CHAPTER 3

MACHINING Al–(SiC)ₚ MMC WITH ADVANCED CUTTING TOOLS

3.1 NEED FOR MACHINING Al–(SiC)ₚ COMPOSITES.

Since the 1970’s the metal matrix composites have been successfully applied in the aerospace industries (Dermarkar 1986 and Trumper 1987). Most of the parts obtained with aluminium matrix composites through different manufacturing processes have different geometry and usually need machining operations with the required dimensions and geometric precision as well as good surface finish. The machining of composite material differs from the conventional material by the way of presence of harder and isolated reinforcements in the path of tool during machining. This characteristic leads to difficulties in machining of these composites, primarily due to rapid wear of the cutting tools.

Performances of cutting tools are usually evaluated based on different criteria. Some of these are: tool wear such as flank wear, crater wear, surface quality and cutting force. Depending upon the requirement either one or more of these criteria is used. In this study the performance of various cutting tools are evaluated by studying the flank wear and its associated mechanism and the surface quality. The cutting tool performance was analyzed by varying the reinforcement SiC in the Al matrix.
In this chapter, the experimental procedure, the results and discussion of the machining studies using carbide, coated carbide, cermet, diamond tools in turning and H.S.S cutters with or without cryogenic treatment and TiN coating in milling of Al-(SiC)_p composites are presented. The performances of the cutting tools were analyzed by varying the SiC volume percentage in 6061 and 6025 base alloy.

3.2 MACHINABILITY STUDIES ON 6061 Al-(SiC)_p COMPOSITES

The SiC reinforced in 6061 aluminium alloy is one of the most common materials in usage among the several composites which are available commercially. A continuous problem with the particle reinforced 6061 Al-(SiC)_p matrix composites is that they are difficult to machine on account of hardness. Ramrattan (1996) reported that conventional tool materials such as high speed steel cannot be used for machining Al-(SiC)_p MMC’s since the reinforcements are significantly harder than the conventional tools. Hence in this study 6061 Al-(SiC)_p composites are machined with carbide, coated carbide and diamond tools and their performance were compared. The performance of the cutting tools is compared in terms of flank wear and surface roughness of the machined component. The cutting tests were carried out while varying the percentage of SiC in the base alloy between 10-25 volume percentages.

3.3 EXPERIMENTAL PROCEDURE

3.3.1 Cutting Tool inserts

Machining tests were carried out using carbide, coated carbide and diamond tools on a precision lathe (P.S.G. model No A:141) having 12 spindle
speeds and 10 table feeds with a maximum speed of 2000 rpm. Three types of cutting tool inserts were used. They are

i. Carbide (P20)
ii. Coated carbide (GC3015) and
iii. Diamond

The geometry of the carbide tool and specifications make of different tools are given below.

<table>
<thead>
<tr>
<th>Back rake angle</th>
<th>Side rake angle</th>
<th>End cutting edge angle</th>
<th>Side cutting edge angle</th>
<th>End relief angle</th>
<th>Side relief angle</th>
<th>Nose radius (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10°</td>
<td>15°</td>
<td>10°</td>
<td>10°</td>
<td>6°</td>
<td>6°</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Carbide tool tip. Grade P20
Coated Carbide tool tip Grade: GC 3015

The coated carbide tool (GC3015) has a thick CVD coating of TiCN, Al₂O₃ and TiN Diamond

3.3.2 Machining Parameters

Machining studies were conducted in 6061 Al-(SiC)p metal matrix composites using the above mentioned cutting tools at different speeds and at
constant feed rate and depth of cut. Since the Al-(SiC)_p MMC is a new type of material, standard cutting data are not readily available. Tomac (1992) selected the cutting parameters to machine Al-SiC composites by considering it as a hard aluminium alloy. Based on this criteria the cutting conditions to machine 6061 Al-(SiC)_p composites were selected and given in Table 3.2. All machining experiments were conducted at dry condition.

Table 3.2 Machining parameters

<table>
<thead>
<tr>
<th>Sl.No</th>
<th>Tool</th>
<th>Speed (m/min)</th>
<th>Feed (mm/rev)</th>
<th>Depth of cut (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Carbide</td>
<td>50, 80, 110</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>2</td>
<td>Coated carbide</td>
<td>65 and 110</td>
<td>0.1</td>
<td>0.8</td>
</tr>
</tbody>
</table>

3.3.3 Work material

A set of 6061 Al-SiC MMC specimens with varying volume percentage of SiC namely 10, 15 and 20 were machined. The composition of the base alloy is given in Table 3.3.

Table 3.3 Composition of 6061 Aluminium alloy

<table>
<thead>
<tr>
<th>Zn</th>
<th>Mg</th>
<th>Cu</th>
<th>Fe</th>
<th>Mn</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.6%</td>
<td>2.8%</td>
<td>0.4%</td>
<td>0.18%</td>
<td>0.56%</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

The base alloy was reinforced with SiC particulate of size (40 microns)
3.3.4 Observation

The main objective of the present study is to evaluate the performance of different cutting tools on machining 6061Al-SiC MMC composites. The performance of the cutting tool was evaluated by measuring the flank wear and surface roughness on machined work piece. The cutting tool wear was measured with a profile projector (MAGOMI) at 25X magnification. The machining time was accurately measured with a stop watch. The machining was stopped periodically to measure tool wear and surface roughness of the material. The profile of the wear on different cutting edges was traced. The surface roughness was measured using surface measuring instrument (Kosaka SE 40 G) and the surface roughness value Ra was recorded. Scanning Electron Microscope (Leo, Model 420, Germany) was used to study the worn surfaces of the cutting tools.

Every cutting tool when put to use is subjected to wear. Among the tool wear, the flank wear that appears on the flank surface parallel to the cutting edge is the most important one. The average width of the wear is normally measured while making a comparison or specifying the end of tool life. The average width of allowable flank wear varies from 0.2mm for a fine turning to 1mm for rough turning for a rough turning operation (Machine tool data handbook 1980).

The flank wear is predominantly influenced by the cutting speed and high feed rate. However, the effect of increased feed rate on flank wear is much less when compared to the influence of the cutting speed. The effect of the
cutting speed, feed rate, while machining Al-SiC composites with different cutting tools are given below.

3.4 PERFORMANCE OF CARBIDE TOOLS ON MACHINING 6061 Al-SiC COMPOSITES

Al-SiC composites with 10% and 20% vol of SiC was machined with carbide tools cutting speeds ranging between 50m/min to 110m/min with a depth of cut of 0.8mm and feed as 0.1 mm/rev. At few selected intervals of time, the profile of the tool tip was observed and shown in Figure 3.1 to 3.6.

Figures 3.1 to 3.3 display the profile of the uncoated carbide tips while machining Al-10 %(SiC)_p at the cutting speeds 50m/min, 80m/min and 110m/min respectively. The profiles of the tool tip traced at cutting speeds 50m/min, 80m/min, 110m/min while machining Al-20 %(SiC)_p are shown in the Figures 3.4 to 3.6 respectively.

From the profile of the tool tip, the shape of the wear area of the tools appears to be an inverted triangle below the corner of the tool. It partially includes the major flank and the minor flank of the cutting tool. It was also found from the tool profiles that abrasion is the major wear mechanism. Abrasion is characterized by the development of grooves and ridges in the direction of the tool sliding against a new machined surface of the work piece. The reinforced SiC which is present in the work piece increases the abrasive wear as it comes in between the work piece and the tool pair.
Studies on the failure pattern of carbide tool in intermittent cutting reveals that the tool edge fracture is invariably preceded by the development of micro or macro cracks (Zorer 1963, Bhatia 1978). Pandey et al (1979) termed this type of failure of carbide tool as fracture.

In Al-(SiC)p composites, the load required to shear the base alloy and the reinforcement SiC are different. The load required to shear the base alloy (Al) is less in comparison with the reinforcement (SiC). Under these conditions repeated stress applications due to the SiC particles in the Al-SiC matrix cause parallel type of cracks appearing very near to the cutting edge. This phenomenon can be correlated to the very high wear lands on the edges. Yanming (2000) observed while cutting the composites reinforced by SiC particles, some abrasive tracks along the cutting direction form the surface of the worn tool. However, since aluminium is an active metal, adhesion wear may also occur on the face of the tool. The combined effect of these severe stresses and adhesion results in brittle crack on the tool edge or at the tool corner of the carbide tools (Yanming 2000, Bhatia et al (1978) and Okushima et al (1967)) correlated the origin of these cracks with cyclic temperature fluctuations of the tool-chip interface and mechanical impact. Pandey (1979) observed that the tool edge at the vicinity of the material is subjected to these severe stresses which can approach the tool materials yield strength. In this case the load required to shear SiC is more than the yield strength of the carbide inserts.

3.4.1 Flank wear

Flank wear is the result of intensive rubbing between the newly generated work piece surface and the flank face adjacent to the cutting edge. Figure 3.7 shows the increasing level of flank wear marks on the flank surface of the carbide tools. In a normal wear curve, there is an initial rapid wear.
Figure 3.1 Profile of the uncoated carbide tool tip on machining Al-10% (SiC)_p at 50m/min

Figure 3.2 Profile of the uncoated carbide tool tip on machining Al-10%(SiC)_p at 80m/min
Figure 3.3  Profile of the uncoated carbide tool tip on machining Al- 10\%(SiC)\textsubscript{p} at 110m/min

Figure 3.4  Profile of the uncoated carbide tool tip on machining Al- 20\%(SiC)\textsubscript{p} at 50m/min
Figure 3.5 Profile of the uncoated carbide tool tip on machining Al-20%(SiC)_p at 80m/min

Figure 3.6 Profile of the uncoated carbide tool tip on machining Al- 20% (SiC)_p at 110m/min
followed by a steady wear period and then the territory stage. The wear on carbide tool on machining Al-10% SiC at 50 m/min reaches the permissible wear limit for fine turning (0.4mm) even before a cutting length of 100m (2min). Maintaining the same cutting condition for Al-20% SiC, it lasted less than 2 minutes. Analyzing Figure 3.7 shows that when the SiC volume percentage in the aluminium alloy is more, then there was no distinct phase difference in the curve. The curves are steeper when the SiC in the matrix is more than 10%.

The reason for aggressive abrasive wear on the tool can be explained by the SiC particle's path in the work piece during the turning process. When MMC work piece is turned, the aluminum alloy matrix will be deformed by the cutting edge to form a chip. When there is a SiC particle at the splitting point, the particle will impinge on the cutting edge. As the tools are brittle, the impingement will initiate a crack or propagate an existing crack without causing much plastic deformation on the cutting edge. Consequently it results in any one of the following two cases.

In the first case, the SiC particles centroid is above the line of the cutting force exerted by the cutting edge. As the SiC particle is much harder than the carbide, it is more likely to be moved than cut or broken (Tomac 1992). As a result of this anticlockwise movement created by the cutting edge, the SiC particles is likely to roll towards the rake face of the cutting tool and move in the direction of the chip flow. Quigley et al (1994) also experienced the above SiC pull out behaviour. During the dislodgement of the SiC particle from the work piece, it ploughs through the work piece.
Figure 3.7 Progress of flank wear on carbide tool
In the second case, the SiC particle's centroid is below the line of cutting force exerted by the cutting edge. In this case, after impinging on the cutting edge, the SiC particle will be pressed into by the tool's flank face such that it is embedded into the matrix, it ploughs on the tool flank face and creates a groove on the flank face as well as on the work piece surface. The dislodged or embedded SiC particle hits a neighboring SiC particle, its movement will be impeded. Due to this impede, SiC particle will receive additional resistant forces from the interface. This additional resisting forces damage the tool, since the hardness of SiC (Knoop hardness$\approx$2400 Kg/mm$^2$) is higher than that of tungsten carbide (Knoop hardness $\approx$1500 Kg/mm$^2$). The interface between SiC particles is a secondary mechanism that increases abrasion and causes excess wear on the cutting tool. The SiC particle interface that increases the tool abrasive wear rates varies with the SiC percentage in the Al-SiC MMC.

3.4.2 SEM Observations of Flank and Rake Surface of the cutting Tool

For efficient machining, the cutting tool has to maintain a correct wedge. The shape of the wedge in machining is decided by many factors like tool material, work material, cutting conditions etc. Difficulty in maintaining the wedge results in flank wear which upsets the wedge geometry and the dimensional tolerance (Buljan and Sarin 1980).

The flank wear is caused by many mechanisms and the dominant ones are

i. Abrasion of the tool flank face and also rake face by the just machined surface and the reinforcing particle.
ii. Possible erosion of the flank face due to impingement of the flying hard machined particles.

iii. Shearing of tool material on the clearance face by the principal cutting force

iv. Possible chemical reaction between the tool and the work piece.

v. Microspalling of the grains near the cutting edge.

During the machining any one or more of the above mentioned mechanism might be operating. To understand the wear mechanism involved in flank wear, scanning electron microscope studies have been carried on the carbide cutting tools.

Flank wear is caused by intense sliding of the just machined surface over the tool. This flank wear could be associated with abrasion, discrete localized small scale deformation of asperities over the tool flank. Flank wear is usually the dominating wear on the flank face which is also observed at the rake face. Gallab and Sklad (2000) has observed that the flank wear in cutting tools while machining Al-(SiC)p composites are caused mainly due to the abrasion of the work piece with the tool at the tool work interface. The severity of the abrasion can be increased in cases where the work piece materials contain more vol% of SiC particles. The wear by abrasion is usually due to crack development at the intersection caused by hard asperities or wear particles acting as small indenters on the cutting face. In many cases, the abrasive action is attributed to special features on the flowing chip which is characterized by a serrated profile along its edges and also by the broken chips of irregular shapes caught in between the tool and the work piece. This type of serrated chips and
broken chips abrade the tool material under high cutting speed creates scar and grooves on the tool material.

The abrasion and flank wear in the carbide tool on machining Al-10% SiC are shown in Figure 3.8(a) and Figure 3.8(b) respectively. These grooves are very deep as vol% of SiC in the base alloy and cutting speed is increased and mostly parallel in direction with the cutting direction which is shown in Figure.3.9. Weinert (1993) observed that these grooves are due to micro cutting of SiC particles. Al-(SiC)p composites have lower plasticity and toughness as well as a low melting temperature. The above properties of these composites results in neither remarkable crater wear nor oxidation or diffusion wear at the rake face. However, rubbing of SiC particles with the cutting tool as well as with the tool leads to the adherence of the Al at the rake face. Even though there was no severe crater wear, it has edge cracking at the nose as well as at the cutting edges (Figure 3.10). The results of machining studies on aluminium (Konig et al 1983) indicate that machining is susceptible to adhesion with the cutting tool and to build up in the chip space. This build up edge starts from the rake face and runs into the flank face also. This build up edge can be seen clearly in Figure 3.8a and Figure 3.9a. Yanming (2000) also reported that the adherence of the Al material with the rake face. These observation show that the carbide tools are subjected to edge breaking and abrasive wear mechanism while machining Al-(SiC)p composites.

Tool wear occurs during the friction between the tool and work piece. Increase in cutting speed would induce the reinforcing particles to scrape and shock the tool more violently. The tool which was subjected to the violent behaviour of the reinforcing particles results in brittle break of the tool more
Figure 3.8 SEM photograph of flank wear surface of carbide tool on machining Al-10 % SiC (a) at low (b) at high magnifications
Figure 3.9  SEM photograph of flank face of carbide tool on machining Al-20 % SiC at (a) low (b) high magnifications
Figure 3.10  SEM photograph of Rake face of carbide tool on machining Al-10 % SiC (a) at 250X (b) at 50 X.
easily and shortens the life. The breaking of flank and rake face of the tool is increased with increased vol % of SiC which is shown in Figure 3.11. The increase in vol % SiC strains the matrix material more and increases the abrasive marks and also grooves and breaking of the edges very quickly.

Examination of the rake face of the tool shows a crater within which are remains of the some of the metallic layer (Figure 3.10 a and b). In other places, where this layer has been removed, the surface is smoothly grooved as though by plastic deformation. Within these grooves, a close examination revealed (Figure 3.10 a and 3.11 b) the occurrence of progressive wear of the carbide substrate as indicated by the parallel scoring in the direction of chip flow. These marks are most likely to have been scored by plastic deformation as SiC and carbide particles are detached and removed from the chip tool interface (Farhat Nabhani 2001). These scoring and plastic deformation are increased with increased SiC volume percentage in the base alloy. Figure 3.11(b) shows these marks when Al-20% SiC was machined. Hence the SEM study confirms that failure of carbide tools while machining Al (SiC)_p composites was due to abrasion and edge breaking mechanism. The size of the BUE formed is reduced during the course of machining and also removes the part of the tool. The removal of the part of the tool results in abnormal increase in wear of the tool.
3.5 PERFORMANCE OF COATED CARBIDE TOOL ON MACHINING 6061 Al–(SiC)p COMPOSITES

Advances in the synthesis of chemically stable and hard coating materials using various chemical and physical vapour deposition techniques have greatly enhanced the machining efficiency. Cemented carbide tools coated with the single or composite nitrides, carbide and oxide layers represent the majority of inserts used in various metal cutting applications. In this present study carbide tool coated with layers of TiCN, Al2O3 and TiN was used to machine Al-(SiC)p composites. The effect of the coating on the carbide was evaluated by varying the cutting speed and vol % of SiC in the base alloy. The cutting conditions selected for this study are cutting speed 65m/min and 110m/min at depth of cut 0.8 mm and at feed 0.1mm/rev. The SiC % in the base alloy was varied between 10 and 20%. The efficiency of the coated tool was evaluated in terms of flank wear of the cutting tool and surface finish produced on the machined component.

3.5.1 Wear profile

The condition of the coated tool cutting edges was traced in a profile projector. The cutting edges traced at different cutting speeds and volume percentage of SiC are shown in Figures 3.12-3.17. The traces of the coated tool tips on machining Al-10%(SiC)p cutting speeds 65m/min and 110m/min are shown in the Figures 3.12 and 3.13 respectively while Figures 3.14 and 3.15 show the same for Al-15%(SiC)p. The profiles of the coated tool while machining Al-20 %(SiC) at cutting speeds 65m/min and 110m/min are shown respectively in Figure 3.16 and 3.17. From the profiles it was observed that the
Figure 3.11SEM photograph of rake face of carbide tool on machining Al-20 % SiC (a) at 200X (b) at 100 X.
Figure 3.12 Profile of the coated carbide tool tip on machining Al-10\%\,(SiC)\_p at 65m/min
Figure 3.13  Profile of the coated carbide tool tip on machining Al- 10%(SiC)$_p$ at 110m/min
wear along different cutting edges is very minimal in comparison with carbide tool at low cutting speed and volume % of SiC. The wear on different cutting edges increases rapidly as the cutting speed and volume % of SiC increases. The chemical affinity of the Al material with TiN tends to form BUE in the rake face. The BUE formed grows and suddenly sheared off due to the SiC particles from the cutting edge are shown in Figures 3.14 to 3.16. Roy et al (2001) confirmed that the function of such BUE was due to the tribological condition at the cutting zone. When ductile material like aluminium was machined with a coated tool in a dry turning process resulted in formation of BUE. The size of the built up edge formed is reduced during the course of cutting action and plucks some part of the tool. The plucking of the tool results in abnormal increase in wear of the tool.

The progress of flank wear as a function of cutting distance in the coated carbide tool is shown in Figure 3.18. From the graphs, it is clear that the flank wear on the coated tool was rapid and uniform.

When turning Al-SiC MMC with coated carbides, the coating was rapidly removed from the tools, and the dominating wear occurs at the flank face of the tool. It was also observed that the wear on the multilayer coated carbide tools was rapid and uniform. Based on the results, the Taylor’s exponent is calculated as n=0.95. This is very high value, which means that the tool life is only to a small extent affected by the cutting speed. As observed by Klocke and Kriegen (1996), even though the hardness of TiN and Ti-(CN) are quiet similar, its resistance to the initial abrasive wear was low. The high chemical affinity of TiN is attributed as the reason for the high wear rate. The coating is dissolved by the mechanical, thermal and tribo-chemical stresses in
Figure 3.14 Profile of the coated carbide tool tip on machining Al-15\%(SiC)\textsubscript{p} at 65\text{m/min}
Figure 3.15 Profile of the coated carbide tool tip on machining Al-15\%(SiC)\_p at 110m/min
Figure 3.16  Profile of the coated carbide tool tip on machining Al-20% (SiC)\textsubscript{p} at 65m/min
Figure 3.17 Profile of the coated carbide tool tip while machining Al-20%SiC at 113m/min
Figure 3.18 Progress of flank wear on coated carbide tool
the contact zone and cannot protect the tool against the wear. Apart from that, the surface hardness of the hard film coated tool may be higher than that of SiC, yet the coating layer is thinner, and there is a transitional structure which is brittle, between the matrix of the tool and coating. Also the process stress of coating exists, so that some of this coating would be scrapped. Consequently the partial coating spalls and cracks spread in the adjacent coating, so that the tool loses the protection of the coating after a very short period. The coating spalling and crack propagation mechanism was also experienced by Yanming (2000).

In metal cutting the study of chip formation is the most effective and cheapest way of understanding the machining characteristic of material. The focus of this study is on the influence of volume reinforcement on chip formation and machining characteristics of these materials.

The chips collected during Al-(SiC)$_p$ machining are presented in Figure 3.19. It was observed that the chips showed a systematic breaking pattern of the chips are analyzed based on the physical characteristic of chips such as the number of circles through which chip curls.

3.5.2 Analysis of chip appearance during Al-(SiC)$_p$ machining:

Chips produced with a coated carbide tool at a cutting condition of cutting speed 65 m/min, depth of cut 0.8 and feed 0.1 mm/rev. In Figure 3.19 the chips are arranged from top to bottom with increasing volume of reinforcement in composites. These Figures show that the number of circles through which chips curl before breaking decreases as the volume of
reinforcement increases. Chips of unreinforced alloy break after producing a long continuous ribbon chip. While the number of chip circle decreases to 5-6 circles in case of Al-10%(SiC)$_p$ composites and 2-3 circles in the case of Al-15%(SiC)$_p$. The number of circles before breaking was decreased to 1-1½ circles with some powdery form in the case of Al-20%(SiC)$_p$ and chips of powdery form with a small circles in the Al-25%(SiC)$_p$. It was also observed that as the volume of reinforcement in the composite material increases, the chips curl through smaller radii.

Joshi (1999) explains the decrease in number of circles curling from the mechanical properties of these materials by observing the variation in the strain at failure during tension testing. The decrease in the number of chip curls is in direct proportion with the decrease in the strain at failure during tension testing. For Al-15% (SiC)$_p$ composites the number of circle curl decreases drastically to 2 to 3 from 5 to 6 as the volume of reinforcement increases from 10 -15%. This decrease may be due to decrease in strain at failure.

3.6 PERFORMANCE OF DIAMOND TOOL ON MACHINING 6061 Al-(SiC)$_p$ COMPOSITES

Turning tests were performed to evaluate the wear resistance of diamond tool in the machining of 6061 Al-(SiC)$_p$ composites. The performance of the diamond tool was evaluated based on the wear on the flank face of the tool. The flank face of the diamond tool was measured while machining Al-(SiC)$_p$ alloy reinforced with 10 and 20% Volume SiC. The cutting conditions selected for this study are as follows.
Cutting speeds : 56 m/min and 93 m/min
Depth of cut : 0.2mm
Feed : 0.1mm

The profiles of the diamond tool while machining 6061 Al-SiC composites were traced at few regular intervals of time are shown in Figures 3.20 to 3.22. Figures 3.20 and 3.21 show the profiles of the diamond tool while machining Al-10% SiC at cutting speeds at 56 m/min and 93 m/min respectively and Figure 3.22 shows the same for Al-20% (SiC)p at 56 m/min.

When Al-10% SiC MMC was machined at low cutting speed of 56 m/min, a small built up edge is formed and the flank wear band width was found to increase with cutting time. As reported by that while machining Al materials with diamond tool, the diamond tool worn flank was covered with a film of matrix material. This is shown as BUE in the Figure 3.20. The covered worn flank will be exposed only after concealed aluminium is removed. Figure 3.20 also shows that there is a difference in flank wear band width during different times of machining. The above phenomenon was attributed to the large deformation of aluminium with high stress shown due to the SiC rubbing and forming as a BUE in the cutting edge.

The progress of the flank wear on the diamond tool is shown in Figure 3.23. The diamond tool, for a 0.1 mm flank wear lasts for 4 minutes (372 m) for 10% SiC and 2 minutes (186 m) for 20% SiC at a cutting speed of 93 m/min. (Figure 3.23) Diamond is having a much higher hardness than SiC. In cutting of composites, SiC particles cannot micro cut these tools, so serious abrasive wear does not take place as rapidly like other tools (Tomac 1992).
Figure 3.19 Physical appearance of chips on machining (a) base alloy (b) Al-10\% (SiC)\(_p\) (c) Al-15\% (SiC)\(_p\)
Figure 3.19 (contd...) Physical appearance of chips on machining
(d) Al-20\%(SiC)_{p}  (e) Al-25\%(SiC)_{p}
Figure 3.20 Profile of the single crystal diamond on machining Al-10%(SiC)p at 56m/min
Figure 3.21 Profile of the single crystal diamond on machining Al-10 % (SiC)$_p$ at 93 m/min
Figure 3.22 Profile of the single crystal diamond on machining Al- 20 \%(SiC)\_p at 56m/min
The initial wear on the PCD flank was caused by the abrasive nature of the hard SiC particles present in the work piece material. As diamond is harder than SiC, this abrasive wear may be associated with micromechanical damage rather than micro cutting (Divakar 1997). Each time an aluminium film is scratched and gouged by the SiC particles, small diamond particles are also removed from the diamond tool surface due to the adhesion between the aluminium film and the surface. A new aluminium film soon covers the worn surface and then is scratched away again. This cyclic process causes the diamond tool to lose its shape during the course of machining (Andrews, 2000). Hence, the wear on the diamond tool was low among the cutting tools tested.

In comparison the wear on the diamond tool was low among the cutting tools in machining Al(SiC)\textsubscript{p} composites.

### 3.7 EFFECT OF FEED RATE ON SURFACE FINISH

The 6061Al alloy with 10, 15, and 25\% SiC was machined with carbide with varying feed rates. The cutting speed and depth of cut for this study were maintained at 65m/min and 0.8mm respectively. The average surface roughness value (Ra) of the machined components was measured with surf coder at different feed values.

The effect of feed rate on surface roughness (Ra) when machining Al-SiC composites is shown in Figure 3.24. As shown from the Figure 3.24 Surface roughness is increasing with increasing feed rate whereas at lower feed rates, little difference exists. It was also observed that with increase in SiC volume percentage, there was decrease in surface roughness value for a
constant cutting speed and feed rate. Generally, the surface finish is improved with a slightly worn tool due to stabilization of the nose and cutting edge radii. While increasing the volume percentage of SiC in the aluminium alloy, the cutting tool quickly worn out and increases the nose radii. This increase in nose radii improves the surface finish by decreasing the Ra. This is supported by Lane (1992) who found that in order to maintain a consistent wear rate with the dimensional tolerance and surface finish, a slightly honed cutting edge is often preferable.
3.8 TURNING OF 6025 Al-(SiC)\textsubscript{p} COMPOSITES

6025 Al-(SiC)\textsubscript{p} composites are a relatively new class of materials characterized by light weight and greater wear resistance than those of conventional materials. Since 6025 is an Al-Si alloy, these materials have been considered for use in automobile brake rotors and various components in internal combustion engines (Kennedy 1997). A continuing problem with particulate metal matrix composites is that they are difficult to machine on account of the hardness and abrasive nature of the SiC. The SiC used in Al-(SiC)\textsubscript{p} are harder than tungsten carbide, the main constituent of hard metal and even then the majority of the cutting tool material. Hence in this study, advanced cutting tools like cermet and polycrystalline diamond were used to turn Al-(SiC)\textsubscript{p} composite.
Figure 3.24 Effect of feed rate on surface roughness
3.9 EXPERIMENTAL PROCEDURE

3.9.1 Work piece material and cutting tools

The work piece material used for the current investigation was 6025 Al-(SiC)p composites. The composite was reinforced with 15, 20 and 25 vol% of SiC. The composition of the base alloy is listed in Table 3.4. The test specimen is 70 mm in diameter and 300 mm in length.

| Table 3.4 Composition 6025 aluminium alloy |
|-----------------|-------|-------|-------|-------|-------|-------|
| Si              | Mg    | Ti    | Fe    | Cu    | Mn    | Zn    | Al    |
| 6.25-7.5%       | 0.2-0.4% | 0.2%  | 0.2%  | 0.2%  | 0.1%  | 0.1%  | balance|

For the machining experiments two different tools namely cermet and polycrystalline diamond were chosen. The cermet (TTI15, WIDIA) has a high TiC/TiN content, effecting a small and uniform grain size as well as high TiC/TiN content, as well as high hot hardness and chemical stability. The high properties of molybdenum enhances the wettability of the carbides and carbonitrides by the binder, but it also increases the volume of the brittle (Ti,Mo)C shells that surround the carbide cores (Porat 1990). The PCD tool (VC728,WIDIA,CNMG 120408) has about 0.5mm PCD layer is sintered to a hard substrate. The PCD tool is of fine grain which is more wear resistant and less resistant to shock.

3.9.2 Machining Parameters

The machine used for the turning test was a kirloskar retro fitted lathe with power 6 KW. The performance of cermet and PCD tool were tested by
varying the cutting time with different volume % of SiC in 6025 Al alloy. The cutting condition selected for this study is presented in Table 3.5. Flank wear on the cutting tools were monitored at suitable intervals using the profile projector. The surface roughness of the machined workpieces were analysed with surf coder (Kosaka, SE 40 G) and worn inserts are inspected by scanning electron microscope (Leo, Model 420, Germany).

Table 3.5 Cutting conditions Turning

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Cutting tool</th>
<th>Cutting speed (m/min)</th>
<th>Depth of cut (mm)</th>
<th>Feed (mm/rev)</th>
<th>Work piece Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cermet</td>
<td>70 108</td>
<td>0.4 0.4</td>
<td>0.1 0.1</td>
<td>Al 15%SiC Al 25%SiC</td>
</tr>
<tr>
<td>2</td>
<td>PCD</td>
<td>90</td>
<td>0.4</td>
<td>0.1</td>
<td>Al 20%SiC Al 25%SiC</td>
</tr>
</tbody>
</table>

A typical microstructure 6025/20/SiCp by stir casting is shown in Figure 3.25. The average size of the SiC particle is 10 micron.

![Figure 3.25 Microstructure of the Al- 20 % (SiC)p composite at 30 X](image-url)
3.10 PERFORMANCE OF CERMET TOOL ON MACHINING 6025 Al-(SiC)\textsubscript{p} COMPOSITES

The cermet tool TTI 15 was used to machine 6025 Al-SiC alloy reinforced with 15 and 25% vol\% SiC. The cutting speed selected for this study was 70 m/min and 108 m/min with a depth of cut of 0.4 mm and feed of 0.1 mm/rev. The composites were machined with the above cutting conditions and flank wear was measured.

The progress of the flank wear of the cermet tool at different cutting condition is shown in Figure 3.26. The cermet tool (TTI 15) failed within 50 seconds (58 m) for a 0.8 mm maximum flank wear at a cutting speed of 70 m/min for an Al alloy reinforced with 25% SiC and in less than 20 seconds (36 m) at 108 m/min. Machining Al-15% SiC, with the same grade of cermet tool, for a 0.8 mm flank wear, it lasted for 72 minutes (5040 m) at 70 m/min and 28 minutes (3020 m) at 108 m/min. (Figure 3.26). With increasing tool load i.e. increase in cutting speed, the flank surface was subjected to more wear. The tool life obtained when machining Al-SiC composites with cermet tool yield better value at low cutting speed with less SiC volume percentage. The increase in SiC volume percentage reduced the tool life drastically. As explained by Tonshoff (1994) with increasing tool load, i.e. increase in cutting speed, the stability of the cutting edge is reduced. While machining Al-SiC the dislocation pile up increases which further adds load on the tool. The combined effect of these loads on the wedge decreases the stability of the cutting edge, which induces chipping. This chipping occurs at the intersection of the chamfer and flank, initiating the formation of wear grooves, especially at the inserts major flank and corner. With increase in cutting speed and volume %of SiC, the
groovy structures deteriorates the tribological condition between the flank and work piece, resulting in rapid growth of flank wear between grooves. With increase in %SiC, it also results in increase in temperature at the cutting zone. As a result of this thermal and mechanical load, the cermet tool was damaged in the flank wear zone resulting in porous structure. The random nature of SiC particle distribution in the base matrix induces frequent changes in the thermo mechanical loads. This frequent change lowers the fatigue life of the cutting tool material. Increase in volume percentage of SiC results in the thermo mechanical loads. The mechanical impacts caused by the SiC particles induce a sporadic micro chipping of the cutting edge and thin growth of the flank wear land.

The effect of cutting speed on machining Al-(SiC)_p composites with cermet was investigated with the means of SEM photo graphs at the flank and crater zone. Figure 3.27, 3.28 and 3.29 show respectively the flank and rake face of the cermet tools on machining Al-15% SiC at 70 m/min. The SEM photograph of the flank and the rake face of the cermet tool on machining Al-25% SiC at 108m/min is shown in Figure.3.30 ,3.31, 3.32 and Figure.3.33. In machining Al-15%SiC, the tool will be subjected to short cycle load type and severe mechanical and thermal load leads to the formation of cracks. These cracks running perpendicular to the cutting edge (Pandey 1979) which is shown in Figure3.26. The intensity of the load increases with increase in volume percentage of SiC and cutting speed. This leads to severe chipping of the cutting edge which is shown in Figures.3.28 and 3.31. The base alloy Al is highly reactive material which has a high affinity towards TiN which is a constituent of the tool matrix. The affinity of TiN results in adherence of the Al with the surface of the flank as well as the rake face (Cho, 1997). The
adherence of Al with the rake face is shown in Figures 3.28, 3.30, 3.32 and 3.33. The cyclic loading caused by the SiC particles plucks part of the cutting edge. The plucked cutting edge which is at the junction of the major cutting edge and rake face is shown in the Figures 3.29 and 3.33. From the observation of SEM, it is concluded that the cermet tool was subjected to less cyclic load while machining Al-15% SiC at low cutting speed than at in 25% volume SiC and high cutting speed.

Figure 3.26 Progress of flank weak on cermet tool
Figure 3.27 SEM photograph of the Flank wear of the cermet tool on machining Al-15% SiC at 70 m/min.

Figure 3.28 SEM photograph of the chipped Flank edge on machining Al-15% SiC at 70 m/min.
Figure 3.29  SEM photograph of the cermet rake face with the chipped edge on machining Al-15% SiC at 70 m/min

Figure 3.30  SEM photograph of the Flank surface on machining Al-25% SiC at 108 m/min
Figure 3.31  SEM photograph of the chipped Flank edge on machining Al-25% SiC at 108 m/min.

Figure 3.32  SEM photograph of the rake surface on machining Al-25% SiC at 108 m/min
Figure 3.33  SEM photograph showing adherences of the Al with the rake face of the cermet tool

3.11 PERFORMANCE OF PCD TOOL ON MACHINING 6025 Al-(SiC)$_p$ COMPOSITES

6025 Al-Si base alloy hardened with 20% and 25% (SiC)$_p$ composites were machined with PCD inserts at cutting speed of 90m/min. The depth of cut and feed selected for this study were 0.4mm and 0.1mm/rev respectively.

Figure 3.34 shows the tool life of turning tests with PCD inserts as a function of cutting distance. The PCD insert reaches a wear land of 0.4 mm at a cutting speed of 90 m/min after 51 minutes (4590 m) for Al-20% SiC, whereas for the same flank wear of 0.4 mm it took 15 minutes (1350 m) for Al-25 % SiC. In the flank wear progression, the initial rapid wear of the sharp cutting edge of the PCD insert could be seen in this Figure 3.34. This break in period was followed by a steady state period characterized by a fairly uniform wear
rate. As explained by Andrews (2000), the initial wear was caused by abrasive nature of the hard SiC particles present in the work piece material. As diamond is harder than SiC, this abrasive wear may be associated with the micro mechanical damage rather than with micro cutting (Divakar 1997). The worn flank encourages the adhesion of the work piece material and is therefore covered with an aluminium film due to the high pressure generated at the tool work piece interface. This suggests that further tool wear in the flank was caused by both the abrasive and adhesive wear mechanism (Schey 1987). The intensity of this cyclic process increases with increase in SiC, which results in poor tool life.

In the machining of Al-(SiC)p composites, the predominant wear mechanism are two body and three body abrasion (Tomac 1992). The resistance to abrasion of the cutting tool material depends directly on the relative hardness of the material involved. SiC used on the reinforcement in this composite is harder than WC and most of the materials used for cutting tools, except for instance, PCD. However PCD inserts, besides the genuine polycrystalline diamond, have cobalt cemented tungsten carbides as a base with a lower hardness than SiC reinforcement particles. In this way, the bonding between and tungsten carbide can be damaged by the hard particles, degrading the tool. The disintegration of the insert material is thought to occur next to the cutting edge. The kinetic energy transferred from the reinforcement particles causes the mechanical damage to the cutting. This mechanical damage depends essentially on the particle size and the relative cutting speed (Lane 1992).

The wear mechanism on the PCD tools is supported with SEM photographs. Figures 3.35 and 3.36 show the flank and crater wear of PCD tool
on machining Al-20\% SiC and Figures 3.37 and 3.38 show the same for Al-25\% SiC. The observation performed in SEM in PCD inserts confirm that the surfaces of the flank wear (Figure 3.35) show a feature predominated by abrasive with some adherence of machined material (Baptista 1997). The intensity of the abrasive wear increases with increase in volume percentage of SiC which is shown in Figure 3.37.

When the rake face is concerned wear manifestation which begins at the cutting edge was identified. In this zone, next to the edge, there is a deposition of adhered material which appears also in the zone, where the chip
leaves the contact with the rake face. Between these two zones there is a region with a typical grooved abrasion almost clean from adherences (Paulo Davim and Andrew 2000). Figure 3.36 shows the rake surface of the PCD tool on machining Al-20% SiC. Gallab (2000) observed that highest temperature occurs at the cutting edge and decreases along the rest of the tool's rake face. This suggests that in the case where crater wear develops, it would start right at the cutting edge i.e. (not shifted from the cutting edge as commonly observed with high speed steel). Gallab (2000) further observed that at the vicinity of the cutting edge high compression and tensile stresses occur which results in fracture of some of the tool if these stresses exceed the ultimate tensile strength of the tool material. The maximum compressive stresses occur in the vicinity of the cutting edge, where high temperature also exists. The combination of high temperatures could lead to the formation of crater wear. The amount of tool material removed at the crater wear locations depends on the abrasive characteristics of the tool material relative to these of the work piece and amount of SiC present in the work piece. The increased crater wear on the PCD tool on machining Al-25% SiC is presented in Figure 3.38 a and close view of the same is presented in Figure 3.38 b. SEM observations confirms that the wear mechanism on the PCD tool is a combination of abrasive and adhesive wear.
Figure 3.35 SEM photograph of PCD tool on showing the intensity of abrasive wear on machining Al-20% SiC

Figure 3.36 SEM photograph of rake surface showing a depression near the cutting edge on machining Al-20% SiC
Figure 3.37  SEM photograph of PCD tool on showing the intensity of abrasive wear on machining Al-25% SiC
Figure 3.38 SEM photograph of rake surface of PCD tool on machining Al-25% SiC (a) 160X (b) 350X
3.12 SUMMARY OF TURNING EXPERIMENTS

In comparison, while machining 6061 aluminium alloy reinforced with 10% SiC, the carbide and coated carbide tools reach 0.8 mm flank wear at a cutting speed 110 m/min after 1.8 minutes (198 m) and 2.5 minutes (256 m) of machining respectively, whereas the diamond tool attains 0.1 mm flank wear after 4 minutes (372 m) at a cutting speed of 93 m/min. Increasing the volume percentage of SiC from 10% to 20%, the carbide and coated carbide tool lasts for only 54 seconds (94 m) and 60 seconds (110 m) respectively at 110 m/min. The diamond tool reaches 0.2 mm flank wear after 6 minutes (558 m) of machining for the same material at 93 m/min. Hence, the diamond tools are effective in machining Al-SiC composites. The cermet tool even though it does not perform very well while machining Al-20% SiC or with more SiC % more, whereas it produces good tool life (72 minutes) when it was used to machine Al-15% SiC or with less SiC % at lower cutting speed (70 m/min). Hence cermet tools can be used for rough machining of Al-SiC composites with 15 or less volume percentage of SiC at low cutting speed and diamond tools can be used for fine finishing. With low cutting speed and less than 10% SiC in the Al matrix, the cermet and coated tools can be used for rough machining.

3.13 MILLING OF Al-(SiC)ₚ COMPOSITES

Invention of coated cutting tools resulted in tremendous improvements in productivity in continuous machining operations. However in the case of intermittent machining operations like milling, the situation is not yet satisfactory. In these operations due to severe fluctuations in tool stresses and temperature, the conventional wear mechanism are further complicated by impact and fatigue effects.
John (1986) reported that the life of HSS tools can be appreciably augmented by cryogenic cooling of the tool. Cryogenic treatment is a process of chilling a part down to relatively very low temperature and maintaining that condition until the material has cold soaked. The part may then be subjected to a normal tempering reheat. Barron (1982), Collins (1998) and Dong (1994) claimed that cryogenic treatment resulted in increase in wear resistance of certain steels. The improvement in wear resistance was attributed to complete transformation of retained austenite. (Barron, 1982). The present study aims at comparing the performance of H.S.S, cryogenic treated H.S.S and cryogenic treated TiN coated H.S.S milling cutters in milling Al-SiC composites.

Cryogenic treatment converts the retained austenite content into martensite. An additional layer of TiN coating to the cryogenic treated cutter will improve the performance of the cutters. Hence, the present study deals with means of finding acceptable cutting conditions while milling Al-(SiC)p composites in milling with cryogenic treated, cryogenic treated and TiN coated milling cutters.

3.14 EXPERIMENTAL PROCEDURE
3.14.1 Cryogenic treatment

Cryogenic treatment is a process of chilling a part down gradually to a relatively near absolute temperature well below zero degree Celsius and maintaining that condition until the material has cold-soaked. The temperature is then allowed to rise gradually until ambient equilibrium is reached. The part may then be subjected to a normal tempering reheat.
In this study a commercial side and face H.S.S milling cutter with a dimension of 75 mm x12 mm x25 mm was used. The number of teeth on the H.S.S cutter was 24 and its nomenclature is given in the Table 3.6.

Table 3.6 Nomenclature of milling cutter

<table>
<thead>
<tr>
<th>Radial Rake angle</th>
<th>Radial relief angle</th>
<th>Axial Rake angle</th>
<th>Axial Relief angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>10°</td>
<td>28°</td>
<td>8°</td>
<td>22°</td>
</tr>
</tbody>
</table>

The selected H.S.S cutter was subjected to a heat treatment by first heating at a rate of 0.17°C (273.17° K) S⁻¹ to 1088° K (815°C) in a vacuum furnace at 4X10⁻³ Pa. Then it was rapidly heated for an austenitizing temperature of 1100°C (1373° K) in a nitrogen atmosphere at 10 Pa, holding for 1 hour, followed by quenching to an ambient temperature in a cool nitrogen gas. The cryogenic treatment was performed by soaking the samples in liquid nitrogen for 1 week. The cryogenic treated H.S.S cutter was further subjected to a TiN coating.

3.14.2 Cutting condition

Milling operation was carried out on Al-6025 Al alloy reinforced with 15% SiC volume content. The composition of the base alloy is given in Table 3.4. The cutting tests were carried out in a horizontal milling machine (Batliboi, model no 0085,1986) with a variable spindle speed.
The flank wear on the milling cutter and the surface finish produced on the work piece was measured for each combination of parameters. A profile projector with an accuracy of 0.001 mm was used to measure the tool wear. A surf-coder (SF40) was used to measure the surface roughness. The arithmetic mean diameter Ra(μm) with sampling length of 0.25mm was applied on the criteria for evaluating the surface roughness. The performance of the milling cutters were tested at cutting speeds 54m/min and 107m/min. An up milling process with 0.25mm depth of cut and 0.0463 mm/teeth as feed were used in dry condition.

3.15 PERFORMANCE OF HSS, TiN COATED AND CRYOGENIC TREATED TiN COATED CUTTER ON MILLING Al-(SiC)p COMPOSITES

The present study was conducted on evaluating the performance of uncoated, TiN coated and cryogenic treated TiN coated cutter. The performance was evaluated based on the flank wear and surface roughness.

3.15.1 Flank wear

The performance of the selected milling cutters were analysed by measuring the flank wear at different cutting speeds. The effect of TiN coating and cryogenic treatment on H.S.S milling cutters while machining Al-15%SiC is shown in Figures 3.39 and 3.40. The results show that TiN coating and Cryogenic treatment have made a marginal improvement in wear behaviour. It was observed that abrasion of the tool surface in milling appears to be the main reason for low tool life of milling cutters. This abrasion is primarily from the hard SiC particles present in the work piece. As observed by Chandrasekaran et al (1989), On machining Al-SiC composites, the tool chip contact appears
Material: Al-15\% SiC
Cutting Speed: 54 m/min
Depth of Cut: 0.25 mm
Feed: 0.0463 mm/teeth

Figure 3.39 Effect of TiN coating and cryogenic treatment of milling cutter on flank wear at 54 m/min
Figure 3.40 Effect of TiN coating and cryogenic treatment on flank wear of milling cutter at 107 m/min
to increase with time in uncoated milling cutters, whereas with TiN coated and Cryogenic treated TiN coated cutters, it was minimum. Increase in tool chip contact increases the flank wear on the milling cutters due to presence of the abrasive SiC particles.
The increase in tool chip contact also paves the way to increase the cutting zone temperature. The enhanced temperature at the cutting zone passes to the cutting tool. Depending on the nature of the substrate of the cutting tool, the deterioration of the tool happens. If the substrate is H.S.S, the temperature flows easily and deforms the cutter. In TiN coated tools, more heat can flow from the contact zone to the temperature sensitive H.S.S substrate. Owing to the good thermal conductivity through the coating, less heat remain in the chip reducing its deformity (Konig 1992). Due to the cryogenic treatment, the retained austenite in the HSS substrate is reduced and the tool hardness is increased. With increased hardness and TiN coating, the TiN coated tool performs better than the uncoated and cryogenic treated cutters. The coating on the strengthened HSS further enhances the performance of the cutter at elevated temperatures (Ganguly 1987).

### 3.15.2 Surface Roughness

The effect of cryogenic treatment and cryogenic treatment plus TiN coating of HSS cutter on average roughness value (Ra) for different speeds is shown in Figures 3.42 and 3.43. Despite the extreme tool wear, the surface roughness on the machined Al-SiC surfaces produced by the TiN coated and cryogenic treated and TiN coated cutters are better than the uncoated cutter. An average roughness value of 2.5 µm - 0.5 µm is achievable. When milling SiC particle reinforced aluminium with either of these cutters, only the surface roughness during the initial stages of cutting was rough. With increased cutting time the cutting edge blunts which helps to produce surfaces with better finish. In summary, the TiN coating and cryogenic treatment of the HSS cutters do not make much impact on the performance in milling of Al-SiC composites.
Material : Al-15% SiC  
Depth of cut : 0.25 mm  
Feed : 0.0463 mm/teeth  

Figure 3.41 Effect of TiN coating and cryogenic treatment of milling cutter on surface roughness at 54 m/min
Figure 3.42  Effect of TiN coating and cryogenic treatment of milling cutters on surface roughness at 107 m/min

Material: Al-15% SiC
Depth of cut: 0.25 mm
Feed: 0.0463 mm/teeth