CHAPTER 5

HOT MACHINING OF Al-(SiC)p COMPOSITES

5.1 HOT MACHINING

In the field of metal cutting, a requirement on the processing of low machinability or difficult to machine materials is still increasing. Many cutting tool materials have been produced to meet this requirement. However the real state does not always fulfill this requirement. A wide variety of methods have been proposed and tested for machining of these advanced materials. During the machining process, instead of increasing the quality of the cutter materials, softening of the work piece is the preferred approach (Kitagawa, 1988). One of the methods of softening the work piece is hot machining. In hot machining, a part or whole of the work piece is heated. Heating is performed before or during machining. Hot machining prevents cold work hardening by heating the piece above the recrystallisation temperature and this reduces the resistance to cutting and consequently favours the machining. The hot machining of mullite and silicon nitride investigation have been carried out by Uehara and Takeshita (1986) and Akasawa et al (1987). Hence in this study hot machining technique has been employed to machine the hard to machine Al-SiC composites.

5.2 HOT MACHINING OF Al-SiC COMPOSITES

Metal matrix composites are new artificial multiphase solid materials composed of a metal matrix phase and a reinforcing phase, which have much
higher levels in strength. Metal matrix composites with resistance to wear are frequently used in industry and these materials are notoriously difficult to machine. The composite material differs from the conventional material by the way of presence of harder and isolated reinforcement in the path of the tool during machining. This character leads to difficulties in machining of these composites by conventional methods, primarily of rapid wear of cutting tools. Therefore, there is a definite need to enhance the machining performance for these materials. The enhancement of machining performance of Al-SiC composites should lead to increased material removal rate, prolonged tool life, or improved surface finish. Hot machining has been conceived as a viable approach to achieve these goals. The very concept of hot machining runs contrary to established metal cutting practice. In the machining of ordinary metals, every effort is made to keep temperatures at the tool-work interface as low as possible to prevent tool damage. Hot machining, on the other hand is an attempt to soften the work by heating it, thus making it easier to cut, and consequently lengthen the life of the tool

Vedani and Gariboldi (2001) investigated the hot deformation behaviour of different metal matrix composites over a range of temperatures and strain rates. At temperatures over 573 K, Al-SiC composites exhibits significantly reduced yield stress and tensile strength.

Ko et al (1999) studied the effects of SiC particle volume fraction on the microstructure and hot workability of Al-(SiC)p composites. It was observed that the flow stress of the above composites decreases with increase in temperature. Since poor machinability stems from the materials proneness to high strain hardening during machining, localized heating, thereby softening the
materials can reduce the shear strength and strain hardening associated with chip formation.

The metal removal by cutting process is mainly due to shear deformation. Hence, the machinability of the material is dependent on the behaviour of material under the conditions of machining such as depth of cut, cutting velocity and temperature. The above parameter are analogous to strain, strain rate and temperature, which are envisaged in the deformation of work material at the tip of the tool. By evaluating the constitute behaviour of the material under the condition of cutting, one can optimize the machinability of the material. This investigation is aimed at the development of a new methodology for the optimisation of the machinability of Al-SiC material using the constitutive flow behaviour and to demonstrate the validity of this new approach with detailed experimentation.

The method used for evaluating constitute behaviour of material was through the Dynamic Material Model (DMM), which finds extensive use in metal forming.

5.3 OPTIMISATION OF HOT MACHINING PARAMETER

Present design and control methods for manufacturing process do not give adequate consideration of the role of materials. Indeed, the criteria used for optimizing the design and control of manufacturing processes are as follows: Maximize the production rate, minimize the production cost and maximize the profit. These approaches are suitable for conventional materials such as steels, copper and aluminium based alloys, which can be processed successfully over a wide range of processing conditions. In other words, these materials can be said
to posses wide “processing windows” in terms of workpiece temperature and strain rate. Such approaches lack information about material behaviour. In contrast, materials such as Super alloys, intermetallics and metal matrix composites have restricted or narrow processing windows. During processing of these materials, variables such as temperature, strain rate must be monitored continuously, lest the materials should experience different type of instabilities (James and Venkat 1992).

The metal removal by cutting process is mainly due to shear deformation. Hence, the machinability of the material is dependant on the behaviour of material under the conditions of machining such as cutting velocity depth of cut and temperature. The above parameter are analogous to strain, strain rate and temperature, which are envisaged in the deformation of work material at the tip of the tool. By evaluating the constitutive behaviour of the material under the condition of cutting, one can optimize the machinability of the material. This investigation is aimed at the development of a new methodology for the optimization of the machinability of the material using the constitutive flow behaviour of material and to demonstrate the validity of this approach with detailed experimentation.

The method used for evaluating constitutive behaviour of material was through the Dynamic Material Model (DMM), which finds extensive use in metal working. In metal cutting our interest is to initiate fracture in the deformation zone for easy metal removal. Then the region of instability predicted by DMM could be the optimal region of metal cutting. Unstable flow during hot deformation of titanium alloy Ti – 24Al – 20Nb was analyzed by Narayanamoorthy et al (2000) using the principle suggested by Semiatin and
Lahoti (1982) and the simplified metallurgical stability criterions suggested by Narayanamorthy and Nagesvara Rao (1998). They identified the useful regions in the processing maps for the Ti alloy.

From the above literature, different metal removal processes were tried to machine these composites. Even though many machining strategies were used to machine 6061 and other class of composite material, yet very few literatures are available to machine 6025 Al- (SiC)$_p$ composites. From the outline of the various literatures, rotary EDM and hot machining are viable methods to machine these material. The proper machining of these material with the above process will lead to better utilization of both 6025Al-SiC composite.

5.4 DYNAMIC MATERIAL MODEL (DMM)

During deformation processing of material under certain combination of temperature and strain rate, the material exhibits poor workability due to phenomenon such as dynamic strain ageing, formation of new phases, adiabatic shear deformation or region of localized deformation, grain boundary and triple point cracks, void formation and hot shortness. The above phenomenon may also introduce non-homogenous deformation and produce components possessing micro structural defects such as non-uniform microstructure, short bands etc. The phenomenon which causes the inhomogeneous deformation can be termed as flow instability and the region of temperature and strain rate where the deformation is not homogenous can be termed as unstable or instability regions. It is therefore necessary to avoid the processing region where the instability is likely to occur in order to manufacture sound products. DMM
stability can be used to identify the stable region or safe processing of materials (James and Venkat 1992). In metal cutting, the metal is removed by shearing and introduction of cracks in the deformation zone. Hence, the unfavourable region in the case of deformation can be considered as a favourable region for machining.

DMM approach makes use of the constitutive equation for plastic flow determined from hot deformation tests at different temperatures and strain rates. Parameters such as the strain rate sensitivity (m) and temperature sensitivity (S) of the flow stress are related to the manner in which the work piece dissipates energy instantaneously during hot deformation. The rate of change of stress with strain rate at constant levels of strain (ε) and temperature (T) is known as the strain rate sensitivity parameter ‘m’ which is defined as follows

\[ m = \frac{\partial (\log \sigma) / \partial (\log \dot{\varepsilon})}{\varepsilon, T} \]  \hspace{1cm} (5.1)

The temperature sensitivity of the flow stress is analyzed in terms of parameter (S).

\[ S = \frac{(\partial \ln \sigma / \partial (1/T))}{\varepsilon, \dot{\varepsilon}} \]  \hspace{1cm} (5.2)

Where \( \sigma \) = flow stress \( \dot{\varepsilon} \) = strain rate

5.5 DMM STABILITY

Stability is an important characteristic of the transient behaviour of a material system and dictates its ability to be controlled. Hence, a stable material
system will respond in some reasonable manner to an applied thermo mechanical condition.

The necessary Lyapunov DMM stability criteria are

\[ 0 < m < 1 \]  
\[ \frac{\partial m}{\partial (\log \dot{\varepsilon})} < 0 \]  
\[ s > 1 \]  
\[ \frac{\partial s}{\partial (\log \dot{\varepsilon})} < 0 \]  

Using the values of stress and strain experimentally determined from the simulative tests conducted at varying strain rates and temperatures, stability parameters were determined. The variation of \( m, \dot{m}, s \) and \( \dot{s} \) with temperature and strain rate constitutes instability maps, which can be used for delineating the region of instability (James and Venkat 1992).

Ravichandran et al (1990) studied the dynamic recrystallisation of aluminum alloy during hot deformation using instability maps. Processing maps were constructed based on the flow stress data and \( m \) value and the domain of dynamic recrystallisation was identified. Processing and instability maps were constructed for an AISI 316 Stainless material using DMM. The temperature and strain rate regions in which instability due to flow localization was identified (Venugopal et al 1990). Narayamoorthy et al (2000) analyzed the unstable flow during hot deformation of Titanium alloy. Instability maps were used to study the unstable region in the deformation process.
Radhakrishna Bhat et al (1992) constructed processing maps for hot working of a 2124 Al-20 Vol % SiC metal matrix composites. It was found that the above MMC undergoes micro structural instability at temperatures lower than 673 K and at strain rates greater than 0.1 s\(^{-1}\). It was also found out by the same authors that the peak efficiency of power dissipation in the dynamic recrystallisation increases continuously with the increase in volume percent of reinforcement (Radhakrishna Bhat, 2000).

In metal cutting, our interest is to initiate fracture in the deformation zone for easy material removal. Unstable regions in DMM in which cracks will be initiated will be the regions of interest for metal cutting.

5.6 EXPERIMENTAL DETAILS OF HOT MACHINING

Al- 20% SiC reinforced metal matrix composites of 70mm diameter was hot machined in a Geedi – Weiler lathe. Hot machining tests were conducted at five different cutting velocities (25 m/min, 70 m/min, 100 m/min, 170 m/min and 300 m/min) and at four different temperatures (298 K, 423 K, 523 K and 573 K). The composite was heated using a removable shell type furnace with a heating capacity of 3 KW. A sheath type thermocouple was used to measure the temperature with an accuracy of ±2°C. K20 carbide tool which has a layer of Al\(_2\)O\(_3\) on the top of Ti(CN) was used for turning the composites. The cutting forces during the machining were measured using a Piezo electric transducer (Mescon instruments, CA 90, Linearity +0.5 %). Safety rules were strictly followed to prevent any damage to the machine or any kind of injuries to the operator due to high temperature chips or work piece.
5.7 FORCE SYSTEM DURING TURNING

The three dimensional and its reduced two dimensional force system in the case of turning is shown in Figure 5.1

\[ R = \sqrt{p_x^2 + p_y^2 + p_z^2}, \quad (5.7) \]

where

\[ p_x = \text{feed force}, \quad p_y = \text{thrust force}, \]
The above three dimensional force system can be reduced to a two dimensional system if the entire cutting forces are contained in the orthogonal plane \( \pi_0 \). This is possible if

\[
R = \sqrt{(F_z)^2 + (F_{xy})^2}
\]

and

\[
F_{xy} = \sqrt{(F_x)^2 + (F_y)^2}
\]

The above conditions are possible under the condition of free orthogonal cutting system. To satisfy the free orthogonal cutting system, the following condition has to be satisfied.

\[0 < \Phi < 90 \text{ and } \lambda = 0 \text{ and chip flow direction lie on plane } \pi_0\]

5.8 RESULTS AND DISCUSSIONS OF HOT MACHINING

The flow stress data for Al-20\%SiC MMC was generated using isothermal, constant strain rate (cutting velocity) turning test. The cutting force measured during the turning tests was resolved to a orthogonal system by adopting a constant cutting tool geometry. The chip thickness was measured during the machining and the shear angle (\( \beta \)) was found out using the relation.

\[
\tan \beta = \frac{r \cos \eta}{1 - r \sin \eta}
\]

Where \( r = \) chip thickness, \( \eta = \) rake angle.
The angle of friction ($\psi$) during the machining was found out using merchant’s equation

$$2\beta + \eta - \psi = \pi/2 \quad \ldots(5.11)$$

where $\beta$ = shear angle, $\eta$ = rake angle, $\psi$ = angle of friction.

With the values of feed, depth of cut, cutting force, shear angle and friction angle, the values of shear stress, shear strain and shear strain rate are calculated by using the relations 5.13-5.15.

The chip reduction coefficient

$$\zeta = 1.9/(S^{0.06}) \quad \ldots(5.12)$$

Shear Stress $\tau = Pz/2St[(\zeta - \sin \gamma)/\cos \gamma]$ \ldots(5.13)

Shear strain $\varepsilon = (\zeta^2 + 2\zeta \sin \gamma + 1)/(\zeta \cos \gamma)$ \ldots(5.14)

Shear strain rate $\varepsilon = 16.67Vc\varepsilon \sin \beta/(\Delta s)$ \ldots(5.15)

Where $Vc =$ cutting velocity in m/min, $\Delta s =$ shear zone in mm.

$S =$ feed in mm/rev, $t =$ depth of cut in mm, $\gamma =$ flow softening rate

The shear stress measured at different temperatures for varying cutting speeds are tabulated in Table 5.1.
Table 5.1 Shear Stress at different temperatures for various cutting speeds

<table>
<thead>
<tr>
<th>S.No</th>
<th>Cutting Speed (m/min)</th>
<th>Cutting Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>298 K</td>
</tr>
<tr>
<td>1.</td>
<td>25</td>
<td>19.3374</td>
</tr>
<tr>
<td>2</td>
<td>70</td>
<td>63.8607</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>127.8013</td>
</tr>
<tr>
<td>4</td>
<td>150</td>
<td>150.4267</td>
</tr>
<tr>
<td>5</td>
<td>170</td>
<td>115.4706</td>
</tr>
<tr>
<td>6</td>
<td>300</td>
<td>115.4226</td>
</tr>
</tbody>
</table>

The variation of shear stress of the Al-20% SiC as a function of temperature at different cutting speeds is shown in Figure 5.2. It was observed that at elevated temperature and cutting speed, the material softens easily except at 300 m/min. At 300 m/min, the material hardens up to 423 K, and then it starts softening. Gallab (1998), Joshi (1995) and others observed that increase in shear stress was due to mismatch in thermal co-efficient of the matrix and reinforcement. When Al-SiC was machined, it was subjected to heavy deformation. During deformation, the SiC particles may pull out of matrix, which inhibits the dislocation movement. This inhibition leads to dislocation pile up which increases the cutting forces there by the shear stress for further deformation. The above behaviour was also experienced by Ko et al (1999).
5.9 INSTABILITY MAPS

The stability maps are constructed based on the strain rate sensitivity parameter ‘m’ and temperature sensitivity ‘s’ of the material during deformation. To determine ‘m’, the values of flow stress at varying strain rates and at constant temperatures were found out. Fig.5.3 shows the variation of flow stress at different temperature and strain rates.

The strain rate sensitivity ‘m’ value is defined by

\[ m = \left[ \frac{\partial (\log \sigma)}{\partial (\log \varepsilon)} \right] \varepsilon, T. \]

To determine m, log(σ) versus log(ε) data corresponding to various strain rates were plotted for various temperatures. Third order polynomials were fitted to the data and their equations were determined for each test temperature. The correlation coefficient for each curve was better than 0.99. The first derivative of these equations provides the ‘m’ value. The m values obtained different temperatures for varying cutting speeds are presented in Table.5.2.
Table 5.2 Strain rate sensitivity parameter ‘m’

<table>
<thead>
<tr>
<th>S.No</th>
<th>Cutting Speed (m/min)</th>
<th>Cutting Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>298 K</td>
</tr>
<tr>
<td>1</td>
<td>25</td>
<td>0.007651</td>
</tr>
<tr>
<td>2</td>
<td>70</td>
<td>0.007779</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>0.007024</td>
</tr>
<tr>
<td>4</td>
<td>150</td>
<td>0.00574</td>
</tr>
<tr>
<td>5</td>
<td>170</td>
<td>0.003738</td>
</tr>
<tr>
<td>6</td>
<td>300</td>
<td>-0.00238</td>
</tr>
</tbody>
</table>

Figure 5.3 Flow Curves
The stable regions are delineated using first of the Lyapunov function that is \( m \) lies between 0 and 1. This criterion is based on the principle that the material will no more be dissipated of power when \( m=0 \) or negative and will undergo fracture. The positive value of \( m \) as well as increased value of \( m \) leads to reduced flow localization and super plasticity. The regions where the ‘\( m \)’ lies between 0 and 1 are shown as a shaded region in the Figure 5.4. The regions where the ‘\( m \)’ value was negative is shown as an unshaded region. These unshaded regions where fracture could be initiated are the favorable regions for machining.

The stability criterion relating to the variation of \( m \) with \( \log \epsilon \) stems from the theoretical requirements for the material system to continuously lower its total energy. If fracture stress is assumed to be independent of strain rate, then increasing \( m (\dot{\epsilon}) \) will probably lead to catastrophic failure at high strain rate. In contrast, a decreasing \( m \) has a lower probability of inducing fractures in the workpiece. This criterion leads to more uniform stress field across the workpiece and decreased tendency for strain localization. The variation of \( m \) with at different temperature and shear strain rates are obtained by fitting a cubic spline curve to the \( m \) Vs \( \log (\epsilon) \) and finding the slope of the curve at constant temperature. This is repeated for different temperatures. The measured values of \( m \) at different temperature for varying cutting speeds are presented in Table 5.3 The regions in which the \( m \) value is negative is shown as a shaded region in Figure 5.5. The favorable region for metal cutting where \( m \) is positive is shown as an unshaded region.
Table 5.3 \( m \) Values at different temperatures and cutting speeds

<table>
<thead>
<tr>
<th>S.No</th>
<th>Cutting Speed (m/min)</th>
<th>Cutting Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>298 K</td>
</tr>
<tr>
<td>1.</td>
<td>25</td>
<td>-0.01073</td>
</tr>
<tr>
<td>2</td>
<td>70</td>
<td>0.00353</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>-0.00651</td>
</tr>
<tr>
<td>4</td>
<td>150</td>
<td>-0.01645</td>
</tr>
<tr>
<td>5</td>
<td>170</td>
<td>-0.02682</td>
</tr>
<tr>
<td>6</td>
<td>300</td>
<td>-0.04637</td>
</tr>
</tbody>
</table>
Using the flow stress values calculated at different temperatures and strain rates, the temperature sensitivity factor $s$, $s=(1/T)\left\{\frac{\partial (\ln \sigma)}{\partial (1/T)} \right\} \varepsilon, \dot{\varepsilon}$ was determined as a function of temperature and effective strain rate. The measured values of $s$ at different temperatures for varying cutting speeds are given in Table 5.4. The stability criterion based on $s$ is derived from the premise that the net entropy in the production rate associated with irreversible process should have sufficiently high temperature dependents of flow stress.
Table 5.4 Values of temperature sensitivity (‘s’) parameter

<table>
<thead>
<tr>
<th>S.No</th>
<th>Cutting Speed (m/min)</th>
<th>Cutting Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>298 K</td>
</tr>
<tr>
<td>1.</td>
<td>25</td>
<td>-1.44075</td>
</tr>
<tr>
<td>2</td>
<td>70</td>
<td>0.192461</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>-15.7041</td>
</tr>
<tr>
<td>4</td>
<td>150</td>
<td>121.4612</td>
</tr>
<tr>
<td>5</td>
<td>170</td>
<td>-14.8303</td>
</tr>
<tr>
<td>6</td>
<td>300</td>
<td>-138.948</td>
</tr>
</tbody>
</table>

Processes that have lower temperature dependence of flow stress are likely to develop flow instabilities. The s value must be positive for a stable process and negative for an unstable process. The region in which the ‘s’ value is positive is shown as a shaded in Figure 5.6. These shaded regions are the unfavorable regions for machining and unshaded region corresponds to the stable region for machining.
Figure 5.6 Contour map of $s$

The variation of $s$ with strain rate, which is specified as $\dot{s}$, is obtained by fitting a cubic polynomial to the $s$ Vs log ($\varepsilon$) data at different temperature and an equation was found. The slope of that equation gives the value for $\dot{s}$. The $\dot{s}$ values found by the above method is listed in Table 5.5. The Lyapunov criterion based on $\dot{s}$ ensures that the material system is continuously lowering its total energy. If $\dot{s}$ increases with strain rate then a thermal softening will be encountered in the regime of the high strain rates, which will produce severe strain localization. The strain localization leads to severe cracking of the work piece and growth of cracks. The regions where the value $\dot{s}$ is greater than zero is shown as an unshaded region in the Figure 5.7. These unshaded regions are the favourable region for machining.
Table 5.5 $\delta$ Values at different temperatures and cutting speeds

<table>
<thead>
<tr>
<th>S.No</th>
<th>Cutting Speed (m/min)</th>
<th>Cutting Temperature</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>$298^4K$</td>
</tr>
<tr>
<td>1.</td>
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<td>0.00994</td>
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<td>2</td>
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<td>0.0049</td>
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<td>6</td>
<td>300</td>
<td>-0.01843</td>
</tr>
</tbody>
</table>

In DMM, if the process to acquire favourability it must satisfy all the four criterions. To show the favourable region for metal cutting, in which cracks can be initiated, the Figures 5.4 to 5.7 are superimposed and common unshaded area was found out. Figure 5.8 shows the superimposed favorable region for machining. In the favorable region at temperature 423 K and cutting speed 150 m/min was selected (E) as the favorable parameters based on easy machining.

Workability problems may arise when deformation localized to a narrow zone. Localization of deformation can also be so severe that it leads to failure in the deformation process. Flow localization may occur during hot working in the absence of frictional or chilling effects. Absence of friction or chilling effects results in flow softening. Flow softening has been correlated with material properties by the parameter for plane strain compression.
Figure 5.7 Contour map of $s$

Figure 5.8 Favourable region for machining
\[
\alpha = -\frac{\gamma}{m} \tag{5.16}
\]

where the normalized flow softening rate

\[
\gamma = \frac{1}{\sigma} \left( \frac{\partial \sigma}{\partial \varepsilon} \right) = \frac{\partial \ln \sigma}{\partial \varepsilon} \tag{5.17}
\]

The normalized flow softening rate \( \gamma \) is obtained by transforming initially the flow stress data into natural logarithmic scale and finding it directly from the first derivative of the spline fit to the data of \( \ln(\sigma) \). \( \varepsilon \) data at the specified \( \varepsilon \) and \( T \). The values of the workability parameter \( \alpha \) are obtained by substituting the values of \( \gamma \) and \( m \) in the equation 5.16. The obtained value of plane strain compression \( \alpha \) is listed in Table 5.6

**Table 5.6** Plane strain compression \( \alpha \) Values at different temperatures and cutting speeds

<table>
<thead>
<tr>
<th>S.No</th>
<th>Cutting Speed (m/min)</th>
<th>Cutting Temperature</th>
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<tbody>
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<td></td>
<td></td>
<td>298 K</td>
</tr>
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<td>170</td>
<td>-131.27</td>
</tr>
<tr>
<td>6</td>
<td>300</td>
<td><strong>206.43</strong></td>
</tr>
</tbody>
</table>
Narayana Moorthy and Nageswara Rao (2000) investigated on the flow localization and plastic instability in formability and workability maps and concluded that flow localization will occur if the parameter \( \alpha > 5 \). In hot machining of Al-SiC composites, the plane strain compression value was 7.46 when the composites was machined at 150 m/min as cutting speed and 423 K as temperature. The plane strain compression value 7.46 indicates the onset of flow localization at the above cutting parameters which leads to instability. This also was experienced by Radhakrishna Bhat et al (2000). It was observed that while studying the effect of volume fraction of Al-SiC composites on processing maps, at temperature less than 573 K, the composite shows a tendency for abnormal grain growth at low strain rates. Hence, the cutting parameters 423 K and 150 m/min are selected as optimum the optimum parameter in hot machining of Al-SiC composites.

5.10 TOOL WEAR TESTS

In order to validate the findings of the DMM maps, tool wear tests were carried out. The Al-SiC composite was hot machined at temperatures ranging from 298 K to 623 K. The flank wear of the cutting tool was measured at cutting speeds ranging from 25 m/min to 300 m/min. Figure 5.9 shows the progress of flank wear at 298 K at different cutting speeds. The wear curve follows a normal wear behavior at room temperature.

The progress of flank wear at 423 K at different cutting speeds is shown in Figure 5.10. Figure 5.11 depicts the progress of flank wear at 523 K. These experiments illustrate that the tool life is increased in hot machining of Al-(SiC)p composites in comparison with that of room temperature machining.
Figure 5.9. Progress of flank wear at 298 K

Figure 5.10. Progress of flank wear at 423 K
at different cutting speeds. When temperature is raised, the abrasion resistance decreases which results in decreased flank wear (Uehara, 1986). The tool life improvement in hot machining was also experienced by Tosun and others (2002) while machining High Manganese Steel.

On comparing the flank wear values, the minimum flank wear was observed when the composite was machined at 150 m/min at 323 K. The above cutting condition observed from the wear tests exactly matches with the optimum results of DMM. This was proved with the help of SEM photographs of the cutting tools and chips collected while machining the Al-SiC composites.
The mechanism involved in machining Al-SiC is different from the mechanism involved in machining conventional metals. In conventional metals and alloys, the work piece was of a uniform and plastic material. During cutting shear deformation takes place on a plane. The chip formation during the process was assumed to be a two dimensional and no side spread occurred and the stress distribution was uniform over the shear plane. The above hypothesis cannot be used for the analysis of the cutting process of SiC particle reinforced aluminium matrix composites. The Al-SiC composites consists of SiC particles and aluminum alloy, which have totally different characteristics in structure as well as mechanical behaviour. These composites are not uniform in structure and have a mechanical behavior which is different from the uniform materials (Kanetake 1990; Zhon Zhoa et al 1991 and Mohri et al 1973). SiC particle high yield strength and their elastic modulus is very high whereas the standard aluminium alloy has low yield strength and good plasticity. Under force, the stress of the matrix is unequal to that of reinforcing particles. In the composites, the later being larger than the former. Thus in the cutting process of composites, when the matrix deforms plastically, the SiC particles may only deform elastically to break and also the boundary of the matrix and the SiC particles may break between the tool and reinforcing particles is particularly remarkable which cause severe abrasive wear on the tool flank.

In machining Al-SiC composites the tool meets the SiC particle in the shear zone, the shear deformation of the matrix is hindered in front of the tool. The cutting force increases and in front of the tool, the matrix changes its slip direction and continues to shear. Around the SiC particles, the matrix suffers a
coordinated deformation, which increases the shear angle, causing the side spread of the chips and reduction in chip thickness. Around the SiC particles, the Stress concentration increases, but the particles is not yet pressed into the chip or the machined surface. This increase in cutting force continues and when the stress of the SiC particles pressed in front of the tool reaches the limit strength of the SiC, particles break along their crystal boundaries or across the crystals. The breaking of the SiC particles and subsequent pushing past of the SiC particles by the tool leads to the decrease in cutting force.

At the same time another part of the broken particle is carried into the chip by the matrix (Xiaoping Li and Seah 2000). The fragments of the particles pushed by the tool edge are pressed in the machined surface or fall out are removed. The edge cuts the matrix again and the shear angle decrease. The above mechanism in cutting Al-(SiC)$_p$ composites can be supported by the chips formed during the process.

Figure 5.12 shows the flank wear of the carbide tool while machining at room temperature and at a cutting speed of 100 m/min and Figure 5.13 shows the crater wear of the cutting tool for the same cutting condition. It was observed from the figures that cutting tool was subjected to abrasive wear at the flank face and also mechanical damage at the rake face.

When the composite was heated at 423 K, the base alloy is getting softened whereas the SiC particles are not subjected to any change. At this condition, when it was machined at 70 m/min, the softened Al matrix is more easily squeezed and pushed out from the machined surface which leads to increase in concentration of the SiC particle in the surface layer of the machined surface. Increase in concentration of the SiC particles resulted in
Figure 5.12  SEM photograph of Flank wear of carbide tool in machining Al-SiC composite at room temperature and at 100 m/min

Figure 5.13  SEM photograph of crater wear of carbide tool in machining Al-SiC composite at room temperature and at 100 m/min
severe abrasive wear in the flank face of the tool. Figure 5.14 shows the SEM photograph of the flank face of the tool when it was used to machine Al-SiC composites at 423 K at 70 m/min. Figure 5.14 shows the severe abrasive wear marks on the flank face of the tool. Accumulation of the SiC particles effected a severe edge breaking of the cutting tool. Figure 5.15 shows the rake face of the tool when it was subjected to hot machining at 423 K at 70 m/min.

When the tool edge only cuts the matrix and does not meet SiC particles it is a plastic deformation cutting. When the reinforcing particle matrix boundary is poor, the boundary cracks can easily link up, so that shear break cutting frequently appears. If the shear deformation of the matrix is hindered by reinforcing particle, squeeze break and collapse cutting will occur (Joshi et al 1999). If the cutting speed is low, the shear strength of a work hardening material is high resulting in an early breakage of chips. Figure 5.16 shows the SEM photograph of the chip obtained while machining Al-SiC composites at 423 K at 70 m/min. Figure 5.16 shows the thinning of the chip and its early breakage.

Figure 5.17 shows the flank face of the carbide tool while hot machining Al-20% SiC at 423 K at 150 m/min and Figure 5.18 shows the rake face of the carbide tool at the same cutting condition. It was already observed that at the above cutting condition, the Al-20% SiC was subjected to flow localization in hot machining. Due to the flow localization, the matrix material easily flows which results in continuous chip and scooping of the SiC particles. The scooping of SiC particles and continuous chip formation reduces the wear on the flank face on the tool. Figure 5.19 a shows the SEM photograph of the continuous chips produced during Al-(SiC)p machining at 423 K at 150 m/min and its close view in b showing the SiC particles.
Figure 5.14  SEM photograph of Flank wear of carbide tool in machining Al-SiC composite at 423 K room temperature and at 70 m/min

Figure 5.15  SEM photograph of crater wear of carbide tool in machining Al-SiC composite at 423 K temperature and at 70 m/min
Figure 5.16 SEM photograph of chip in machining Al-SiC composite at 423 K temperature and at 70 m/min

Figure 5.17 SEM photograph of Flank wear of carbide tool in machining Al-SiC composite at 423 K room temperature and at 150 m/min
Figure 5.18  SEM photograph of crater wear of carbide tool in machining Al-SiC composite at 423 K temperature and at 150 m/min
Figure 5.19 (a) SEM photograph of continuous chip in machining Al-SiC composite at 423 K temperature and at 150 m/min and (b) close view
When the temperature of the Al-SiC composite was increased from 423 K to 523 K, the material was easily getting softened. When the softened material was machined at 70 m/min, the material was not strained much. Less straining of the material allows the material to flow easily and results in less wear on the flank. Even though it was strained less, since the material was subjected to a elevated temperature, BUE forms on the cutting edge which was shown in Figure 5.20. This BUE removes part of the tool and results in increased crater wear which is shown in Figure 5.21. Chipping of the cutting edge results in early breakage of the chip which is shown in Figure 5.22.

Increasing the cutting from 70 m/min to 150 m/min resulted in severe straining of the material which increases the chipping of the tool at the cutting edge as well as increased flank wear. The increase in flank wear was resulted due to the increase in concentration of the SiC particles at the surface of the machined surface. The SEM photograph of the increased flank wear while machining Al-20% SiC at temperature 523 K and cutting speed 150 m/min is shown in Figure 5.23. The rake surface of the tool showing the crater wear at the above cutting condition is shown in Figure 5.24. The increase in straining of the material results in thinning of the chips and still reduces the chip size. The reduced chips obtained while machining Al-SiC composites at the above mentioned cutting condition is shown in Figure 5.25.

Hence the SEM study establishes that the optimum cutting parameter for hot machining Al-20% SiC was 423 K as temperature and 150 m/min as cutting speed.
Figure 5.20 SEM photograph of Flank wear of carbide tool in machining Al-SiC composite at 523 K and at 70 m/min

Figure 5.21 SEM photograph of crater wear of carbide tool in machining Al-SiC composite at 523 K temperature and at 70 m/min
Figure 5.22  SEM photograph of chip in machining Al-SiC composite at 523 K temperature and at 70 m/min

Figure 5.23  SEM photograph of Flank wear of carbide tool in machining Al-SiC composite at 523 K and at 150 m/min
Figure 5.24 SEM photograph of crater wear of carbide tool in machining Al-SiC composite at 523 K temperature and at 150 m/min

Figure 5.25 SEM photograph of chip in machining Al-SiC composite at 523 K temperature and at 150 m/min
5.12 HARDNESS TEST

When a material was subjected to elevated temperature, there will be change in the hardness of the material. The hardness of the machined surface was tested at different temperature and cutting speed. The variation of hardness at different cutting speeds is shown in Figure 5.26. The hardness of the work piece before it was subjected to machining was only 47 HV. After machining, at different cutting speeds and temperatures, the surface hardness increases. When the material is subjected to machining at high speeds and temperatures, there is high straining of the material and either fracture of SiC or scooping out from the matrix takes place. This results in dislocation pile up, which increases the hardness (Sklad 1998).

![Figure 5.26 Hardness Vs Velocity](image-url)
5.13 SURFACE ROUGHNESS TEST

The effect of surface temperature and cutting velocity on surface roughness (Ra) while machining Al-20%SiC is presented in Figure 5.27. It was observed that at a particular cutting speed, the surface roughness value (Ra) increases with increase in temperature due to the built up edge formation. Ability of the material to retain strength and hardness at elevated temperatures, which induces dislocation pile up during machining increases the surface roughness value (Ramakrishnan 1999).

It was observed from the Figures 5.26 and 5.27 that the hardness and surface finish of the component at the optimum cutting condition of 150 m/min and 423 K as 60 HV and 2.4 μm (Ra) respectively, which are acceptable for engineering applications. Therefore, based on the criterion of minimum flank wear and smooth surface, it could be concluded that the optimum machining conditions for Al-20% SiC are a cutting speed of 150 m/min and temperature 423 K. Hence Dynamic material modeling can be used to optimize hot machining of Al-SiC metal matrix composites with minimum flank wear on the tool.
Figure 5.27 Effect of temperature on Surface Roughness (Ra)