15th International Plansee Seminar, Eds. G. Kneringer, P. Rödhammer and H. Wildner, Plansee Holding AG, Reutte (2001), Vol. 2

High Speed Dry Machining of MMCs With Diamond Tools

J. L. Collins
De Beers Industrial Diamonds (UK) Ltd, Charters,
Ascot, Berkshire, SL5 9PX, UK

Summary

The increasing use of Metal Matrix Composites (MMCs) has raised new issues in their machining. Industrial demands for higher speed and dry machining of MMCs with improved component production to closer tolerances have driven the development of new tool materials. In particular, the wear characteristics of synthetic diamond tooling satisfy many of the requirements imposed in cutting these highly abrasive workpieces. The use of diamond tool materials, such as Polycrystalline Diamond (PCD), has resulted in tool life improvements which, allied with environmental considerations, show great potential for the development of dry cutting. This paper explores the wear characteristics of PCD, which is highly suited to the dry machining of particulate silicon carbide MMCs. Also, two further diamond tool materials are evaluated - Chemical Vapour Deposition (CVD) thick layer diamond and synthetic single crystal diamond. Their suitability for the efficient machining of high volume fraction MMC materials is shown and their potential impact on the subsequent acceptance and integration of MMCs into engineering components is discussed.

Keywords

Diamond; Metal Matrix Composites; MMC; PCD; Chemical Vapour Deposition; CVD; Synthetic Single Crystal Diamond;

1. MMC Machining in a New Millennium

For several years, metal matrix composites (MMCs) have been widely available in a variety of forms, engineered for specialist industrial use. In particular, because of their excellent abrasion resistance and ease of manufacture, silicon carbide particle reinforced and short fibre reinforced aluminium alloys are increasingly desired by industry to replace existing components in a mass-production environment (1). In 1999, the world-wide sales of MMCs was $102.7 million, representing approximately 2.5 million kilogrammes of metal

15th International Plansee Seminar, Eds. G. Kneringer, P. Rödhammer and H. Wildner, Plansee Holding AG, Reutte (2001), Vol. 2

matrix materials, including aluminium, beryllium, copper, nickel-based superalloys, refractory metal and titanium-matrix composites reinforced with particles, short fibres or continuous fibres (2). Sought-after for their excellent strength-to-weight ratios, increased stiffness and wear resistance, the production and cost-efficient machining of, for example, squeeze cast near-net-shape silicon carbide particle reinforced aluminium MMC brake discs has been limited by extensive tool wear, poor tolerances and poor surface finish when using conventional tooling. Despite this, the growth rate of the use of MMCs is steady and the volume of MMCs currently used is expected to double by 2004 (2). High yields of close tolerance components are especially important when considering MMCs because of the comparatively high cost of these materials. Casting to near-net-shape is an essential cost saving factor. Machining with maximum component yield is paramount.

It is generally agreed that the two main requirements for efficient manufacture of near-net-shape components - high cutting speeds together with low feed rates - produce the worst conditions for tool wear (3). Under such conditions, the tool has been shown to wear primarily through abrasive wear mechanisms caused by the reinforcement rubbing along the rake and flank faces of the cutting tool (4). This can be reduced by allowing a built-up edge to form, at the expense of workpiece surface finish (5). The poor results achieved with conventional tooling are more clearly understood when the properties of the reinforcing material are taken into consideration. Silicon carbide (SiC) is used as the typical particle reinforcement because it is light, low cost, hard and highly abrasion resistant and often used in highly abrasive grinding wheels.

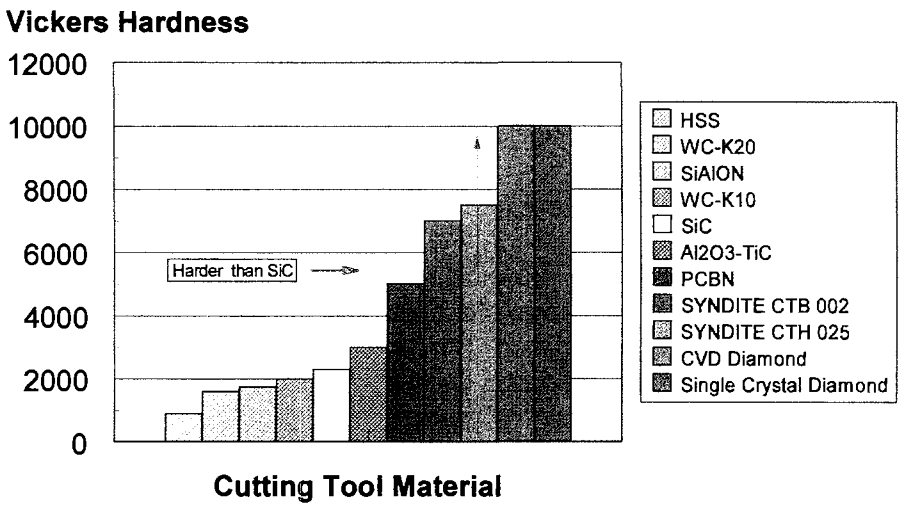

Figure 1: The Vickers hardness of various cutting tool materials compared to

15th International Plansee Seminar, Eds. G. Kneringer, P. Rödhammer and H. Wildner, Plansee Holding AG, Reutte (2001), Vol. 2

Figure 1 shows the relative Vickers hardness of various cutting tool materials compared to that of SiC. Only ultrahard materials and novel coated tools will be resilient against the abrasive SiC particle reinforcement, their comparatively high thermal conductivity also reducing tool wear caused by temperature generation during machining. However, economic constraints often limit the tool material used to those less durable materials, where tool life is short but surface finish is adequate, thus limiting the mass-production of high tolerance components. Machining using coolant to improve surface finish and tool life has been shown to be moderately effective, but it has been noted that this, in fact, can reduce the tendency for built-up edge formation, thereby improving workpiece surface finish. However, the abrasive slurry which is formed from the MMC reinforcement can accelerates tool wear (6). The difficulties encountered in industrial applications have led to grinding with superabrasive materials being used as the main operation employed to achieve the desired component surface finish and dimensional tolerances. The use of SiC particulate reinforced aluminium alloy MMC has, until relatively recently, been predominantly in specialist applications rather than in mass production.

Over the past decade the machining of MMCs to the stringent requirements of industry by techniques other than grinding has been made possible through research using ultrahard materials such as PCD. In particular, dry machining is increasingly used to reduce costs and fulfil environmental obligations set by current legislation (7). As MMC technology and usage have evolved, so too has the development of improved ultrahard and wear-resistant grades of PCD for dry machining with enhanced tool performance, improved workpiece surface integrity, better machining tolerances and the potential for reduced machining costs (8). The more recent development of novel ultrahard materials - such as CVD diamond - offers an exciting alternative to currently used tool materials, their excellent abrasion resistance and high thermal stability allowing increased cutting speeds during dry machining.

This paper examines the performance of two grades of PCD (SYNDITE CTB 002 and SYNDITE CTH 025), two grades of thick layer CVD diamond (CVDITE CDM and CVDITE CDE), and synthetic single crystal diamond (MONODITE) in single point turning a typical SiC particulate reinforced aluminium alloy MMC over a range of cutting speeds in terms of surface finish, monitoring wear progression and cutting forces to estimate overall tool life.

15th International Plansee Seminar, Eds. G. Kneringer, P. Rödhammer and H. Wildner, Plansee Holding AG, Reutte (2001), Vol. 2

2 Tool Materials, Cutting Tools and Test Material

2.1 Tool Materials and Cutting Tools

Cutting tool materials used today range from high speed steel, tungsten carbide, cermet and ceramic inserts, perhaps with additional hard coatings, through to PCD, PCBN, CVD diamond and single-crystal diamond to cover the entire spectrum of machining operations, strongly influenced by workpiece properties and industrial demands for more economic production to ever increasing standards. Figure 2 shows the spectrum of most frequently used cutting tool materials in terms of their most important properties: abrasion resistance, toughness and hot hardness.

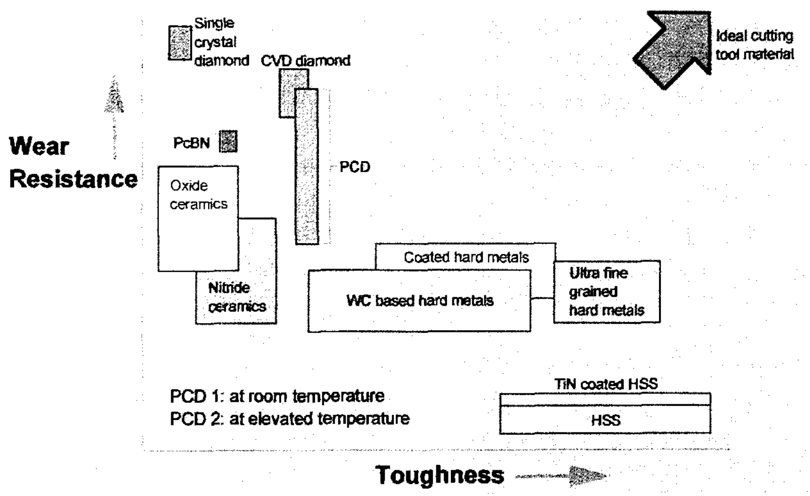

Figure 2: The spectrum of cutting tool materials shown in terms of their abrasion resistance, toughness and hot hardness

In general, performance-based economic constraints limit the viable range of tool materials for MMC machining to PCD. However, new developments in the production of CVD diamond and synthetic single crystal diamond have extended the range of suitable tool materials. Figure 3 outlines workpiece abrasion resistance against the machining operation required, showing where CVD diamond and single-crystal diamond might be used. In particular, these materials show great promise in dry machining MMC materials because of their excellent abrasion resistance (compared with, for example, the wear

15th International Plansee Seminar, Eds. G. Kneringer, P. Rödhammer and H. Wildner, Plansee Holding AG, Reutte (2001), Vol. 2

resistance coefficient of ISO K10 WC of 1 (9)) and superior thermal properties (compared with, for example, the thermal conductivity of ISO K10 WC of 100 W/m.K (9)).

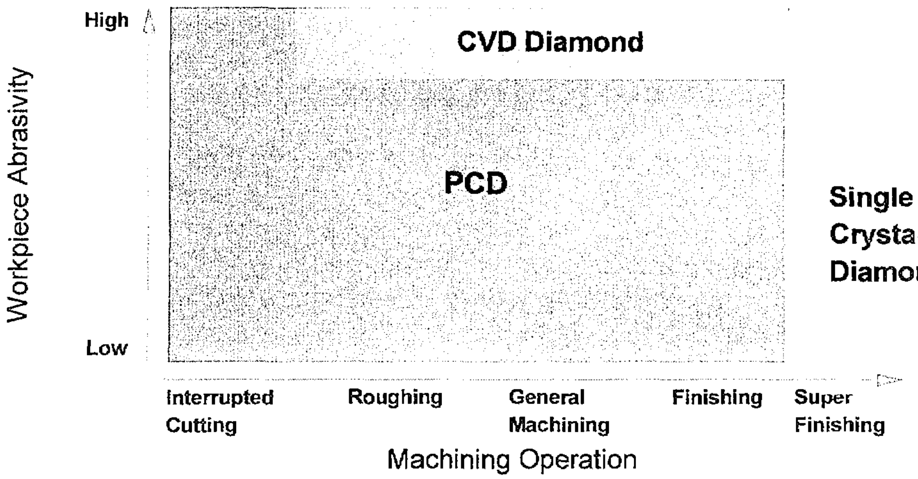

Figure 3: The applications arena for PCD, CVD diamond and single crystal diamond

In this study, five different diamond tool materials have been compared, as described in Table 1.

Tool Identification	*Tool Type*	*Grain Size (μm)*	*Diamond Thickness (mm)*	*Knoop Hardness (GPa)*	*Wear Coefficient*
CTB 002	SYNDITE CTB 002 polycrystalline diamond	2	0.5	48	3.9
CTH 025	SYNDITE CTH 025 polycrystalline diamond	25	0.5	52	4.5
CVDITE CDM	Non-electrically conducting CVD diamond	60-80	0.5	100	5.5
CVDITE CDE	Electrically conducting CVD diamond	60-80	0.5	100	5.5
MONODITE MTL	Synthetic single crystal diamond plate	~3500	1.2	50-100	6.3

Table 1: The tool materials used in this study. The wear coefficient of ISO K10 WC is taken as 1.0, for comparison. The grain size of the MONODITE MTL plate is taken to be the plate size.

15th International Plansee Seminar, Eds. G. Kneringer, P. Rödhammer and H. Wildner, Plansee Holding AG, Reutte (2001), Vol. 2

2.2 Cutting Tools

The diamond materials described in Table 1 were used to fabricate cutting tool inserts (five of each type were manufactured and tested) with an ISO standard TPMA160408 geometry according to manufacturers' guidelines (10). These were ground to shape with suitable edge preparation using conventional diamond grinding techniques (10). This tool geometry gives a clearance of 11°± 0.5°, a top rake of +6° and tip radius of 0.8±0.05mm. A neutral toolholder was used with an approach angle of 60°. The synthetic single-crystal MONODITE (MTL) tools were produced with a {110} cutting tip in the TPMA160408 format, which is that recommended as the most abrasion resistant and tough direction in single-crystal diamond tooling (11). This particular tool geometry was chosen according to machining guidelines for PCD tooling turning MMC materials (12).

2.3 MMC Test Material

The MMC test pieces used in this study were in the form of spray deposited cylinders 250mm in diameter and 300mm long produced using standard technology. The MMC composition was primarily a 1.5% Mg modified A2618 7%Si-Al alloy with 1.2%Fe, 2.3%Cu and 1.1%Ni which was reinforced with 20% by volume of 10-15μm SiC particles. Since the Si level is below the eutectic of 9%, the amount of free Si to act as an abrasive during machining is limited. However, the Mg, Fe, Cu and Ni precipitates in the alloy strengthen the matrix by hindering dislocation movement and, as a result, the yield strength for this MMC is approximately 30-35% higher than that for A356 MMC (which is often used in trials but atypical of that seen in industrial applications). The precipitates formed act as secondary hard inclusions which accelerate the flank wear process. Figure 4 shows an SEM micrograph of the MMC microstructure and its angular SiC particulates and Al particles surrounded by the Al alloy. An SEM micrograph and combined X-ray map (Figure 5) clearly show the distribution of the SiC particulates, the Al alloy containing the precipitates of Mg, Fe, Cu, Ni and Si and several blade-like Si particles approximately 10μm long.

15th International Plansee Seminar, Eds. G. Kneringer, P. Rödhammer and H. Wildner, Plansee Holding AG, Reutte (2001), Vol. 2

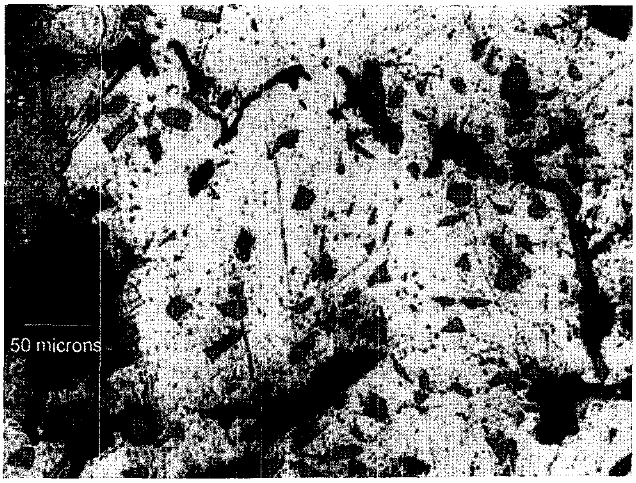

Figure 4: An SEM micrograph of the MMC microstructure and its angular SiC particulates and Al particles surrounded by the Al alloy

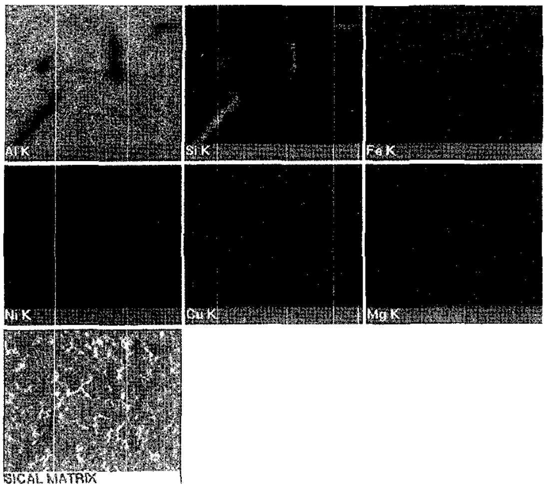

Figure 5: An SEM micrograph and combined X-ray map clearly show the distribution of the SiC particulates, the Al alloy containing the precipitates of Mg, Fe, Cu, Ni and Si and several blade-like Si particles approximately 10μm long.

15th International Plansee Seminar, Eds. G. Kneringer, P. Rödhammer and H. Wildner, Plansee Holding AG, Reutte (2001), Vol. 2

3 Experimental Procedure

Single point turning tests have been performed over a range of cutting speeds and monitored in terms of wear progression, cutting forces and surface finish. The types and geometry of the tools have been described in sections 2.1 and 2.2; and the test material in section 2.3. The tests were carried out using five tools of each of the tool materials described on a Heyligenstaedt Heynumat 5 CNC lathe at five speeds: 300m/min, 500m/min, 800m/min, 1200m/min and 1500m/min using a 0.1mm/rev feed and constant depth of cut of 0.1mm. Tool wear was monitored using a Wild M7 S microscope with a calibrated graticule through-lens measuring system and an average was taken from the five tools tested. Surface finish was measured in-situ using a digital Mahr Perthen M4P stylus system for R_a, R_z and R_{max}. The radial, feed and tangential cutting forces were measured using a Kistler Type 9121 three-axis dynamometer and Kistler Type 5017A multichannel charge amplifier and computer logged.

4 Results and Discussion

Machinability data is usually presented as the relationship between tool life and cutting speed with the tool life set at a fixed value of tool flank wear. The time taken for the tool to wear to this fixed value depends on the cutting speed. Figure 6 shows this for all five materials tested for each of the cutting speeds used.

It can clearly be seen that the best results (lowest wear rates) can be ranked for the diamond materials in three ways across the range of machining speeds used. The first ranking property is grain size (the single crystal material having, effectively, a single "grain"). If abrasive wear mechanisms are predominant, then the smaller the grain of the tool material, the greater the wear expected. Since the grain size of the tool material in the case of the PCD 002 grade is smaller than the grain size of the SiC abrasive particulates in the MMC, greater microcracking and fatigue at the tool surface would lead to whole diamond grains or clumps of grains which have been abraded from the tool to cause further damage to the tool edge, increasing the effective wear rate in a three-body interaction between the tool edge, the SiC particulates and abrasive detritus from the workpiece and tool combined.

15th International Plansee Seminar, Eds. G. Kneringer, P. Rödhammer and H. Wildner, Plansee Holding AG, Reutte (2001), Vol. 2

Conversely, when the grain size of the tool material is larger than the SiC particulates (as is the case for the PCD 025, CDE, CDM and MTL materials), then the wear mechanism is a pure 2-body interaction between the particulates and the tool, and the tool hardness becomes the dominant support against abrasive wear - the second ranking of the tool materials. As shown in Table 1, the hardness of the different tool materials matches the wear rates, as would be expected with an abrasive wear mechanism. Thirdly, although temperatures generated during dry machining do not usually become excessive over the cutting speed range investigated, the low coefficient of friction for the materials suggests that tribo-thermal wear is minimal in the higher thermal conductivity tool materials compared with that for the lower thermal conductivity materials. The effect of tool table and edge polishing and using a positive rake angle is to lower cutting temperatures and cutting forces in order to reduce thermal and mechanical loading on the cutting edge.

Figure 7 shows scanning electron microscope (SEM) micrographs of the flank wear on typical examples of each tool after 10 minutes machining which support evidence for a purely abrasive wear mechanism. Close inspection of the high magnification SEM micrographs shown in Figure 7 of the PCD 002 and PCD 025 tools shows grooving on the tool flank which (approximately) corresponds to the size of the SiC grain size in the case of PCD 002 and with the PCD grain size in the case of PCD 025. Similarly, inspection of the high magnification images of the CVDITE CDE, CDM and MONODITE MTL tools shows grooving commensurate with the 15μm SiC particulate maximum size. Thus, a purely abrasive wear mechanism based on tool grain size and hardness is evident.

The generation of Taylor lines for the various materials (a series of logarithmic plots of tool life versus cutting speed, a characteristic of the tool material for a given feed rate, depth of cut, tool geometry and workpiece) is shown in Figure 8, where the expected tool life (and performance) of the single crystal material can be seen to be considerably better than the CVD diamond and PCD tool materials, although all three compare extremely favourably in comparison with conventional tool materials (13,14,15).

15th International Plansee Seminar, Eds. G. Kneringer, P. Rödhammer and H. Wildner, Plansee Holding AG, Reutte (2001), Vol. 2

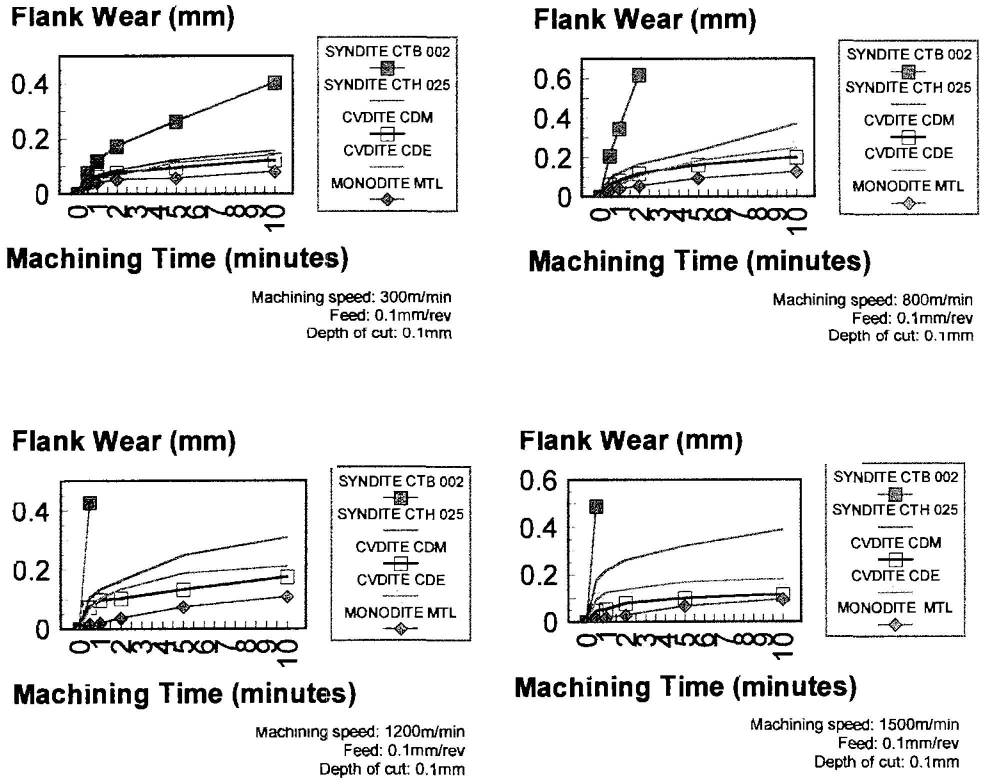

Figure 6: Machining data for all five materials tested at four cutting speeds

15th International Plansee Seminar, Eds. G. Kneringer, P. Rödhammer and H. Wildner, Plansee Holding AG, Reutte (2001), Vol. 2

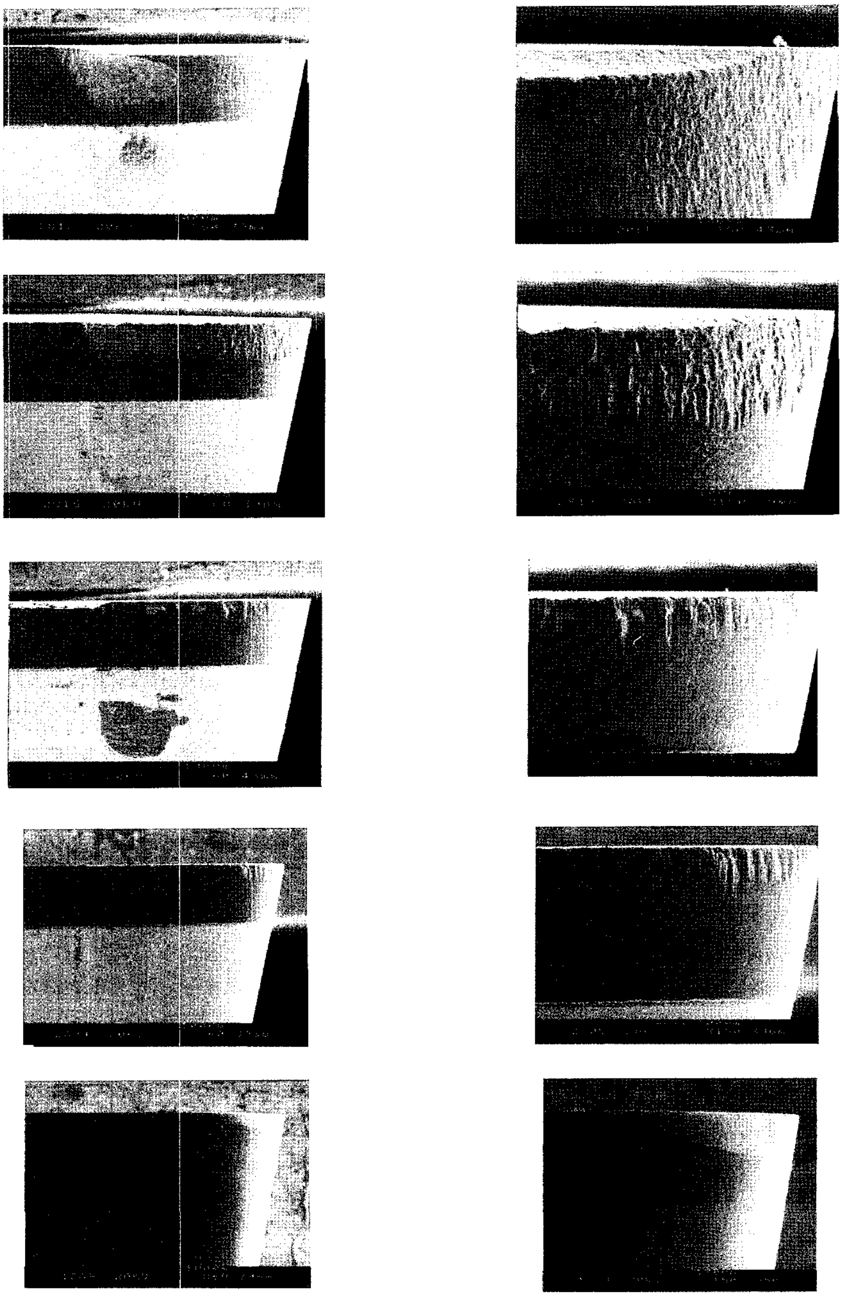

Figure 7: SEM micrographs of the cutting edges of five typical tools used, top-to-bottom: CTB002, CTH025,CDM, CDE, and MTL respectively

15th International Plansee Seminar, Eds. G. Kneringer, P. Rödhammer and H. Wildner, Plansee Holding AG, Reutte (2001), Vol. 2

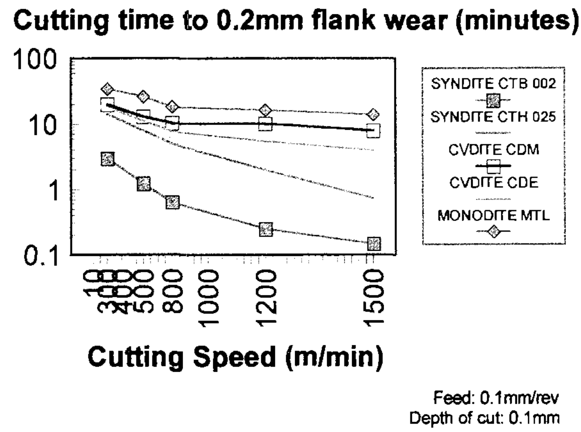

Figure 8: Taylor lines for the various materials showing the performance advantages of using the different grades of diamond in machining 20%SiCAl MMC

The cutting forces developed in the tools measured throughout turning are summarised in Figure 9, showing the feed (axial) and radial forces developed at the end of testing versus cutting speed. It is clear that the lower the coefficient of friction and the lower the tool wear (and hence sharper tool edge), the lower are the axial (or feed) and radial cutting forces developed. This is a good ranking of the potential overall lifetime of the tools and supports the argument for a wear mechanism based on the hardness and coefficient of friction of the tool materials rather than tribo-thermal effects.

It is well known that the quality of the cut surface produced by diamond tools on Al and Al alloys is significantly better than that produced by cemented WC, cermet and ceramic tooling (15). Al tends to stick and bond to non-diamond surfaces, but, since the coefficient of friction and wear rate of diamond tooling is very low, the tools cut more cleanly, with less tendency to rub or burnish the workpiece surface. Diamond tooling produces a minimal built-up edge (BUE) and removes material as clean chips compared with non-diamond tooling (13), as is evident from the SEM micrographs shown in Figure 7 and Figure 8. The formation of a BUE tends to limit tool wear, but as the BUE decomposes it provides abrasive particles which affect the machining surface (as if a secondary abrasive has been added), as described above.

15th International Plansee Seminar, Eds. G. Kneringer, P. Rödhammer and H. Wildner, Plansee Holding AG, Reutte (2001), Vol. 2

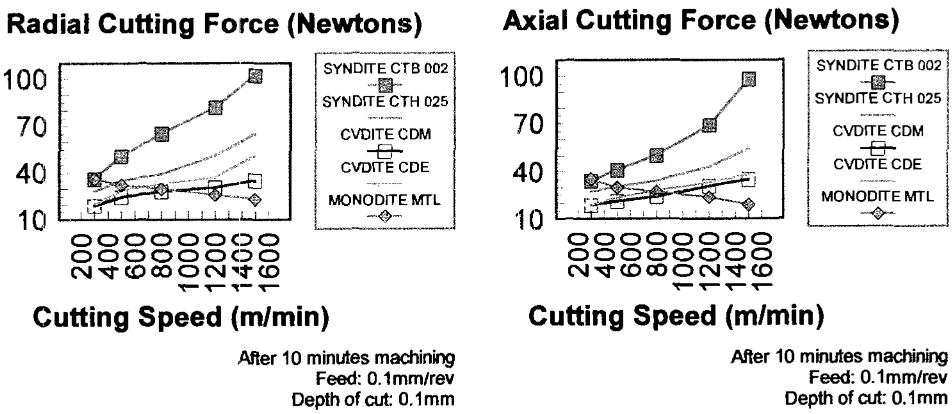

Figure 9: Cutting forces developed in the tools at the end of turning the 20%SiCAl-Al MMC for 10 minutes.

Also, because diamond tooling cuts more cleanly it produces substantially less sub-surface damage than the rubbing or burnishing action seen with non-diamond tooling (15). Figure 10 shows the surface finish of the workpiece for the various diamond tools tested versus cutting speed in terms of R_a and R_{max} respectively. These are commensurate with the description given for the diamond tooling options for machining highly abrasive workpieces, described in Figure 3, and demonstrate that new tooling options such as CVD diamond and synthetic single-crystal diamond are viable options for machining such highly abrasive MMC materials in terms of their tool life and performance.

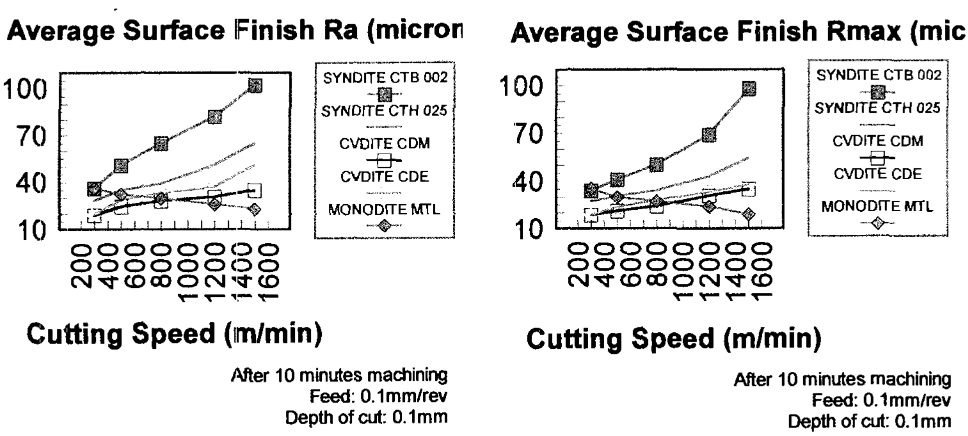

Figure 10: Surface finish developed on the 20%SiCAl-Al MMC workpiece by the tools at the end of turning for 10 minutes.

15th International Plansee Seminar, Eds. G. Kneringer, P. Rödhammer and H. Wildner, Plansee Holding AG, Reutte (2001), Vol. 2

5 Conclusions

The predominant tool wear mechanism has been determined to be through abrasive wear dependent on the hardness of the tool material compared with the SiC particulate MMC reinforcement and on the grain size of the tool material in comparison with the size of the reinforcement. Tribo-thermal effects seem to play little part in the wear of such highly thermally conductive materials. The cutting forces observed increase as expected and are commensurate with the ranking of the abrasion resistance of the tool materials, suggesting that good tool lifetimes are achievable. As expected, tool flank wear increases with cutting speed, but Taylor lines for the various materials demonstrate that this is very low compared with conventional tool materials. Workpiece surface finish is dependent on the tool hardness and deteriorates with both machining time and cutting speed. However, the surface finish achieved in this study is typical of a roughing through to finishing operation, and improvements could be made with refined tool geometry.

Whereas little use is currently made of the newer synthetic single-crystal diamond and CVD diamond materials compared with PCD 025 grades, these materials show great promise for the high-speed dry machining of particularly abrasive SiC particulate Al MMCs for producing components to good tolerance and surface finish.

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