

Corrosion Behaviour of Al-based Metal Matrix Composites - A Review

A. Chennakesava Reddy

Department of Mechanical Engineering
Jawaharlal Nehru Technological University
Hyderabad; India
chennakesava@jntuh.ac.in

Abstract— Metal matrix composites have entered in industry with extreme interest from the automobile and aerospace sectors due to their superior mechanical properties and applications. From several studies it is concluded that there are different types of MMCs available. During last few years, researchers have uncovered many secrets relating to these advanced materials. This paper briefly reviews the turning operations carried on MMCs using uncoated carbide tool and coated tool. Due to the abrasive nature of the reinforcements, MMC is considered as a difficult to cut material. Turning test were performed at various speed, feed rate, depth of cut and percentage of alumina inclusion in MMCs. From most of the studies it has been concluded that poor machinability is due to abrasive nature of the reinforcements and hardness of MMC material. It is also concluded that with increase in the hardness and volume fraction of particle machinability decreases.

Keywords- MMC; turning, chip formation; tool wear; surface roughness; metal removal rate; cutting forces.

I. INTRODUCTION

Aluminium alloys have been used successfully in a variety of applications for many years, often in aggressive environments. They obtain their corrosion resistance from a stable oxide surface film which forms when the bare metal surface is exposed to an oxidizing environment. Aluminium surfaces suffer from various types of corrosion in many urban, rural and industrial situations as shown in figure 1.



Figure 1. Corrosion of Al products.

If in metal matrix composites (MMCs) the protective film is affected by the incorporation of a reinforcing phase, the general corrosion resistance may be compromised. Where MMCs are considered as a structural component for use in an aggressive environment, the susceptibility to stress corrosion and corrosion fatigue may cause concern as the resistance to these modes of failure has yet to be characterized. This paper provides a review of the mechanisms of corrosion characteristic of Al-based metal matrix composites.

II. CORROSION CHARACTERISTICS OF AL-BASED MATRIX ALLOYS

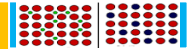
when a metal is placed in an aqueous environment it can behave in three ways: corrode, show immunity or passive. If corrosion was occurred metal dissolution would result. Under conditions of immunity the potential of the metal is lowered sufficiently to prevent metal dissolution. Under passivation the potential of the metal is raised as the metal becomes covered with a protective film which removes it from direct contact with the environment.

The usefulness of this graphical representation of thermodynamic data for corrosion studies was discussed by Pourbaix who showed three possible states of a metallic material:

Immunity region: In the conditions of potential and pH of that region a metal is considered to be totally immune from corrosion attack and safe to use.

Passive region: In such region a metal tends to become coated with an oxide or hydroxide that may form on the metal either as a compact and adherent film practically preventing all direct contact between the metal itself and the environment, or as a porous deposit which only partially prevents contact between the metal and the environment.

Corrosion region: Thermodynamic calculations indicate that, in such region of an E-pH diagram,



a metal is stable as an ionic (soluble) product and therefore susceptible to corrosion attack. Experience is required to find out the extent and form of the corrosion attack that may occur in the corrosion region(s) of a Pourbaix diagram (figure 2).

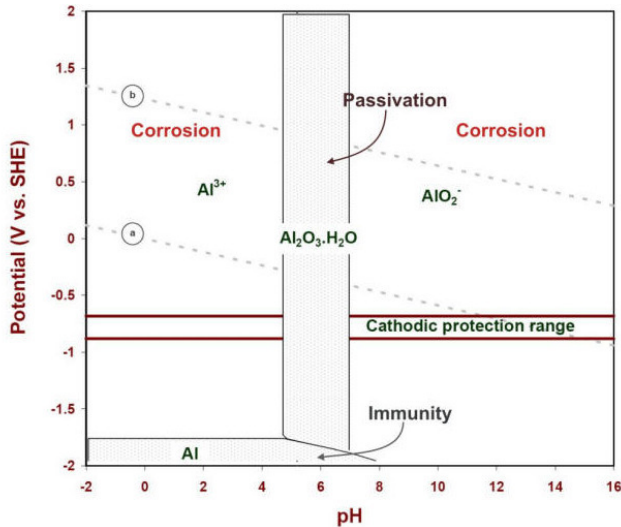


Figure 2. E-pH corrosion diagram of aluminum at 25°C [p26].

Environmental factors such as temperature and solution turbulence can have a profound effect on the corrosion resistance of aluminium. Factors dictated by the aluminium alloy itself include the surface-to-volume ratio, heat capacity of the surface, surface finish, alloying additions and the presence of surface defects. The composition, volume, location and potential of microconstituents relative to aluminium solid solutions also have a direct influence on the amount, form and distribution of corrosion attack.

Wrought alloys in the 3XXX (Al-Mn), 5XXX (Al-Mg) and 6XXX (Al-Mg-Si) series are resistant to corrosion. In these alloys, the alloying elements tend to form second phases. In the 3XXX series manganese forms $Al_6(Mn.Fe)$ and $Al_{12}(Mn.Fe)_3Si$ precipitates. In the 5XXX series magnesium forms Al_3Mg_5 precipitates which are evenly dispersed throughout the matrix. In the 6XXX series magnesium and silicon together form Mg_2Si phase which provides the basis for precipitation hardening.

III. FORMS OF CORROSION

Corrosion is the chemical reaction of a metal, in this case aluminum, with its environment. Different forms of corrosion are as follows:

- Pitting corrosion

- Intergranular corrosion
- Exfoliation
- Stress corrosion
- Corrosion fatigue
- Corrosion protection

A. Pitting Corrosion

Pitting Corrosion is the localized corrosion of a metal surface confined to a point or small area, that takes the form of cavities as shown in figure 3. Pitting of aluminum alloys occurs if the electrolyte contains a low level of chloride anions, and if the alloy is at a potential above the "pitting potential." Pitting initiates at defects on the surface of the aluminum, such as at second phase particles or on grain boundaries.

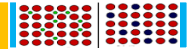


Figure 3. Pit corrosion.

Mechanism of pitting corrosion includes dissolution of the passivating film and gradual acidification of the electrolyte caused by its insufficient aeration (Oxygen penetration). Stages of pitting corrosion are as follows:

1. Pit initiation. An initial pit may form on the surface covered by a passive oxide film as a result of the following:

- Mechanical damage of the passive film caused by scratches. Anodic reaction starts on the metal surface exposed to the electrolyte. The passivated surrounding surface act as the cathode.
- Particles of a second phase (non-metallic inclusions, intermetallic inclusions, metallic particles, Micro-segregation) emerging on the metal surface. These particles precipitating along the grain boundaries may function as local anodes causing localized galvanic corrosion and formation of initial pits.
- Localized stresses in form of dislocations emerging on the surface may become anodes and initiate pits.



- Non-homogeneous environment may dissolve the passive film at certain locations where initial pits form.

2. Pit growth. In presence of chloride ions pits are growing by autocatalytic mechanism. Pitting corrosion of a stainless steel is illustrated in the figure.

The pitting density is defined as the number of pit units formed per cm^2 of test piece surface. The pitting corrosion of commercial grade aluminium exposed to ethanol is shown in figure 4.

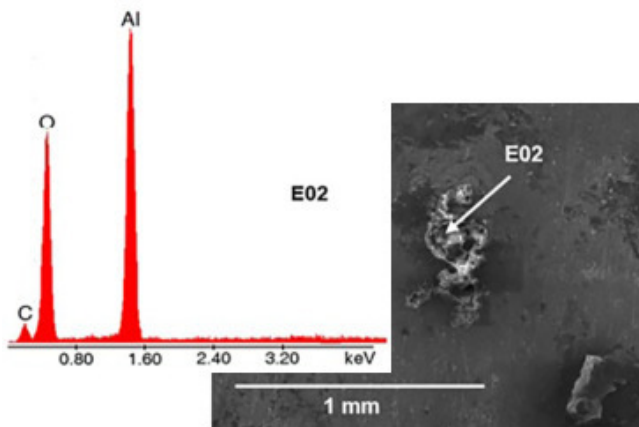


Figure 4. Pitting corrosion of commercial grade aluminium exposed to ethanol.

B. Intergranular Corrosion

Aluminium alloys are subject to intergranular corrosion where precipitation or formation of more anodic or cathodic phases, with respect to the matrix, occurs at the grain boundaries. Depending on the alloy system, this results in selective corrosion at the grain boundaries or any precipitate-free zones (PFZs) adjacent to them, with the bulk matrix remaining relatively unaffected. Intergranular corrosion is caused by potential differences between the grain-boundary region and the adjacent grain bodies.

In 2XXX Al alloys Al_2Cu , Al_2CuMg precipitations may occur at the grain boundaries. In the case of AA2024-T3 alloy, second-phase particles function in initiation of intergranular corrosion. Copper content is low in the vicinity of second-phase particles, making these regions vulnerable to corrosion. As soon as dissolution is accelerated in such regions, damage nucleated at a grain boundary in contact with the vicinity of the second-phase particle. Copper-depleted region is present along grain boundaries. Figure 5 shows SEM image of clustered intermetallic

particles. EDX analysis was carried out at two positions in the cluster, as shown in Figures 5 (b)-(c). Interestingly, the spectrum from point 1 exhibits a higher Mg peak than that from point 2 with both spectra showing similar intensity at Al and Cu. Thus, point 1 is rich in aluminium, copper and magnesium, indicating S-phase (Al_2CuMg); point 2 is only rich in aluminium and copper, indicating θ -phase (Al_2Cu). This suggests variation in composition at different parts of the cluster.

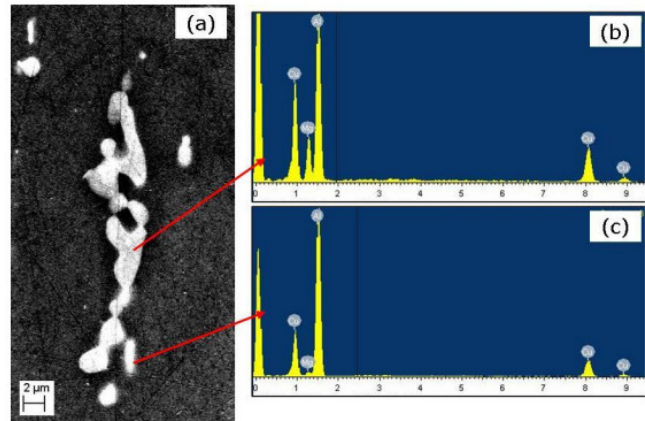


Figure 5. (a) Scanning electron micrograph of a cluster of S-phase and θ -phase particles; and (b)-(c) EDX spectra of the cluster.

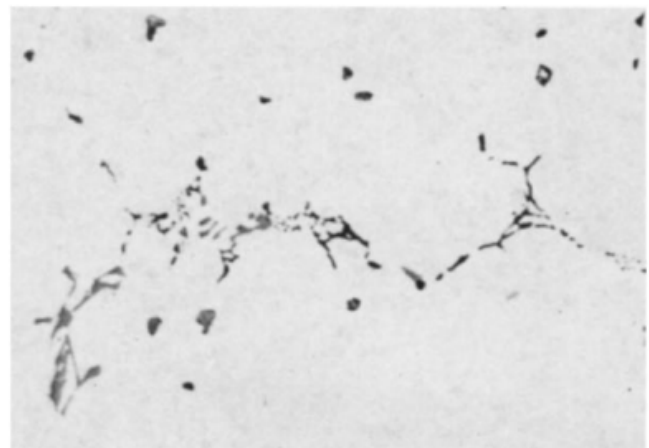
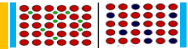


Figure 6. 5056 as-cast ingot showing $(\text{Fe, Cr})_3\text{SiAl}_{12}$ (gray), Mg_2Si (dark), and Mg_2Al_3 (mottled, outlined) in dendrite interstices.

When magnesium content exceeds about 3.5%, Mg_2Al_3 , or metastable Mg_2Al_3 may precipitate in grain boundaries of 5XXX Al alloys as shown in figure 6. In 6XXX Al alloys Mg_2Si constituent forms at the grain boundaries. Figure 7(a) depicts a large grain boundary phase ($\sim 2 \mu\text{m}$ length) in a sample that was air-cooled after the solution heat



treatment and subsequently aged for 23 h at 160 °C. Extensive grain boundary precipitate nucleation and growth then already occur during the slow cooling process. The structure at all parts of the particle was found to be hexagonal with $a = 10.4 \text{ \AA}$ and $c = 4.1 \text{ \AA}$. The chemical composition, on the other hand, varies significantly, as can be seen from figure 7 (b). Here, the relative Mg-, Si- and Cu-concentrations are plotted for different equidistant locations on the particle, which are given in figure 7(a). Especially the relative Mg- and Si-concentration can be seen to vary significantly along the grain boundary phase.

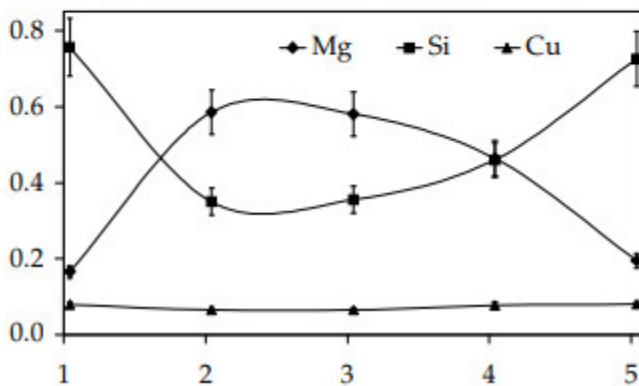
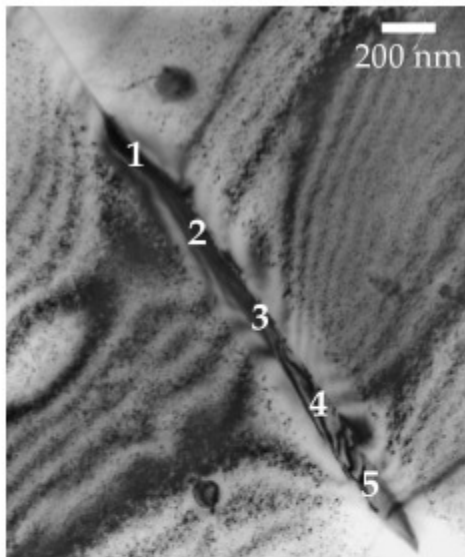


Figure 7. (a) TEM-micrograph of grain boundary phase in air-cooled AA6061; (b) Relative concentrations of solute elements at different spots on the grain boundary phase.

Mg_2Al_3 constituent and CuAl_2 constituent form in Cu-free 7XXX and Cu-bearing 7XXX Al alloys. For 7XXX Al alloy, the scan was carried out across a selected GBP with a step of 1 nm along the path, marked with a red line in figure 8a. The

curves shown in figure 8b demonstrate the concentration profiles of solutes obtained from the scan. The intensity ratio (C_i/Al) reveals the relative content of each solute in GBs and PFZs. Zn concentration in GBPs is the most intense, with a highest intensity ratio CZn/Al of 0.62 being detected. Meanwhile, the depletion of Zn in PFZ is most evident as the lowest intensity ratio ($\text{CZn}/\text{Al} = 0.02$) observed. The CZn/Al detected within grains is 0.03–0.04, much lower than that in GBPs, but notably higher than that in PFZs. A similar behavior of enrichment and depletion is observed for Mg and Cu, but the intensities vary one from each other.

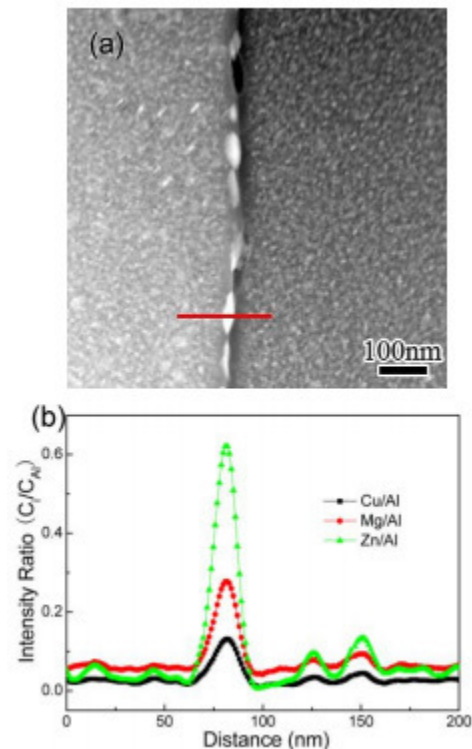
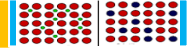


Figure 8. The location of the EDS line-scan, as indicated in red line in (a), and (b) the obtained concentration profile of solute.

C. Exfoliation

Exfoliation is a special form of intergranular corrosion that proceeds laterally from the sites of initiation along planes parallel to the surface, generally at grain boundaries, forming corrosion products that force metal away from the body of the material, giving rise to a layered appearance. Exfoliation occurs predominantly in Al-alloys that have marked directional structures.

Exfoliation is characteristic for the 2XXX (Al-Cu), 5XXX (Al-Mg), and 7XXX (Al-Zn-Mg) series alloys



which have grain boundary precipitation or depleted grain boundary regions. For 7178 Al alloy, EDS line profiling was performed across grain boundaries at locations that include precipitates and locations away from precipitates to analyze the PFZ. The concentration profiles in the form of concentration ratios for various elements relative to Al are shown in figure 9. Al-Zn-Mg-Cu-Cr precipitate (concentration profiles across these precipitates are shown.

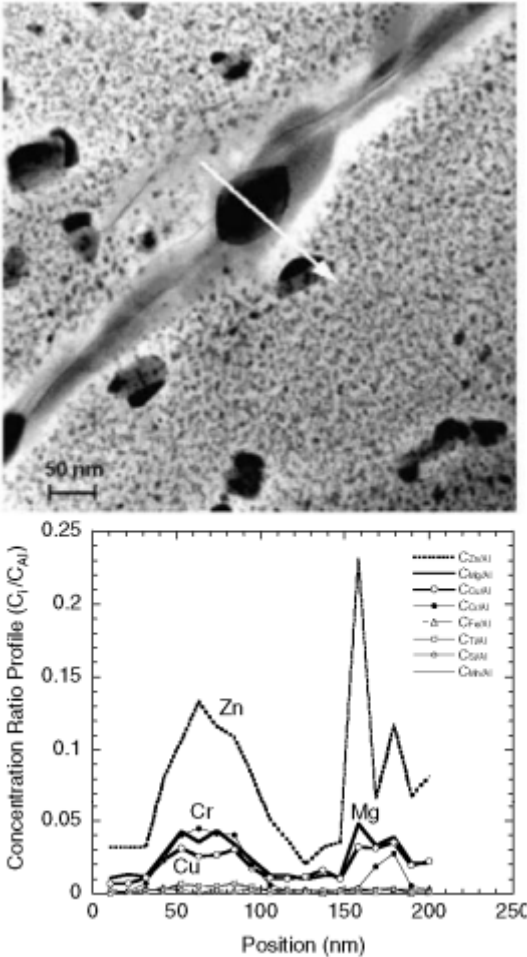


Figure 9. TEM micrographs of grain-boundary in AA7178 showing Nano EDS line profiling across the GB precipitate.

D. Stress Corrosion Cracking

Stress corrosion cracking (SCC) is the growth of crack formation in a corrosive environment. It can lead to unexpected sudden failure of normally ductile metal alloys subjected to a tensile stress, especially at elevated temperature. SCC requires three simultaneous conditions, first a susceptible alloy, second a humid or water environment, and third a tensile stress which will

open the crack and enable crack propagation. SCC can occur in two modes, intergranular stress corrosion cracking (IGSCC) which is the more common form, or transgranular SCC (TGSCC). In IGSCC, the crack follows the grain boundaries. In transgranular stress corrosion cracking (TGSCC), the cracks cut through the grains and are oblivious to the grain boundaries.

Crack growth: The subcritical nature of propagation may be attributed to the chemical energy released as the crack propagates. That is,

$$\text{elastic energy released} + \text{chemical energy} = \text{surface energy} + \text{deformation energy}$$

The crack initiates at K_{Isc} and thereafter propagates at a rate governed by the slowest process, which most of the time is the rate at which corrosive ions can diffuse to the crack tip. As the crack advances so K rises (because crack length appears in the calculation of stress intensity). Finally, it reaches K_{Ic} , whereupon fast fracture ensues and the component fails. One of the practical difficulties with SCC is its unexpected nature.

Figure 10 shows the regions of different crack propagation under stress corrosion cracking. In region I, crack propagation is dominated by chemical attack of strained bonds in the crack. In region II, propagation is controlled by diffusion of chemical into the crack. In region III, the stress intensity reaches its critical value and propagates independent of its environment.

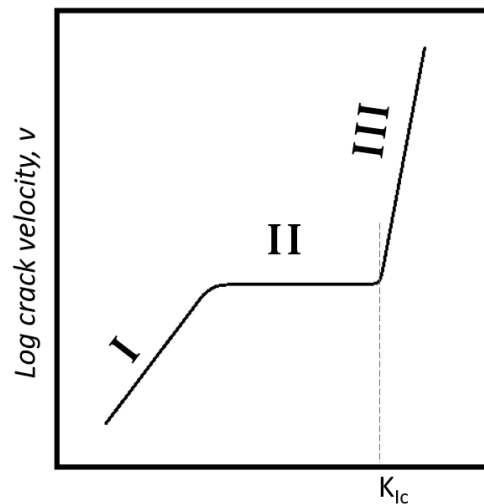
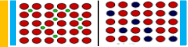


Figure 10. Crack growth



The poor resistance to stress corrosion cracking is exhibited by Al alloys such as 2XXX, 7XXX and 8XXX Al alloys. In Al alloys, SCC is characteristically intergranular and requires an anodic phase at the grain boundaries for crack propagation to occur. A cleavage-like fracture surface with the presence of striations is prevailed in 2650 T6 Al alloy as shown in figure 11.

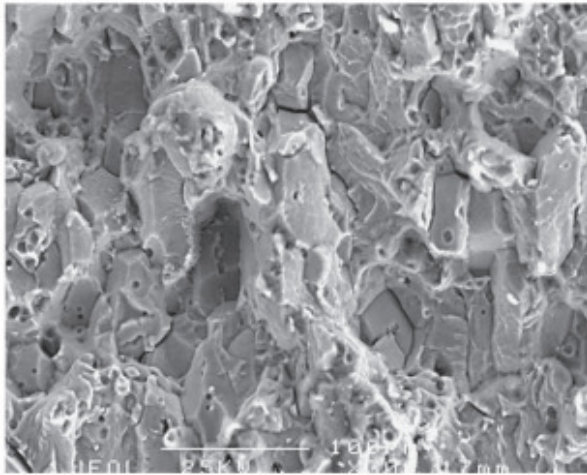


Figure 11. Fracture surfaces produced during fatigue crack growth in the 2650 T6 alloy.

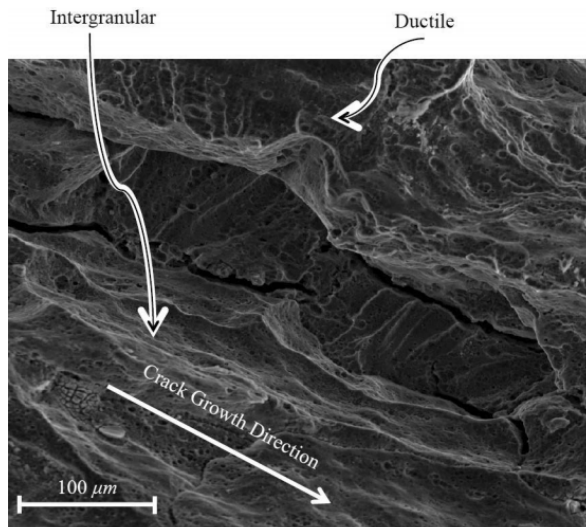


Figure 11. SEM micrograph of fracture surface within elongated grain structure of AA6005A-T6 CGR sample exposed to a solution of 3.5% NaCl at pH = 1.5. Micrograph was taken near the tip of the stress corrosion crack at the midplane of the sample. Evidence of both brittle intergranular fracture and ductile fracture were observed in regions of SCC.

Fractures surfaces of AA6005A-T6 CT specimens showed evidence of both brittle intergranular fracture and ductile fracture in regions of SCC

(figure 11). The mix of ductile and brittle fracture along the fracture surface suggests that SCC is occurring along small “channels” in the material, and the remainder of the material between these channels is failing by overload. The mix of brittle and ductile fracture along the fracture surface suggests that SCC growth is discontinuous along the crack front. In this case, SCC would occur only along discrete corrosion paths (regions of intergranular fracture), and regions between the intergranular SCC are fractured in a ductile manner when the fracture criterion is satisfied for the remaining ligament.

E. Corrosion Fatigue

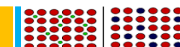
Corrosion fatigue can occur when an aluminum structure is repeatedly stressed at low stress levels in a corrosive environment. A fatigue crack can initiate and propagate under the influence of the crack-opening stress and the environment. Similar striations may sometimes be found on corrosion fatigued samples, but often the subsequent crevice corrosion in the narrow fatigue crack dissolves them.

Fatigue strengths of aluminum alloys are lower in such corrosive environments as seawater and other salt solutions than in air, especially when evaluated by low-stress long-duration tests. Like SCC of aluminum alloys, corrosion fatigue requires the presence of water. In contrast to SCC, however, corrosion fatigue is not appreciably affected by test direction, because the fracture that results from this type of attack is predominantly transgranular.

IV. Atmospheric Corrosion

Atmospheric corrosion is defined as the corrosion or degradation of material exposed to the air and its pollutants rather than immersed in a liquid. This has been identified as one of the oldest forms of corrosion and has been reported to account for more failures in terms of cost and tonnage than any other single environment. Many authors classify atmospheric corrosion under categories of dry, damp, and wet, thus emphasizing the different mechanisms of attack under increasing humidity or moisture.

Corrosivity of the atmosphere to metals varies greatly from one geographic location to another, depending on such weather factors as wind direction, precipitation and temperature changes, amount and type of urban and industrial



pollutants, and proximity to natural bodies of water. Service life may also be affected by the design of the structure if weather conditions cause repeated moisture condensation in unsealed crevices or in channels with no provision for drainage.

V. Uniform Corrosion

General corrosion, or uniform corrosion, occurs in the solutions where pH is either very high or very low, or at high potentials in electrolytes with high chloride concentrations. In acidic (low pH) or alkaline (high pH) solutions, the aluminum oxide is unstable and thus non-protective.

VI. Galvanic Corrosion

Economically, galvanic corrosion creates the largest number of corrosion problems for aluminum alloys. Galvanic corrosion, also known as dissimilar metal corrosion, occurs when aluminum is electrically connected to a more noble metal, and both are in contact with the same electrolyte.

VII. Crevice Corrosion

Crevice corrosion requires the presence of a crevice, a salt water environment, oxygen (Fig. 1). The crevice can result from the overlap of two parts, or gap between a bolt and a structure. When aluminum is wetted with the saltwater and water enters the crevice, little happens initially. Over time, inside the crevice oxygen is consumed due to the dissolution and precipitation of aluminum.

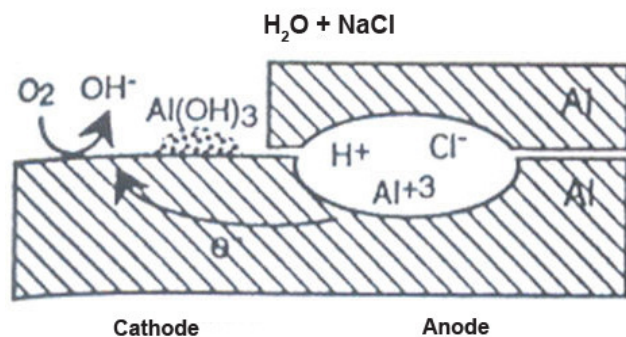


Figure 1: Crevice corrosion can occur in a saltwater environment if the crevice becomes deaerated, and the oxygen reduction reaction occurs outside of the crevice mouth. Under these conditions, the crevice becomes more acidic, and corrosion occurs at an increasing rate.

VIII. Deposition Corrosion

In designing aluminum and aluminum alloys for satisfactory corrosion resistance, it is important to keep in mind that ions of several metals have reduction potentials that are more cathodic than the solution potential of aluminum and therefore

can be reduced to metallic form by aluminum. For each chemical equivalent of so-called heavy-metal ions reduced, a chemical equivalent of aluminum is oxidized. Reduction of only a small amount of these ions can lead to severe localized corrosion of aluminum, because the metal reduced from them plates onto the aluminum and sets up galvanic cells.

The more important heavy metals are copper, lead, mercury, nickel, and tin. The effects of these metals on aluminum are of greatest concern in acidic solutions; in alkaline solutions, they have much lower solubilities and therefore much less severe effects.

IX. Erosion-Corrosion

Erosion-corrosion of aluminum occurs in high velocity water and is similar to jet-impingement corrosion. Erosion-corrosion of aluminum is very slow in pure water, but is accelerated at pH > 9, especially with high carbonate and high silica content of the water.

Aluminum is very stable in neutral water; however it will corrode in either acidic or alkaline waters. To prevent erosion-corrosion, one may change the water chemistry or reduce the velocity of the water, or both. For the water chemistry, the pH must be below 9, and the carbonate and the silica levels must be reduced.

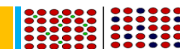
X. Filiform Corrosion

Filiform corrosion (also known as wormtrack corrosion) is a cosmetic problem for painted aluminum. Pinholes or defects in the paint from scratches or stone bruises can be the initiation site where corrosion begins with salt water pitting. Filiform corrosion requires chlorides for initiation and both high humidity and chlorides for the propagation of the track.

The propagation depends on where and how the alloy is used. The filament must be initiated by chlorides, and then it proceeds by a mechanism similar to crevice corrosion. The head is acidic, high in chlorides, and deaerated and is the anodic site. Oxygen and water vapor diffuse through the filiform tail, and drive the cathodic reaction. Filiform corrosion can be prevented by sealing defects with paint or wax, and keeping the relative humidity low.

XI. Microbiological Induced Corrosion

Microbiological Induced Corrosion (MIC) applies to a corrosive situation which is caused or aggravated by the biological organisms. A classic case of MIC is the growth of fungus at the water/fuel interface in aluminum aircraft fuel tanks. The fungus consumes the high octane fuel, and excretes an acid which attacks and pits



the aluminum fuel tank and causes leaking. The solution for this problem is to control the fuel quality and prevent water from entering or

IV. CONCLUSION

Metal matrix composites have entered in industry with extreme interest from the automobile and aerospace sectors due to their superior mechanical properties and applications. Many researchers have been worked for the machining of metal matrix composites. In this paper a brief overview is provided related research, focusing on turning mechanisms. The PCD cutting tool has been found better for turning of MMCs than PCBN, SCD and carbide based cutting tool materials. The coated cutting tool performs better as compared to the uncoated cutting tools but leads in high wears after rupture of coating. The performances of multi-layer coated tool were found near to PCD turning tool. Surface Roughness increase with the process variables except the speed, speed made adverse effect on surface roughness. MRR increases with the process parameters except the concentration of reinforced particles due the presence of hard ceramic particles. Even though, for the conventional alloys the deformation behavior and the friction law governing chip-tool interface friction during machining has not yet been well defined. In addition, the effect of reinforcement particles on the deformation mechanisms during machining of MMCs is also not fully understood. There is still research required to clarify these interactions before we can go deep into the new possible concepts and further developments regarding MMCs and machining.

REFERENCES

1. C. R. Alavala, Influence of Debris on Wear Rate of Metal Matrix Composites, *Journal of Materials Science & Surface Engineering*, vol.4, no.6, pp.458-462, 2016.
2. C. R. Alavala, Nano-mechanical modeling of thermoelastic behavior of AA6061/silicon oxide nanoparticulate metal matrix composites, *International Journal of Science and Research*, vol.5, no.1, pp.550-553, 2016.
3. A. C. Reddy, Thermal Expansion Behavior of Aluminum Matrix Composites Reinforced with Fused Quartz Nanoparticles, *National Conference on Advanced Materials and Manufacturing Techniques*, Hyderabad, 8-09th March 2004, pp.350-355.
4. A. C. Reddy, Evaluation of mechanical behavior of Al-alloy/Al₂O₃ metal matrix composites with respect to their constituents using Taguchi, *International Journal of Emerging Technologies and Applications in Engineering Technology and Sciences*, vol.4, no.2, pp.26-30, 2011.
5. A. C. Reddy, Essa Zitoun, Tensile properties and fracture behavior of 6061/Al₂O₃ metal matrix composites fabricated by low pressure die casting process, *International Journal of Materials Sciences*, vol.6, no.2, pp.147-157, 2011.
6. A. C. Reddy, Cause and Catastrophe of Strengthening Mechanisms in 6061/Al₂O₃ Composites Prepared by Stir Casting Process and Validation Using FEA, *International Journal of Science and Research*, vol.4, no.2, pp.1272-1281, 2015.
7. A. C. Reddy, Cause and Catastrophe of Strengthening Mechanisms in 6063/Al₂O₃ Composites Prepared by Stir Casting Process: Validation

remaining in the fuel tanks. If fuel quality control is not feasible, then fungicides are sometimes added to the aircraft fuel.

through FEA, *International Journal of Scientific & Engineering Research*, vol.6, no.3, pp.75-83, 2015.

8. A. C. Reddy, Cause and catastrophe of strengthening mechanisms in 7020/Al₂O₃ composites prepared by stir casting process and validation through FEA, *International Journal of Advanced Research*, vol.3, no.3, pp.603-614, 2015.

9. A. C. Reddy, Reduction of Vibrations and Noise using AA7020/Fe₂O₃ Nanocomposite Gear Box in Lathe, *International Journal of Scientific & Engineering Research*, vol.6, no.9, pp.685-691, 2015.

10. A. C. Reddy, Tribological Behavior of AA8090/MgO Composites, *5th National Conference on Materials and Manufacturing Processes*, Hyderabad, 9-10th June 2006, pp.169-173.

11. C. R. Alavala, Thermal Expansion Behavior of Al/Magnesia Metal Matrix Composites, *International Journal of Science and Research*, vol.5, no.8, pp.1817-1821, 2016.

12. C. R. Alavala, Micromechanics of Thermoelastic Behavior of AA2024/MgO Metal Matrix Composites, *International Journal of Advanced Technology in Engineering and Science*, vol.4, no.1, pp.33-40, 2016.

13. A. C. Reddy, Stir Casting Process on Porosity Development and Micromechanical Properties of AA5050/Titanium Oxide Metal Matrix Composites, *5th National Conference on Materials and Manufacturing Processes*, Hyderabad, 9-10th June 2006, pp.144-148.

14. A. C. Reddy, Effect of Clustering Induced Porosity on Micromechanical Properties of AA6061/Titanium Oxide Particulate Metal Matrix Composites, *6th International Conference on Composite Materials and Characterization*, Hyderabad, 8-9th June 2007, pp.149-154.

15. A. C. Reddy, Sliding Wear and Micromechanical Behavior of AA1100/Titanium Oxide Metal Matrix Composites Cast by Bottom-Up Pouring, *7th International Conference on Composite Materials and Characterization*, Bangalore, 11-12th December 2009, pp.205-210.

16. A. C. Reddy, Hardness Contours and Worn Surfaces of AA1100 Alloy/TiO₂ Metal Matrix Composites, *2nd International Conference on Modern Materials and Manufacturing*, Pune, 10-11th December 2010, pp.292-296.

17. C. R. Alavala, Influence of Temperature on Particulate Fracture of AA2024 Alloy/Titanium Oxide nanoparticulate Metal Matrix Composites, *International Journal of Scientific Engineering and Applied Science*, vol.2, no.4, pp.1-6, 2016.

18. A. C. Reddy, Experimental Validation of Dry Wear Formulation of AA7020/Zirconia Nanoparticle Metal Matrix Composites, *3rd International Conference on Modern Materials and Manufacturing*, New Delhi, 9-10th December 2011, pp.357-361.

19. C. R. Alavala, Micromechanics of Thermoelastic Behavior of AA6070 Alloy/Zirconium Oxide Nanoparticle Metal Matrix Composites, *International Journal of Engineering Research & Science*, vol.2, no.2, pp.1-8, 2016.

20. A. C. Reddy, B. Kotiveerachari, Effect of aging condition on structure and the properties of Al-alloy / SiC composite, *International Journal of Engineering and Technology*, vol.02, no.06, pp.462-465, 2010.

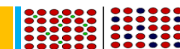
21. A. C. Reddy, Evaluation of mechanical behavior of Al-alloy/SiC metal matrix composites with respect to their constituents using Taguchi techniques, *i-manager's Journal of Mechanical Engineering*, vol.1, no.2, pp.31-41, 2011.

22. A. C. Reddy, Influence of strain rate and temperature on superplastic behavior of sinter forged Al6061/SiC metal matrix composites, *International Journal of Engineering Research & Technology*, vol.4, no.2, pp.189-198, 2011.

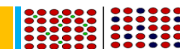
23. A. C. Reddy, B. Kotiveerachari, Influence of microstructural changes caused by ageing on wear behaviour of Al6061/SiC composites, *Journal of Metallurgy & Materials Science*, vol.53, no.1, pp.31-39, 2011.

24. A. C. Reddy, Influence of volume fraction, size, cracking, clustering of particulates and porosity on the strength and stiffness of 6063/SiCp metal matrix composites, *International Journal of Research in Engineering and Technology*, vol.4, no.1, pp.434-442, 2015.

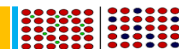
25. A. C. Reddy, Influence of Particle Size, Precipitates, Particle Cracking, Porosity and Clustering of Particles on Tensile Strength of 6061/SiCp Metal Matrix Composites and Validation Using FEA, *International Journal of Material Sciences and Manufacturing Engineering*, vol.42, no.1, pp.1176-1186, 2015.



26. A. C. Reddy, Studies on loading, cracking and clustering of particulates on the strength and stiffness of 7020/SiCp metal matrix composites, *International Journal of Metallurgical & Materials Science and Engineering*, vol.5, no.1, pp.53-66, 2015.
27. A. C. Reddy, Reduction of Vibrations and Noise using AA7020/SiC Nanocomposite Gear Box in Lathe, *International Journal of Scientific & Engineering Research*, vol.6, no.9, pp.678-684, 2015.
28. C. R. Alavala, Synthesis and Tribological Characterization of Cast AA1100-B₄C Composites, *International Journal of Science and Research*, vol.5, no.6, pp.2404-2407, 2016.
29. A. C. Reddy, Evaluation of Thermal Expansion of Al/B₄C Metal Matrix Composites, 3rd National Conference on Materials and Manufacturing Processes, Hyderabad, India, 22-25th February 2002, pp.196-200.
30. A. C. Reddy, Significance of Testing Parameters on the Wear Behavior of AA1100/B₄C Metal Matrix Composites based on the Taguchi Method, 3rd International Conference on Composite Materials and Characterization, Chennai, India, 11-12th May 2001, 276-280.
31. A. C. Reddy, Role of Porosity and Clustering on Performance of AA1100/Boron Carbide Particle-Reinforced Metal Matrix Composites, 6th International Conference on Composite Materials and Characterization, Hyderabad, 8-9th June 2007, 122-127.
32. A. C. Reddy, Estimation of Thermoelastic Behavior of Three-phase: AA1100/Ni-Coated Boron Carbide Nanoparticle Metal Matrix Composites, *International Journal of Scientific & Engineering Research*, vol.6, no.10, pp.662-667, 2015.
33. A. C. Reddy, Wear Characteristics of AA5050/TiC Metal Matrix Composites, National Conference on Advanced Materials and Manufacturing Techniques, Hyderabad, 08-09th March, 2004, pp.356-360.
34. A. C. Reddy, Effect of TiC Nanoparticles on the Coefficient of Thermal Expansion Behavior of the Aluminum Metal Matrix Composites, 5th National Conference on Materials and Manufacturing Processes, Hyderabad, 9-10th June 2006, 164-168.
35. C.R. Alavala, Micromechanical Modelling of Thermoelastic Behavior of AA7020/TiC Metal Matrix Composites, *International Journal of Scientific Engineering and Research*, vol.4, no.2, pp.1-5, 2016.
36. C. R. Alavala, Influence of CTE Mismatch on Debonding and Particulate Damage in AA1100 Alloy/ZrC Nanoparticulate Metal Matrix Composites, *International Journal of Innovative Research in Science, Engineering and Technology*, vol.5, no.3, pp.3489-3495, 2016.
37. A. C. Reddy, Reckoning of Micro-stresses and interfacial Traction in Titanium Boride/AA2024 Alloy Metal Matrix Composites, 1st International Conference on Composite Materials and Characterization, Bangalore, 14-15th March 1997, pp.195-197.
38. A. C. Reddy, Investigation of the Clustering Behavior of Titanium Diboride Particles in TiB₂/AA2024 Alloy Metal Matrix Composites, 4th International Conference on Composite Materials and Characterization, Hyderabad, India, 7-8th March 2003, pp.216-220.
39. A. C. Reddy, Wear Resistant Titanium Boride Metal Matrix Composites, 3rd National Conference on Materials and Manufacturing Processes, Hyderabad, India, 22-25th February 2002, pp.201-205.
40. A. C. Reddy, Thermal Expansion Studies on Aluminum Matrix Composites with Different Reinforcement Volume Fractions of Si₃N₄ Nanoparticles, 4th International Conference on Composite Materials and Characterization, Hyderabad, India, 7-8th March 2003, pp.221-225.
41. C.R. Alavala, Nanomodeling of nonlinear thermoelastic behavior of AA5454/ silicon nitride nanoparticulate metal matrix composites, *International Journal of Engineering Research and Application*, vol.6, no.1, pp.104-109, 2016.
42. A. C. Reddy, Necessity of Strain Hardening to Augment Load Bearing Capacity of AA1050/AlN Nanocomposites, *International Journal of Advanced Research*, vol.3, no.6, pp.1211-1219, 2015.
43. A. C. Reddy, Influence of Interphase on Tensile Behavior of Strain Hardened AA1100/AlN Nanocomposites Using RVE Models and Experimental Validation, *International Journal of Engineering, Science and Technology*, vol.7, no.7, pp.239-250, 2015.
44. A. C. Reddy, Effects of Adhesive and Interphase Characteristics between Matrix and Reinforced Nanoparticle of AA2124/AlN Nanocomposites: Mathematical and Experimental Validation, *International Journal of Engineering and Advanced Technology*, vol.5, no.1, pp.5-12, 2015.
45. C.R. Alavala, Weight Loss Functions for Tolerable Wear Rate of AA1100/BN Metal Matrix Composites, *International Journal of Mechanical Engineering and Technology*, vol.7, no.5, pp.9-17, 2016.
46. C.R. Alavala, Thermoelastic Behavior of Nanoparticulate BN/AA5050 Alloy Metal Matrix Composites, *International Journal of Engineering and Advanced Research Technology*, vol.2, no.1, pp.6-8, 2016.
47. A. C. Reddy, Impact of Particle Size on Dry Wear Formulation of AA2024/Titanium Nitride Macro-Particle Metal Matrix Composites, 3rd International Conference on Modern Materials and Manufacturing, New Delhi, 9-10th December 2011, pp.362-366.
48. C.R. Alavala, Effect of Thermoelastic Behavior on interfacial debonding and Particulate Fracture in AA1100/TiN Nanoparticulate Metal Matrix Composites, *International Journal of Science and Research*, vol.5, no. 3, pp.1295-1300, 2016.
49. A. C. Reddy, Effect of Porosity Formation during Synthesis of Cast AA4015/Titanium Nitride Particle-Metal Matrix Composites, 5th National Conference on Materials and Manufacturing Processes, Hyderabad, 9-10th June 2006, pp.139-143.
50. A. C. Reddy, Finite Element Analysis Study of Micromechanical Clustering Characteristics of Graphite/AA7020 Alloy Particle Reinforced Composites, 4th International Conference on Composite Materials and Characterization, Hyderabad, India, 7-8th March 2003, pp.206-210.
51. A. C. Reddy, Wear and Mechanical Behavior of Bottom-Up Poured AA4015/Graphite Particle-Reinforced Metal Matrix Composites, 6th National Conference on Materials and Manufacturing Processes, Hyderabad, 8-9th August 2008, pp.120-126.
52. A. C. Reddy, Correlation of Surface Profiles and Worn Surfaces of AA6061/Graphite Metal Matrix Composites, 2nd International Conference on Modern Materials and Manufacturing, Pune, 10-11th December 2010, pp.307-311.
53. R. N. Yadav, Machining of hybrid-metal matrix composite using erosion-abrasion based compound wheel in electrical discharge grinding, *Particulate Science and Technology*, 2016.
54. A. A. Premnath, T. Alwarsamy and T. Rajmohan T. Experimental investigation and optimization of process parameters in milling of hybrid metal matrix composites, *Materials and Manufacturing Processes*, vol.27, pp. 1035-1044, 2012.
55. M. Saini, R. N. Yadav and S. Kuma, An overview on turning process, in proceedings of the 1st International Conference on Advancements and Recent Innovations in Mechanical, Production and Industrial Engineering (ARIMPIE-2015), Noida, India, April 10-11th 2015, pp.377-386.
56. S. Madhava Reddy, A. C. Reddy, Studies on machining characteristics of silicon nitride ceramics, National Conference on Advanced Materials and Manufacturing Techniques, Hyderabad, 08-09th March 2004, pp.88-90.
57. N. P. Hung, S. H. Yeo, K. K. Lee, K. J. Ng. Chip formation in machining particle-reinforced metal matrix composites, *Materials and Manufacturing Processes*, vol.13, pp.85-100, 1998.
58. I. Ciftci, M. Turker, U. Seker, Evaluation of tool wear when machining SiCp-reinforced Al-2014 alloy matrix composites, *Materials & Design*, Vol.25, pp.251-255, 2004.
59. O. Quigley, J. Monaghan, P. O. Reilly, Factors affecting the machinability of an Al/SiC metal-matrix composite, *Journal of Materials Processing Technology*, Vol.43, pp.21-36, 1994.
60. J. P. Davim, Diamond tool performance in machining metal-matrix composites, *Journal of Material Processing Technology*, vol.128, pp. 100-105, 2002.
61. R. M. Hooper, J. L. Henshall, A. Klopfer, The wear of polycrystalline diamond tools used in the cutting of metal matrix composites, *International Journal of Refractory Metals and Hard Materials*, vol.17, pp.103-109, 1999.
62. A. R. Chambers, The machinability of light alloy MMCs, *Composites A*, vol.27A, pp.143-147, 1996.
63. J. Monaghan, P. O. Reilly, Machinability of aluminum alloy: silicon carbide metal matrix composite, *Advanced Materials & Processes*, vol.2, pp.37-46, 1992.
64. X. Ding, W. Y. H. Liew, and X. D. Liu, Evaluation of machining performance of MMC with PCBN and PCD tools, *Wear*, vol.259, pp. 1225-1234, 2005.
65. N. P. Hung, C. H. Zhong, Cumulative tool wear in machining metal matrix composites. Part II: Machinability, *Journal of Materials Processing Technology*, vol.58, pp.114-120, 1996.



66. N. Tomac and K. Tonnessen, Machinability of particulate aluminium matrix composites, *CIRP Annals*, vol.41, pp.55–58, 1992.
67. K. Weinert and D. Biermann, Turning of fiber and particle reinforced aluminium. In: *Proceedings of the international conference on machining of advanced materials*, pp. 437–53, 1993.
68. L.A. Looney, J.M. Monaghan, O. P. Reilly, D. M. R Taplin, The turning of an Al/SiC metal–matrix composite, *Journal of Materials Processing Technology*, vol.33, pp.453–468, 1992.
69. H. A. Kishawy, S. Kannan, M. Balazinski, Analytical modeling of tool wear progression during turning particulate reinforced metal matrix composites, *CIRP Annals - Manufacturing Technology*, vol.54, no.1, pp.55–58, 2005.
70. S. S. Joshi, N. Ramakrishnan and P. Ramakrishnan, Analysis of chip breaking during orthogonal machining of Al/SiCp composites, *Journal of Materials Processing Technology*, vol.88, pp.90–96, 1999.
71. K. Nakayama, A study on the chip breaker, *Bulletin of JSME*, vol.5, pp.142–150, 1962.
72. Y.Z. Zang, J. Peklenik, Chip curl, breaking and chip control of difficult-to-cut materials. *CIRP Annals*, vol.29, pp.79–83, 1980.
73. M. E. Gallab and M. Sklad, Machining of Al:SiC particulate metal-matrix composites Part I: Tool performance, *Journal of Materials Processing Technology*, vol.83, pp.151–158, 1998.
74. J. T. Lin, D. Bhattacharyya and C. Lane, Machinability of a silicon carbide reinforced aluminium metal matrix composite, *Wear*, vol.181–183, pp. 883–888, 1995.
75. S. Kannan, H. A. Kishawy, I. Deiab, Cutting forces and TEM analysis of the generated surface during machining metal matrix composites, *Journal of Materials Processing Technology*, vol.209, no.5, pp.2260–2269, 2009.
76. A. Manna and B. Bhattacharyya, A study on machinability of Al/SiC-MMC, *Journal of Materials Processing Technology*, Vol.140, pp.711–716, 2003.
77. S. Durante, G. Rutelli and F. Rabezzan, Aluminum-based MMC machining with diamond-coated cutting tools, *Surface and Coatings Technology*, vol.94–95, pp.632–640, 1997.
78. L. Iuliano, L. Settineri and A. Gatto, High-speed turning experiments on metal matrix composites, *Composites Part A*, vol.29A, pp. 1501–1509, 1998.
79. M. E. Gallab. and M. Sklad, Machining of Al:SiC particulate metal-matrix composites Part I: Tool performance, *Journal of Materials Processing Technology*, vol.83, pp.151–158, 1998.
80. M. E. Gallab and M. Sklad, Machining of Al:SiC particulate metal matrix composites Part II: workpiece surface integrity, *Journal of Materials Processing Technology*, vol.83, pp.277–285, 1998.
81. V. Songmene and M. Balazinski, Machinability of graphitic metal matrix composites as a function of reinforcing particles, *CIRP Annals*, vol.48, pp. 77–80, 1999.
82. N. P. Hung, T. Tan, Z. W. Zhong and G. W. Yeow, Ductile-regime machining of particle reinforced metal matrix composites, *Machining Science and Technology*, vol.3, pp. 255–271, 1999.
83. Z. Zhong and N. P. Hung, Diamond turning and grinding of aluminum-based metal matrix composites, *Materials and Manufacturing Processes*, vol.15, pp. 853–865, 2000.
84. C. J. E. Andrewes, H. Y. Feng and W. M. Lau, Machining of an aluminum/SiC composite using diamond inserts, *Journal of Materials Processing Technology*, vol.102, pp.25–29, 2000.
85. M. V. Ramesh, W. B. Lee, C. F. Cheung and K. C. Chan, A parametric analysis of cutting forces in single –point diamond turning of Al6061/ SiCp metal matrix composites (MMCs), *Materials and Manufacturing Processes*, vol.16, pp.61–78, 2001.
86. G. E. D. Errico, R. Calzavarini, (Turning of metal matrix composites, *Journal of material processing technology*, vol.119, pp. 257–260, 2001.
87. Y. Sahin, M. Kok and H. Celik, Tool wear and surface roughness of Al₂O₃ particle-reinforced aluminium alloy composites, *Journal of Materials Processing Technology*, vol.128, pp. 280–291, 2002.
88. Y.S. Varadarajan, L. Vijayaraghavan and R. Krishnamurthy, The machinability characteristics of aluminosilicate fiber reinforced Al alloy composite, *Materials and Manufacturing Processes*, vol.17, pp. 811–824, 2002.
89. A. Manna and B. Bhattacharyya, A study on machinability of Al/SiC-MMC, *Journal of Materials Processing Technology*, vol.140, pp.711–716, 2003.
90. Y. Sahin and G. Sur, The effect of Al₂O₃, TiN and Ti (C, N) based CVD coatings on tool wear in machining metal matrix composites, *Surface and Coatings Technology*, vol.179, pp. 349–355, 2004.
91. I. Ciftci, M. Turker and U. Seker, CBN cutting tool wear during machining of particulate reinforced MMCs, *Wear*, vol.257, pp.1041–1046, 2004.
92. Y. Sahin, The effects of various multilayer ceramic coatings on the wear of carbide cutting tools when machining metal matrix composites, *Surface and Coatings Technology*, vol.199, pp.112–117, 2005.
93. S. Kannan and H.A. Kishawy, Surface characteristics of machined aluminium metal matrix composites, *International Journal of Machine Tools and Manufacture*, vol.46, pp.2017–2025, 2006.
94. J. P. Davim, J. Silva and A. M. Baptista, Experimental cutting model of metal matrix composites (MMCs), *Journal of Materials Processing Technology*, vol.183, pp.358–362, 2007.
95. N. Muthukrishnan, M. Murugan and P. Rao, Machinability issues in turning of Al-SiC (10p) metal matrix composites, *International Journal of Advanced Manufacturing Technology*, vol.39, pp. 211–218, 2008.
96. S. Basavarajappa, Tool wear in turning of graphitic hybrid metal matrix composites, *Materials and Manufacturing Processes*, vol.24, pp. 484–487, 2009.
97. U. A. Dabade and S. S. Joshi, Analysis of chip formation mechanism in machining of Al/SiCp metal matrix composites, *Journal of Materials Processing Technology*, vol.209, pp. 4704–4710, 2009.
98. M. Seeman, G. Ganesan, R. Karthikeyan and A. Velayudham, Study on tool wear and surface roughness in machining of particulate aluminum metal matrix composite-response surface methodology approach, *International Journal of Advanced Manufacturing Technology*, vol.48, pp.613–624, 2010.
99. V. Anandakrishnan and A. Mahamani, Investigations of flank wear, cutting force, and surface roughness in the machining of Al-6061–TiB₂ in situ metal matrix composites produced by flux-assisted synthesis, *International Journal of Advanced Manufacturing Technology*, vol. 55, pp. 65–73, 2011.
100. A. Schubert and A. Nestler Enhancement of Surface Integrity in Turning of Particle Reinforced Aluminium Matrix Composites by Tool Design, *Procedia Engineering*, vol.19 pp.300 – 305, 2011.
101. N. Muthukrishnan, T. S. M. Babu and R. Ramanujam, Fabrication and turning of Al/SiC/B 4 C hybrid metal matrix composites optimization using desirability analysis, *Journal of the Chinese Institute of Industrial Engineers*, vol.29, pp. 515–525, 2012.
102. S. P. Dwivedi, S. Kumar and A. Kumar. Effect of turning parameters on surface roughness of A356/5% SiC composite produced by electromagnetic stir casting, *Journal of Mechanical Science and Technology*, vol.26, pp. 3973–3979, 2012.
103. S. Basavarajappa and J. P. Davim, Influence of graphite particles on surface roughness and chip formation studies in turning metal matrix composites, *Materials Research*, vol.16, pp.990–996, 2013.
104. P. Bansal and L. Upadhyay, Experimental investigations to study tool wear during turning of alumina reinforced aluminium composite, *Procedia Engineering*, vol. 52, pp. 818–827, 2013.
105. A. Kumar, M. M. Mahapatra. and P. K. Jha, Effect of machining parameters on cutting force and surface roughness of in situ Al-4.5%Cu/TiC metal matrix composites, *Measurement*, vol.48, pp.325–332, 2014.
106. P. Suresh, K. Marimuthu, S. Ranganathan and T. Rajmohan, Optimization of machining parameters in turning of Al–SiC–Gr hybrid metal matrix composites using grey-fuzzy algorithm, *Transaction of Nonferrous Metal Society of China*, vol. 24, pp.2805–2814, 2014.
107. S. K. Tamang and M. Chandrasekaran, Modeling and optimization of parameters for minimizing surface roughness and tool wear in turning Al/SiCp MMC, using conventional and soft computing techniques, *Advances in Production Engineering and Management*, vol.10, pp.59–72, 2015.
108. R. Kumar and S. Chauhan, Study on surface roughness measurement for turning of Al 7075/10/SiCp and Al 7075 hybrid composites by using response surface methodology (RSM) and artificial neural networking (ANN), *Measurement*, vol.65, pp. 166–180, 2015.



109. J. N. Muguthu, G. Dong and B. W. Ikuu, Optimization of machining parameters influencing machinability of Al₂124SiCp (45%wt) metal matrix composite, vol. 49, no.2, pp.217–229, 2015.

110. A. Gatto, L. Iuliano, E. Atzeni, P. Minetola and A. Salmi, On the behaviour of reinforcements beneath the surface in turning of metal-matrix composites (MMCs), Journal of Composite Materials, vol.50, pp. 2487-2494, 2016.

111. V. Hiremath, P. Badiger, V. Auradi, S. T. Dundur and S. A. Kori, Influence of particle size on Cutting Forces and Surface Roughness in Machining of B₄Cp – 6061 Aluminium Matrix Composites, Materials Science and Engineering, vol.114, pp. 1-10, 2016.

112. P. Bansala and L. Upadhyay, Effect of turning parameters on tool wear, surface roughness and metal removal rate of alumina reinforced aluminum composite, Procedia Technology, vol.23, pp. 304-310, 2016.

113. K. Erdogan and G. Ali, Investigations on Machinability of Al₂O₃ Reinforced Al6061 Metal Matrix Composites, Journal of Natural and Applied Sciences, vol.20, no.3, pp.434-441, 2016.