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A review on the mechanical properties, tribological behavior and the microstructural characterization of Aluminium metal matrix composites (AMMCs).

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Abstract— In this present generation, due to extensive demands of low cost, high efficiency and performance along with superior quality has led to a decline in the simple and traditional research and new advance research has taken over. Hybrid composites have proved their great performance with excellent versatility. In case of Metal Matrix Composites of Aluminium, due to their high strength to weight ratio, high corrosion and wear resistance with relatively low cost are extensively produced and is employed in several applications like structural, aerospace, automobile sector due to its thermal stability and tremendous specific strength. These MMCs are advanced engineering materials which are reinforced with materials having improved mechanical and tribological behavior. Reinforcement like alumina, silicon carbide, TiO_2, graphite and fly ash are mainly used. This paper presents a review on the mechanical properties and tribological behavior along with their microstructural evolution that is obtained after their reinforcement at various concentrations. Different reinforcements have different effect on aluminium composites like graphite addition enhances the tensile strength, elastic modulus, thermal and electrical conductivity due to its lubricating property. Alumina addition results in good tribological behavior. Fly ash addition caused an increase in tensile strength, yield strength and overall mechanical properties. Similarly other reinforcements have their particular effect on the Al composites.

Index Terms— Aluminium metal matrix composite, Mechanical properties, Microstructural Characterization, Tribological behavior, Wear.

1 INTRODUCTION

MMCs are those materials that are fabricated by reinforcing a parent tough metal matrix with a ceramic hard material like SiC. The Al-MMCs have drawn most of the attention in the past decades because it exhibits superior mechanical properties like tensile strength, fatigue, fracture toughness etc. as compared to the un-reinforced composites. The Aluminum MMCs have high strength to weight, high strength to cost ratio, high thermal and electrical conductivities, high wear and corrosion resistance, high damping capacity and precipitation strengthening [1]. These Al-MMCs are mostly used in the automobile, defense and aerospace industries due to all of the above mentioned properties [2]. The fabrication cost of Al-MMCs is also low so it is manufactured on a large scale and is one of the most extensively used product worldwide. The mechanical properties exhibited depend mainly on the chemical compositions of the Al-matrix.

Al composites are mainly reinforced using hard ceramic particles like TiB_2, SiC, Al_2O_3, B_4N, AlN and organic reinforcements are also used like fly ash [3-5]. Apart from these, there is a range of materials that are used as reinforcement to enhance the mechanical properties of Al composites. Theses MMCs exhibit poor ductility at room temperature so they are fabricated at elevated temperature [6]. SiC is known to have better chemical compatibility with aluminium because it doesn't forms any inter-metallic phases during its interaction with the Al matrix, so it is a very common type of reinforcement used in Al-MMCs [7]. It has additional advantages like better thermal conductivity, good workability and it is economical. Fly ash is one of the most little expensive and very low weight reinforcement which is available in abundance. With addition of fly ash the density of the composite decreases and the hardness increases. Incorporation of fly ash lowers the overall weight of the MMCs and thereby reduces the cost of the Al products [8].
Graphite and graphite powders are extensively used in various applications in industries due to its self-lubricating tendency. If graphite content is increased more than 4 %, the hardness values reduces considerably while the ductility and tensile strength is increased. If excessive graphite is added, then it may lead to the rejection of graphite from the matrix [9].

TiB_2 is also an excellent reinforcement due to its outstanding features like high melting point, good thermal stability, high strength, and high elastic modulus. It doesn't forms any brittle phases at the TiB_2-Al interface because it does not react with the molten aluminium matrix. Al-TiB_2 MMCs exhibit higher values of tensile strength and hardness as compared to the parent alloy [10].

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Al_2O_3 is one of the widely used reinforcement but it has certain disadvantages like poor wetting behavior with Al and more weight percentage which leads to increased porosity in the manufactured AMMCs. With alumina, tribological and mechanical properties are improved. Micro-hardness values increase when alumina is added to aluminium composites [11]. Ceramic particles like B_4C improve the wear properties by lowering the specific wear rate. As its composition is increased, the wear properties are improved thereby improving the overall tribological behavior [12].

Different manufacturing processes are adopted for preparation of AMMCs. Most commonly used manufacturing techniques are stir casting, squeeze casting and powder metallurgy. Stir casting method is generally used for the reinforcement because of its wider availability and also it is relatively economical than other methods. Stir casting processes also enhances the bonding strength between the reinforced particle and matrix because of its better stirring actions. The major problem with the stir casting is the segregation or clustering of reinforced particles because, after wetting some particles sink or float due to density difference during solidification. Due to this, many casting defects like porosities, blow holes and inclusions may arise [13].

Although the powder metallurgy process is not much economical but, more uniform distribution of reinforced particles in the matrix can be achieved by powder metallurgy than stir casting. Mixing of reinforced and metal powders through powder metallurgy can be done by high-temperature and high-pressure (HTHP), hot pressing or spark plasma sintering (SPS). However, powder metallurgy is constrained for simple shaped components having less reinforced particles [14]. Combination of casting and forging processes are employed for squeeze casting at high pressure by which the solidification rate enhances.

2 Mechanical Properties

It is very important to understand mechanical properties of any material because they are used in various areas. The mechanical properties of Al-MMCs depend upon the parent composite, type of reinforcement, particle size and shape. Various ceramic hard particles, organic polymers, fibers etc. are added as reinforcement to increase the mechanical properties of aluminium composite.

Kamat et al. (1989) included Al_2O_3 as the reinforcing agent in Al (2024) alloy and the results showed that the yield strength and tensile strength of the Al-MMC increased with an increase in the volume fraction of the Al_2O_3 particulates [15]. Some researchers also used Al_2O_3 and the results showed an increase in the yield strength and a decrease in the ductility and ultimate tensile strength [16].

Su et al. (2012) reinforced Al (2024) using nanoparticles of Al_2O_3 and found that yield strength and tensile strength of the composite increased [17]. Kok (2005) used Al_20_3 as reinforcement in Al (2024) and observed an increase in tensile strength and hardness value of the metal matrix composite [18].

Akbari et al. (2013) also investigated the effect of mixing of nano Al_2O_3 and Al particles and with nano Al_2O_3 and Cu particles as reinforcement in Al (A356) alloy and found the increase in ultimate tensile strength and compressive strength of the fabricated composite. Also, they observed that there more increment in mechanical properties of Al (A356)/Al_2O_3/Cu composite as compared to Al (A356)/ Al_2O_3/Al composite [19].

Amirkhanlou et al. (2010) used SiC as reinforcement in Al (A356) and found an increase in hardness and impact energy of the composite [20]. Sajjadi et al. (2011) evaluated the hardness and the compressive strength of Al (A356)/ Al_2O_{3p} and observed that with increase in weight percent of alumina or decrease in particle size the hardness and compressive strength increases [21]. Yar et al. (2009) fabricated Al (A356.1) metal matrix composite using nanoparticles of MgO as reinforcement and observed that the hardness and compressive strength of the composite increased [22].

James et al. (2014) used SiC and TiB_2 particles as reinforcement in Al 6061 alloy. When TiB_2 is added to the alloy, there is a considerable reduction in the tensile strength which can be seen in fig. 1 (a). This is due to the cluster formation during the fabrication of the composite which lead to porosity. The hardness values increases upto 2.5 wt. % of TiB_2 and then a sudden decrease in the hardness values is observed. So, the optimum TiB_2 concentration is 2.5 wt. % for the hardness value which can be seen in fig. 1 (b) [23].

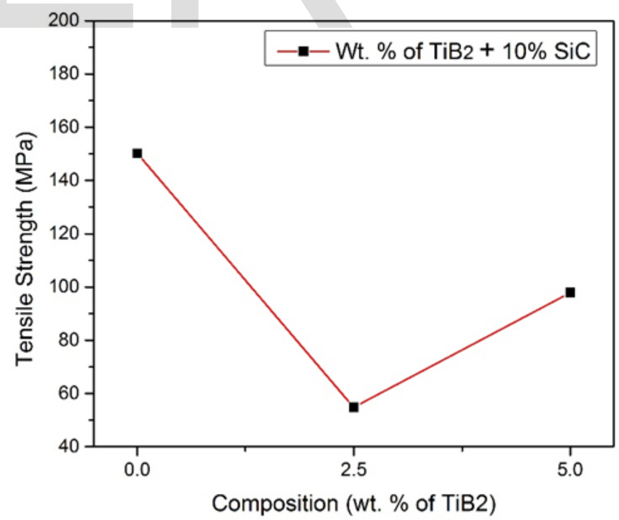

Fig. 1 (a). Showing the variation of tensile strength with composition of TiB_2 and SiC. (James et al. (2014))

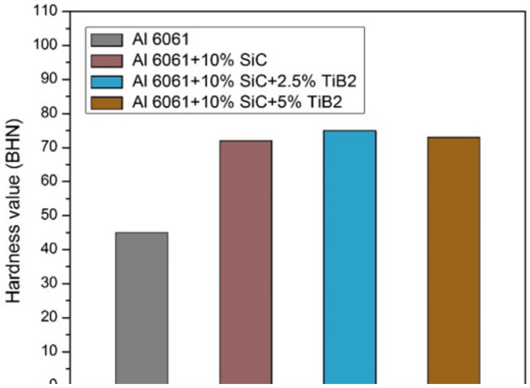

Fig. 1 (b). Showing the variation of hardness value with composition of TiB_2 and SiC. (James et al. (2014))

Mazahery et al. (2009) fabricated a metal matrix composite using nano Al_2O_3 particles in A356 alloy using stir casting technique. The results exhibited that the tensile strength, yield strength and ductility of the composite increased with an increase in the concentration of alumina nano particles which is shown in fig. 2 (a). The hardness of the metal matrix composite also improved as compared to the parent alloy, fig. 2 (b) [24].

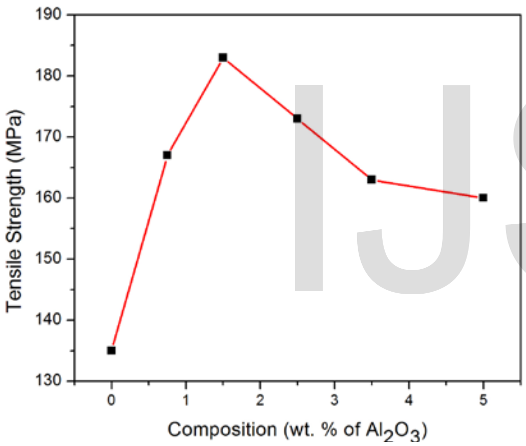

Fig. 2 (a). Showing the variation of tensile strength with composition of Al_2O_3. (Mazahery et al. (2009))

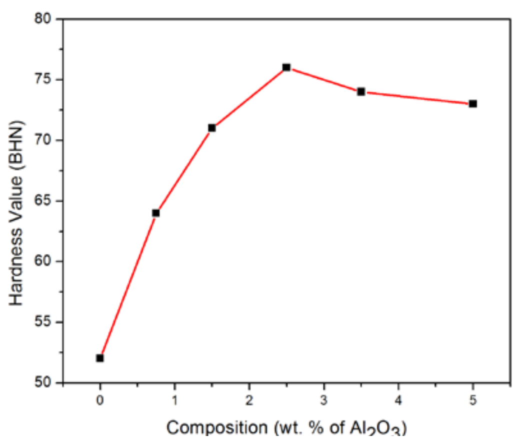

Fig. 2 (b). Showing the variation of hardness value with composition of Al_2O_3. (Mazahery et al. (2009))

Rahman et al. (2014) reinforced pure Al with SiC hard particles to form metal matrix composite. To increase the wettability of SiC particles in Al matrix, 1 wt. % of Mg was used. The tensile strength of the Al-MMC is greater than the unreinforced aluminium as shown in fig. 3 (a). This increase in the tensile strength is due to the strong interfacial bond between SiC and Al matrix. There is a decrease in the tensile strength when 10 wt. % SiC is added to Al matrix due to segregation of SiC particles. Addition of SiC particles in Al matrix caused an increase in the hardness values which can be observed in fig. 3 (b). This is due to the restriction of dislocation motion caused by the strongly bonded SiC particles with Al matrix [25].

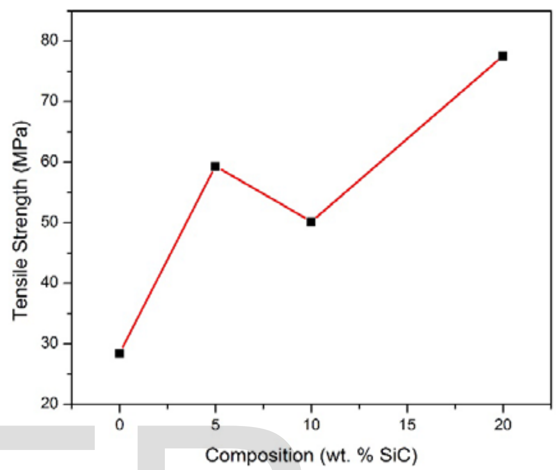

Fig. 3 (a). Showing the variation of tensile strength with composition of SiC. (Rahman et al. (2014))

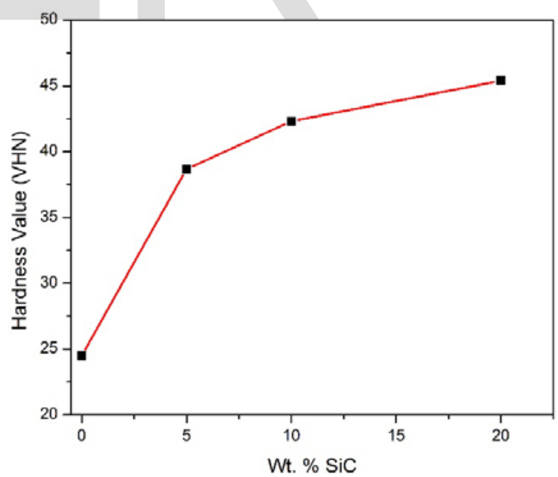

Fig. 3 (b). Showing the variation of hardness value with composition of SiC. (Rahman et al. (2014))

Kakaiselvan et al. (2011) fabricated the Al (6061)/B_4C composite and revealed its mechanical properties. They observed that with increase in wt. % of B_4C particulate the tensile strength of the fabricated Al-MMC also increased as shown in fig. 4 (a). There is a linear increase in tensile strength with B_4C concentration. Hardness value of the Al (6061)/B_4C composite increased continuously. Both macro-hardness and micro-hardness values showed an increment with B_4C concentration as shown in fig. 4 (b) [26].

Bhargavi et al. (2014) reinforced Al 2024 with MoS_2 particles to fabricate Al 2024/MoS_2 metal matrix composite. Tensile strength initially decreases as MoS_2 is added to Al 2024 alloy, then there is further increase in the tensile strength upto 4 wt. % of MoS_2. Again a sudden decrease in tensile strength is observed beyond 4 wt. % MoS_2 as shown in fig. 5 (a). Hardness values increases gradually upto 4 wt. % MoS_2 then it decreases because of cluster formation at the interface of the matrix and the reinforcement as depicted in fig. 5 (b) [27].

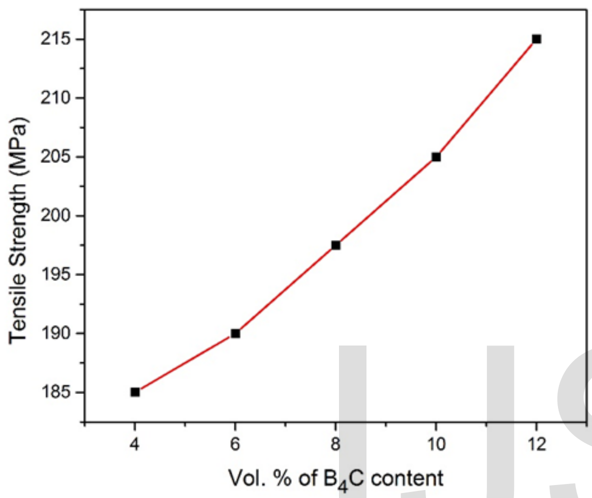

Fig. 4 (a). Showing the variation of tensile strength with composition of B_4C. (Kakaiselvan et al. (2011))

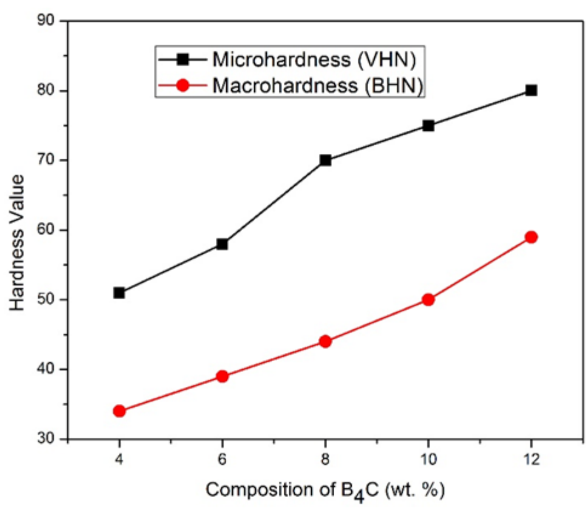

Fig. 4 (b). Showing the variation of hardness value with composition of B_4C. (Kakaiselvan et al. (2011))

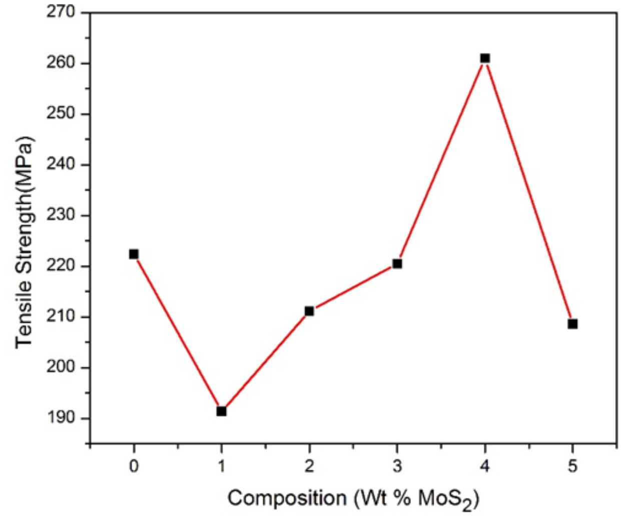

Fig. 5 (a). Showing the variation of tensile strength with composition of MoS_2. (Bhargavi et al. (2014))

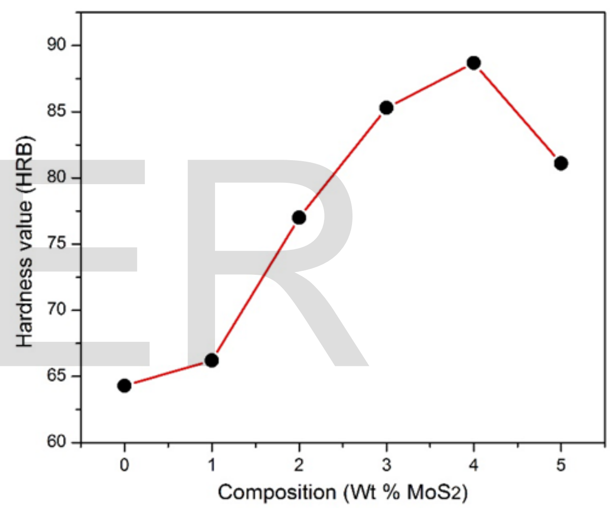

Fig. 5 (b). Showing the variation of hardness value with composition of MoS_2. (Bhargavi et al. (2014))

Kumar et al. (2014) used Al 6061 and reinforced it with fly ash and (fly ash + graphite). The tensile strength was more when only fly ash was used as single reinforcement as shown in fig. 6 (a). With the addition of graphite, the tensile strength decreased significantly. Hardness values also showed a similar trend as shown in fig. 6 (b). This is due to the rejection of graphite particles from the aluminium melt [28].

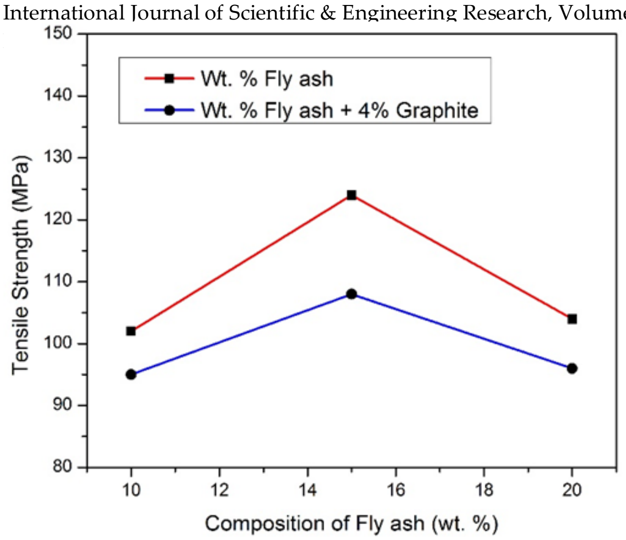

Fig. 6 (a). Showing the variation of tensile strength with composition of fly ash and graphite. (Kumar et al. (2014))

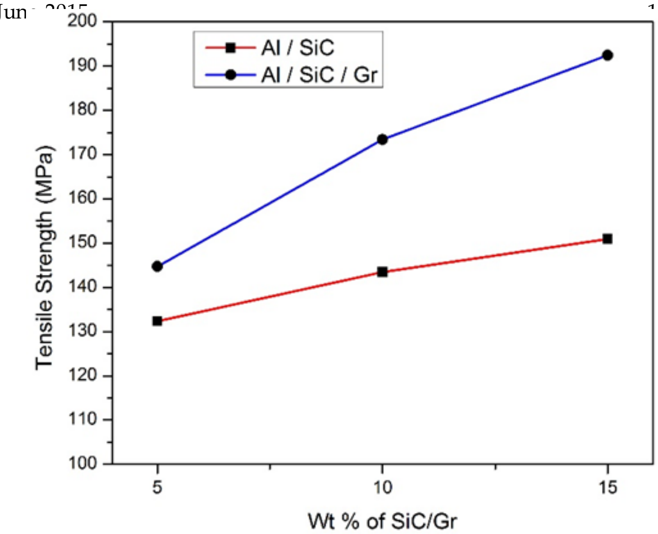

Fig. 7. Showing the variation of tensile strength with composition of SiC/Graphite. (Krishna et al. (2014))

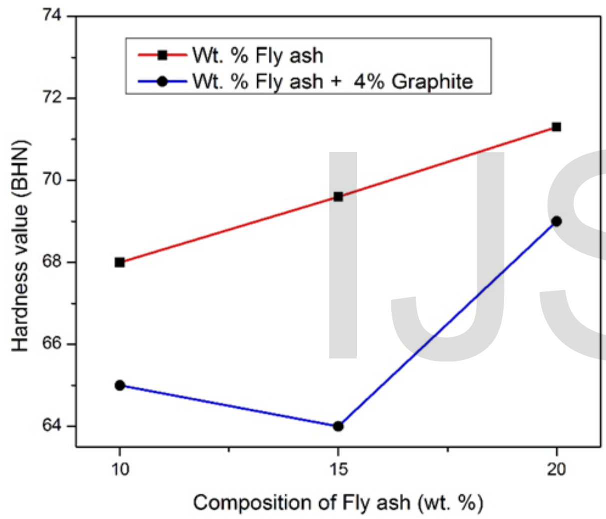

Fig. 6 (b). Showing the variation of hardness value with composition of fly ash and graphite. (Kumar et al. (2014))

Krishna et al. (2014) used Al 6061 alloy and reinforced it with SiC from 5 to 15 wt. % using stir casting technique. The tensile strength of the metal matrix composite was observed to increase more when graphite was added to Al/SiC as compared to SiC addition in Al matrix as shown in fig. 7. This is due to the dispersion of SiC and graphite in Al 6061 [29].

Ashwath et al. (2014) used Al2O3, SiC and graphene as reinforcement agents for AA 2900 alloy. The hardness values due to alumina and SiC increases as their concentration increases as shown in fig. 8. It is also observed that hardness value is enhanced more due to SiC particles as compared to alumina particles. Due to graphene addition above 10 wt. %, the sinter couldn't be formed because the number of graphene particles exceeded the number of metal matrix particles [30].

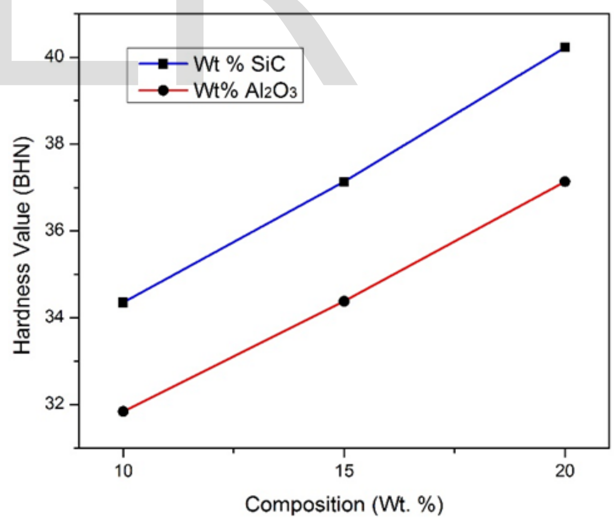

Fig. 8. Showing the variation of hardness value with composition of Al_2O_3 and SiC. (Ashwath et al. (2014))

3 Tribological Behavior

Wear is the progressive loss of the material due to frictional resistance between the contact surfaces [31]. Aluminium-matrix composite are widely used in various applications due to its high specific strength and high wear resistance. Due to

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its wear resistance, it is mainly used as contact strips and bearing materials. Different reinforcements have different effect on the tribological behavior of aluminium metal matrix composite. Various research have been made to fabricate such Al-MMC with high wear resistance. Wear and friction performance is dependent on various tribological factors like material composition, sliding velocity and environmental conditions. The addition of hard ceramic reinforcement like SiC, Al2O3, TiB2 TiC, B4C etc. decreases the wear loss and enhances the tribological behavior as compared to the base alloy.

The study of wear characteristics of a material is quite an empirical approach. The pin on disc method is used mostly but it could not simulate the exact application conditions. There are many factors that determine the wearing of a material. Temperature generated at the tip of the interface, mode of wear test, stresses generated at the interface and the environmental conditions. The pin on disc doesn't incorporate all these factors so we cannot comment on the tribological behavior just by the results obtained through experiment. Simulating the exact application conditions can take a close approach towards the wear behavior of the material.

Suresha et al. (2012) studied the wear behavior of Al-MMC in which SiC and graphite was used as reinforcement. They concluded that the coefficient of friction is mainly dependent on load and sliding velocity. There was a gradual increase in the coefficient of friction with increasing load and sliding velocity. They also concluded that the average coefficient value was lower as compared to the base alloy [32]. Asif et al. studied the comparative wear behavior of Al/SiC and Al/ SiC/Gr and both the composites were fabricated with the application of powder metallurgy technique. The results showed a lower wear rate for the Al/SiC/Gr and compared to the binary Al/ SiC composite [33].

Venkat Prasad et al. studied the wear characteristics of Al/Gr/fly ash hybrid metal matrix composite and observed that addition of fly ash and graphite lowered the wear rate [34]. Sivaprasad et al. (2008) used TiB2 as reinforcement in Al 6063 and analyzed the wear behavior. The author observed that the wear rate and the volume loss decreased with an increase in the TiB2 concentration [35].

Ramachandra et al. studied the tribological behavior of Al/SiC/Fly ash metal matrix composite. The wear resistance is improved for the MMC as the concentration of fly ash is increased. Load and sliding velocity lowered the wear resistance gradually [36]. Pramila Bai et al. studied the wear characteristics of Al/SiC metal matrix composite and observed an improvement in the tribological properties when the concentration of SiC is between 10-20 wt. % [37].

Kumar et al. (2014) used Al 6061 and reinforced it with fly ash and (fly ash + graphite). They varied the rpm of the disc and concentration of fly ash and graphite and then measured the specific wear rate. The results revealed that the optimum concentration for best wear resistance is 4 wt. % graphite and 15 wt. % fly ash which can be seen in fig 9 (a-b) [28].

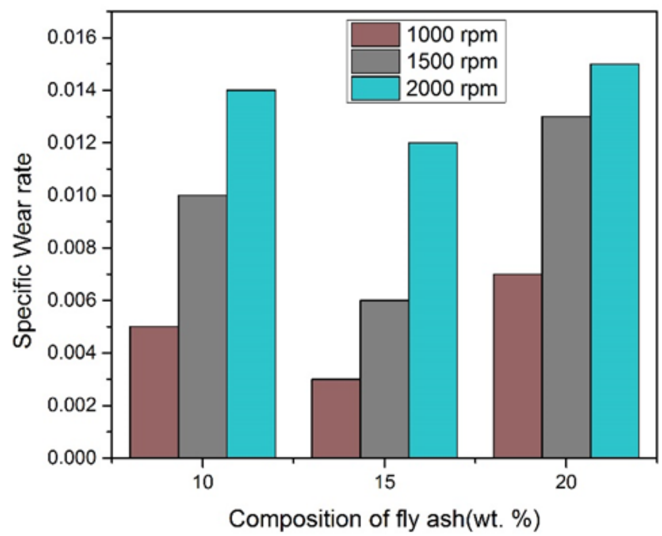

Fig. 9 (a). Showing the variation of specific wear rate with various composition of fly ash at different rpm. (Kumar et al. (2014))

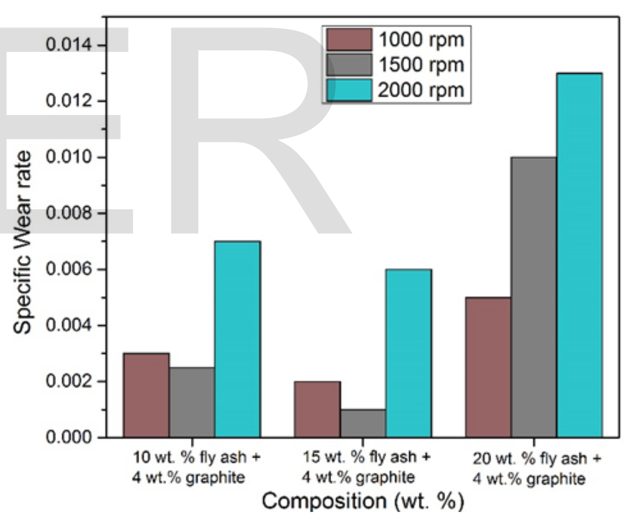

Fig. 9 (b). Showing the variation of specific wear rate with various composition of fly ash with 4 wt. % graphite mixed at different rpm. (Kumar et al. (2014))

Elango et al. (2013) reinforced LM25Al alloy with TiO2 and Sic particles to form metal matrix composite. The author varied the composition of TiO2 and SiC to create a batch of specimens for the study of wear characteristics. With the addition of SiC and TiO2 the coefficient of friction value decreases with an increase in the load applied. At 5 wt. % TiO2 and 7.5 wt. % SiC, the coefficient of friction values are lowest and the wear rate simultaneously increases. The results concluded that LM25Al + SiC 7.5 % + 5 wt. % TiO2 had the minimum wear rate as compared to the parent alloy thereby enhancing the tribological behavior as shown in fig. 10 [28].

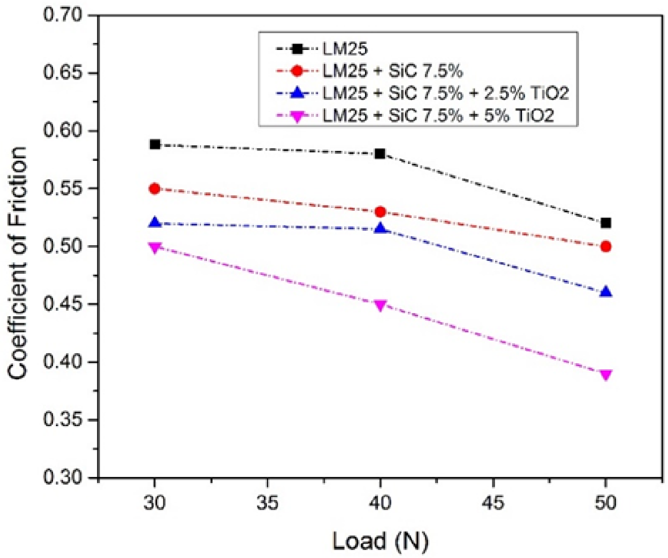

Fig. 10. Showing the variation of coefficient of friction for LM25 mixed with SiC and TiO2 at various composition. (Elango et al. (2013))

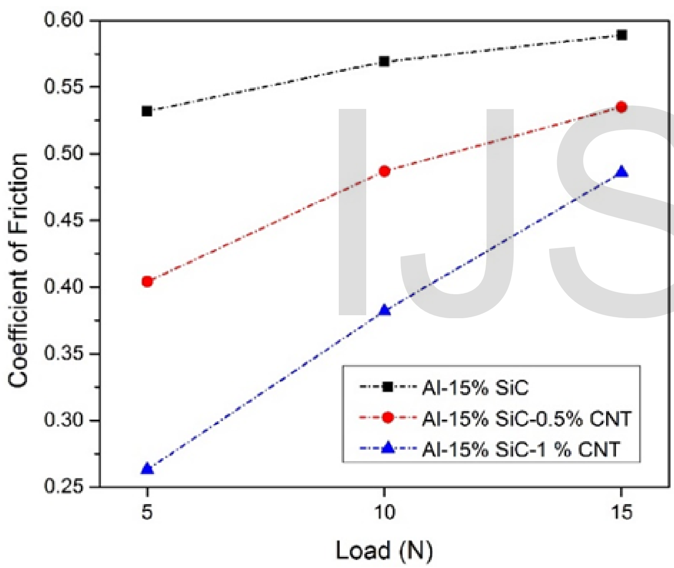

Fig. 11. Showing the variation of coefficient of friction with SiC and MWCNT composition. (Padmavathi et al. (2014))

Ahmad et al. (2013) fabricated a metal matrix composite reinforced aluminium alloy-242 with 30 vol. % alumina particles and wear test were carried out at fixed rpm of 250 to determine the tribological behavior of the composite. The results concluded that with an increase in load the weight loss of the composite is increasing as shown in the fig. 12 [39].

Siddesh et al. (2014) reinforced Al 2219 with MoS2 and B4C particles. Fig. 13 shows the variation of wear rate with the different compositions at various load from 10N to 50N. The results exhibited that at a particular load, if we increase the concentration of reinforcement, the wear rate decreases as shown in fig. 13. With an increase in load, the pressure between the pin and disc increases but the reinforcements like B4C and MoS2 being hard in nature resists the applied pressure and due to the strong bonds between Al/B4C-MoS2 the wear rate is reduced [40].

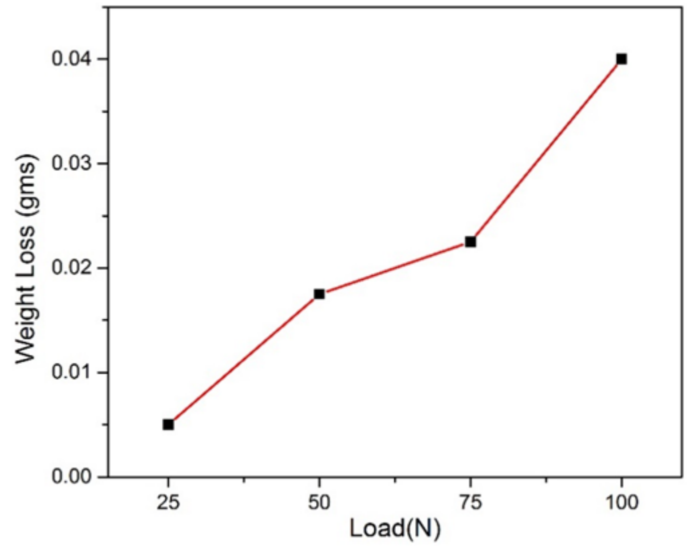

Fig. 12. Showing the variation of weight loss of the composite with increasing load. (Ahmad et al. (2013))

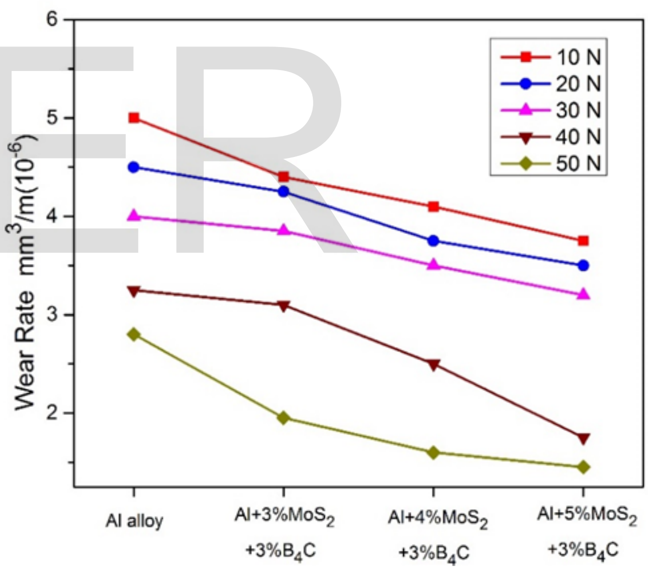

Fig. 13. Showing the variation of wear rate with different composition of MoS_2 and B_4C at various loads. (Siddesh et al. (2014))

4 MICROSTRUCTURAL CHARACTERIZATION

The mechanical and tribological properties of various Al metal matrix composites depend on the microstructure that is obtained after reinforcement with the various ceramic, organic etc. reinforcements. The microstructure evolution depends upon the fabrication techniques, rate of solidification and composition of the composite. It reveals the distribution of the ceramic particles in the aluminium matrix. It is also used to detect the micro defects such as porosity, micro cracks etc. that are formed during fabrication process due to the cluster for-

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mation or agglomeration of reinforcement particulates.

James et al. (2014) used SiC and TiB2 particles as reinforcement in Al 6061 alloy. From fig. 14, it can be concluded that cluster formation is taking place around the SiC particles due to increase in the wt. % of TiB2. Due to this cluster formation, porosity is developed around this region which leads to lower tensile strength. [23].

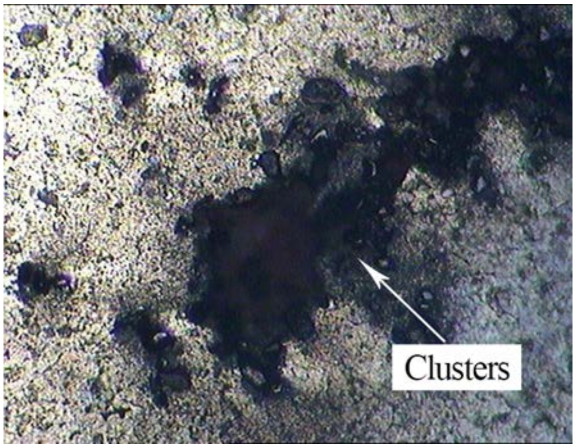

Fig 14 (a): Optical micrographs showing the cluster formation. (James et al. (2014))

Zakaria (2014) studied the microstructural behavior of Al/SiC metal matrix composite. 10 wt. % SiC was added and the particle size was varied as 11 µm, 6 µm and 3 µm. The SEM images for the various particles are shown in figure 15 (a-c). Fig. 15 (d) shows the magnified image of 3 µm particle distribution in the metal matrix composite. As the concentration of TiB2 increases, grain refinement was clearly seen and thus the mechanical and tribological properties were improved [41].

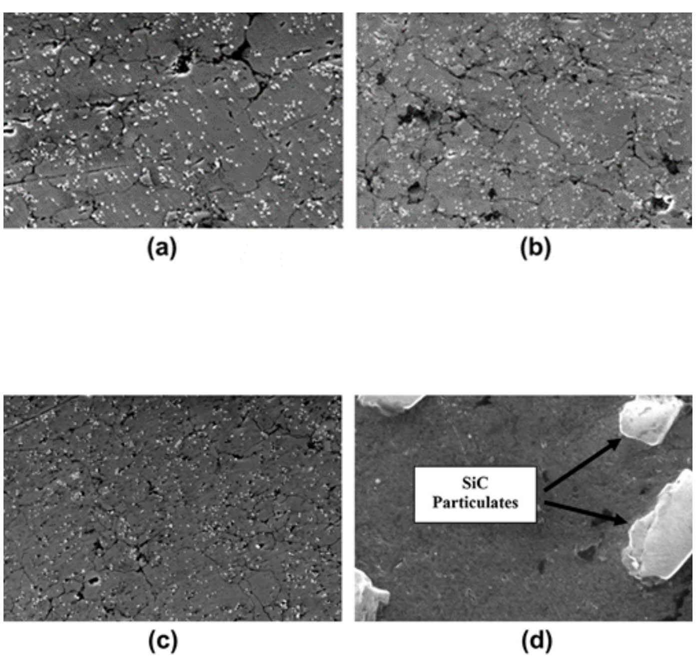

Fig. 15 shows the SEM images of Al/SiC MMC having 10 vol. % of reinforced SiC particles of different sizes (a) 11µm (b) 6µm (c) 3µm and (d) magnified image of 3µm specimen showing SiC particulates. (Zakaria (2014))

Rajkumar et al. (2014) used B4C and graphite particles as reinforcement into Al matrix and examined the microstructure obtained. The microstructures showed that there was uniform distribution of boron carbide and graphite particles in the entire matrix which resulted in lower porosity as shown in fig. 16. The hardness values were high due to low porosity. The microstructure revealed that there was strong bonding between the reinforcements and the matrix which eased the transfer of load [42].

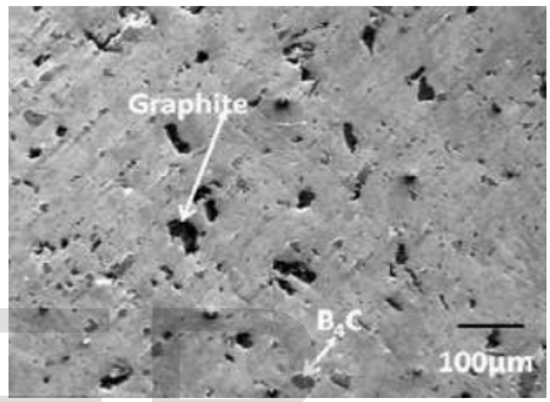

Fig. 16. Showing the distribution of B4C and graphite particles in the matrix. (Rajkumar et al. (2014))

Bansal et al. (2014) used alumina particles to reinforce Al composite. Figure 17 (a-c) shows the SEM images of the composite reinforced with alumina particles as (a) 2, (b) 4, (c) 6 wt. % of alumina. The images shows a homogenous distribution of alumina particles, The EDAX analysis confirmed the presence of alumina particles throughout the matrix which caused improvement in the mechanical behavior of the composite [43].

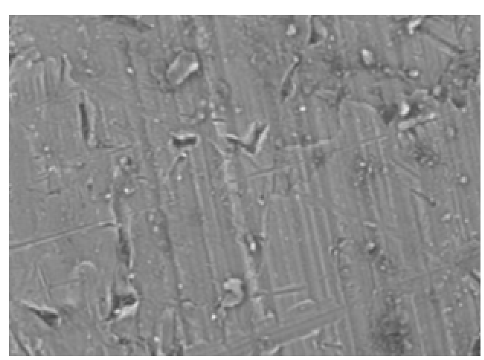
Figure 17 (a)

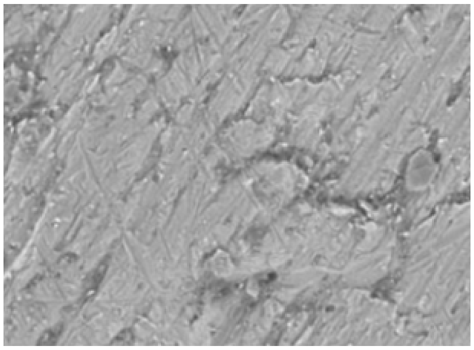

Figure 17 (b)

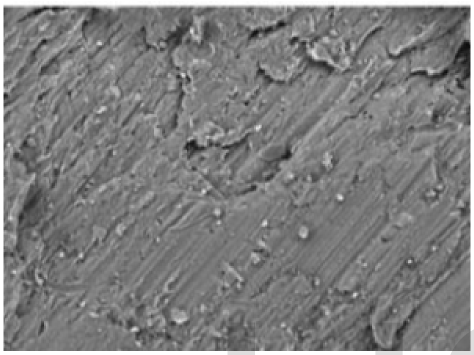

Figure 17 (c)

Fig. 17 (a-c). Showing the various compositions as a) 2 wt. %, b) 4 wt. % c) 6 wt. % of alumina reinforced aluminium metal matrix composite. (Bansal et al. (2014))

Saravanan et al. (2013) reinforced AlSi10Mg with rice husk ash and then studied the mechanical properties of the composite. The composition of RHA was varied and then the mechanical properties like hardness, elongation and tensile strength were examined. The microstructures were studied and there was uniform distribution of RHA in the Al matrix without any micro-voids which can be seen in fig. 18 (a-d). The bonding between the reinforcing RHA and the matrix is the reason for better mechanical properties [44].

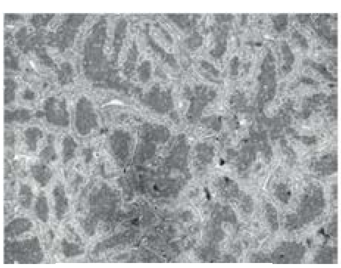

Figure 18 (a)

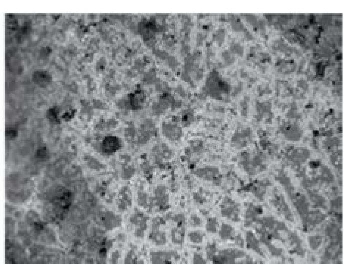

Figure 18 (b)

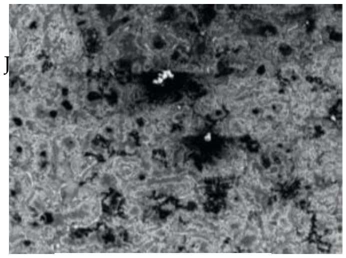

Figure 18 (c)

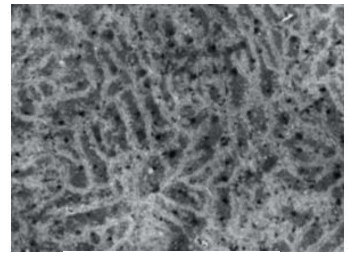

Figure 18 (d)

Fig. 18 (a-d). Showing the microstructure of (a) AlSi10Mg, (b) AlSi10Mg + 6 % RHA, (c) AlSi10Mg + 9 % RHA, d) AlSi10Mg + 12 % RHA. (Saravanan et al. (2013))

Krishna et al. (2014) used Al 6061 alloy and reinforced it with SiC from 5 to 15 wt. % using stir casting technique. The microstructure obtained after solidification showed homogenous and complete dispersion of hard SiC particles in the matrix which can be seen in fig. 19. Due to homogenous distribution, the tensile strength gradually increased [29].

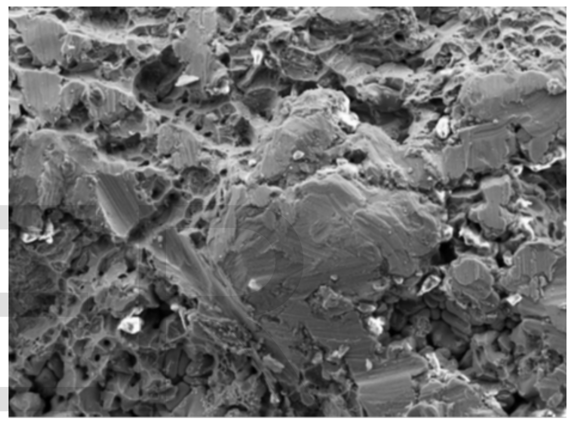

Fig. 19. SEM image of fractured tensile specimen of 5 wt. % SiC/Al 6061 MMC. (Krishna et al. (2014))

Bhargavi et al. (2014) reinforced Al 2024 with MoS2 particles to fabricate Al 2024/MoS2 metal matrix composite. The microstructure of the metal matrix composite revealed that MoS2 particles were dispersed throughout the matrix. Fig. 20 shows the 2 wt. % MoS2 image at 250x. These MoS2 particles bind with the matrix and increase the tensile strength and hardness values. EDAX analysis was done to confirm the MoS2 distribution in the MMC matrix [27].

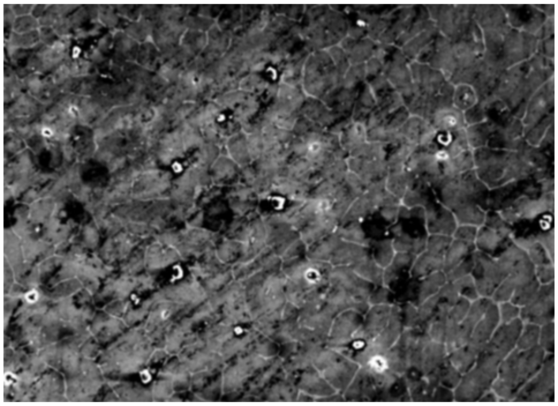

Fig. 20. SEM image of 2% MoS2-Al 2024 metal matrix composite at 250X. (Bhargavi et al. (2014))

5 Conclusion

The above review for Aluminium metal matrix composites leads to the following conclusions:

- Reinforcing aluminium or its alloy with the hard ceramic particulates like B_4C, TiB_2, SiC etc. improve the mechanical and tribological behavior of metal matrix composites mainly due to the strong interfacial bonding between the reinforcements and the Al matrix.

- Addition of organic reinforcement like Rice husk ash (RHA), Coconut ash, fly ash etc. to the aluminium or its alloy has also shown an appreciable increase in mechanical along with tribological behavior of the Al metal matrix composite. These MMCs do not possess any micro-voids which results in excellent tensile and hardness properties of the composite.

- Reinforcement of aluminium alloys with alumina nanoparticles increases the tensile strength and hardness along with ductility.

- Reinforcing Al matrix with SiC or TiB_2 improves the tensile and hardness behavior upto certain wt. % of TiB_2 or SiC addition and thereafter a considerable amount of decrement is seen in tensile strength and hardness because of cluster formation or agglomeration of these hard ceramic particles in aluminium matrix and which leads to porosity.

- Although various manufacturing techniques like stir casting, squeeze casting and powder metallurgy are employed for the fabrication of various Al metal matrix composite but still stir casting method is successfully used because of its wider availability and also it is relatively economical than other methods.

- The addition of graphite as reinforcement has also shown a significant increase in tensile strength but decrease in hardness value. The tribological analysis of the composites revealed that with decrease in coefficient of friction, there is increment in the wear rate which enhances the machining properties. Excessive graphite addition may lead to rejection from the molten melt of Al matrix.

- The area of organic reinforcement with aluminium or its alloy is not well explored and very limited work has been done in this field. However, it some results showed a significant increase in mechanical as well as tribological behavior. So, more investigation is required in this field for further development of AMMCs.

- Further development is also required in improving the wettability and controlling the interfacial structure of the composite. Also, the carbon and diamond metal composites has not been explored much which can be advantageous in improving the mechanical and tribological behavior of AMMCs.

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