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ORIGINAL ARTICLE

An investigation on the machinability of Al-SiC metal matrix composites using pcd inserts

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Abstract The paper attempts to study the machinability issues of aluminium-silicon carbide (Al-SiC) metal matrix composites (MMC) in turning using different grades of poly crystalline diamond (PCD) inserts. Al-SiC composite containing 15%wt of SiC was used as work material for turning and PCD inserts of three different grades were used as cutting tools. Experiments were conducted at various cutting speeds, feeds and depth of cuts and parameters, such as surface roughness, specific power consumed, and material removal rate were measured. The worn surface of the insert was examined by scanning electron microscope (SEM). The surface finish observed was found to be much lower than the theoretical surface roughness. The influence of cut was examined for the different grades of PCD inserts. It was observed that the 1600 grade PCD inserts performed well from the surface finish and specific power consumption points of view closely followed by the 1500 grade.

Keywords Metal matrix composites · Machining · Machinability · Specific power consumption · Surface finish

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Nomenclature

b	Depth of cut in mm
f	Feed in mm/rev
MRR	Material removal rate in m^3/s
P	Power in W
Ra	Arithmetic average surface roughness
V	Cutting speed in m/min

1 Introduction

Metal matrix composites (MMC) are a relatively new class of materials characterized by lighter weight and greater strength and wear resistance than those of conventional materials. Due to their superior strength and stiffness, MMCs have good potential for application in the automotive and aerospace industries [1–3]. One factor that prevents more manufacturers from embracing MMC technology is the difficulty of machining these materials. The machining of MMCs is very difficult due to the highly abrasive and intermittent nature of the reinforcements. MMC components are mostly produced using near net shape manufacturing methods and are subsequently finish machined to the final dimensions and surface finishes. Figure 1 shows the microstructure of the work material Al-SiC composite.

Conventional tool materials, such as high-speed steel, cannot be used for MMCs as the cutting tool undergoes very rapid wear. Carbides, either plain or coated, sustain significant levels of tool wear after a very short period of machining [4]. Diamond tools are considered the most cost effective and by far the best choice for the machining of MMCs [5]. Cutting tools based on polycrystalline diamond (PCD) have been used for some years for the machining of such abrasive composites as fiber-reinforced composites.

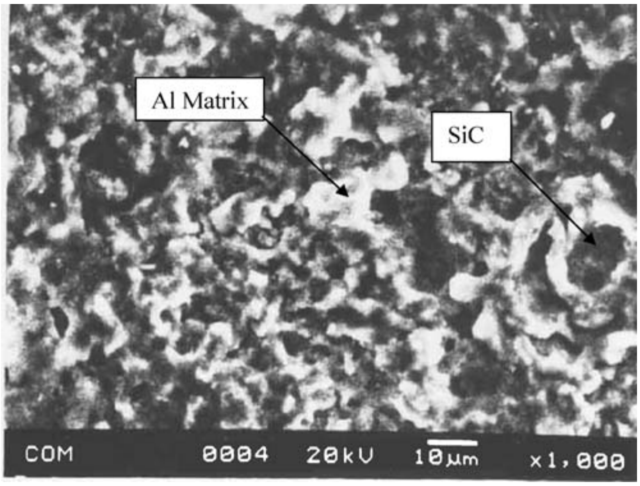

Fig. 1 The microstructure of the work material (Al - SiC Composite)

PCD had also been used successfully for machining MMCs.

To study the difficulties in machining of MMCs, previous investigations on the machinability of MMCs have covered the effects of machining parameters and the properties of MMCs on the tool wear and the mechanism of the tool wear. Tomac and Tonnessen [6] investigated the effect of cutting speed when turning Al-SiC MMCs with poly crystalline diamond (PCD) and coated tungsten carbide tools and found that high cutting speeds shorten tool life by causing excessive flank wear. They investigated the effect of feed rate and found that high feed rate setting can reduce the tool wear. This is because, at higher feed rates the temperature of the cutting zone increases. This leads to the softening of the metallic matrix enabling easier removal of the embedded SiC particle in the work piece. In the work done by Yuan et al. [7], they have shown that, when a PCD cutting tool is used, the depth of cut has no significant effect on the surface roughness of the machined work piece. However, it was reported by Lane [8] that the tool life of the PCD cutting tool was found to be inversely proportional to the depth of cut.

In an experimental investigation on turning MMCs with PCD inserts, Davim [9] observed all the components of cutting forces and surface roughness to increase with tool wear and time. While studying the relative influence of cutting conditions on the various parameters of machinability, Davim [10] used the orthogonal array approach. The author concluded that tool wear and power are primarily influenced by cutting speed and the surface roughness by feed. All the interaction effects are considered to be minimal.

Tomac and Tonnessen [6] observed that the tool wear produced during turning of Al-SiC MMCs using coated carbide inserts was very rapid and uniform at the clearance face. While turning with PCD inserts, again the flank wear of the inserts were found to be the predominant mode of tool wear. They also observed that, as the tool made contact with the SiC particles, the tool moved the particles rather than cutting and breaking them because of the high hardness of the reinforcement particles. This resulted in deep grooves on the work piece surface, which were mostly parallel to the cutting direction. Winert [11] noted that the wear process at the rake face and clearance face of the cutting tool could be classified as sliding wear. He observed that the reasons for the occurrence of the tool wear when machining MMCs are the direct contact between the particles and the cutting edge and their relative motion to the rake and clearance faces. Therefore the hardness of the reinforcement should be the dominant factor for tool wear and by observing the topography of the worn cutting edges the main tool wear mechanism was observed to be abrasion. At high speeds, tool wear becomes very significant and adversely affects the quality as well as the rate of production [12].

At certain cutting conditions, particularly at low cutting speeds, the aluminum matrix of the MMC becomes soft and sticky thereby forming a built up edge (BUE) which increases the surface roughness of the job. But, since a stable BUE protects the cutting edge, the wear was observed to be minimal. El-Gallab and Sklab [13] found that the built-up edge that is formed during machining could protect the cutting tool from abrasion wear. However, the unstable built-up edge may induce tool chipping and adversely affect the surface finish [13–15].

Li and Seah [16] observed that tool wear becomes acute when the percentage of reinforcement in the MMC substrate exceeds a critical value, which is determined by the density and size of the particles. The good surface finish is produced when the particles are cut cleanly instead of being pulled from the matrix material [17].

Various studies have proven that PCD is the ideal cutting tool material for machining aluminum matrix-MMCs with high efficiency [18]. PCD tools showed better wear resistance and produced better surface finish than carbide or alumina tools [19–21]. This was due to the higher hardness of the diamond tools and the lower affinity with the MMC material.

The grain size of the cutting tools has significant influence on the tool wear during machining of MMC. While a tool with coarse grain has a high abrasion resistance required for increased performance, increasing the size of the grains can result in drop in the rupture strength, which also influences over all tool performance [8].

Attempts have been made to extend the classical metal cutting theory to the machining of MMCs and to find a FEM-based solution to issues of machining MMCs. Pramanik et al. [22] developed the analytical model extending the classical merchants' theory, slip line theory

Table 1 Chemical composition of the aluminum matrix of Al - SiC (15 p) composite work piece

Element *	Cu	Si	Mg	Mn	Fe	Ti	Ni	Zn	Pb	Sn	Cr	V	Zr
% Weight	0.88	7.98	0.64	0.01	0.11	0.01	0.01	0.10	0.046	0.036	0.034	0.005	0.001

* The remaining % is aluminum

and Griffith’s theory of brittle fracture to the machining of ceramic particle reinforced MMCs for predicting the cutting forces and found the predicted cutting forces in good agreement with the experimentally observed values. The authors also contend that the classical metal cutting theories are also, by and large, valid for understanding the machining of MMCs. Davim et al. [23] extended the classical merchants' theory of metal cutting to machining of MMCs. and concluded that while machining MMCs the Merchants prediction of shear angle was an overestimate of the observed shear angle.

Pramanik et al. [24] used FEM modeling to investigate the tool-particle interaction during machining of MMCs. One of the major conclusions of the authors was the complete de-bonding of the reinforcement particles, which get separated from the chip also leading to three body wear observed in machining MMCs.

The present work attempts to study the influence of the grain size of the PCD cutting tool on the general machinability, particularly in power consumed, specific power consumed and surface roughness.

2 Experimental procedure

In the Al-SiC MMC, the aluminum matrix was experimentally found to contain 7.98% Si and 0.64% Mg apart from traces of other elements. The complete composition of the aluminum matrix is given in Table 1. The reinforcement was SiC. The percentage of SiC in the metal matrix is 15% by weight. Samples of the material in the form of cylindrical rods of 18 mm diameter and 112 mm length were obtained form the Defense Materials and Research Laboratory (DMRL), Hyderabad, India. The tools used for machining are PCD 1300, 1500 and 1600. The insert geometry and the specification of the tool holder are given in Table 2. The average particle size, volume fraction of diamond and other mechanical properties of different grades of the inserts are given in Table 3. A self-centering lathe was used for the left hand machining tests under dry machining conditions. The turning of the composite was performed at five different cutting speeds ranging from 12 m/min to 60 m/min. Higher cutting speeds could not be reached because of work piece material and maximum rpm available. The feed rates were 0.108, 0.20 and 0.368 mm/rev. The depth of cut used for machining was 0.50 and 0.75 mm. All the tests were carried out under dry machining conditions. Table 4 depicts the various cutting conditions used in the experiments.

Table 2 Specification of the cutting tool (PCD insert)

Characteristic	Metal
Insert	PCD (grades 1300,1500, & 1600)
Substrate (for PCD)	Tungsten Carbide
Type	CNMA 120408
Nose Radius	0.8 mm
Shank size	25*25 mm
Tool holder specification	PCLNR 25 25 M 12
Product name	Diapax

One of the important characteristics indicating the machinability is the power consumed in machining and the specific power. The power consumed by the main spindle was measured by two wattmeter method using two 600 V/5A, UPF wattmeter for all the cutting conditions. The specific power was calculated using the relation.

$$P_S = \frac{P}{MRR} \tag{1}$$

and

$$MRR = \frac{(V * f * b)}{60 * 10^6} \tag{2}$$

The surface roughness of the machined component was measured using a surface roughness tester Mitutoyo Surftest 301. The Ra value of the surface roughness corresponding to each machining condition was measured. During machining, the condition of the PCD inserts were visually observed using a tool maker’s microscope Mitutoyo TM 500. After the machining process the worn insert tips were observed under the scanning electron Mmicroscope (SEM) and the SEM images of the worn inserts were obtained.

Table 3 Characteristics of the various grades of PCD inserts used

Characteristics	Grade 1300	Grade 1500	Grade 1600
Average particle size (μm)	5	25	4
Volumetric % of diamond (%)	92	94	90
Compressive strength (GPa)	7.5	7.5	7.5
Elastic modulus (GPa)	950	1100	850
Transverse rupture strength (GPa)	1.4	0.85	1.7
Knoop hardness - 3 kg Load (kg/mm^2)	4000	4000	4000

Table 4 Experimental details

Part or material	Manufacturing process
Work piece material	Direct chill cast A359/SiC/15p (18 mm * 112 mm l)
Machine	Self-centering lathe
Tool insert	CNMA 120408, nose radius - 0.8 mm, Poly Crystalline Diamond (PCD)
Cutting parameters	Cutting speed - 12 m/min - 60 m/min Feed rate - 0.108,0.200, and 0.368 mm/rev Depth of cut - 0.5, 0.75 mm
Coolant	Dry turning

3 Results and discussion

All the turning tests were performed on three grades of PCD inserts. Generally it was observed that during machining under varying cutting conditions there was no abnormal raise in cutting forces or catastrophic failure of the tool. Also there was no apparent degradation of work piece surface quality.

3.1 Specific power consumption

Specific power consumption, i.e., power consumed per unit volume of material removed per minute, is one of the important indications of the machinability of the material. The material removal rate pertaining to a particular cutting condition was computed and the power consumed was experimentally measured. From these data specific power consumed was calculated. The results are plotted against the cutting speed for various feed - depth combinations. Figure 2 shows the plots for the 1300 grades of the PCD inserts. Figure 2, clearly shows the specific power decreasing with the increasing cutting speed. This is expected because generally as rule specific power consumption decreases as MRR increases. Also higher cutting speeds increase the efficiency of machining. Similarly Fig. 3, shows the variation of specific power consumption at various feed rates. Here also the specific power consumption decreases at increasing feed rates. Both Figs. 2 and 3 is drawn for the tool of grade 1300. The other grades of PCD inserts also reveal a similar trend.

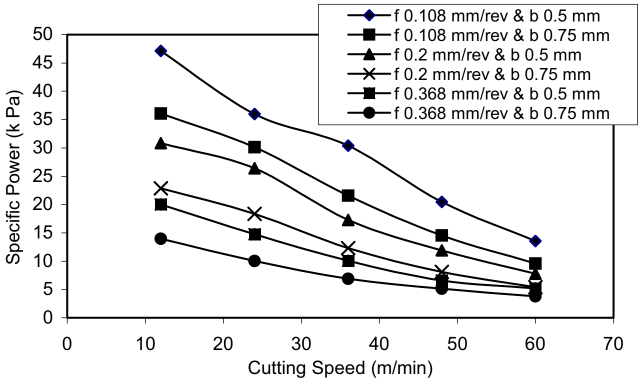

Fig. 2 PCD Gr 1300 specific power vs. cutting speed

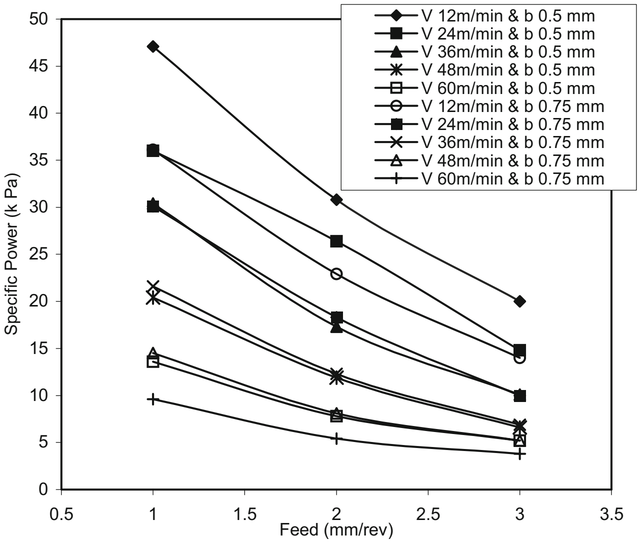

Fig. 3 PCD Gr 1300 specific power vs. feed

3.2 Performance of various grades at different cutting conditions

The Figs. 4, 5, 6, 7, 8 and 9 plot the specific power consumption against cutting speed for the various feed depth of cut combinations for the various grades of PCD inserts. Under the range of chosen cutting conditions the grade 1600 PCD inserts, performed extremely well. It is expected that coarse grain PCD tools perform better as they exhibit higher abrasion resistance and impact resistance.

The decreasing trend of specific power with increasing feed and cutting speed is the primary reason why the machining of MMCs is to be carried out at higher cutting speeds. Since PCD inserts have very high hardness the tool wear rate is quiet low even at cutting speeds in the range of

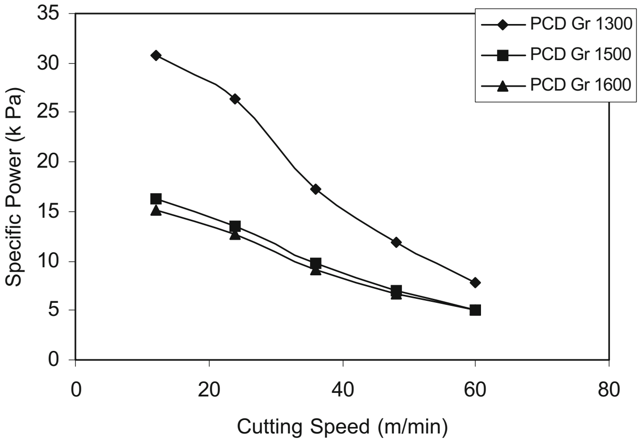

Fig. 4 Specific power vs. cutting speed (Feed 0.108 mm/rev & DOC 0.5 mm)

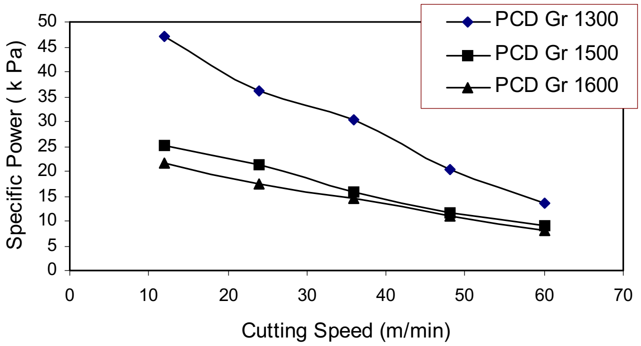

Fig. 5 Specific power vs. cutting speed (Feed 0.2 mm/rev & DOC 0.5 mm)

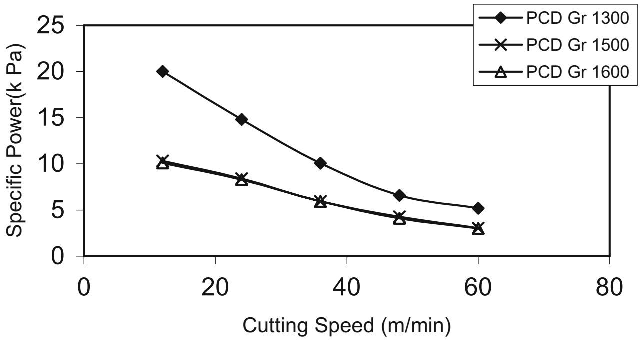

Fig. 6 Specific power vs. cutting speed (Feed 0.368 mm/rev &DOC 0.5 mm)

hundreds of m/min. Since PCD permits higher cutting speeds and since power consumption is also low, MMC machining using PCD insert is usually carried out at very high cutting speeds.

Figure 10 shows the scatter diagram representing the variation in specific power consumption as MRR varies for various grades of PCD inserts. The specific power consumption decreases exponentially with the MRR. The 1600 grade results in a lower specific power consumption value for the entire MRR range, for which experiments were conducted.

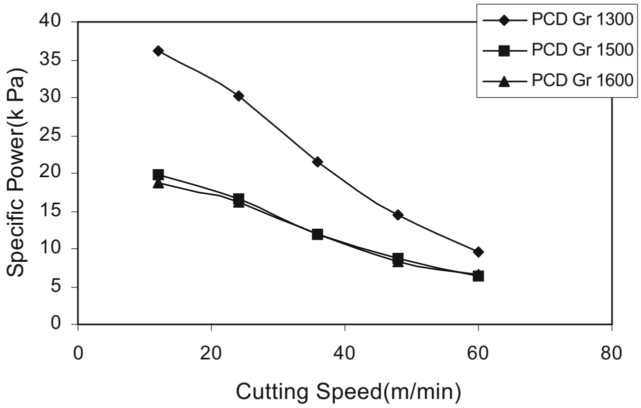

Fig. 7 Specific power vs. cutting speed (Feed 0.108 mm/rev & DOC 0.75 mm)

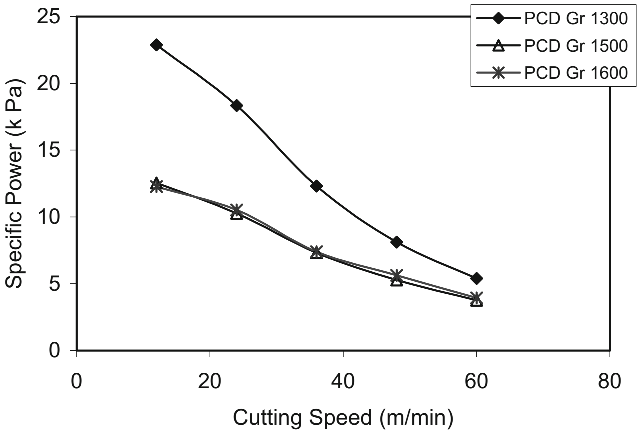

Fig. 8 Specific power vs. cutting speed (Feed 0.2 mm/rev &DOC 0.75 mm)

3.3 Surface roughness

The turning operations were performed at feed rates 0.108, 0.20 and 0.368 mm/rev and 0.50 and 0.75 mm depth of cut. The influence of cutting speed on surface roughness is represented in Figs. 11 and 12. The figures represent the relation pertaining to feed 0.108 mm/rev & depth of cut 0.5 mm and Feed 0.108 mm/rev & depth of cut 0.75 mm for all the three grades of PCD inserts. The general trend of the graphs shows the surface roughness value Ra decreasing as the cutting speed increases. Also the surface roughness performance of the grade 1500 and grade 1600 PCD inserts were much better than the grade 1300 inserts. Other feed and depth of cut combinations also show a similar trend.

Figures 13 and 14 represent the variation of the surface roughness at varying feed rates. The figures represent the

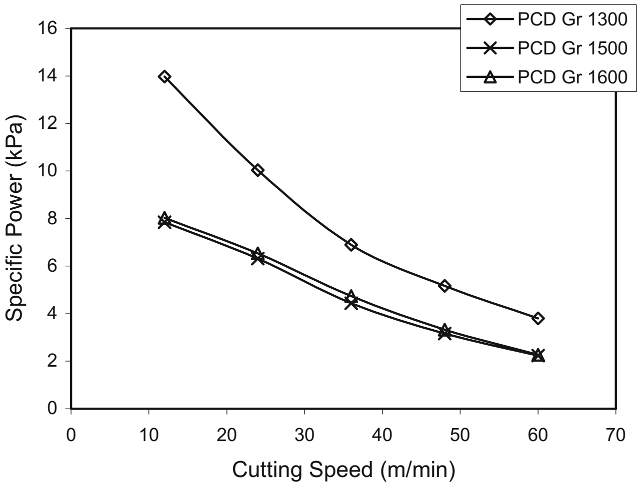

Fig. 9 Specific power vs. cutting speed (Feed 0.368 mm/rev & DOC 0.75 mm)

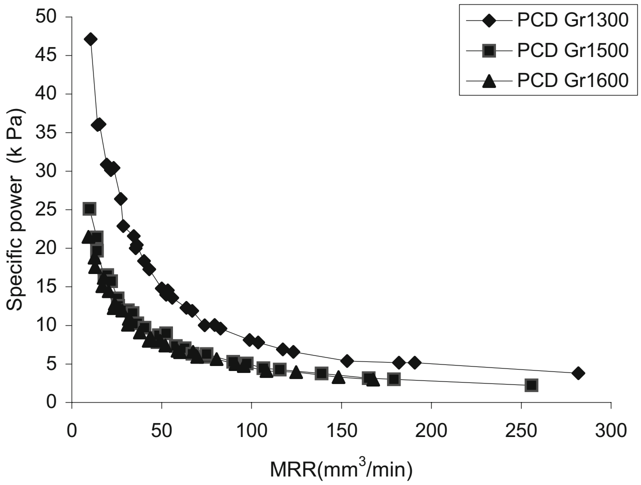

Fig. 10 Specific power vs. metal removal rate

roughness variations at a cutting speed of 12 m/min & depth of cut 0.5 mm and cutting speed 60 m/min & depth of cut 0.5 mm. It can be observed from the graph that the surface roughness value Ra increases at increasing feed rates. Also here again, the grade 1500 and grade 1600 PCD inserts performed much better than the grade 1300 inserts. Combinations of other cutting conditions also reveal similar trends.

From Figs. 13 and 14, it can be observed that the surface roughness values experimentally observed are much higher than the theoretical surface roughness value that can be computed to taking in to account the feed rate and the nose radius. As observed by Paulo Davim [25] this is primarily due to the material in-homogeneity which is characteristic of MMCs. Other factors leading to the high surface roughness value in the experiments are the influence of cutting speed, insufficient rigidity of the tool and work holding systems and the highly dynamic nature of cutting forces because of inhomogeneous cutting.

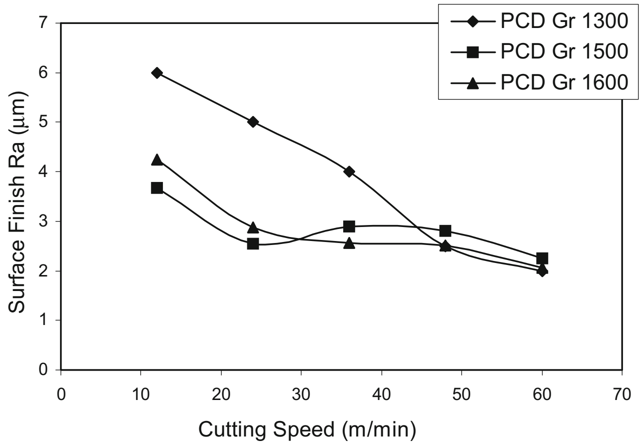

Fig. 11 Surface finish vs. cutting speed (feed 0.108 mm/rev & DOC 0.5 mm)

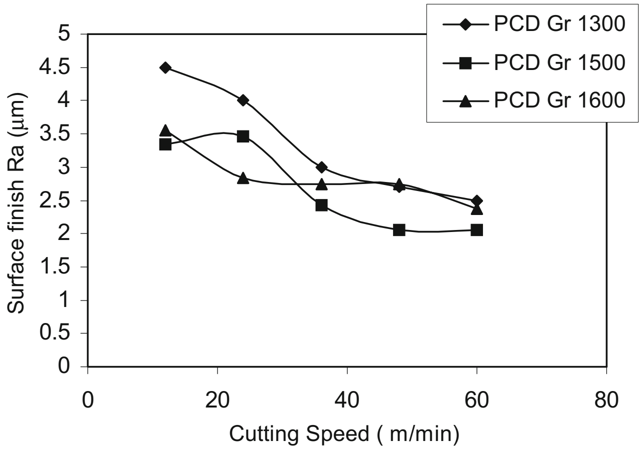

Fig. 12 Surface finish vs. cutting speed (feed 0.108 mm/rev & DOC 0.75 mm)

3.4 Tool wear

The tool was monitored for normal types of tool wear namely crater wear, flank wear and nose wear as machining progressed using a tool makers microscope. The wear on the PCD tool was caused by the abrasive nature of the hard particles present in the work piece material. As diamond is harder than SiC, this abrasive wear may be associated with micro-mechanical damage rather than with micro cutting [26]. At low cutting speeds, the worn flank encourages the adhesion of the work piece material and was therefore often covered with an aluminum film due to the high pressure generated.

Typical SEM micrographs of the rake face of the PCD inserts are shown in Figs. 15, 16 and 17, (grades 1300, 1500 and 1600, respectively). The formation of crater wear, the dark section on the rake face of the tool, is seen in Fig. 16. Crater wear is formed by the high stress and high temperature sliding action of the chip against the tool rake face. Since diamond has an extremely low coefficient of

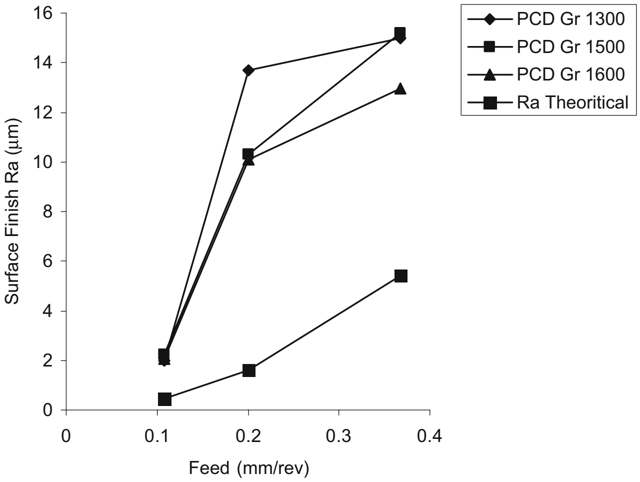

Fig. 13 Surface finish vs. feed (cutting speed 12 m/min & DOC 0.5 mm)

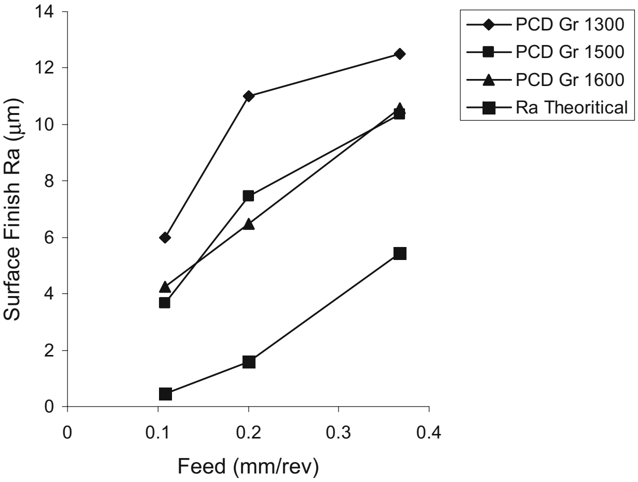

Fig. 14 Surface finish vs. feed (cutting speed 60 m/min & DOC 0.5 mm)

friction and high thermal conductivity, crater wear is not a significant wear mode of tool failure in PCD inserts. Hence only in Fig. 16 we see a very shallow crater formation and absolutely no indication of crater wear in other inserts.

In machining Al - SiC composites using PCD inserts, the predominant mode of tool wear is by abrasion [25]. Figure 17 also shows significant wear in the nose region of the cutting tool, which could be attributed to the abrasion and micro chipping of the sharp cutting edge.

The examination of the worn tool under optical microscope revealed a relatively stable built-up-edge over the entire range of cutting speeds for which machining experiments were conducted. This is expected because of the low cutting speeds at which experiments were conducted and the soft aluminum matrix, which adheres to the cutting edge at low temperature cutting. Even the hard, intermittent SiC reinforcements did not disturb the relatively stable BUE.

The optical inspection of the flank face of the cutting tool revealed the beginning of the flank wear. No substantial groove wear was observed. Also significant amount of de-brazing of the insert could be observed. This is due to the shock loads associated with machining of Al-SiC, MMC.

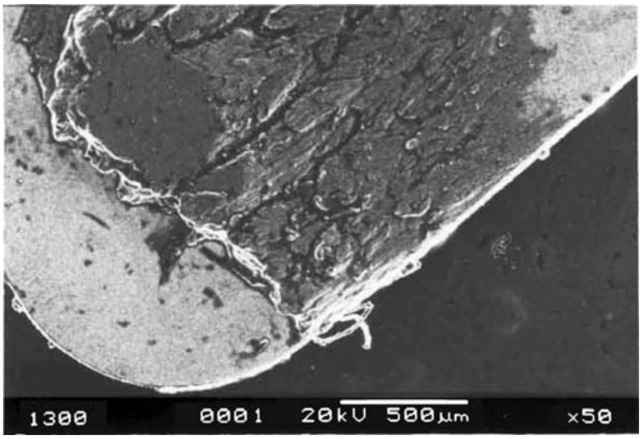

Fig. 15 Scanning electron micrograph showing tool top rake of PCD Gr 1300

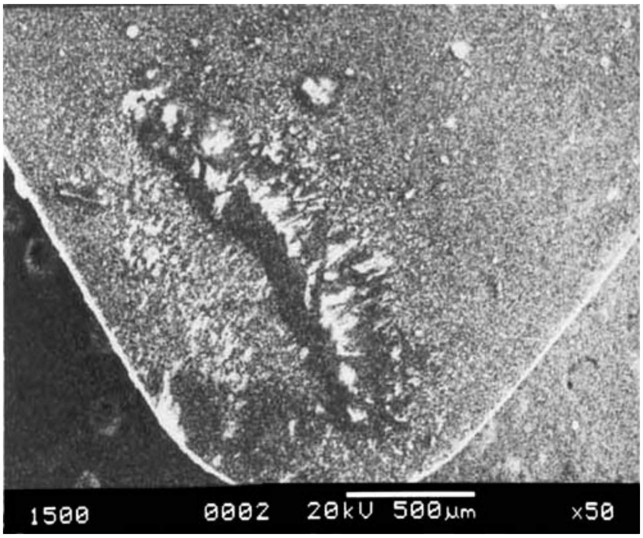

Fig. 16 Scanning electron micrograph showing tool top rake of PCD Gr 1500

4 Conclusions

1. The specific power was observed to be minimum at cutting conditions leading to maximum material removal rate. That is, for the chosen cutting conditions, minimum specific power was obtained for the maximum values of cutting speed, feed and depth of cut for all the three grades of PCD inserts.
2. For all the three grades of PCD inserts and for the chosen cutting conditions, the surface finish was found to be superior at higher cutting speeds and at lower feed rates.

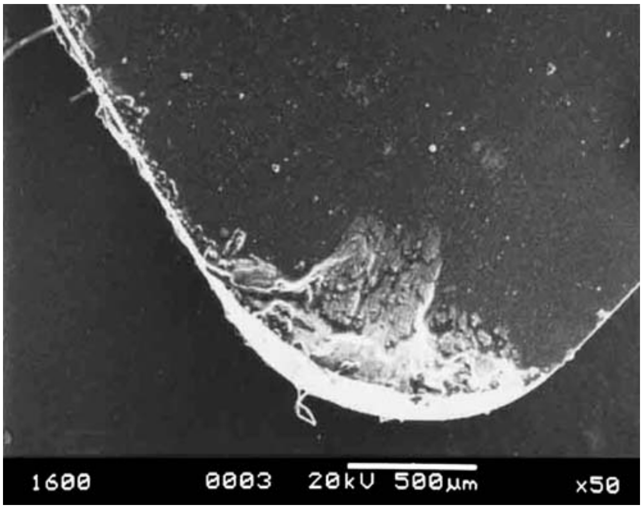

Fig. 17 Scanning electron micrograph showing tool top rake of PCD Gr1600

3. The surface finishes obtained in the experiments were found to be much higher than the theoretically calculated surface roughness. This is due to the inhomogeneity of the MMCs and the other factors like tool and work piece rigidity.
4. Under the cutting conditions for which machining experiments were carried out the 1600 grade PCD insert was observed to be consistently superior in terms of specific power and surface finish, closely followed by the 1500 grade PCD inserts.
5. The optical and SEM observation of the worn inserts indicate the presence of stable built up edge. The beginning of flank and crater wear can also be observed.

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