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High-speed turning experiments on metal matrix composites

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The hard abrasive ceramic component which increases the mechanical characteristics of metal matrix composites (MMC) causes quick wear and premature tool failure in the machining operations. The aim of the paper is to compare the behaviour of high rake angle carbide tools with their diamond coated versions in high-speed machining of an Al_2O_3Al 6061 MMC. The influence of the cutting parameters, in particular cutting feed and speed, on tool wear and surface finish has been investigated. The higher abrasion resistance of the coatings results in increased tool life performances and different chip formation mechanisms. © 1998 Published by Elsevier Science Ltd. All rights reserved.

(Keywords: metal matrix composites (MMCs); high-speed machining; tool wear)

INTRODUCTION

The benefit of using composite materials, and the cause of their increasing adoption is to be looked for in the advantage of attaining property combinations, that can result in a number of service benefits. Among these are: increased strength, decreased weight, higher service temperature, improved wear resistance and higher elastic module.

The main advantage of composites lies in the taylorability of their mechanical and physical properties to meet specific design criteria.

In recent years, a new generation of materials known as metal matrix composites (MMC) [1,2] has been developed, in order to satisfy the demand for a high strength and toughness material, capable of operating effectively under adverse conditions.

The development of these materials began in the 1960s with the introduction of boron, graphite and aramide fibres. Work on MMCs resulted in several boron/aluminium MMCs parts. However, interest in MMCs diminished in the early 1970s as polymer matrix composites became the dominant material. The introduction of new fibre reinforcement materials in the late 1980s encouraged once again the new development of MMCs.

These materials are generally formed by a matrix which can be made of any suitable metal (aluminium, magnesium, titanium and some superalloys being the most popular), reinforced with SiC or Al_2O_3 in the form of continuous or discontinuous fibres, whiskers or particles of the ceramic material.

These advanced composites are considered excellent candidates for high temperature applications. The specific mass of most MMCs is about one third that of steel, and the specific strength and stiffness of these materials is quite high [3]. These properties are important in automotive and aerospace applications because of the potential for large reductions in weight—up to 25%. Furthermore, their high temperature strength retention is also an important feature, making them suitable candidate materials for use in automotive and aircraft-engine applications.

The properties that make MMCs appealing to engineering designers can, however, present a major challenge when attempting to machine these materials because of their brittle behaviour and high hardness.

For instance, the presence of hard Al_2O_3 particles in Al_2O_3/Al-alloy MMC materials involves considerable difficulties when machining these materials using conventional methods such as turning, drilling, milling and sawing, etc., due to the high wear rate [4–7]. This is not surprising given that Al_2O_3 forms the basis of many cutting-tool materials. Therefore, machining MMCs using these conventional methods often involves frequent and expensive tool changes and therefore increased job-completion times. Turning, milling and drilling of MMCs, therefore, requires the use of carbide, diamond or hard-nitride-coated tools. Even then machining times tend to be two to four times greater than those for unreinforced matrix material because of increased tool wear, the necessity to use reduced

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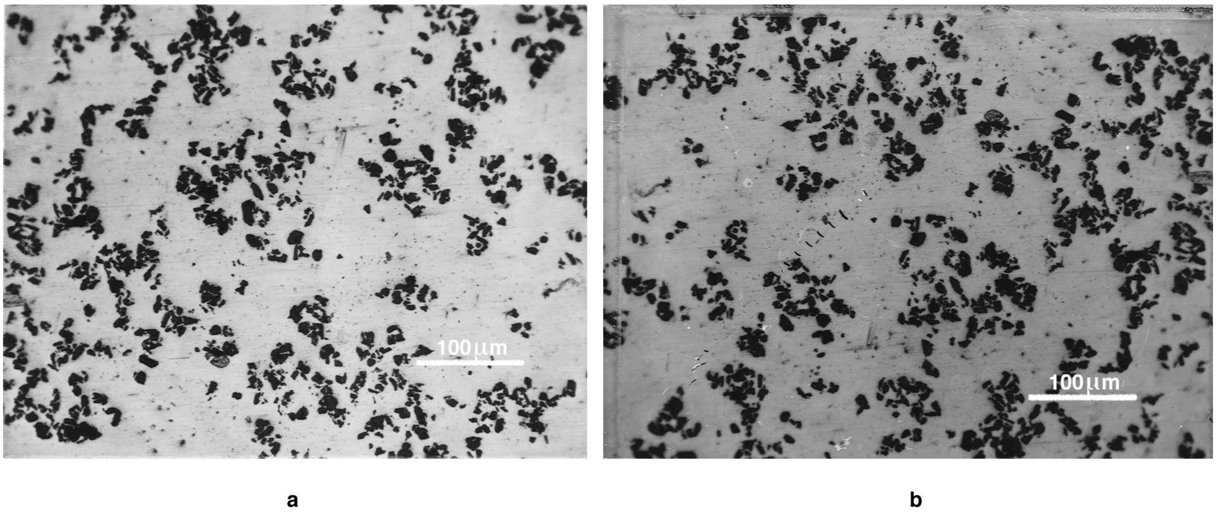

Figure 1 Al_2O_3 particle distribution parallel (a) and perpendicular (b) to the extrusion direction

Table 1 Chemical composition of the 6061 aluminium matrix

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Ni	Al
% weight	0.59	0.15	0.27	0.004	1.04	0.09	0.002	0.006	0.001	bal.

Table 2 Cutting conditions

Inserts	Uncoated carbide grade ISO K Diamond coated carbide grade ISO K
Rake angle (γ)	$+20°$
Nose radius (r)	0.4 mm
Machined volume (Y)	150×10^3 mm^3
Depth of cut (a)	2 mm
Speed (V_t)	(630, 800, 1000, 1260) m/min
Feed (f)	(0.03, 0.10, 0.17) mm/rev
Cooling	none

feed-rates, and the need to achieve good surface finish, which is required by the brittle behaviour of the metal-matrix composites [8–10].

The difficulties associated with the machining of MMCs must be minimised if these materials are to be used more extensively. Therefore, the machining of MMCs is now considered to be one of the most interesting areas of manufacturing science requiring urgent attention. Since MMCs are relatively new materials, comprehensive machinability data have yet to be established and this has aroused some research interest [5,6,8–13].

In this paper the results of some investigation are outlined, involving the high-speed machining of a 10% particulate Al_2O_3/6061 T6 aluminium matrix composite by conventional lathe-turning. Carbide and diamond-coated carbide tools of the same geometry were used for the tests and measurements of tool wear and part-surface finish were carried out. Tests were performed over a range of cutting speeds and feed rates.

SEM observations of the chips, as well as the wear results have enabled assessments to be made of the mechanisms of chip formation at different cutting speeds and feeds.

The authors have previously reported [13] the results of investigations on a (Ti,Al)N coating to improve tool life. However, these results indicated that the coating would not be economically feasible, due to the small advantage in tool duration compared with the relatively higher costs.

EXPERIMENTAL SET-UP

Turning tests were performed on a numerically controlled vertical lathe which has a stiff, sturdy spindle with special purpose roller bearings, allowing spindle speeds to reach 5000 rpm. The spindle is powered by a DC motor rated 80 kW in continuous duty, with a peak power of 120 kW.

Commercial uncoated and CVD diamond-coated carbide tools in the form of triangular indexable inserts were used, the geometry of these inserts being typical for the machining of aluminium alloys. Polycrystalline diamond tools were not tested due to their high cost compared with the uncoated carbide tools. A tool holder with a lead angle $\chi = 91°$ and inclination angle of $\lambda = 0°$ was used.

Tests were carried on in continuous cutting on a 10% particulate Al_2O_3/6061 T6 aluminium matrix alloy, whose composition is reported in *Table 1*. In *Figure 1* the homogeneous reinforcing Al_2O_3 particle distribution is shown, parallel and perpendicular to the extrusion direction.

Following preliminary tests, the cutting conditions were chosen to avoid catastrophic failure. The selected cutting conditions are reported in *Table 2*. Overall, 12 tests for each tool type were carried out.

After the machining of 150×10^3 mm^3 and verifying that the pattern of tool wear was uniform, the flank wear V_B was measured according to the ANSI/ASME B94 55M standards. A SEM picture of the cutting edge area of a worn carbide tool is shown in *Figure 2* to show the uniform pattern of the flank wear.

Surface roughness R_a was measured on the machined surfaces by a Hommel T1000 stylus instrument. Measurements were made in four positions spaced at $\theta = 90°$ around the workpiece to obtain medium values and their distributions.

Chips and tools were prepared metallographically and examined by SEM microscope using both secondary electrons (SE) and backscattered electrons (BSE). EDAX semi-quantitative analysis was also carried out.

RESULTS AND DISCUSSION

The tool wear V_B and the average surface roughness R_a values obtained for each parameter couple V_t–f using uncoated and diamond-coated tools were statistically analysed using multiple linear regression. The independent variables are feed, cutting speed and their selected second order terms. The models, explaining a fair percentage of total variation, fitted the observed responses in terms of main factor and second terms. The significance of the models and the parameters were checked using variance analysis; the percentage of variability explained by both models is greater than 80%.

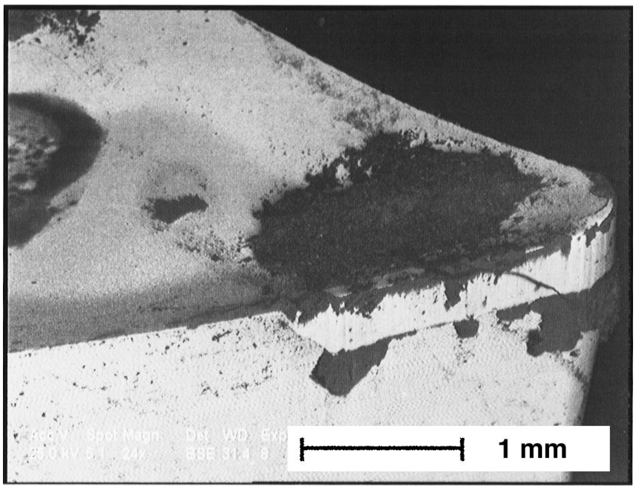

Figure 2 SEM picture of the cutting edge area of a worn uncoated carbide tool, $V_t = 630$ m/min, $f = 0.03$ mm/rev

The analysis criteria did not allow us to exclude the effects of some variables because they merely pinpointed which associations were the stronger. It should be underlined that the validity of the models, for predictive purposes, did not exceed the relevant sample space defined by the combination of the tested independent variables. Notice that the preliminary analysis of the experimental data excluded that the behaviour of tool duration versus cutting speed agrees with Taylor's law. Statistical analysis showed the data to fit a second order polynomial model.

Tool wear

In *Figures 3* and *4* the wear behaviour of the uncoated and diamond-coated tools is shown. The main affecting factors are: feed, square feed, square cutting speed and cutting speed times feed, according to the following models:

$$V_B = 0.33 - 4.63 \times f + 23 \times 10^{-8} \times V_t^2 + 24.74 \times f^2 - 0.002 \times V_t \times f$$

for the uncoated tools, and

$$V_B = 0.11 - 0.95 \times f + 2.3 \times 10^{-8} \times V_t^2 + 3.82 \times f^2 - 0.0003 \times V_t \times f$$

for the diamond-coated tools.

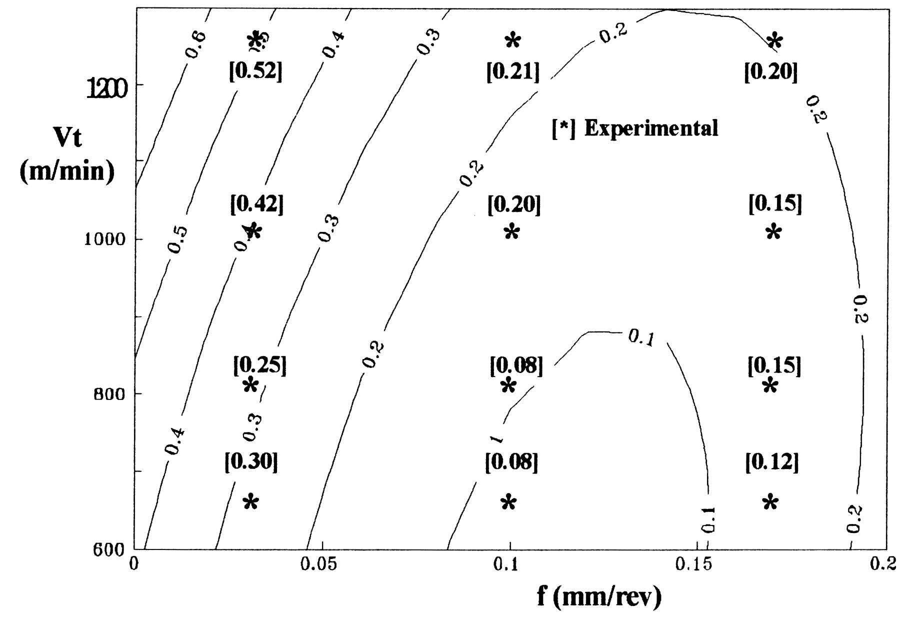

Figure 3 Computed model of the flank wear V_B (mm) for uncoated carbide tools versus cutting speed and feed. The stars indicate the experimental results over which the model has been computed. Model used: $V_B = 0.33 - 4.63 \times f + 23 \times 10^{-8} \times V_t^2 + 24.74 \times f^2 - 0.002 \times V_t \times f$. Statistical parameter: R^2, Adj = 0.92

In fact it can be observed that, for a given removed material volume, minimum flank wear is achieved with a particular combination of low cutting speed and relatively high feed. The combination of low feed and high cutting speed is, on the other hand, not desirable. From a comparison of the two pictures it can be noticed that the diamond-coated tools show, as expected, a much higher wear resistance and the minimum for the flank wear is achieved at higher cutting feed and speed. In *Figure 5* a grey zone is shown, representing the parameters' combination area that can be explored safely only with diamond-coated cutting tools.

The higher wear resistance of the coated tools is due to the higher abrasion resistance of the diamond coatings with respect to the carbide.

Surface finish

The analysis of surface roughness R_a values clearly shows that the roughness does not depend on the position angle θ, this fact being due to the uniform distribution of the Al_2O_3 reinforcement on the matrix.

The four R_a values measured for each of the machining tests performed with the uncoated tools were processed to

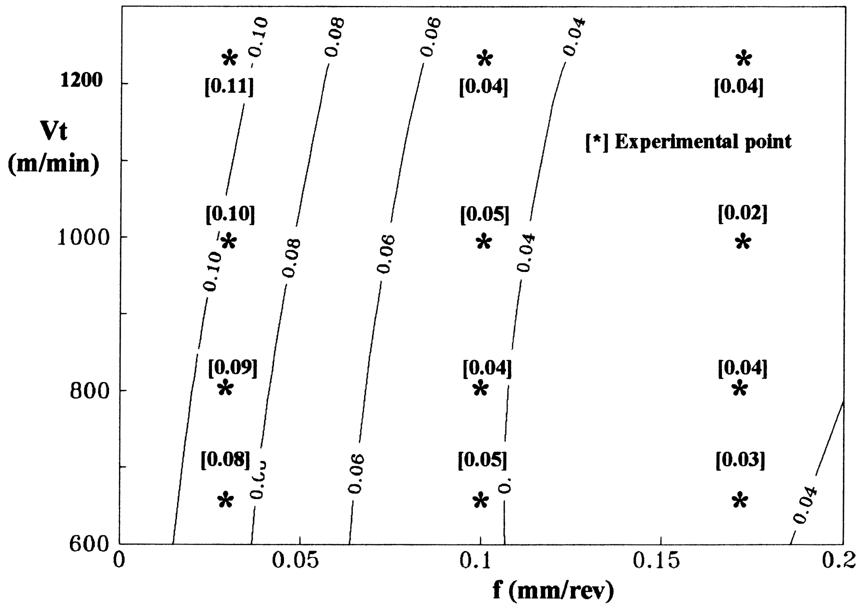

Figure 4 Computed model of the flank wear V_B (mm) for diamond-coated carbide tools versus cutting speed and feed. The stars indicate the experimental results over which the model has been computed. Model used: $V_B = 0.11 - 0.95 \times f + 2.3 \times 10^{-8} \times V_t^2 + 3.82 \times f^2 - 0.0003 \times V_t \times f$. Statistical parameter: R^2, Adj = 0.91

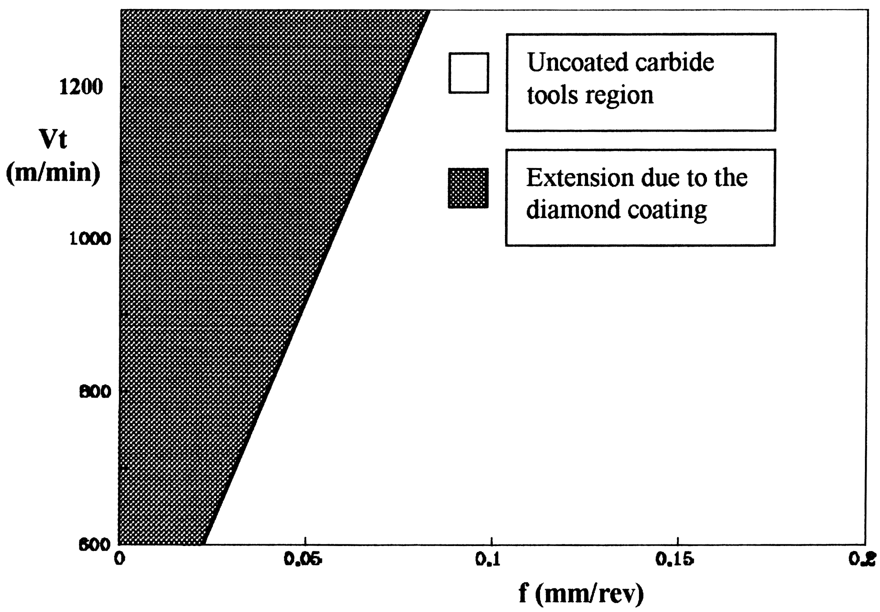

Figure 5 The feed–speed combinations falling into the grey area can only be safely explored with the diamond-coated cutting tools

obtain the average values R_{am} which were used in the statistical analysis, which yielded the following model:

$$R_{am} = -0.36 + 0.0013 \times V_t + 18.40 \times f$$

In *Figure 6* the surface roughness behaviour of the uncoated tools is shown. Second order terms of cutting speed and feed and their product have no significant effects, therefore the dominant factors are cutting speed and feed.

The parts machined with the diamond-coated tools did not show any significant correlation between the cutting parameters and the surface roughness.

Chip formation

The tool, chip and workpiece surfaces were observed by SEM, using SE and BSE techniques.

From the analysis of the chips' images it can be observed that, at $f = 0.03$ mm/rev, a detachment between the matrix and reinforcing particles occurs. This phenomenon, independent of the cutting tool material, becomes more evident as the cutting speed increases (*Figure 7*).

At higher feedrates, the effect of the cutting speed is less strong. From the SEM observations of the lower surfaces of chips machined at $f = 0.17$ mm/rev, no differences can be noticed between $V_t = 630$ m/min and $V_t = 1260$ m/min (*Figure 8*).

At a cutting speed of 630 m/min, some scraps parallel to the flow speed have been noticed, which become more evident as cutting speed and feedrate increase. At the end of the scraps, a reinforcing particle partially emerging from the matrix can often be observed. A simple explanation of this could be that the reinforcing particles are stuck on the tool rake and engrave the scratches on the chip, until they sink, at least partially, in the chip matrix

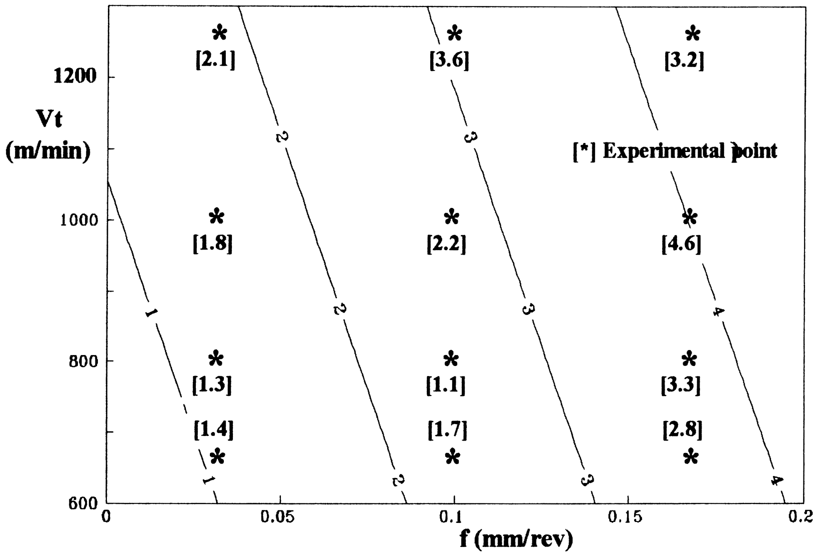

Figure 6 Computed model of the average surface roughness R_{am} (μm) for uncoated carbide tools versus cutting speed and feed. The stars indicate the experimental results over which the model has been computed. Model used: $R_{am} = -0.36 + 0.0013 \times V_t + 18.40 \times f$. Statistical parameter: R^2, Adj = 0.83

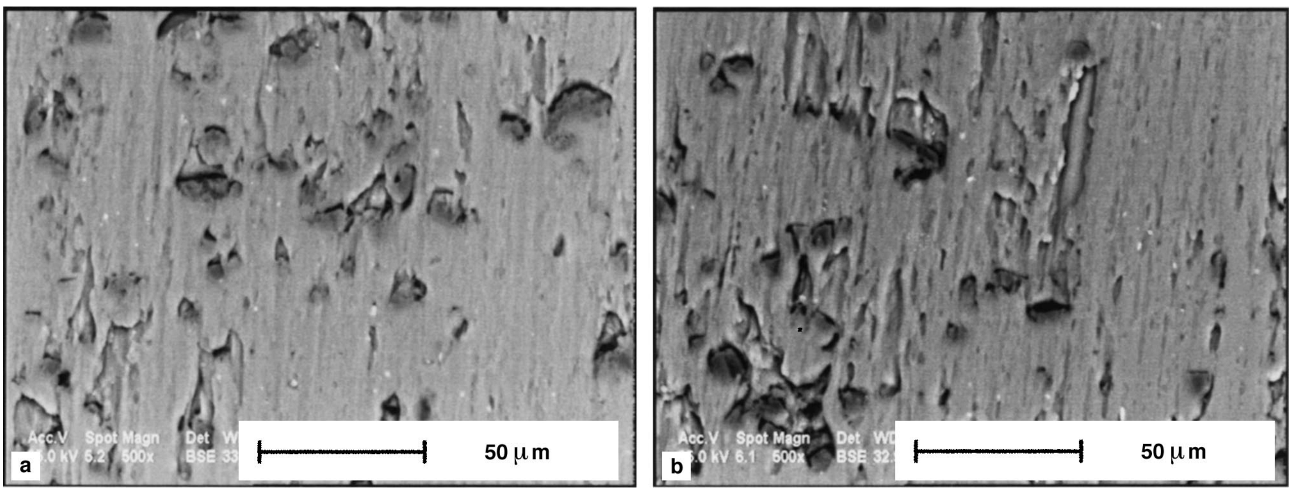

Figure 7 Lower surfaces of chips cut with the diamond-coated tools; the emerging particles are visible: (a) $V_t = 630$ m/min, $f = 0.03$ mm/rev; (b) $V_t = 1260$ m/min, $f = 0.03$ mm/rev

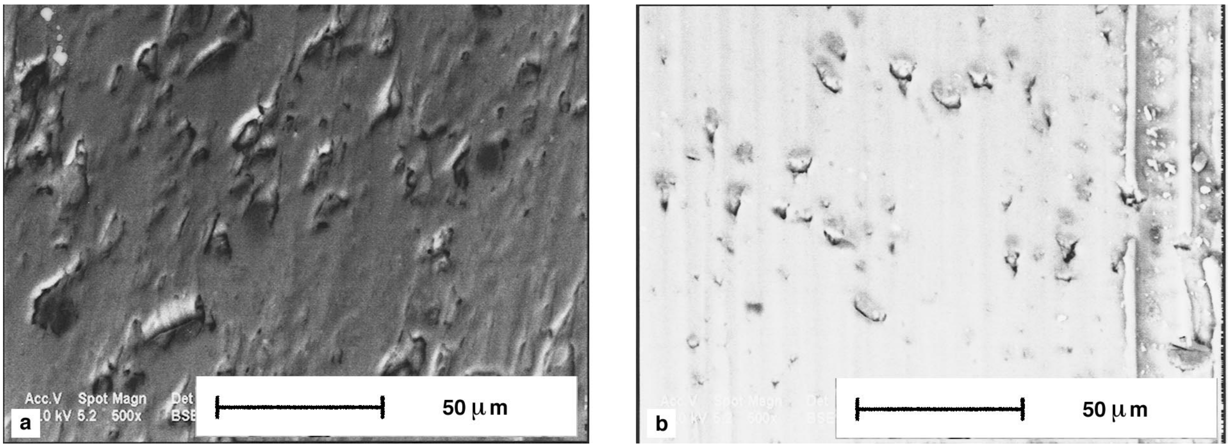

Figure 8 Lower surfaces of chips cut with the diamond-coated tools; the piling-up of the particles can be seen: (a) $V_t = 630$ m/min, $f = 0.17$ mm/rev; (b) $V_t = 1260$ m/min, $f = 0.17$ mm/rev

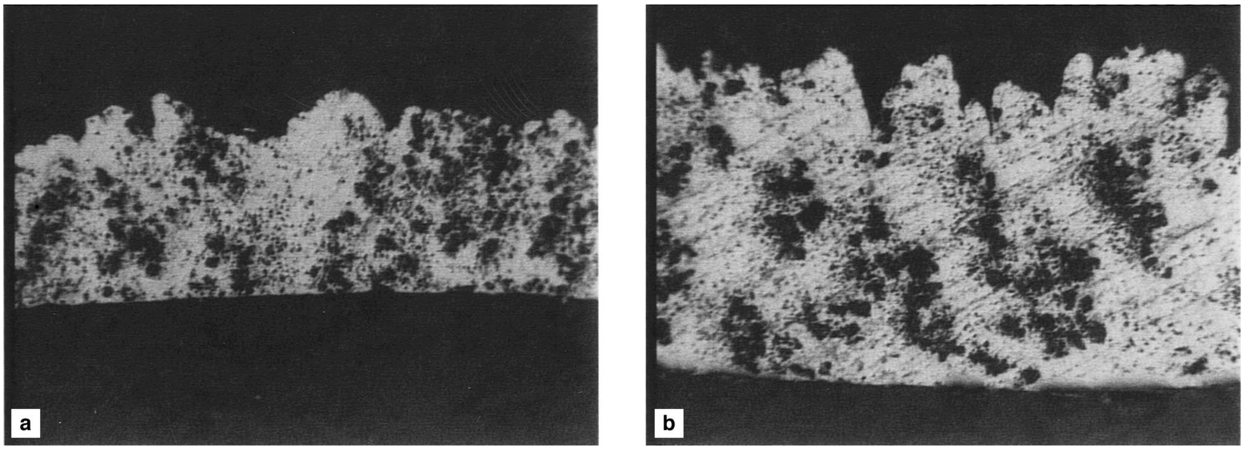

Figure 9 Longitudinal chip sections ($\times$ 50) machined with uncoated tools: (a) $V_t = 630$ m/min, $f = 0.03$ mm/rev; (b) $V_t = 1000$ m/min, $f = 0.03$ mm/rev

and are carried away from the tool rake. To verify this, some longitudinal sections of the chips have been cut and observed (*Figure 9*).

From the section images it is evident that the reinforcing particles tend to sink and pile up in the matrix along the shear planes described by the Pijspanen model (*Figure 10*). When enough particles have piled up to prevent another particle from sinking, this last one sticks out partially from the matrix. The effect is stronger in chips obtained at higher cutting speeds. The higher temperatures developed at higher cutting speeds ease the transportation of the particle along the shear planes. Furthermore, the shear planes become more irregular and the number of scratches and ridges visible on the lower surfaces increases.

The same behaviour is induced by an increase in cutting feed: the distance between the shear plane grows (*Figures 11–13*).

As regards the influence of the coatings, it can be said that, under unchanged machining parameters, with diamond coatings, the distance between the shear planes is higher than the one obtained using a carbide tool and that the chips' lower surfaces are more

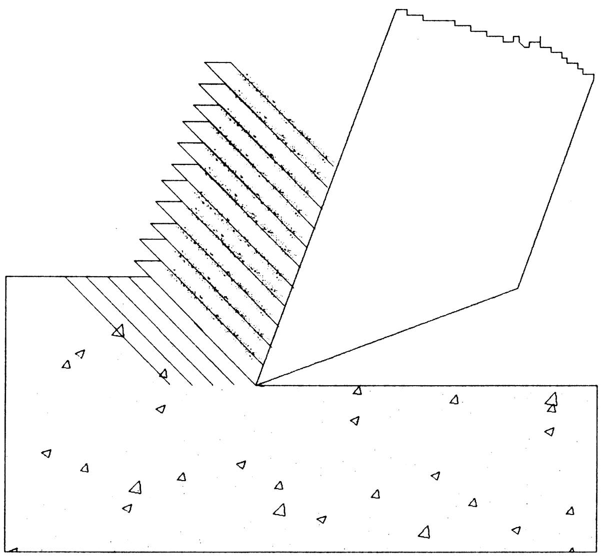

Figure 10 Model of dispersion of reinforcing particles along the shear planes

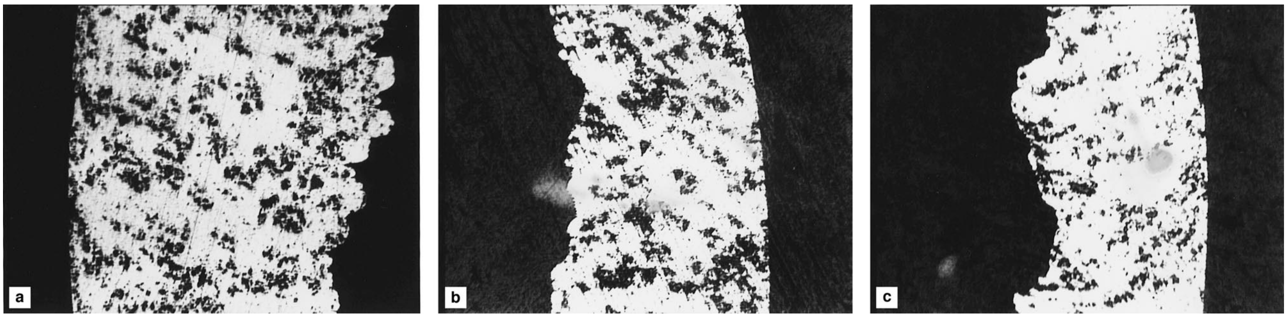

Figure 11 Longitudinal sections of chips (× 50) machined with diamond-coated tools at $f = 0.17$ mm/rev: (a) $V_t = 630$ m/min; (b) $V_t = 1000$ m/min; (c) $V_t = 1260$ m/min; the piling-up of the particles can be clearly observed

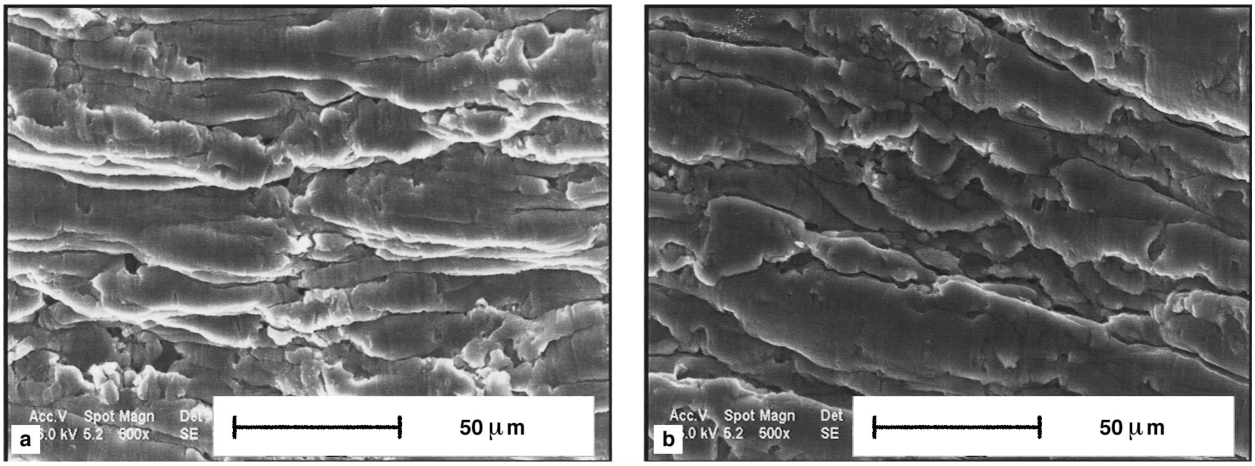

Figure 12 Shear planes on the upper surface of chips cut with the diamond-coated tools: (a) $V_t = 630$ m/min, $f = 0.03$ mm/rev; (b) $V_t = 630$ m/min, $f = 0.17$ mm/rev

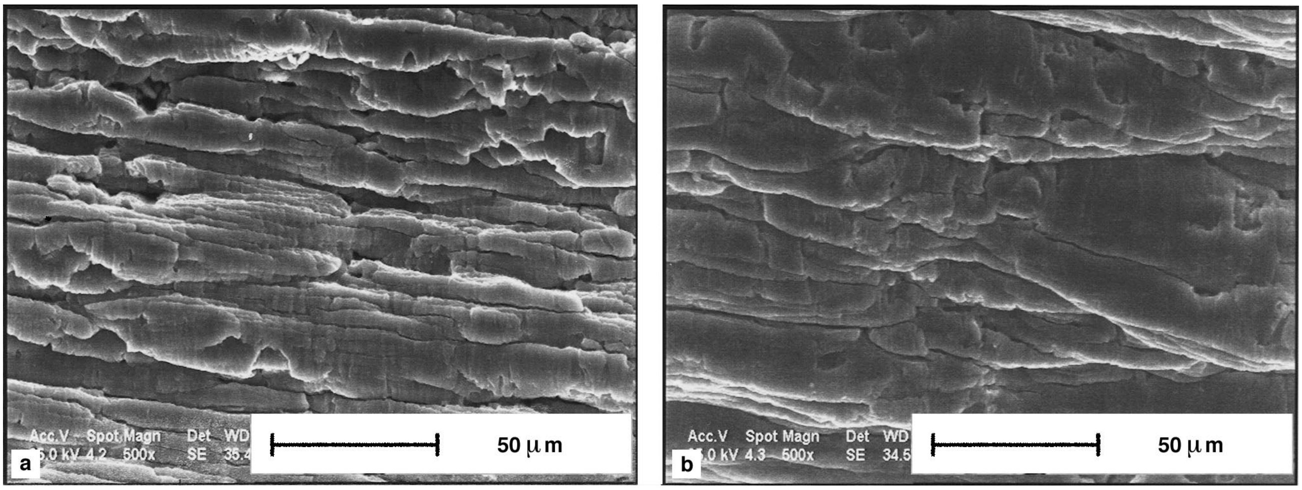

Figure 13 Shear planes on the upper surface of chips machined with uncoated tools: (a) $V_t = 630$ m/min, $f = 0.03$ mm/rev; (b) $V_t = 630$ m/min, $f = 0.17$

homogeneous and regular when machined with a coated tool. This might be explained by the lower friction coefficient of the coatings [14–16].

Worn cutting tools

The thermal conductivity of the diamond coatings is about 10–20 times higher than that of the cemented carbide (1000–2000 W/mK vs. 100 W/mK). However, along the growth direction its value is twice that measured perpendicularly to the growth direction. This fact promotes the high temperature gradient at the interface between the coating and the substrate and relatively low temperature in the chip [16]: there is a great difference between Al_2O_3 reinforcement hardness value and the soft matrix one, so that when the hard diamond tool edge comes into contact with the hard

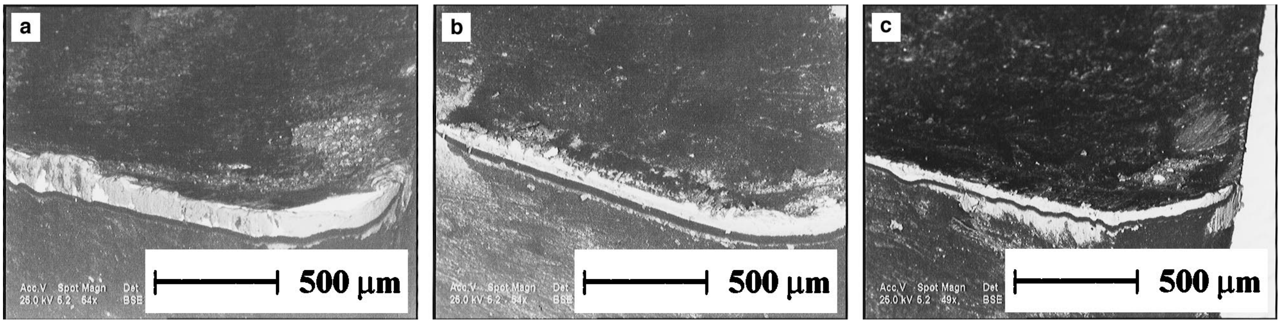

Figure 14 Diamond-coated carbide tools after the machining operations: (a) $V_t = 1260$ m/min, $f = 0.03$ mm/rev; (b) $V_t = 630$ m/min, $f = 0.03$ mm/rev; (c) $V_t = 1260$ m/min, $f = 0.17$ mm/rev

particles these are moved; the same effect has been described for PCD tools in Ref. [9]. The observed chip formation mechanism is not much different from the one described by the authors in Ref. [13] for (Ti,Al)N coated tools, but here higher localised forces are required to move the particles in the matrix due to the lower chip temperature. The effects of these localised forces and thermal load can be observed on the diamond coated tools after machining (*Figure 14*). A large material adhesion area (white zone) can be noticed on the tool flank; the extension of such an area increases with the cutting speed. The adhesion area decreases as the feedrate increases. Immediately underneath the adhesion zone a dark line is evident, parallel to the cutting edge in which the tool coating has been removed. Another area in which the coating has disappeared can be seen on the tool rake, close to the cutting edge. It must be taken into account that adhesion between diamond coating and its substrate still continues to be the critical factor, particularly in case of a carbide substrate [17].

CONCLUSIVE REMARKS

The following conclusions can be drawn from the results of the experimental tests.

(1) In the chip formation process, the reinforcing particles pile up along shear planes which divide the deformed chip into layers. The phenomenon is more evident as the cutting speed or feed increase, because the increased temperature enables the alumina particles to move more freely.
(2) As regards the effects of the coating on the chip formation, the lower friction coefficient causes the distance between the shear planes to be higher and the chip's lower surfaces to be more homogeneous and regular.
(3) The effects of localised forces and thermal load cause the coating to be removed along a line parallel to the cutting edge.
(4) The statistical model of the flank wear shows how at any cutting speed, and up to certain values, flank wear lowers as feed rate increases. The highly abrasion resistant diamond coating on the tools dramatically improves the wear behaviour, making them excellent candidates for the machining of abrasive materials such as those investigated here.
(5) Due to the limited wear shown by the diamond-coated carbide tools, more investigation is needed in order to explore their behaviour in machining composite materials under more severe conditions, especially in terms of the amount of material removed.

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REFERENCES

1. Trumper, D. Metal matrix composites applications and prospects. *Metals and materials*, 1987, **15**, 662–7.
2. Ibrahim, I.A., Mohamed, F.A. and Lavernia, E.J., Particulate reinforced metal matrix composites—a review. *Journal of Materials Science*, 1991, **26**, 1137–1156.
3. Hamouda, A.M.S. and Hashmi, M.S.J., Mechanical properties of aluminium metal matrix composites under impact loading. *Journal of Materials Processing Technology*, 1996, **56**(1/4), 743–748.
4. Chadwik, C.H. and Heath, P.J., Machining of metal matrix composites. *Metals and Materials*, 1990, **18 February**, 73–76.
5. Looney, R.P., Monaghan, J.M., O'Really, P. and Taplin, D.M.R., The turning of an Al/SiC metal matrix composites. *International Journal of Materials Processing Technology*, 1992, **33**, 453–468.
6. Cronjager, W.M. and Meister, D., Machining of fibre and particle reinforced aluminium. *Annals of the CIRP*, 1992, **41**(1), 63–66.
7. Abrate G., Walton D.A. Machining of composites materials. Part I: Traditional methods. Composites Manufacturing, Long Beach, CA, 7–10 December 1987, MR87-827.
8. Weinert, S., A consideration of tool wear mechanisms when machining metal matrix composites. *Annals of the CIRP*, 1993, **42**(1), 95–98.
9. Tomac, N. and Tonnessen, K., Machinability of particulate aluminium matrix composite. *Annals of the CIRP*, 1992, **41**(1), 55–58.
10. Yuan, C., Geng, L and Dong, S, Ultraprecision machining of SiCw/Al composites. *Annals of the CIRP*, 1993, **42**(1), 107–109.
11. Gatto A, Ippolito R, Iuliano L, Tagliaferri V. Surface finish of metal matrix composites under high speed turning. In Veniali, F., Erta, A. (eds), ASME Proceedings of the 1994 Engineering System Design and Analysis Conference, London, 4–7 July, vol. 2, 1994:35–42.
12. Gatto A., Iuliano L., Tagliaferri V. High speed turning of metal matrix composites with tools of different material and geometry. ASME Material and Design Technology, Kssuraona, T. (ed) 29 January–1 February, Houston, TX, 1995:89–95.
13. Iuliano L., Settineri L., Gatto A. High-speed turning of metal matrix composites with coated and uncoated carbide tools. Proceedings of the 30th ISATA Conference, Florence, 1997, Automotive Automation, Croydon, 1997.

14. Pulker F. Wear and Corrosion Resistant Coatings by CVD and PVD. Chichester (UK): Ellis Horwood Limited, 1990.
15. Konig, W., Fritsch, R. and Kammermeier, D., New approaches to characterising the performance of coated cutting tools. *Annals of the CIRP*, 1992, **41**(1), 49–54.
16. Jawahir I.S., Van Luttervelt C.A. Recent developments in chip control research and application. Keynote paper in Annals of the CIRP 1994;43/1.
17. Townsend, P.P., Defects in coatings. *Thin Solid Films*, 1990, **193/194**, 342–349.