Controlling Factors in Aluminum Matrix Composites Fabrication

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ABSTRACT
The aluminum matrix composite (AMCs) is one the promising material for automobile and aircraft industry. It has numerous applications due to their excellent prosperities and light in weight. The properties of the aluminum matrix composite depends on the factor like fabrication methods, process parameters, properties of reinforcement and their wet ability with aluminum, interfacial bonding between matrix material and reinforcement; and microstructure exist in composite. This paper discusses all responsible factors which affect the properties of aluminum metal matrix composite.

***Keywords*:** AMCs, Wet ability, Reinforcements microstructure, mach inability, Wearbility.

I INTRODUCTION

In the field of material science this is the era of composite and smart materials. Every industry required high performance material, so that the component can perform better service at desired condition. In the category of light weight high performance material, the Aluminum matrix composites (AMCs) are widely used by several industries. The composites formed out of aluminum alloys are of wide interest owing to their high strength, fracture toughness, wear temperature application when reinforced with ceramic particle. The reinforcement materials may be oxides, carbides, borides and nitrides of ceramics. The important reinforcement materials used in the aluminum metal matrix composites are carbon/ graphite, silicon carbide, alumina, zirconia and zircon in particulate, whisker or in fibre form. The foremost fabrication methods used for aluminum metal matrix composites are stir casting, squeeze casting, compo-casting, infiltration, spray deposition; direct melt oxidation process and powder metallurgy. The liquid phase processing which involves molten metals such as melt stirring or melt infiltration is mostly used for composite fabrications. But interfacial problematic is much more of a concern in this due to inherent process peculiarities. A weak interface will lead crack propagation at the interface, while a strong matrix associated with a strong interface will reveal cracks across both the matrix and the reinforcements. If however the matrix is weak in comparison with both the interface and the particle strength, the failure will propagate through the matrix itself. The surface roughness of the reinforcing material improves the mechanical interlocking at the interface, though the contribution of the resulting interfacial shear strength is secondary compared to chemical bonding. The large differences in thermal expansion coefficient between the matrix and the reinforcement should be avoided as they can induce internal matrix stresses and ultimately give rise to interfacial failures. In the case of continuous fiber reinforced metals (CFRM), high strength is achieved by preventing chemical reactions between the matrix and the inorganic fibers. While a weak interface is desirable to enhance longitudinal strength and toughness, a strong interface is desirable to achieve good transverse properties in CFRM. Considering physical and chemical properties of both the matrix and the reinforcement material, the actual strength and toughness desired for the final AMC, can be achieved by balancing between them according to conflicting requirements. The physical, mechanical, tribological and others desired properties of composite depends upon factors like processes root and temperature, shape, size, chemical affinity, wet ability and interfacial bonding and reactions of reinforcements materials with matrix material in composite.

II WETTABILITY AND REACTION PHASE

The wet ability of the reinforcement material by the liquid metallic matrix plays a major role in the formation of strong chemical bonds at the interface. It mainly depends on temperature of formation, electronic structure of the reinforcement and the molten metal, temperature, time, atmosphere, roughness and crystallography of the reinforcement. The presence of oxide films on the surface of molten metal and contaminant adsorbed on the reinforcement surface generally leads to non-wetting of the reinforcement with molten metal. The lower wet ability adversely affects the properties of composite. Some of the techniques which improve metal-reinforcement wet ability include metallic coatings on the reinforcement materials, addition of reactive elements, such as magnesium, calcium or titanium, to the melt and heat treatment of reinforcement particles before addition. In the case of fabrication AMCs of Al alloys/ Al_2O_3, the Al_2O_3 reacts with alloying elements of matrix material such as magnesium. In order to enhance its wet ability, metallic coatings such as nickel**,** cobalt and palladium are applied to alumina. It was found that MgO-coated alumina particles improve the properties of composites. The cobalt coating increases its wet ability during processing. The tensile properties and fracture behavior of cobalt-coated Al_2O_3 fiber-reinforced Al alloy composites shown improved properties compared to that with uncoated fibres. The major problems encountered during the fabrication of SiC-reinforced aluminum matrix composites are the reactivity of SiC with molten aluminum at higher processing temperatures and the poor wet ability of SiC at lower processing temperature (900-1000 K).The wet ability of SiC in aluminum also depend upon the factors like free silicon in silicon carbide, wetting angle, kinetics of SiC and incorporation time [1].It was found that silicon carbide does not incorporate into the liquid aluminum immediately and it is gradually wetted by liquid aluminum. Therefore incorporation time is necessary for full particulates wetting. The incorporation time can be shortened by alloying magnesium and titanium [2,3]. The reaction between SiC and liquid aluminum during processing causes significant degradation in the properties of the composites**.** In order to prevent the degradation of SiC (particles, whiskers or fibres) and improve wet ability, various treatments and coatings are used. The metallic coatings given to SiC are copper, nickel, antimony and silver**.** The wet ability of copper, nickel and silver-coated SiC fiber with aluminum is better than as received fiber**.** The driving force for wetting can be increased by the interfacial reaction. In silicon carbide-reinforced AMCs, SiC is thermodynamically unstable in molten aluminum at around temperatures exceeding 1000 K**.** The SiC reacts with molten aluminum form Al_4C_3 and rejecting metallic silicon [36-39]. These reaction products cover SiCp and reduce wet ability. This reaction can be suppressed by having matrix alloy containing higher silicon content and maintaining the proper melt temperature**.** The figure 1(a) and1 (b) shows the formation of Al_4C_3 and silicon level required in the matrix to prevent the formation of Al_4C_3as a function of the melt temperature in Al or Al/SiC composite [40]. In case of Al/SiC composite where matrix is as pure aluminum, it was found that no Al_3C_4 forms at the interface [31].

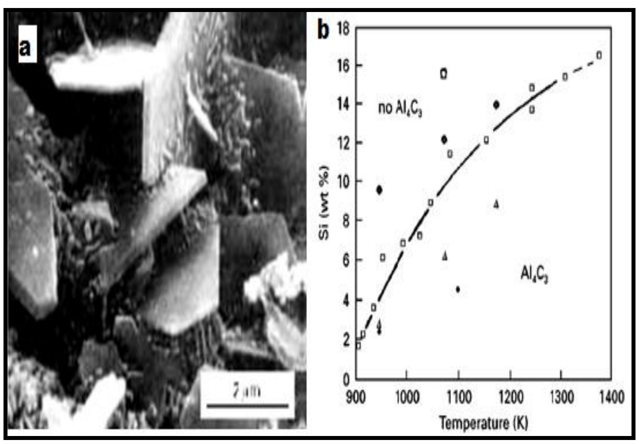

Fig. 1: SiC covered with Al_4C_3 crystals having hexagonal platelet shape [15] and 1(b) Silicon levels required in the matrix to prevent the formation of aluminum carbide as a function of melt temperature [16].

In Al-TiO_2-B_2O_3 system, when the B_2O_3/TiO_2 mole ratio is below 1, the reaction products are composed of particle-like α-Al_2O_3, TiB_2 and rod-like Al_3Ti. The α-Al_2O_3 forms at the grain boundaries due to a lower wet ability with the matrix. When the B_2O_3/TiO_2 mole ratio is around 1, the Al_3Ti phase almost disappears in the composites and the distribution of α-Al_2O_3 particulates is improved evidently[4]. In the system AlMg-Al_2O_3 the formation of magnesium oxide and mixed oxides $MgAl_2O_4$ (spinel) is governed by the magnesium content. At higher contents, MgO is formed while spinal formation decreases as Mg is reduced below 4wt% and non-existent under 1wt% Mg content. However at 1wt% Mg, the wetting of particulate alumina is not extensive. Despite its positive effect on interfacial reactions a high content of Mg is however not desirable from the matrix properties point of view. A strategy to avoid brittle spinal formation while maximizing matrix properties is to mix the alumina first with an aluminum matrix having a content of Mg beyond 8wt%, so that a thin passivation layer of MgO is formed at the surface of the alumina. In a second step, the Mg-content can be decreased at will by adding more Al to the melt, while the MgO layer prevents any spinal formation. The figure 2(a) and 2(b) shows the formation of spinal ($MgAl_2O_4$) on Al_2O_3 and at fiber matrix surface. The figure 3(a) shows that formation of magnesium oxide and magnesium silicate at the fiber surface and figure 3(b) depicted the formation of Al_3C_4 at the interface in Al/C composite system.

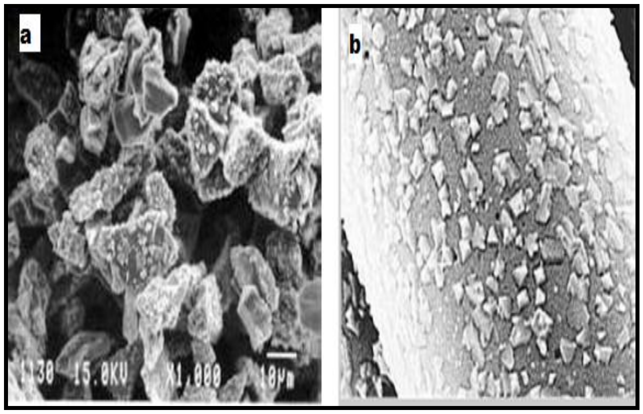

Fig.:2 Aluminum oxide particles covered with spinal ($MgAl_2O_4$) and 2(b) Spinal crystals on the surface of Al 6061 matrix fiber [32,29].

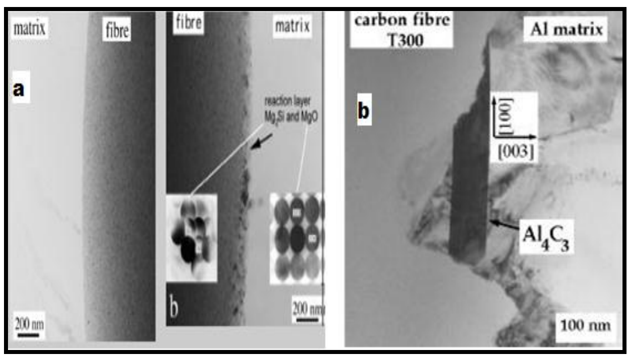

Fig. 3: One side of the fiber is unaffected while the other side shows Mg_2Si and MgO[28] and (b) Formation of Al_4C_3 at the interface [30].

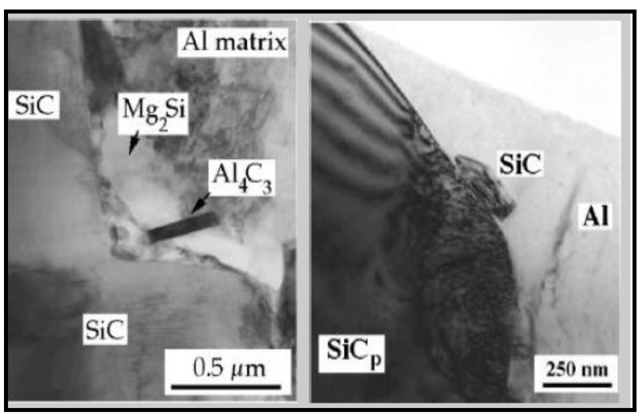

Fig. 4:Al-4Cu-1Mg-0.5Ag/SiC/60p (left) ; Al/SiC/60p (right) : the presence of Mg produces Mg2Si and enhances the formation of Al4C3 While no interfacial reaction if found when pure aluminum is used [31].

Table 1
Interfacial reactions and precipitates.

Element	Al	Mg+Al	Mg	Cu	Ti
C	$4Al + 3C \rightarrow Al_4C_3$	$2Al + Mg + 2C \rightarrow Al_2MgC_2$ (< 2% Al) $4Al + 3C \rightarrow Al_4C_3$ (>2% Al)	no reaction	no reaction	$Ti + C \rightarrow TiC$
Si	AlSi alloy formed	$Si + 2Mg \rightarrow Mg2Si$	$Si + 2Mg \rightarrow Mg_2Si$	no data	no data
B_4C	$6B_4C + 27Al \rightarrow 6Al3BC + 9AlB2$. AlB10, Al3B48C2, AlB24C4 also formed	$6B_4C + 27Al \rightarrow 6Al_3BC + 9AlB_2$ Al B10, Al3B48C2, AlB24C4 also formed	no data	no data	no data
SiC	$4Al + 3SiC \rightarrow Al_4C_3 + 3Si$	$4Al + 3SiC \rightarrow Al_4C_3 + 3Si$	no data	no reaction	$SiC + Ti \rightarrow TiC + Si$
TiC	$4Al + 3TiC \rightarrow Al_4C_3 + 3Ti$ $13Al + 3TiC \rightarrow Al_4C_3 + 3Al3Ti$	no data	no data	no data	no data
Al_2O_3	no reaction	$3Mg + 4Al_2O_3 \rightarrow 3MgAl2O4 + 2Al$ $3Mg + Al_2O_3 \rightarrow 3MgO + 2Al$	$3Mg + 4 Al_2O_3 \rightarrow 3MgAl2O4 + 2Al$	no data	no data
SiO_2	no reaction	$Mg + 2SiO_2 + 2Al \rightarrow MgAl_2O_4 + 2Si$ $2MgAl_2O_4 + 3Si \rightarrow 2MgO + 3SiO_2 + 4Al$	$2Mg + SiO_2 \rightarrow 2MgO + 2Si$	no data	no data

The figure 4 shows the different interfacial precipitates in Al alloys/SiC and Al/SiC composite system. The Al-B_4C system is reactive at any temperature under 1000°C and reaction products are Al_3BC and AlB_2 [33,34, 35]. The continuous layer of Al_3BC can constitute a efficient diffusion barrier protection of B_4C as shown in figure 5[33, 36].

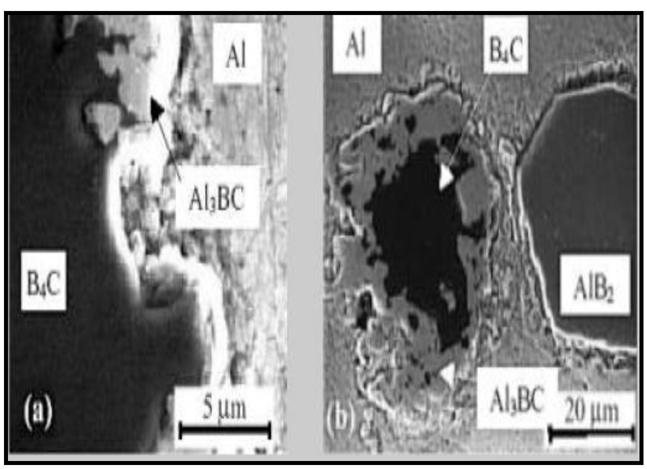

Fig. 5:Al/B4C interface at 727 °C: (a) after 15 h reaction (beginning of the interaction); (b) after 160 h (Passivation stage attained)[33,34,35,36]

The different reaction and reaction products form during the composite formation is depicted in table1.The various materials used for coating the reinforcement and their effects is depicted in table 2.

Table 2
Reinforcement coating and their effects.

Metallic coatings on carbon fiber and their effects on interfaces in AMCs with aluminum.		
Coating Material	Matrix Material	Effects
Copper	Al	Improved wetting and uniform distribution of the fibers.
Nickel	Al	Improved wetting and $NiAl_3$ formation around fibers.
Titanium	Al	1. Promoted wetting. 2. Interfacial reaction between Al and C 3.Difficult to coat due to reaction.
SiC	Al	Effective protection of fibers during processing and improved mechanical properties.
SiO_2	Al	1.Higher modulus of elasticity. 2.Lower strength due to fiber degradation.
Al_2O_3	Al	1.Good reaction barrier but poor wet ability.
TiO_2	Al	1. No reaction at TiO_2/C. 2.Improved wetting with formation of (Al, Ti)O_2 mixed oxide
SiO_2	Al and Al-Mg	1. Significant reduction of Al4C3 process formation at 973K and no protection above 1073K. 2.Once Al reacts with SiO2, the reaction between Al and SiC proceeds. 3.Interfacial reaction is dependent on alloy composition and thickness of SiO2 layer.
Al_2O_3	Al and Al-Mg	1.Good protection in whiskers but no protection in Particulates. 2.Interfacial reaction is
TiO_2	Al and Al-Mg	1.MgO/Ti reaction layer formed [119] in the interface is responsible for the protection of particles. 2.Remarkable reduction in Al4C3 formation.

III REINFORCEMENT MATERIALS AND ITS EFFFECTS ON PROPERTIES

The selection of reinforcements materials depend upon the properties desired for the particular application of composite and chemical suitability with matrix material. In Aluminum matrix composites (AMCs) the ceramic reinforcements are mainly oxides or carbides or borides (Al_2O_3 or SiC or TiB_2). The properties and chemical affinity of these reinforcement materials are discussed as below.

(a) Titanium Diboride (TiB_2): It has superior hardness and corrosion resistance with a high melting point (>2900°C) and good oxidation resistance to 1000°C. Titanium diboride is an extremely hard ceramic compound composed of titanium and boron which has excellent resistance to mechanical erosion. TiB_2 is also a reasonable electrical conductor.

(i) Properties:

- Extreme Hardness nearly as hard as diamond when its sintered.
- TiB_2 is tough enough to be used as military armor and improves the fracture toughness of ceramic cutting tools and other components.
- As an excellent conductor of both electricity and heat, TiB2 is valuable in electronic and specialty applications.
- TiB_2 enhances thermal conductivity when used as filler in polymeric matrices.
- Chemical resistance.
- Titanium diboride will not react with molten, nonferrous metals including Cu, Zn and Al.
- TiB_2 is used as crucibles, vacuum metallization components and electrodes for processing these materials.

(ii) Applications:

- Electrically conductive composites such as aluminum evaporation boats.
- Additives for producing specialty ceramic composite materials.
- Refractory material and antioxidant additive that is nonreactive to most molten nonferrous metals and alloys.
- Thermal management materials.

(b) Silicon Carbide (SiC): The aluminium-SiC composite system finds potential applications as structural elements in the automotive and aerospace industries. These composites possess unique properties such as improved strength, modulus and wear resistance and good resistance to corrosion. But several drawbacks of these materials such as low temperature, ductility and poor toughness hinder their wide range of application.

(c) Alumina (Al_2O_3): The alumina-reinforced aluminum metal matrix composites find wide application next to carbon and silicon carbide-reinforced composites in the areas of automotive and aerospace industries. Al-Al_2O_3 metal matrix composites possess high elevated-temperature strength, wear resistance, damping properties, electrical conductivity, thermal conductivity and coefficient of thermal expansion. The alumina can be in the form of particulates, whiskers and fibres. The alumina in a pure aluminum matrix is considered to be the ideal dispersoid with no chemical reactions. But, when aluminum alloys are used as the matrix, the Al_2O_3 reacts with alloying elements such as magnesium. The other major problem is its lower wet ability below 900K**.**

(d) Effects of reinforcement materials on mechanical and topological Properties: G. B. Veeresh et. al.[5], they prepared two composite Al6061-SiC and Al7075-Al_2O_3 with varying wt % of particles from 2 to 6 by using vortex stir casting and investigated mechanical properties. It was found that hardness increased to 60-97VHN & 80-109VHN respectively. The tensile strength of composite increased 68% & 24% increased respectively. It was found that Al6061-SiC exhibit superior mechanical and tribological properties due to Sic reinforcement. The processing temperature also play important role in composite fabrication. The effect of temperature on properties is depicted in table 1.

Table 3
Effect of temperature on tensile strength of Al/SiC composite.

Materials	Temperature (°C)	Tensile strength (MPa)
6061 Al/SiC	700	0.241
6061 Al/SiC	750	0.352
6061 Al/SiC	800	0.41

Christyet.al.[6], prepared Al6061-TiB_2 (12%wt)composite using the in-situ salt-metal reaction process and compare the mechanical properties and the microstructure of Al 6061 alloy & composite. The hardness, tensile strength and young's modulus of composite increased but ductility of the composite was found to be slightly lower than that of the aluminum 6061 alloy as depicted in table 2. **D. Danels[7],** examined mechanical properties and stress-strain behavior for several fabricated aluminum matrix composites containing up to 40 vol. % discontinuous silicon carbide whisker, nodule or particulate reinforcement. The four types of aluminum matrices are used: 6061, 2024/2124, 7075 and 5083. Silicon carbide reinforced into the matrix material in a form of discontinuous, whisker, nodule and particulate. They found that the modulus of elasticity increased with increasing reinforcement content. When the factors influencing strength are considered, the effect of the matrix type is found to be the most important. The SiC/Al composites with as 2024/2124 or 7075 Al, has higher strengths but lower ductility. Composites with a 6061 Al matrix showed good strength and higher ductility. The results are shown in figure 6.

Table 4
Effects of Reinforcement on Mechanical Properties

Material	Hardness (BHN)	Tensile Strength(Gpa)	Young's Modulus	% Elongation
Al-6061	62.8	134.8	79.8	8.0
Al-TiB_2	88.6	173.6	94.2	7.0

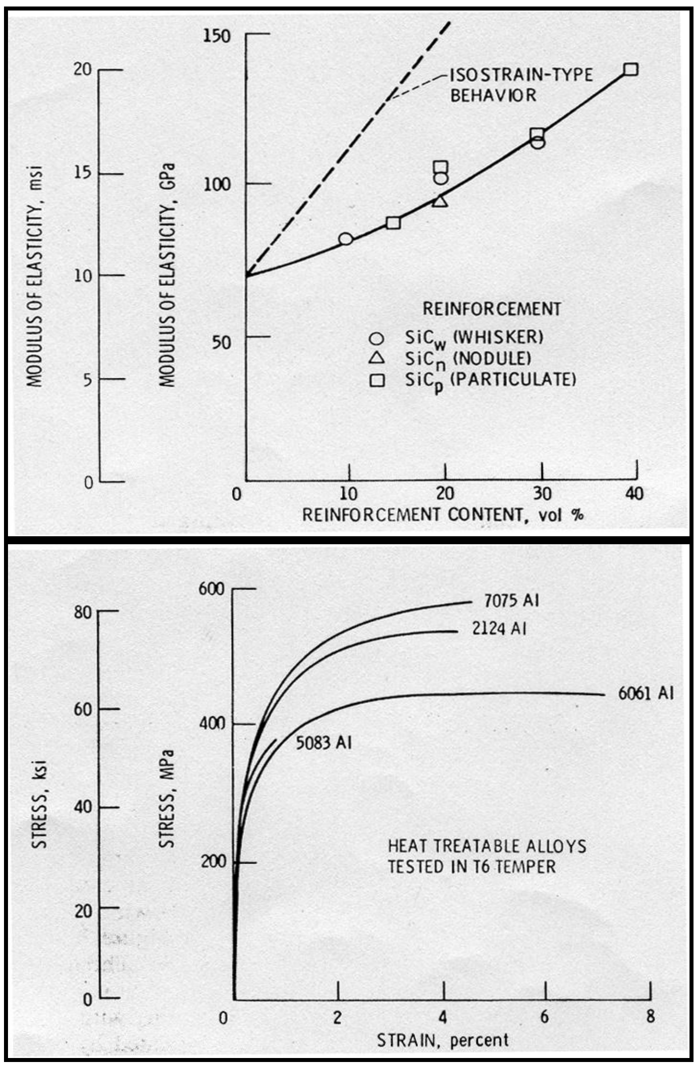

Fig. 6: Effects on shape, size, % wt. of reinforcement and matrix materials [7].

A. Sreenivasan, et.al[8], they prepared Al6061-TiB_2 (5,10,15%wt) composite using combo stir casting technique and microstructure and wear characteristics of TiB_2 reinforced aluminium metal matrix composites (MMCs) was examined. The result showed that the wear rate was decreased with increase in TiB_2 content in the Al/TiB_2MMC specimens as depicted in figure 7. **L. Lu et.al [9],** the composite of Al/TiB_2/B_2O_3 prepared by in situ process, the yield and ultimate stress increased with increase of TiB_2 in composite. When the percentage of TiB_2 in composite is 15% the yield and ultimate stress increased 53% and 44% respectively as compare to its unreinforced. **M.D. Kulkarni, et. l [10],** examined the role of percentage volume of SiCp on the tensile properties and fracture behavior of Al 7075 Al alloys at various test temperatures. They found that as the percentage of SiC increases the yield strength, ultimate strength and young's modulus of composite increases. The effect on wear (trobological properties) is depicted in figure7.

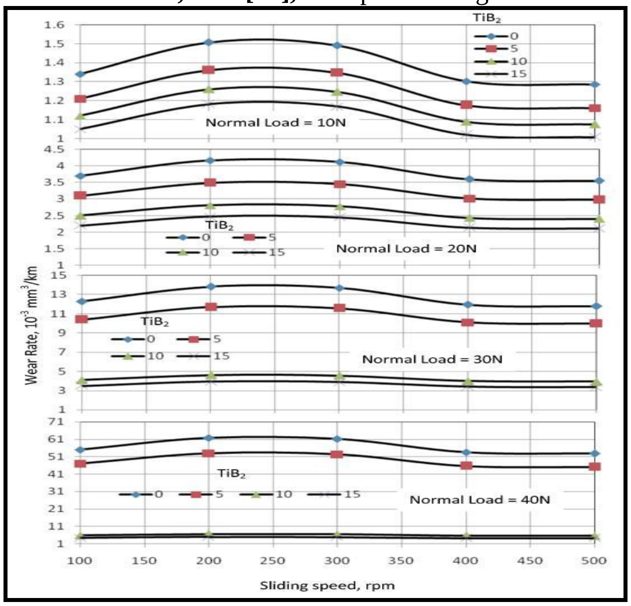

Fig. 7 (a): Wear rate of Al matrix and Al/TiB_2 for different load [8].

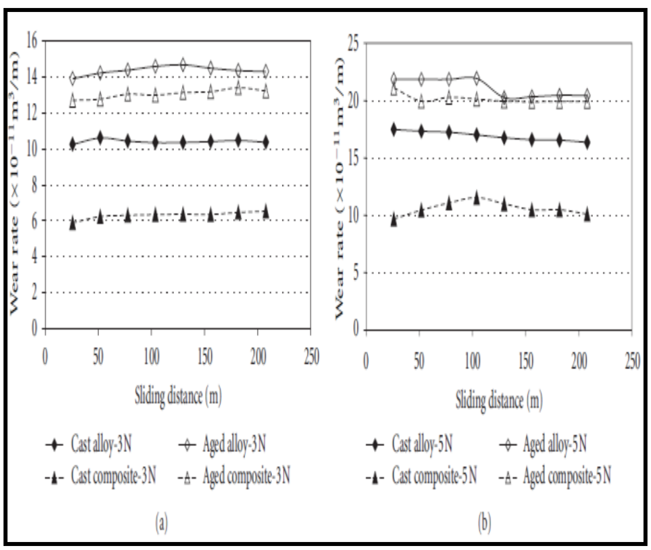

Fig. 7 (b): Wear rate behavior for 7075(a) alloy and (b) composite [10].

(e) Effects Reinforcement on Mach inability: Mach inability of AMCs is one of the important properties of the composite and has vital role during the machining. So that it has to be consider during fabrication and development of new composite. As AMCs contain softer matrix reinforced with very hard particulate, machining of such material becomes difficult. The major challenges in the machining of AMCs are to obtain desired the dimensional accuracy and surface finish. The traditional tool materials such as high speed steel are not suitable for machining MMCs due to rapid growth of tool wear. Generally Poly Crystalline Diamond (PDC), tungsten coated carbide tool, Chemical Vapor Deposition (CVD) diamond coated carbide insert, poly crystalline boron nitride (PCBN) tool, Al_2O_3, TiN and Ti (C,N) based CVD coatings on tool and non-conventional machining process are preferred for machining these materials. The costly tool material and processes, increases the machining cost and make component expensive. In this regard many approaches such as optimization technique for optimizing the cutting parameters, new tooling system, improved cutting tool materials, coating the particulate before mixing in the matrix material, addition graphite particles were suggested by researchers **[11, 12, 13, 16, 19, 20, 21, 22, 23, 24, 25, 26, 27].** The effects of percentage weight of reinforcement in composite on surface finish and cutting parameters are depicted in figures 8 and 9.

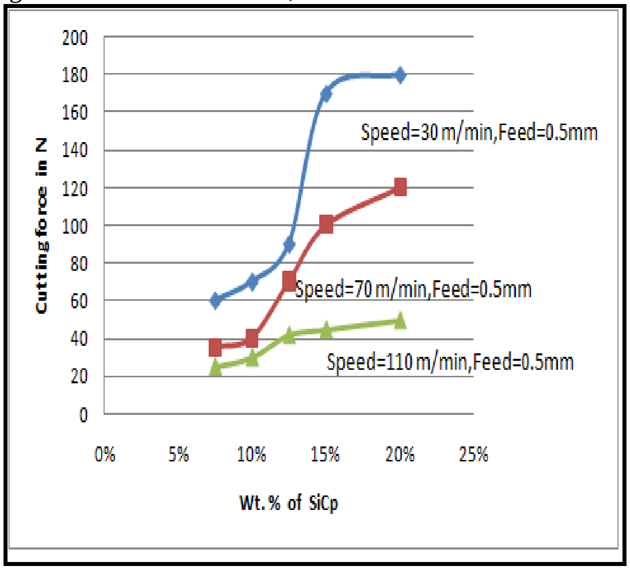

Fig. 8:Effects of weight % SiCp on cutting force.

Metin Kök[14], investigated the effects of cutting speed, size and volume fraction of particle on the surface roughness in turning of 2024Al alloy composites reinforced with Al_2O_3 particles. It was found that surface roughness decreased with increasing the size and volume fraction of particles for all cutting conditions. The dependency of the surface roughness on the cutting speed was smaller when the particle size was smaller.

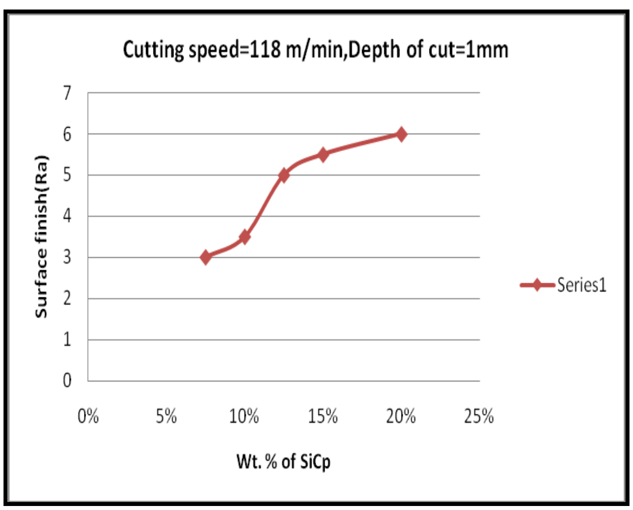

Fig. 9: Effects of SiCp weight % on surface finish.

Y. Altunpak et. al.[15], in their work, the influence of cutting parameters on cutting force and surface roughness in drilling of Al/20%SiC/5%Gr and l/20%SiC/10%Gr was investigated. The composite was fabricated by vortex method. The results indicate that inclusion of graphite as an additional reinforcement in Al/SiCp reinforced composite reduces the cutting force. For all cutting conditions, Al/20%SiC/10%Gr composite has lower surface roughness values than Al/20%SiC/5%Gr composite. **V. Anandakrishnan & A. Mahamani [17],** they investigated flank wear, cutting force, and surface roughness in the machining of Al-6061–TiB_2 in situ metal matrix composites produced by flux-assisted synthesis. Their finding was higher

TiB_2 reinforcement ratio produces higher tool wear, surface roughness and minimizes the cutting forces. The mach inability of in situ MMC is better from traditional MMC, because of the presence of fine and uniformly distributed reinforcement, which reduces flank wear. The hardness of the composite also increased with increase of the ratio of TiB2 in composite. **C. Tijun, et. al.[18],** The Al_3Ti intermetallic reinforced with pure Al, Al/Si and Al/Cu matrix composites were prepared by casting method. Their microstructures and dry sliding wear behaviors at room temperature and 100℃ were particularly investigated. It was found that Al-Cu matrix composite has the best wear resistance, while the pure Al matrix composite showed the worst for the same Ti content. The wear resistance of pure Al matrix composite increases with increase Ti or Al_3Ti content

IV CONCLUSION

The controlling factors of AMCs are process rout, temperature, alloys elements of matrix materials, types of reinforcement materials with their shape, size, wettibility, weight and volume percentage and reaction during composite preparation. These factors determine the properties of composites. The stir casting process for making the composite is most popular amongst the researcher but the composite made by in-situ and other process exhibits superior properties than this process. The selection of matrix and reinforcement material for the development and fabrication of composite required lot of attention otherwise their chemical incompatibility may adversely affect on their properties. It is also found that the properties of reinforced metal and alloys have always superior properties than the unreinforced materials.

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