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Mechanical Machining and Surface Technology

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A

Project report on

METAL MATRIX COMPOSITES MACHINING

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INTRODUCTION:

Metal matrix composites (MMCs) are the materials with less density and higher specific properties such as strength and stiffness. These materials are combinations of two or more materials, exhibiting properties that are hard to obtain from a single material otherwise. In these combinations, one material acts as a matrix and the other acts as reinforcement. The matrix material distributes the stress applied over it to the reinforcement constituents which also protects and gives shape to the matrix material. The reinforcement provides the desired mechanical strength to the composite material in preferential direction. Probably the single most important difference between the fiber reinforcement and particulate composites or conventional metallic materials is the directionality of properties. Particulate composites and conventional metallic materials are isotropic, while the fiber reinforcement composites are generally anisotropic. Particulate reinforced composites offer higher ductility and their isotropic nature as compared to fiber reinforced composites makes them an attractive alternative. This particular material structure leads to the advantage of achieving higher performance when compared to their equivalent non-reinforced metallic alloys; where an increased strength of the MMCs compared with the monolithic material is depicted. On one hand, this is advantageous when using these materials in demanding applications but, on the other hand, makes the use of conventional machining processes more difficult. Particular hurdles to good machinability of MMC include, heterogeneous structure which leads to anisotropic thermal and mechanical properties thus the variable thermal and mechanical loading on cutting tools, as well as the abrasive nature of the reinforcing constituents which highly affects the tool life. Furthermore, the low machinability of MMCs could also lead to severe workpiece surface defects (e.g., micro/macro cracks of the matrix, pull-out of the reinforcement particles), which would further deteriorate the materials performance in their service life. Meanwhile, nonconventional machining methods, such as electro discharge machining-EDM, laser and abrasive waterjet machining, have also been employed for the machining of this type of materials aiming to achieve a high productivity. However, although these methods have a higher potential for MMCs machining over the conventional machining methods, different non-conventional machining processes have their own drawbacks in this application, which would lead to low unfavorable workpiece surface integrity.

METAL MATRIX COMPOSITES: MATERIAL DEFINATION

As a special type of advanced composites, MMCs have been applied in numerous industrial applications by providing better performance when compared with monolithic metals. MMCs refer to the composites consisting of at least two phases, in which the matrix maintains the shape of the material while the reinforcements provide the desired physical and mechanical properties. As shown in Figure 1, the main constituents used in MMCs are:

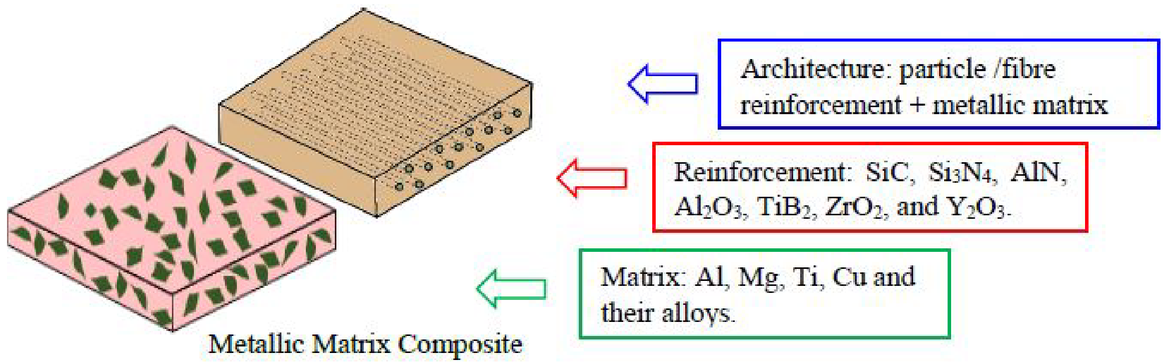

Figure 1: Generic structure of Metal Matrix Composites

i. Matrix: refers to monolithic metals which provides the compliant support for the reinforcements. The most common matrix for MMCs are light weight metals such as Al, Mg, Ti and their alloys.
ii. Reinforcement: refers to the constituents embedded in the matrix as either discontinuous particles (e.g., Sic, Al_2o_3, NiTi, Fullerene, Tio_2 and Graphite), monofilament continues fibers (e.g., SiC, W) or whiskers (e.g., C, SiC, W). The reinforcement is added mainly to change the physical properties such as thermal conductivity expansion coefficient and/or to modify the mechanical performance such as yield strength, wear resistance, creep resistance, matrix-reinforcement interfacial bonding strength.

In comparison with polymer composites, MMCs, generally, have higher quasi-isotropic stiffness, strength, hardness, and high thermal resistance in addition to, improved creep resistance, fatigue performance, toughness, and electrical properties. This improved performance results in an increased utilization of MMCs in high value-added industries such as nuclear, defense, automobile, aerospace, marine and electronics, as well as other commercial industries such as sport goods and medical equipment.

Machining of particulate reinforced Metal Matrix Composites:

After reviewing and studying about the reinforced MMCs from research papers, I got to know about the certain parameter and criteria for the MMCs that can affect the machining process. From the available literature on the machining of MMCs it is obvious that the reinforcement material, type of reinforcement (particle or whisker), volume fraction of reinforcement and matrix properties as well as the distribution of these particles in the matrix are the factors that affect the overall machinability of these composites. The most commonly used tool is polycrystalline diamond (PCD), although cubic boron nitrite (CBN), alumina, silicon nitride and tungsten carbide (WC) tooling are also used as cutting materials. Cutting speed, feed rate, depth of cut in machining of particulate MMCs have a similar effect on the tool life and surface finish to that of machining metals although some differences are noticeable due to the ceramic particles because it tends to dislodge from the matrix and roll in front of the cutting tool that is why the groove are there on the surface.

1) **Effect of cutting speed:**
   In most cases cutting speed does not significantly influence the cutting forces but there are some contradictory reports that shows during machining of MMCs a built-up edge has observed. Due to the BUE the cutting force at low cutting speeds is lower than the cutting force observed at higher speeds which resulted in either higher tool wear or increase the actual rake angle of the tool. For Al/SiC composite the feed force and cutting force decreased with an increase the cutting speed. The tool life decreases while the surface finish improves slightly with an increase in cutting speed since the tool temperature increase with cutting speed.

2) **Effect of Feed:**
   Feed has a significant effect on the cutting forces in that the cutting forces rise considerably with an increase in the feed. On the other hand, it influences negatively the surface roughness, where the surface finish deteriorates with an increase in feed. The interesting thing is that the high feed can reduce the tool wear rate due to improvement of the conduction of heat from the cutting zone to the workpiece. Yes, it increases the flank wear but only marginally as compared to the cutting speed.

3) **Effect of Depth of Cut:**
   Depth of cut has negative effect on the surface finish and the sub-surface damage. An increase in depth of cut decreases the quality of the surface finish and the sub-surface damage. Additionally, an increase in the depth of cut increases the machining forces during the machining od MMCs.

4) **Effect of Reinforcement:**
   The presence of the reinforcement affects the machinability of composites substantially. The hard ceramic particles in the matrix cause numerous problems, especially the excessive tool wear. The size and percentage volume fraction of the reinforcement play a significant role on the machinability of composites. The result

of machining according to some researcher that the tool wear and the surface finish are negatively affected by the particle size but according to other report that as the volume fraction of composites decrease the tool wear also decreases and subsequently affects the surface finish of the machined workpiece. In some research it is seen that the cutting speed and percentage volume fraction were the dominant factors in limiting the machinability of composites.

5) **Tooling:**
PCD diamond tools are the most preferred, while carbide tools are preferred over ceramic tools. In case of carbide tooling low-cutting speeds and high feed rates are utilized to maximize the tool life. High tool wear observed while machining of these composites is generally associated with carbide tooling. At higher speed the carbide tool demonstrates catastrophic failure and hence literature cutting speed is generally limited up to 300 m/min. In modern era tools with coatings such as TiN, TiCN and Al_2O_3 are used but with TiN coating performed the best in maximizing the tool life. Some research shows that to improve the tool life in carbide tools, machined at cutting conditions that sustained a astable built-up edge so as to protect the cutting tool. To minimize the surface roughness and sub-surface damage PCD tools are preferred since the wear associated with them is the lowest among the available tool materials. Although PCD tools are used for machining Al/SiC composites, the high cost associated with them limits their use.

Machinability of Metal Matrix Composites:

Machining of MMCs is known to be difficult due to both the presence of two or more distinct phases, one of which is very abrasive, and for the marked differences between the two constituents: the hard ceramic reinforcement and the ductile metal matrix. So that such parts always have to be machined to match the final design requirements. However, there are some approaches to take into account like toll performance, workpiece surface integrity, power required for material removal as well as type and shape of the chips, which can represent a serious problem to draw the removed material away from the cutting zone. In general, machinability can be described from an operating point of view by means of one or more than one of the following factors:

- Cutting tool wear and tool life
- Surface and sub-surface integrity
- Cutting forces and power

- Tendency to form BUE
- Chip formation

I. Cutting Tool wear and Tool Life:

The main wear mechanism when machining MMCs is abrasive wear. The predominant wear develops principally at the flank face of the tool, but abrasion marks also present on the rake face. Adhesion wear which can be associated with the formation of BUE, has often by detected in the material. Carter wear may also be present especially at the highest speed though it does not represent the determinant cause of toll failure. From one of the experiments with the SEM found that edge chipping can occur when machining Al-SiC using uncoated carbides can produce surface finish poorer than the coated ones, which is an opposite behavior to what generally occurs when machining homogeneous materials such as aluminum alloys.

Owing to the extremely abrasive nature of MMCs, only polycrystalline Diamond (PCD) brazed tools reach an acceptable life, since diamond is harder than SiC and Al_2O_3 and does not exhibit any chemical tendency to react with the workpiece. So as a general rule, HSS tools must be excluded, while cemented carbide tools, both coated and uncoated and even TiN coated high-speed steels can be an economic choice for short run productions.

II. Surface and sub-surface Integrity:

MMCs are usually designed to be applied in harsh conditions for various industries (i.e., nuclear, aerospace and defense) with their main advantages such as light weight, high wear resistance, elevated corrosion resistance, high strength and high stiffness. Thus, the workpiece surface integrity of MMCs after machining is a critical aspect which influences the components functional performance as well as the service life.

Surface integrity from the metallurgical point of view includes physical, chemical and metallurgical alterations or defects generated by plastic deformation, phase transformation and recrystallisation on the free surface and subsurface of the machined workpiece. The method called as Scanning Electron Microscopy (SEM) has been widely used to examine the microstructural changes of machined surfaces of MMCs, where the grain deformation voids, particles cracks and matrix tearing caused by high plastic deformation on metallic matrix as well as particles removal have been found on the workpiece surface and subsurface.

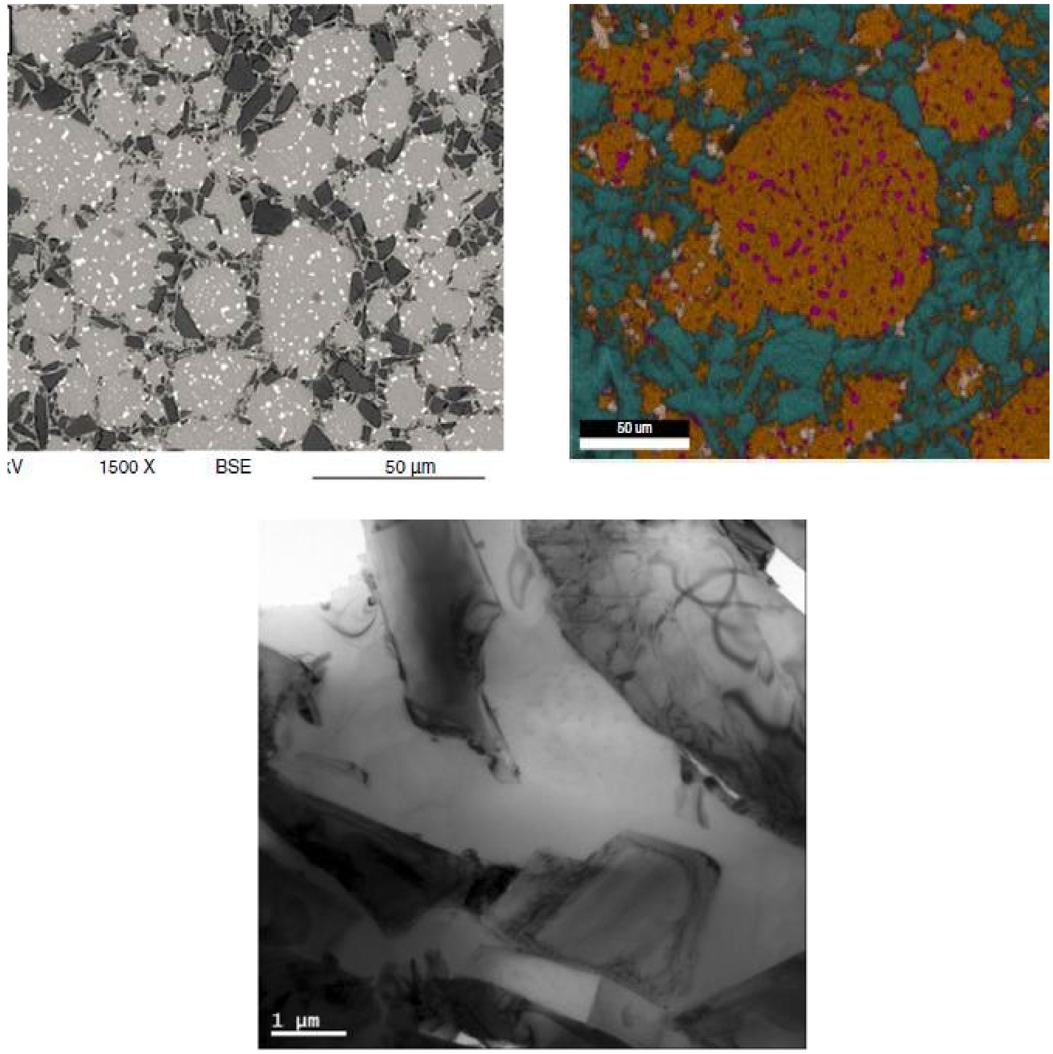

Figure 2: Surface metallurgical characteristics of MMCs detected by various measurement techniques like SEM, EDS mopping, EBSD

The changes in mechanical characteristics of MMCs after manufacturing operations are mainly contributed by the process induced stress, deformations and temperatures. The main mechanical characteristics, microhardness which are detected by the micro indentation tests is highly related to intergranular fractures, dislocation density and porosity distributions as well as the formation of a surface hardening layer. After reading the few research papers, the surface integrity mainly described by **Surface Roughness**, **Residual Stress** and **Hardness**. It is well recognized that the surface quality depends on cutting parameters and workpiece material properties.

III. Cutting Forces:

Cutting forces represent an important factor of machinability evaluation: Higher cutting forces means higher stresses on the tool, causing wear and vibrations and higher stresses on the material causing more damage at higher depth from the machined surface. Moreover, higher forces means that a larger energy is transformed into heat, thus giving rise to higher temperature of both tool and workpiece surface. The damage can consist of strain hardening, structural variations, debonding as well as residual stresses. In finish machining cutting forces should be kept low in order to minimize such damage, as well as to achieve better surface finish and tolerances.

The specific cutting force depends not only upon the material, but also on the cutting speed and chip thickness, which in turn depends on the feed rate and inclination angle of the cutting edge. Many authors have found that lower abrasive tool wear occurs at high feed rate and low cutting speeds, it follows that a reasonable compromise should be adopted in order to allow reduced tool wear and low cutting forces. Cutting forces also depend on the coefficient of friction between the tool and the material, therefore all conditions promoting the rising of BUE lead to an increase the cutting forces. Unfortunately, this tendency is particularly high for MMCs and the remedy consists in adopting high cutting speeds, though it has been noted that also at the highest speeds BUE cannot be totally eliminated.

1. The use of cutting fluids is not always recommended, since they can give crater tool wear by helping to maintain in contact the abrasive particles to the cutting tool. Since the cutting forces grow as the tool wear increases, due to the larger contact area against the workpiece, the quality of the machining, in terms of tolerances reduces if the tool material does not have a sufficient abrasion resistance.

IV. Chip Formation:

For good machinability, it is desirable to have continuous chips in short segments without the use of chip breakers. Even minor changes in the chip formation process can cause degradation of surface finish, poor dimensional accuracy as well as shorter tool life. Therefore, it is important to have short chips without employing tool breaker in order to have a continuous machining operation. Chip formation, and the related influence on the material removal from the cutting zone, is considered a crucial factor for increasing the number of applications of MMCs in industry.

Chip formation is influenced by ductility, thermal conductivity and microstructure; however, physical phenomena such as instability in the cutting process, e.g., the variation in the inclination angle can change the chip formation mechanism. Thermal conductivity influences both the thickness of the material undergoing temperature increase and mean temperature. In fact, as the thermal conductivity increases a thicker layer of material undergoes warming, while the mean temperature of the cutting zone decreases. This fact produces a change in the chip formation which tends to be more fragmented due to the more brittleness.

From one of the papers, I found that the chips produced in machining Al-Al_2O_3 MMCs, it has been noted that the particles tend to pile-up along the shear plane dividing the chip in small fragments. This phenomenon can further explain why MMCs tend to give discontinuous chips in a wide range of cutting speeds. In fact, the phenomenon has been found to be more evident as the cutting speed or feed increases due to the increased temperature which allows the particles to move more freely through the matrix. The same results have been obtained also when machining Al-SiC composites both in turning and in drilling.

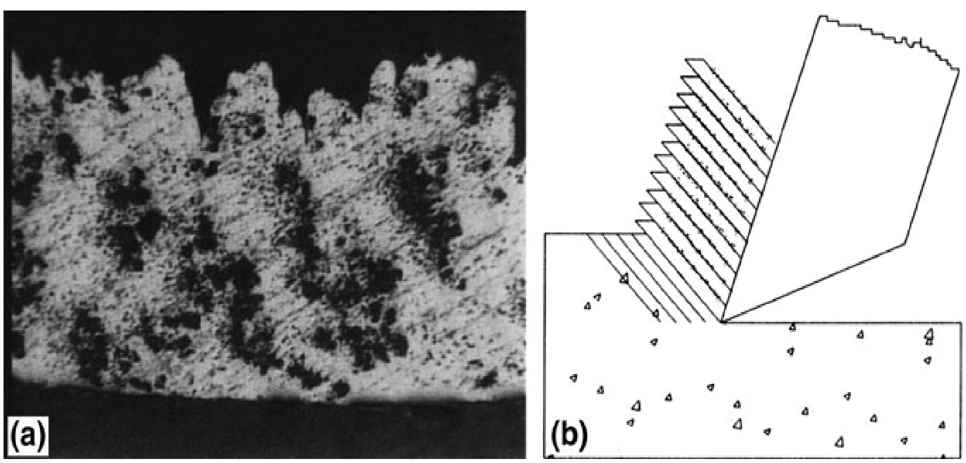

Figure 3: Concentration of reinforcing particles along the shear planes: a V_c = 1,000 m/min, f = 0.03 mm/rev; b pile-up formation according to the Pijspanen model

The crack formation is also influenced by the tensile residual stresses acting on the ductile matrix. These stresses are generated in the manufacturing process of the composite during cooling from the process temperature to the ambient one. Due to the larger coefficient of thermal expansion of the aluminum matrix with respect to that of the ceramic reinforcement, the residual stresses are tensile in the matrix and compressive in the reinforcement particles.

Conventional Machining of Metal Matrix Composites:

Conventional machining operations generally provide high geometrical quality of surfaces compared to non-conventional ones. By involving cutting tools, conventional machining can introduce high levels of plastic deformation and heat generation that lead to subsequent alterations of workpiece surface properties.

1. **Orthogonal cutting and turning of MMCs:**
   As a simplified cutting process, orthogonal cutting provides accessible tool for studying the cutting mechanics and surface integrity, which are not only controlled by process parameters but also by geometry, physical properties and volumetric concentration of the reinforcing constituents.
   Generally, in orthogonal cutting of MMCs the geometrical defects like micro-cracks, voids, pits and craters are predominantly formed due to particle fracture, complete pull-out and reinforcement/matrix interfacial debonding with particle left within the matrix, as shown in Figure. These defects are mainly relevant to the reinforcing constituents (e.g., average particle size and volume fraction) as well as selection of cutting parameters, which could lead to excessive cutting forces and temperature. It was found that strain hardening variation and hardened layer depth increased with decreasing cutting speed, increasing undeformed chip thickness and decreasing particle volume fraction.

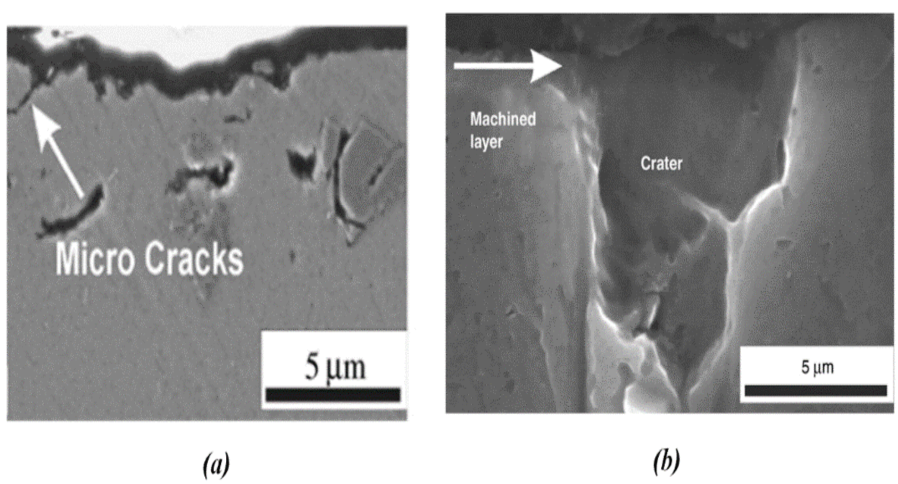

Figure 4: Typical machined surface/subsurface damage encountered when orthogonal cutting of Alumina reinforced aluminum 6061 matrix composite

One Author also found the same while examine the dislocation within the machined subsurface of Alumina reinforced AA6061 MMC. As shown in the figure below, with an increase in reinforcement density or size, the length of dislocation lines are increased due to larger activation energy required to subsequently deform at the same cutting parameters and tool/workpiece configuration.

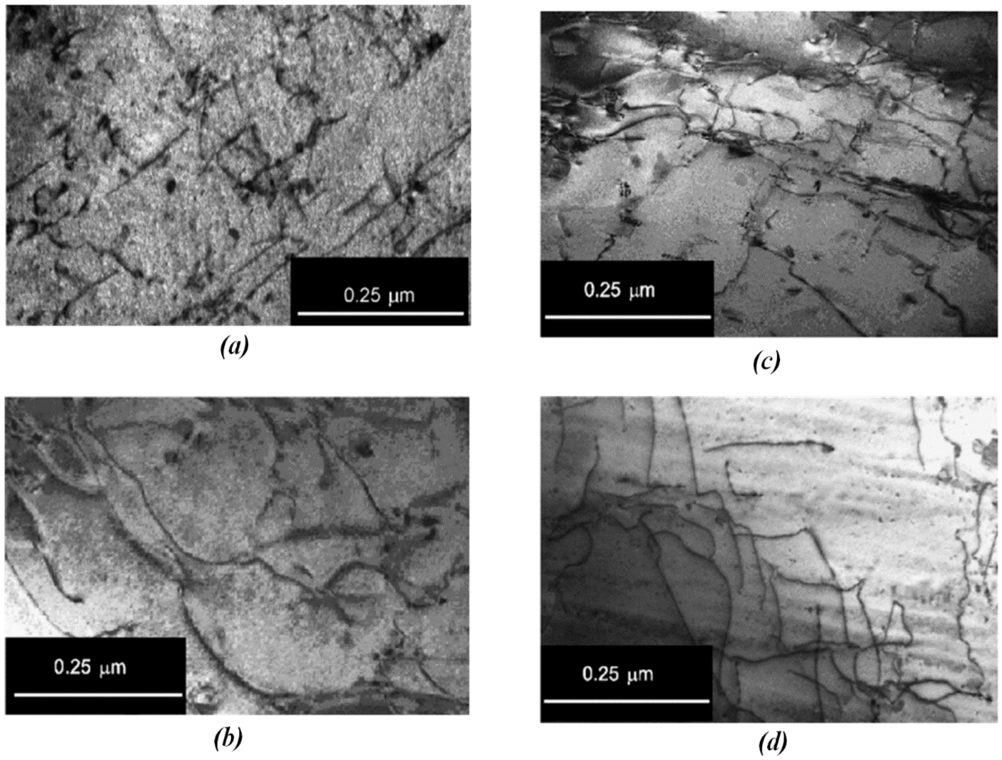

Figure 5: Line defects/dislocations formation during cutting Alumina reinforced 6061 MMC (v: 30-60 m/min, uncut chip thickness: 0.1 mm, DoC: 3 mm) with particle size 9.5 µm (a), 25 µm (b), volume fraction 10% Alumina (c) and 20% Alumina (d)

One more thing from the point of view of geometrical accuracy that the greater thermal loads on the workpiece during the machining process could also be overcompensated the significantly lower coefficients of thermal expansion of the MMC that is influenced by the reinforcement constituents. These significantly lower coefficients of thermal expansions cause a smaller expansion of the MMC workpiece, despite the greater the thermal load.

Among other conventional cutting process, turning of MMCs is facing the challenge of intense tool wear with alteration of the surface integrity for a given tool life. One Author showed that coolant usage detrimentally affected the surface integrity when turning process carried out for AA7075-10% Alumina. For Alumina matrix, being cut under dry conditions would have higher tensile residual stresses in the aluminum matrix than in wet conditions due to the thermal expansion of affected layer. The introduction of higher tensile residual stresses leads to tearing of the softened material under tool flank and formation of surface cracks in dry conditions, as shown in figure below.

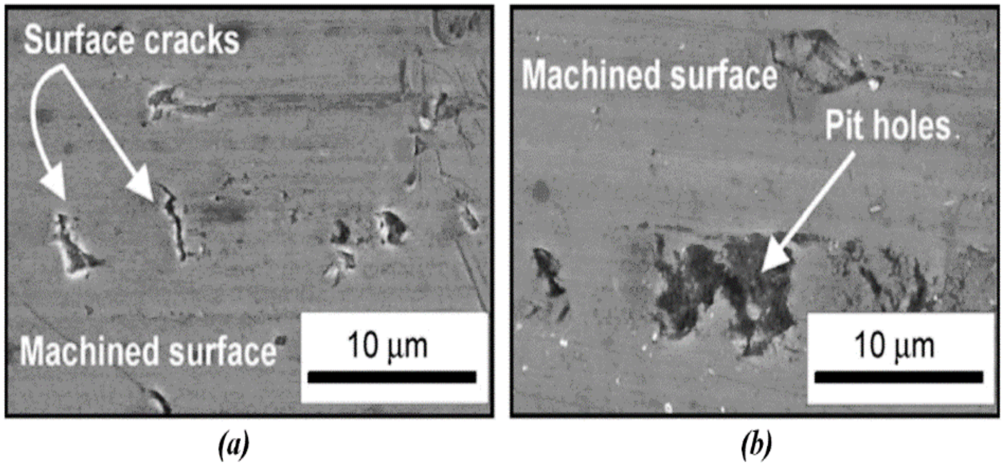

FIGURE 6: Influence of coolant on the nature of defects on the machined surface (a) Dry Cutting & (b) Wet Cutting

2. **Drilling, Milling and Grinding:**

Drilling and milling involve multi-cutting edges tools with complex geometrical features and tool move trajectories, whereby built-up of the temperature or dynamic loads could be generated that would affect the surface finish. From studied of AL356/SiC-Mica MMC using WC coated and uncoated drills beside PCD tools there are two results were there.

(1) The increased percentage of Mica in the MMC reduced the cutting forces, tool wear and surface roughness significantly due to the probable solid lubricant effect.

(2) The increase of feed rate exhibited extensive surface damage due to increased contact pressure at the tool nose/flank.

These two later results in surface crack sue to work hardening and heat generation which cause matrix reinforcements interface fracturing under mismatched thermal expansion and subsequent particles pull-out.

High dimensional accuracy and surface finish are generally achieved using grinding process. Nevertheless, the dissimilar physical and mechanical properties of reinforcement (hard) versus matrix (soft) of the composites complicates the grinding process of MMCs. In fact, during the grinding process the soft matrix tend to adhere to the grains and close the grinding wheel structure, thus increasing the forces and consequently the temperature of the ground material. Recent studies on the grinding of MMCs showed that electroplated wheels are generally used for grinding of MMCs due to their high hardness, low wear rate and high thermal conductivity but using resin-bonded abrasive wheels and single-layer brazed wheels has been reported to show better performance in terms of reduced cutting forces, reduced workpiece temperature and enhanced surface finish.

Literature Survey:

As MMCs contain certain amount of hard abrasive and ceramic reinforcements hence they are considered as most difficult materials for machining. The study done on machining of hybrid Al-SiC metal matrix composite using polycrystalline diamond (PCD) tool on a CNC lathe they concluded that % volume fraction of SiC shows more effect on forces, whereas spindle speed and feed rate are highly affected parameters for flank wear and surface roughness. The investigation of turning of Al/SiC/Gr MMC component and concluded that surface roughness increases with the increase in feed rate and depth of cut. The investigation on the machining behavior of metal matrix composite using PCD inserts and concluded that PCD 1600 grade is subjected to less force due to the fine grains and its stability at high cutting speeds, the machining with low feed has resulted in decreased cutting force in all grades of PCD. Machining of MMCs can be classified in two major groups: (a) particulate reinforced and (b) fiber reinforced. Depending on the type of reinforcement the cutting mechanics differ considerably, hence the tool – reinforcement-matrix interaction play a major role in the machinability of MMC’s and affect the surface roughness, cutting forces, tool wear and the subsurface damage. The most commonly used tool material is polycrystalline diamond (PCD) also cubic boron nitride (CBN), alumina, silicon nitride and tungsten carbide (WC) tooling are used as cutting materials. Cutting speed, feed and depth of cut in machining of particulate MMC’s have a similar effect on tool life and surface finish to that of machining metals but some differences are noticeable due to the ceramic particles. The ceramic-reinforced particles tend to dislodge from the matrix and roll in front of the cutting tool hence plowing through the machined surface and generating grooves on it. In many cases cutting speed doesn’t significantly affect the cutting forces there are some differences in reports on the effect of cutting speed on the cutting forces. During machining of MMC’s built - up edge (BUE) has been seen by many researchers while machining these composites at low cutting speeds, due to the built – up edge the cutting force at low cutting speeds is lower than the cutting force observed at higher cutting speeds. The presence of BUE increases the actual rake angle of the tool resulting in a lower cutting force, there are some reports which have shown a decrease in the cutting forces with an increase in the cutting speed. For broad machining applications there is wide range of cutting tool materials of different properties and performance capabilities are available today. These include High speed steels, Satellite, cemented carbides (coated & uncoated), Ceramics, Cubic Boron Nitride (CBN) and Diamond (synthetic& natural) as MMC's have high hardness, CBN and diamond are also referred as super or ultra-hard materials. The published research on the machining of particulate MMC's indicates that only cutting tools harder than the reinforcements have acceptable performance. The poly-crystalline diamond (PCD) tools given their high hardness compared with most of the common reinforcements provide longer tool life but due to high cost of PCD tools other tools such as cemented carbides and ceramics are also been used to machine particulate MMC's. Ceramics tools were performed unsatisfactory while the carbides were preferred over other types when machining at low cutting speeds and high feed rates. Some researchers observed the effect of different coatings on the performance of carbide cutting tools during machining MMC's and suggested that coatings with less hardness than those of the reinforcement do not improve tool performance. Many researchers have observed that the change in average particulate size and volume fraction of reinforcement greatly affects the machining characteristics of MMC's. The available coated tools having coating such as titanium nitride and titanium carbide perform well while cutting steel but show very poor performance in cutting MMC's. Also, TiAIN coated tools show mediocre results in machining of Al + 20% SiC. The tool wear increases rapidly when the percentages of reinforcement particles in the MMC exceed a critical value. This critical value is determined by the size and density of the reinforcement particles by the use of conventional single-point cutting tool during machining, a small part of the cutting edge is continuously subjected to extremely high temperatures and cutting forces due to this there is excessive wear along the area of contact.

CONCLUSION:

- From literature survey it is concluded that the metal matrix composite has unique properties due to which they are replacing traditional metals and alloys in several applications, there widespread applications is limited due to the difficulty in machining because of the presence of reinforcement particles which are hard, stiff and abrasive in nature.
- Many researchers indicated that poly-crystalline diamond (PCD) is the only tool material which gives useful tool life while machining SiC/Al particulate metal matrix composite, also the selection of appropriate grade poly-crystalline diamond

(PCD) tool is a right decision while considering tool life and quality of machined surface required.

- Several researchers used self- propelled rotating tools while machining MMC's and compared with conventional cutting tools and observed that rotating cutting tools shows excellent performance in terms of progression of tool wear and tool life and at high feed and cutting speeds rotary tools shows super wear resistance.

- For the improvement of production rate rotary tools are the best suitable candidate, as poly–crystalline diamond (PCD)most commonly used tool material although cubic boron nitride (CBN), alumina, silicon nitride and tungsten carbide (WC) tooling are also used as cutting materials.

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