. The parent aluminium alloys materials used in the research work possesses a Rockwell hardness B scale (HRB) values between 60 to 75. At engineering conditions aluminium alloy 2024 exhibits higher hardness value of all aluminium alloy series but 6061 and LM6 grades exhibited lower hardness values even after the addition of nano alumina [16]. As alumina added is in nano size, the surface on which the hardness is measured for P/M processed samples exhibits good hardness compared to squeeze casted samples as shown in Table 2 and Fig. 5. The squeeze casted samples possessed surface and near subsurface defects like micro pores and free of surface defects because of which the hardness values are observed to have a reducing trend in the hardness compared to the P/M processed samples. The processing technique plays a significant role in getting the better strength to microstructural relation in obtaining better properties.

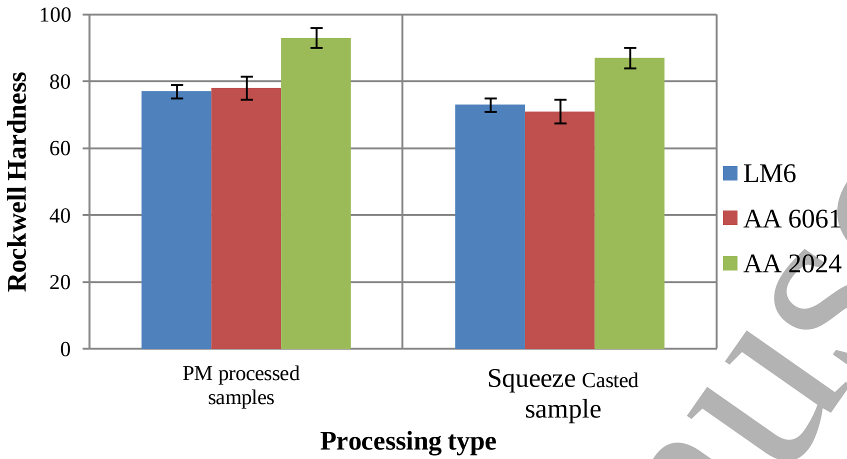

Figure 5: Comparison of Rockwell hardness of composites with 6 wt% Al_2O_3

The composite samples based on AA 2024 exhibits a higher hardness for both PM process and squeeze casting process due to the reinforcement mixture and the presence of Copper as the major alloying element when compared to the AA 6061 and LM6. Compression strength is the capacity of a material or structure to withstand loads tending to reduce size, as opposed to tensile strength, which withstands loads tending to elongation. Some materials fracture at their compressive strength limit; others deform irreversibly [17].

Table 3: Compressive strength data of Sintered and Casted materials with 6 wt% Al_2O_3

S.No.	Metal Matrix	Method of fabrication	Compressive strength Mpa
1	**LM6**	**PM**	**300.5**
2	**LM6**	**SC**	**284.9**
3	**AA 6061**	**PM**	**284.7**
4	**AA 6061**	**SC**	**273**
5	**AA 2024**	**PM**	**325.5**
6	**AA 2024**	**SC**	**304.5**

Measurements of compressive strength are affected by the specific test method and conditions of measurement. Compressive strengths are usually reported in relationship to a specific technical standard. From Table 3 and Fig. 6 the compressive strength of AA 2024 with nano alumina addition exhibits the highest compressive strength of 325.5 MPa [18-21]. The highest compressive strength is reported for P/M Processed samples. P/M processed samples which undergo processing conditions like ball milling and ultra-sonication leads to homogeneous mixing of the nano alumina into the matrix material [21]. Additionally, the major alloying element in the aluminium alloy also governs the strength property of the composite. This phenomenon is seen in shear strength as shown in Table 4 and Fig. 7.

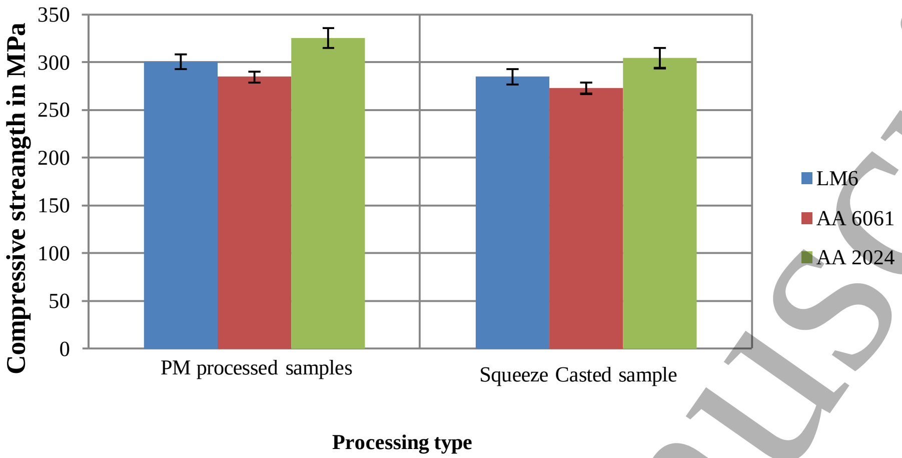

Figure 6: Comparison of compressive strength between composites

The compressive strength and shear strength of aluminium alloy 2024 shows a better result in both PM processed samples and in squeeze casted samples comparatively. But in terms of PM processed samples shows an even higher result in aluminium alloy 2024 is due to the compaction of the material followed by sintering process helps the material to increase in compressive strength. Since aluminium alloy 2024 is a copper-based alloy it tends to have a low compressive strength as referred the overall compressive strength will reduces up to 5 percentage with 1 percentage increase in copper alloying element [20-23]. A shear load is a force that tends to produce a sliding failure on a material along a plane that is parallel to the direction of the force. Shear is defined as the force that causes two contiguous parts of the same body to slide relative to each other in a direction parallel to their plane of contact. Shear strength is the stress required to yield or fracture the material in the plane of material cross-section. The increase in strength of the composites is due to the increase in dislocation density [19-21].

Table 4: Shear strength data of Sintered and Casted materials with 6 wt% Al_2O_3

S.No.	Metal Matrix	Method of fabrication	Shear Strength Mpa
1	**LM6**	**PM**	**70.5**
2	**LM6**	**SC**	**68.2**
3	**AA 6061**	**PM**	**65.7**
4	**AA 6061**	**SC**	**63**
5	**AA 2024**	**PM**	**74.4**
6	**AA 2024**	**SC**	**69.6**

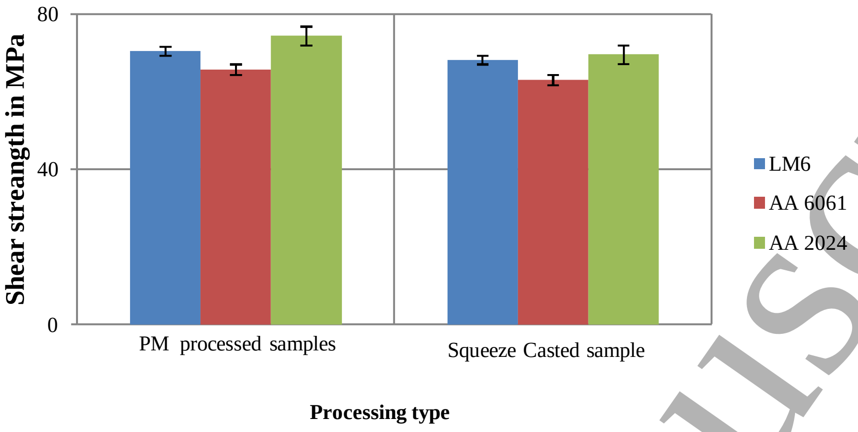

Figure 7: Comparison of Shear strength between composites with 6 wt% Al_2O_3

Hence shear strength is important in this work since it has to withstand frictional force in pin on wear test apparatus, and also in the manufacturing of brake pads the capacity to withstand shear force should be high. The comparison clearly shows that Aluminium alloy 2024 and LM6 shows up a better result compared to Aluminium alloy 6061. The shear strength data rise in aluminium 2024 is because of the alloying element. In general, the PM processed samples hold higher shear strength than squeeze casted samples. The 2024 alloys hold the least shear strength value due to the higher silicon content and which internally affects the shear strength [15-17].

Brake pads materials bench mark evaluation

The wear analysis is carried out in a pin on disc wear testing machine which is designated to study the friction and wear characteristics in sliding contacts. To initiate the wear analysis the samples has to be prepared for the following requirements. The requirements are as follows, the hole on the top surface of the 6mm diameter pin for the temperature sensor to monitor and the contact surface has to be polished for the wear rate to be smooth at the initial stage as shown in Figs. 8, 9 and 10.

Fig 8: Squeeze casted drilled samples

Fig 9: PM drilled samples

The composite samples of length 25mm with a drilled hole depth of about 20mm were used for wear studies. There will be negligible length allocated in which the wear can be tracked around the wear testing apparatus. Pin on disc wear apparatus with a circular disc of diameter 100 mm is loaded which is used as the surface to place the pin. The wear disc consists of a thickness of around 6mm minimum and a maximum of 8mm. The pin diameter can be changed with the slots used inside with a difference of 6mm to 8mm in diameter of the samples. ASTM standard G99-17 was used to study the wear test of the samples. Eventually, as the wear test is studied in correlation with the practical problem definition of studying with the aircraft landing service period of the brake pads. So the ASTM standards in many places are replaced with the feasible samples size fabrication to match the sample standards. The wear testing parameters are selected based on the aspect of the existing brake pads materials used in the aircraft materials.

Fig 10: Polished wear samples

Fig 11: Experimental setup

The experiment begins with greasing of the samples because, during wear analysis a lot of heat will be generated which, at extreme cases promotes softening of the materials that are not in contact with the wear disc. The generated heat may be transferred and softens the material which causes the pin sample to stick with the slots used to hold the samples. In order to avoid such problems industrial grease is applied on the samples and loaded into the slots as shown in Figs. 12 and 13. Greasing and loading of the wear samples is followed by the attachment of the temperature sensor to the system, the sensor is capable of measuring temperature up to a variant of 800 degree Celsius in total.

Fig 12: Greasing of sample

Fig 13: Contact of pin and wear disc

The wear and coefficient of friction calculated in the pin on disc setup is correlated with the benchmark data of the existing aerospace brake pads material as shown in Table 1b. The specimen used for wear evaluation is around 5 x 5 mm. The dry braking pressure adapted in pin on disc setup is around 100 MPa. The force used is also derived as 100 N load. This input parameter is used to calculate to test the sample for the total life time of the brake pads used. The total life time of the brake pads is around 120 landings or the 3 mm of wear depth of the surface. Which ever reach earlier the pads will be replaced with the new pads. The pads used are of copper-based composites for which effective replacement with aluminium composites in aspects of both mechanical and wear characteristics are studied in this research work. Figure 14 displays the wear graph and the temperature profile graph obtained from the software used.

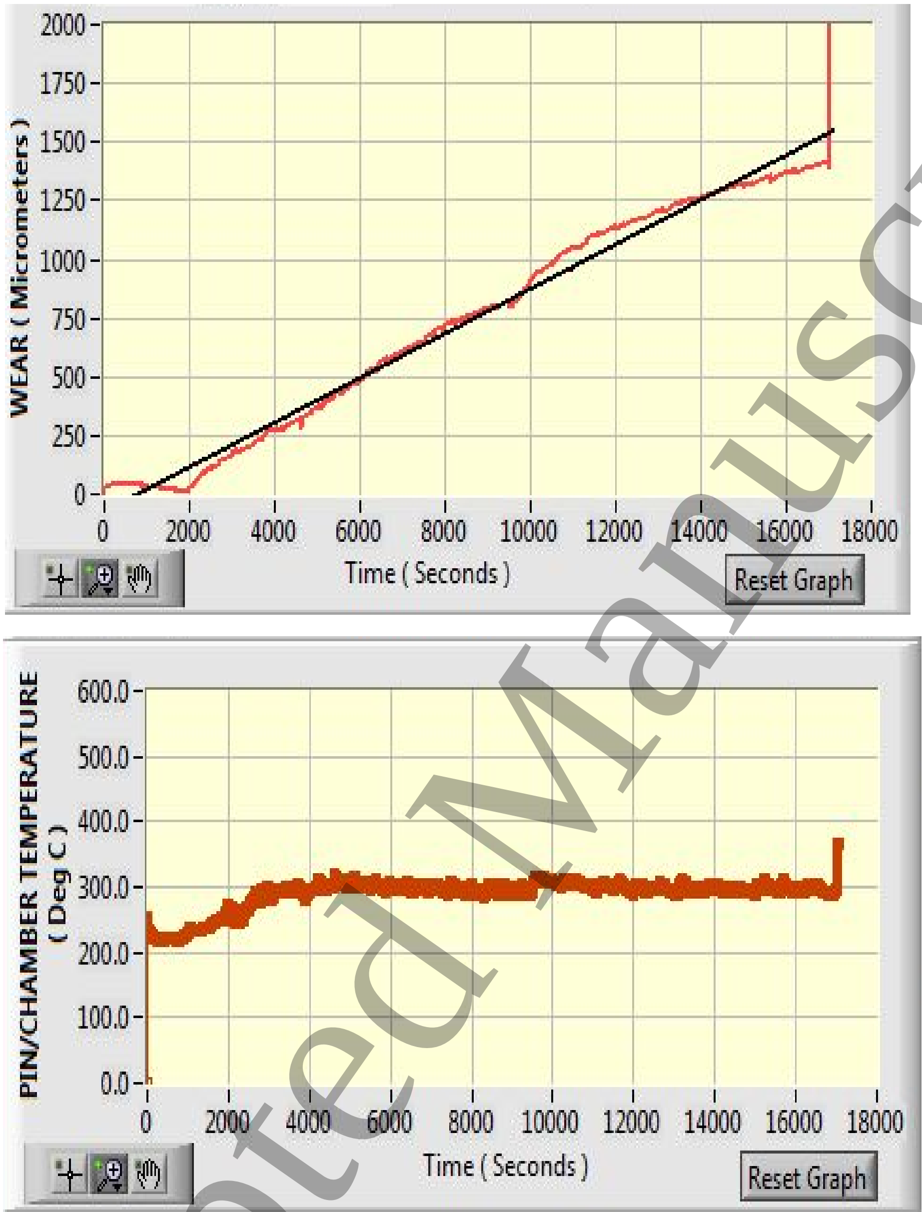

Fig 14: Wear Graph and temperature recorded graph for the powder metallurgy processed samples

In general, an aircraft's brake pads will be replaced after 120 landings since after 120 landings the brake pads crosses the negligible wear and moves to the breakage zone, so the primary objective of the paper is to evaluate whether the selected aluminium alloy based composites can withstand the threshold value of wear. The temperature profile from Fig. 14 shows the consistency in pin heating which is much more helpful in studying the wear aspects in actual aerospace dry braking conditions.

Table 5: Wear at 300°C Temperature – microwave sintered and squeeze casted

S.No.	Metal Matrix	Method of fabrication	Wear in microns	COF	No of landing completed (>8200 kg aircraft)	No of landings completed(<8200 kg aircraft)
1	**LM6**	**PM**	**1.6**	**0.376**	**119**	**112**
2	**LM6**	**SC**	**1.81**	**0.391**	**75**	**71**
3	**AA 6061**	**PM**	**2.1**	**0.412**	**87**	**80**
4	**AA 6061**	**SC**	**2.3**	**0.433**	**78**	**75**
5	**AA 2024**	**PM**	**1.8**	**0.371**	**118**	**106**
6	**AA 2024**	**SC**	**1.65**	**0.379**	**104**	**97**

Table 5 shows the landing completed by the current samples under 300 °C temperature. The samples have been evaluated for several terms such as landings completed for aircrafts less than **8200 kg** and landings completed for larger aircrafts also. The landing distance required for an aircraft greater than **8200 kg** requires about 2500 meters and the landing distance required for an aircraft less than **8200 kg** is 1800 meters. By separating it with the occurrence of powder metallurgy samples with that of squeeze casted samples in general and also by applying the criteria of number of landings completed for the light weight aircrafts with that middle range aircrafts with respect to the variation in landing distance required.

Thus, aluminium alloy 2024 and LM6 based composites holds a higher landing distance completed in both light weight aircraft and medium weight aircraft. It is due to the alloying element in it such as Silicon in case of LM6 and copper in case of 2024 which possess a good heat dissipation property along the various alloying element [21, 25-27]. The heat dissipation property decreases the pin temperature and decreases the wear rate. The lesser pin temperature due to fast dissipation leads to lesser energy involved in wearing the surface especially in case of aluminium alloys used. Aluminium in aspect of wear considerably has special characteristics of good heat dissipation property compared to other existing brake pads material. This phenomenon is evident from Table 5. Hence a composite based on AA 2024 possesses a higher rate of landing comparatively [23, 25].

Factors additional to type of aluminium alloys the reinforcement and processing technique also played a vital role in deciding the performance of the disc pad materials. The service requirement for the existing brake pad material with respect to the total wear is 2.3 mm depth and CoF requirement is around 0.35. Experimental data indicates that LM6 and AA 2024 based nano alumina reinforced composites exhibited enhanced strength properties and closer wear properties [20-23].

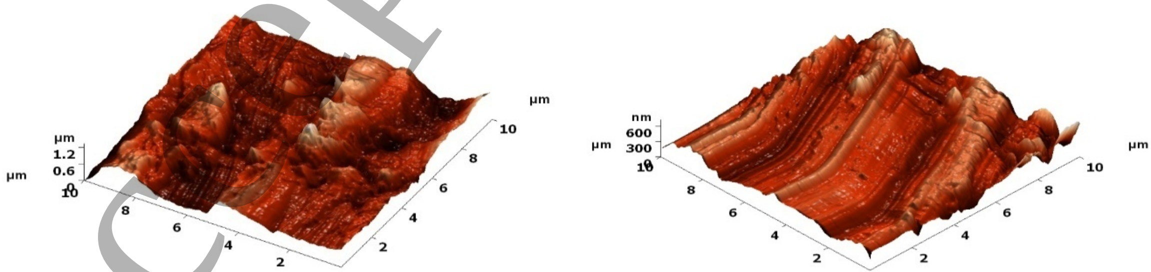

Figure 15: AFM Image of the AA 2024 P/M Pin wear track and Counter disc part wear track

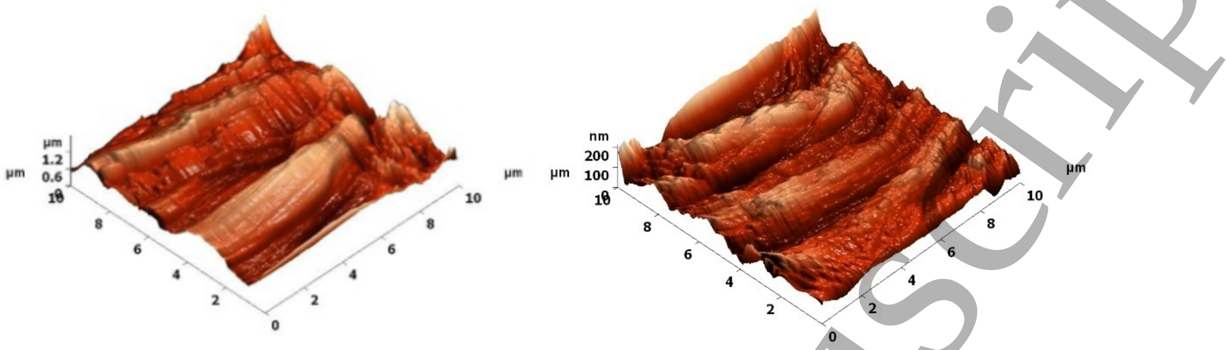

Figure 16: AFM Image of the AA 2024 P/M Pin wear track and Counter disc part wear track

From Figs 15 and 16 it is clearly understood that Atomic Field Microscopy (AFM) on the wear track of both the composite pin samples and the counter disc part wear are studied clearly. The pin wear on both the samples of LM6 and AA 2024 are found to be lesser than actual service condition expected in existing brake pads used in aircrafts. One more aspect to consider is the landing scenario which is at intervals where brake pads get into function during landing but in pin on disc setup the wear scenario is continuous [18-21]. The wear data is promising because the pins are evaluated under continuous dry wear condition. More over the counter part wear is found to be minimal in all cases due to the presence of Al_2O_3 which is not much abrasive in nature.

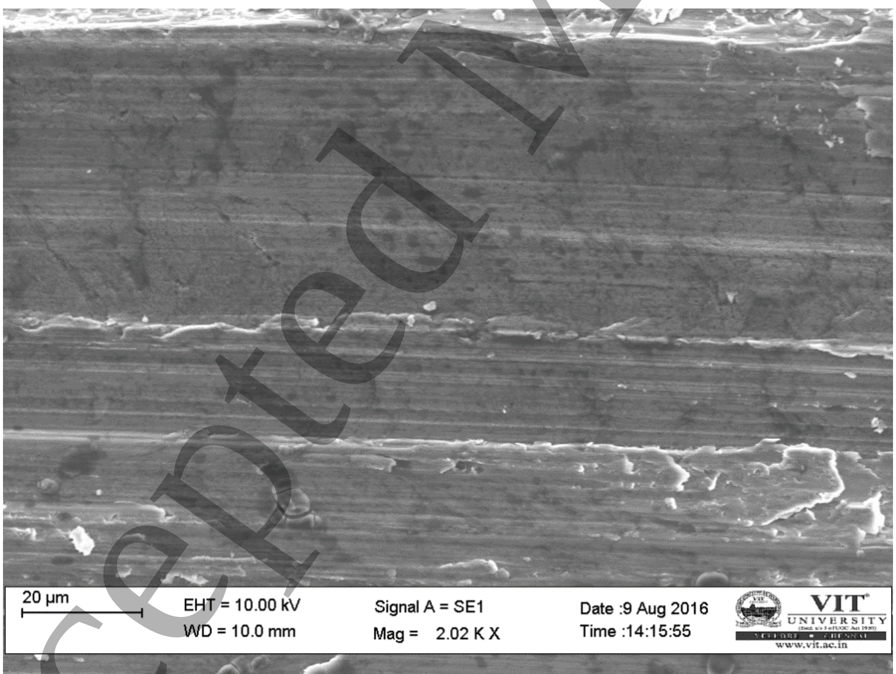

Figure 17: SEM micrographs of the AA 2024 P/M Pin wear track

Figure 18: SEM Micrograph of the AA LM6 P/M Pin wear track

Figures 17 and 18 exhibits very few surface seizures in both AA2024 and LM6 based composite samples. This phenomenon is supported only for samples processed by P/M route and specially processed by microwave sintering. The surface and as a bulk the composite sintered properly had exhibited excellent strength characteristics closer to existing brake pad material [22-27]. No third body abrasion has been noticed on the surface and no severe plastic deformation has been noticed for the entire landing distance or for the wear depth service period.

Conclusions

The composites are fabricated successfully by powder metallurgy route and squeeze casting route. Comparing the P/M route and squeeze casting, P/M samples exhibited good strength to wear characteristics irrespective of alloy used. Nano alumina addition to the composite improved the mechanical strength properties in both P/M process and squeeze casting process. On evaluating for the benchmark data of the existing brake pads materials with the aluminium alloy composite the P/M processed samples with AA2024 and LM6 matrix exhibited promising data for being a potential replacement for the existing brake pad material used in aerospace application. The service requirement for the existing brake pad material with respect to the total wear is 2.3 mm depth and CoF requirement is around 0.35 which is observed in the both the process of fabrication and considering the microstructural aspect and the reduction of cost obtaining direct component the powder metallurgy route is preferred to be chosen.

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