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Development of diamond coated tool and its performance in machining Al–11%Si alloy

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Abstract. An attempt has been made to deposit CVD diamond coating on conventional carbide tool using hot filament CVD process. ISO grade K10 turning inserts with SPGN 120308 geometry were used to deposit diamond coating. This diamond coating well covering the rake surface, cutting edges and flank surfaces could be successfully deposited. The coatings were characterized by SEM, XRD and Raman spectroscopy for coating quality, morphology etc. Performance of diamond coated tool relative to that of uncoated carbide tool was evaluated in turning Al–11%Si alloy under dry environment. The diamond coated tool outperformed the uncoated carbide tool which severely suffered from sizeable built-up edge formation leading not only to escalation of cutting forces but also poorer surface finish. In contrast, the diamond coated tool, owing to chemical inertness of diamond coating towards the work material, did not show any trace of edge built-up even in dry environment and could maintain low level of cutting forces and remarkably improved surface finish. It has been further revealed that success of the diamond coated tool depends primarily on adhesion of the diamond coating with the carbide substrate and this is strongly influenced by the pre-treatment of the carbide substrate surface before coating.

Keywords. Machining; CVD diamond coating; Al–Si alloy.

1. Introduction

Wear resistant coating on cutting tools is the most significant development in cutting tool technology. Hard coatings like TiC, TiN, Al_2O_3, AlN etc have established their effectiveness in high performance machining of ferrous materials. However, aforesaid hard coatings reveal their weakness in machining materials like Al–Si alloy whose demand is increasing rapidly because of rapid growth of automobile industries. The coatings suffer from rapid wear because of strong adhesion and chemical reaction with Al–Si (Klocke and Krieg 1999; Roy 2001). In contrast, diamond as a tool material can provide anti-welding characteristics because of chemical inertness towards Al–Si alloy. Diamond can also offer remarkable abrasive wear resistance because of its super hardness.

In recent years, low pressure synthesis of diamond coating from gas phase on a suitable tool substrate has opened up new opportunities to expand applications of diamond tools widely. In fact a coated diamond tool combines the strengths of both single crystal diamond and PCD compact in one cutting tool and has better flexibility to produce tool with complex geometry than with PCD compact tool (Hintermann and Chattopadhyay 1993; Kanda *et al* 1995; Taher *et al* 1996; Chatterjee *et al* 1997). However, it is contended that good throwing power and ability to control properties such as nucleation, grain size, adhesion with the substrate and surface smoothness of the film are critical to the application of the CVD technique for the reliability and performance capabilities of the CVD diamond coated tools (Ravi *et al* 1990).

Considering the potential of diamond coated tool, an attempt has been made here to develop a diamond coated cutting tool and evaluate its performance in machining Al–11%Si alloy.

2. Experimental

Cemented carbide turning inserts of geometry SPGN120308, ISO K10 grade containing 6% cobalt were used as the substrate for CVD diamond deposition. Prior to deposition,

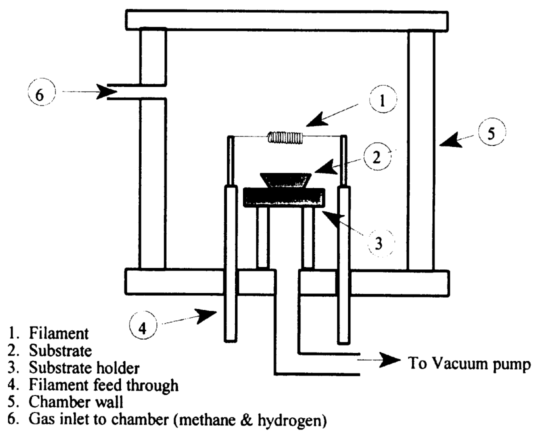

Figure 1. Schematic diagram of hot-filament CVD process.

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the samples were cleaned with trichloroethylene and iso-propyl alcohol to remove contaminants from the surface. Samples were etched with $HNO_3 + HCl + H_2O$ (1 : 1 : 1) solution at room temperature under ultrasonic vibration for removal of detrimental cobalt from the substrate surface (Sahoo 2000). Thin CVD diamond films were deposited on these samples in a specially developed hot filament CVD set-up. The schematic diagram of the process is shown in figure 1. Different deposition conditions are shown in table 1.

The uncoated, surface treated and diamond coated tools were characterized under scanning electron microscope for cutting edge and surface morphology, X-ray diffraction for crystal structure and under micro-Raman spectroscopy for chemical quality evaluation.

Uncoated and CVD diamond coated turning inserts of the above mentioned geometry were used for machining test. The machining test set-up for performance evaluation which carries cutting force measuring system is schematically shown in figure 2. Different parameters and machining conditions are shown in table 2. Tangential cutting force, P_z, and axial force, P_x, were measured by the force measuring system at suitable intervals. Corresponding surface roughness, R_z and R_a values were measured by Talysurf on the machined surface.

Table 1. Deposition conditions.

Substrate	WC–6% Co, ISO K10 cemented carbide inserts
Filament	Tungsten (0·25 mm dia.)
Filament temperature	2000°C
Filament–sub. distance	4·5 mm
Substrate temperature	740°C
Gas composition	0·5% CH_4 in H_2
Gas flow rate	100 SCCM
Reaction pressure	30 torr

Table 2. Machining parameters and conditions.

Workpiece	Al–10%Si alloy (150 mm dia. × 600 mm long cast bar)
Tool	SPGN120308, ISOK 10 Turning inserts
Tool holder	ISO CSBPR 2525 16 M
Cutting speed (V_c)	400 m/min
Feed (s)	0·1 mm/rev
Depth of cut (d)	0·5 mm
Environment	Dry

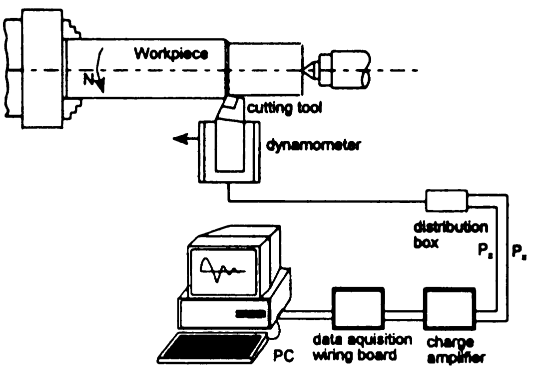
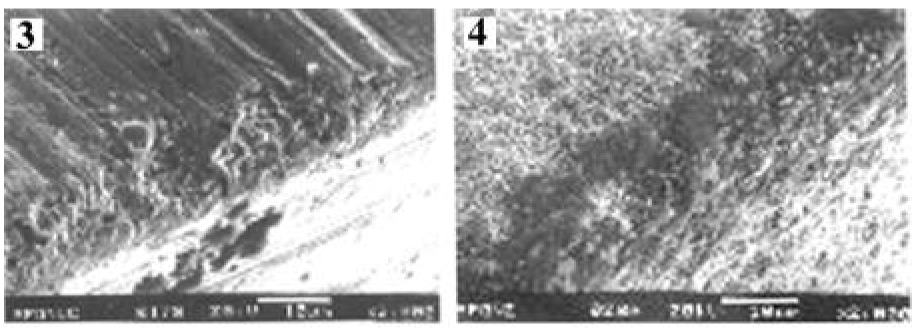


Figure 2. Schematic representation of experimental set-up.

3. Results and discussion

Figure 3 clearly shows that the uncoated tool is covered with smeared cobalt. The bulk cobalt content on the substrate surface was found out to be about 5·15%. Figure 4 shows the WC + Co substrate when treated with a solution of $HNO_3 + HCl + H_2O$ (1 : 1 : 1) with ultrasonic vibrations for 15 min. The smeared layer of cobalt was totally removed exposing WC grains. The bulk content of surface cobalt was also reduced to 0·45%.

SEM micrograph in figure 5 shows the diamond coating at the cutting edge covering the rake face and flank surface. Well faceted crystals predominantly with ⟨111⟩ morphology can be seen from the same figure. The size of the crystals appears to be mostly in the range of 3–4 μm. Coating appears to be free from defects like outgrowths and pinholes. The fractograph of the cutting edge of the diamond coated tool is shown in figure 6. Uniform coverage of the face and flank can be clearly



Figures 3 and 4. SEM micrographs of cutting edge tool **3.** before and **4.** after treatment.

noticed from the fractograph. Thickness of the diamond coating appears to be in the range of 5–6 μm. The wide edge rounding of the cutting edge is also well evident from the same figure.

The existence of diamond coating with a clear ⟨111⟩ morphology has been further confirmed by X-ray diffraction (XRD) diagram of figure 7. The low height of the diamond peak as compared to tungsten carbide peaks is due to the low thickness of the CVD diamond coating which is only 5–6 μm thick. A sharp peak at 1337·5 cm^{-1} of the Raman spectra obtained on the coating of the tool in figure 8 confirms the quality of the film to be good. However, a positive shift of the diamond peak could possibly have resulted from the stress in the film or distortion of crystal structure. The inherent roughness of the coating at the edges due to crystal structure could be well noticed. The roughness value of the coating has been found to be $R_a = 0{\cdot}65$ μm, $R_z = 4{\cdot}2$ μm as compared to the values for uncoated tool as $R_a = 0{\cdot}15$ μm, $R_z = 0{\cdot}73$ μm.

The cutting forces, P_z and P_x, for uncoated tool appear to be very high as shown in figure 9. In contrast, the cutting forces for diamond coated tool were substantially low as shown in the same figure. Such low cutting forces for diamond coated tool could be attributed to the poor affinity of diamond to non-ferrous materials like aluminium alloys.

Surface roughness values, R_a and R_z, for machined surface produced by uncoated tool was observed to be very high as shown in figure 10. On the other hand, surface roughness of the workpiece produced by the diamond coated tool was very low as shown in the same figure. Interestingly diamond tool continued to give a glossy surface till 16·5 min of machining after which it started

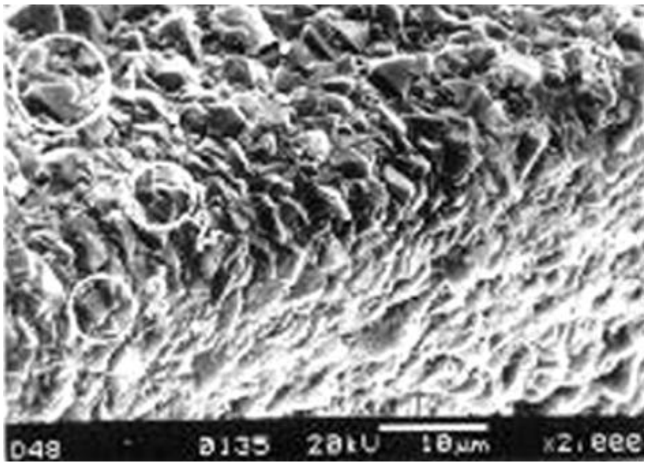


Figure 5. SEM micrograph of cutting edge after diamond deposition.

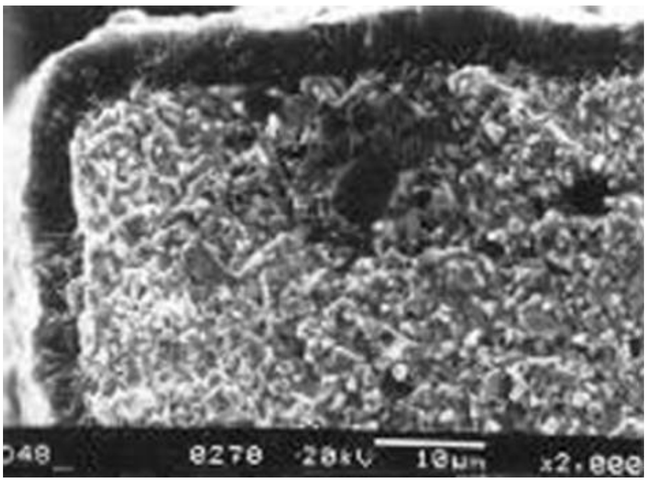


Figure 6. SEM fractograph of cutting edge after diamond deposition.

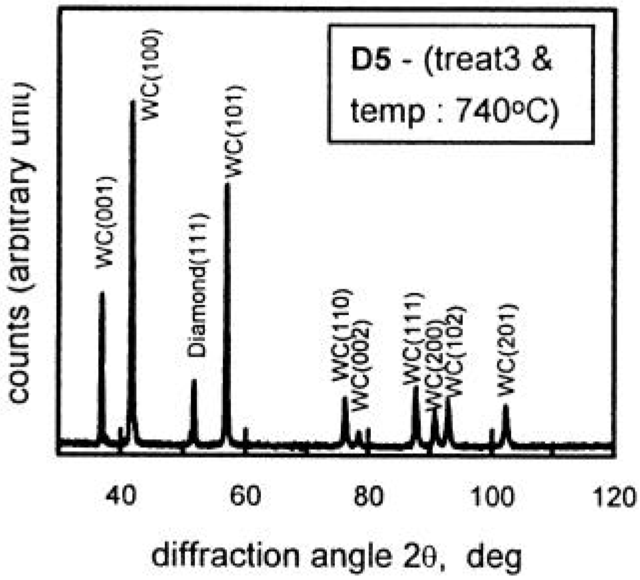


Figure 7. X-ray diffraction spectra of diamond coated WC insert.

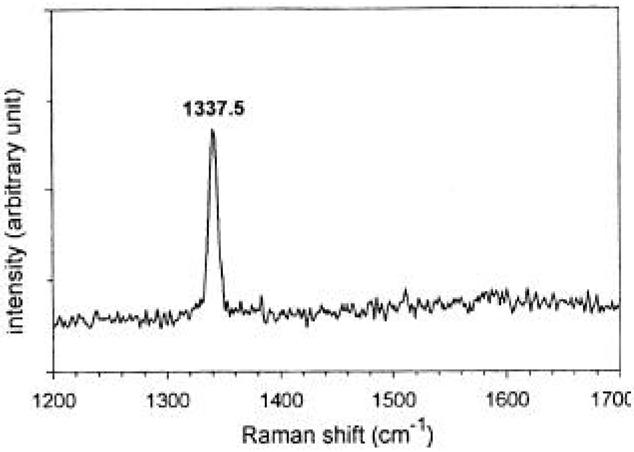
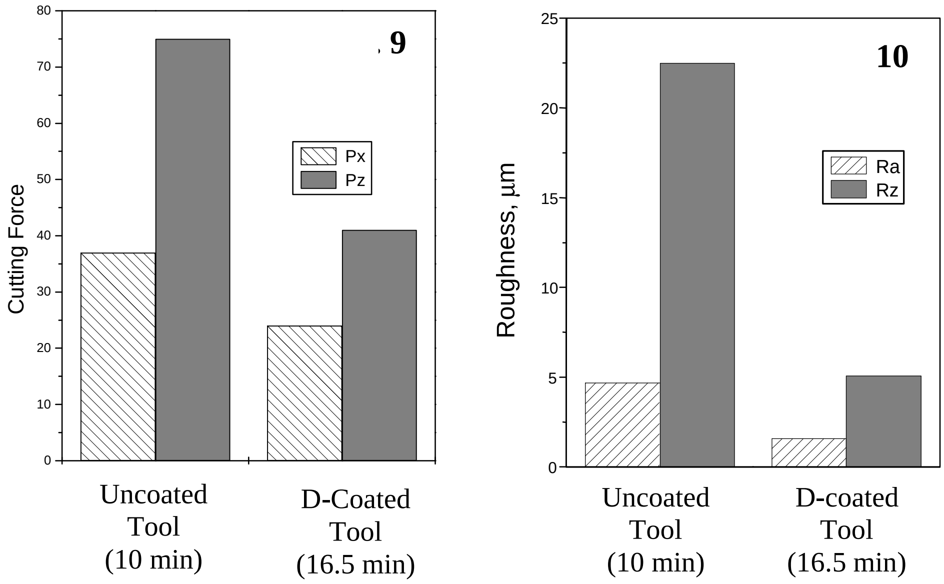


Figure 8. Raman spectra of diamond film on WC insert.



Figures 9 and 10. Roughness and cutting force with diamond coated and uncoated WC insert.

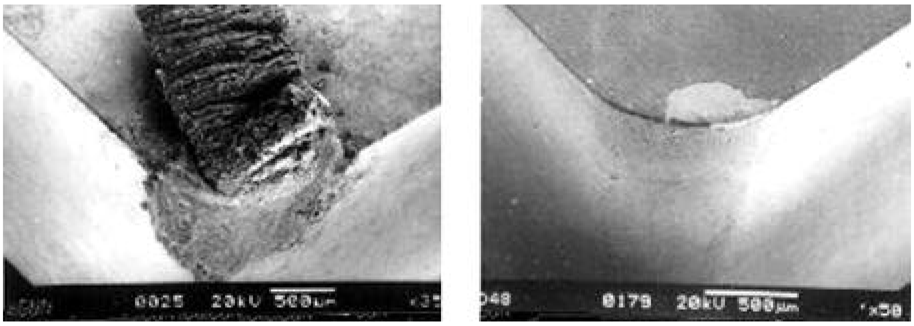


Figure 11. SEM micrograph of the cutting tips after machining by uncoated and *d*-coated WC insert.

giving few tearing marks on the surface. The tool was withdrawn from machining after 16·5 min.

SEM micrograph (figure 11) shows heavy built-up of workpiece material on the face and flank of the uncoated tool covering the cutting edge after 10 min of machining. Such well adherent layer of the work material at the tool tip was responsible for high cutting force and high workpiece surface roughness for uncoated tool as already shown in figures 9 and 10. The SEM picture (figure 11) of diamond coated tool shows that even after 16·5 min of machining the tool tip experienced absolutely no built-up edge formation. However, removal of coating was observed on the rake surface. Interestingly no coating was removed from the portion of the cutting edge that contributes to the workpiece surface finish. This could be the major reason of producing glossy surface even after 16 min of machining.

4. Conclusions

It was possible to deposit CVD diamond coating on tungsten carbide tool inserts which underwent a special treatment to reduce the surface cobalt content below 0·5%. The diamond coating was found to be well grown, dense and continuous with hardly any trace of non diamond phase. However, roughness of diamond coating was higher than that of the uncoated substrate. The performance of the diamond coated tool in comparison to uncoated tungsten carbide tool in dry machining of Al–Si alloy was remarkable in that the cutting forces and the workpiece surface roughness with diamond coated tool were significantly low. However, the shortcomings like higher surface roughness at the cutting edge and lack of strong adhesion at coating–substrate interface also have been observed and those need to be improved substantially in order to obtain acceptance of machining industries.

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