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# Machining and morphological evaluation of diamond coated tungsten carbide drills

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This paper reports the results of drilling tests on various workpiece materials using diamond coated tungsten carbide drills. The performance of the coated drills were compared with uncoated control drills. Hot filament chemical vapor deposition was used for coating the pre-treated drills and film coating morphology and stress characteristics were studied prior to drilling. Forces and torques were measured during drilling and the results indicate catastrophic failure and short tool-life of the coated drills for all workpiece materials. Drill failure reasons are attributed to crystal clustering and point loading of the cutting edges. Further research issues are also identified. 

## 1. Introduction

Various ceramic thin films are used as coatings for cutting tools for machining diverse workpiece materials. The advantages of using coated tools include increased tool life and improved workpiece surface finish through diminished friction at the tool-workpiece interface and reduced abrasive tool wear, reduced chemical interaction between tool and the workpiece with reduced tool wear, improved chip flow, better thermal conductivity, and tool hot hardness [1].

Machining applications requiring extreme cutting tool abrasion resistance and refractoriness limit the use of thin film coatings because most films wear under such conditions. A diamond thin film coating is an ideal material for machining highly abrasive, non-ferrous materials because of its extreme hardness and refractoriness. However, the application of diamond thin films is a nascent technology and significant work is required to standardize the technology for film quality and substrate preparation methods, establish film-substrate adhesion standards, film growth parameters, and correlate film quality with machining performance.

There is significant machining performance variability of diamond coated cutting tools [2] which may be attributed to surface preparation methods, substrate grain sizes, deposition techniques, film roughness, and film-substrate adhesion. Commercially successful application of diamond thin film coated cutting tools will require a cost-effective reduction of performance variability. This can be achieved through a better understanding of the fundamental relationships between film preparation and quality and machining performance.

The remainder of this paper is organized as follows. In the next section, previous research relating to characterization and machining performance of diamond thin film coated tungsten carbide cutting tools, is reviewed. This is followed by a description of the experimental procedures used in this work and a discussion of the results. Finally, future research issues are identified.

## 2. Literature review

There has been limited characterization of mechanical and metal cutting properties of diamond coated tungsten carbide cutting tools. These include adhesion and indentation studies of the WC-diamond composite [3–5], the use of X-ray diffraction for the measurement of film stresses [6], and review of diamond coated inserts in machining [2, 7, 8].

Chatterjee *et al*. [9–11] examined the effects of substrate grain size and surface pretreatment on the deposited film quality, film stresses, and drilling performance of diamond coated WC drills. The film quality was found to be strongly dependent on the substrate surface treatment method for cobalt removal; however, grain size did not significantly influence film quality [9]. The stress measurements indicated various levels of compressive stresses in the film and at the film substrate interface [10]. Intrinsic film stresses were also computed for diamond films and found to be tensile with significant variations between the drill flank and flute stresses. The drilling test indicated catastrophic failure of the coated drills and poorer tool life in comparison to the uncoated drills [11]. The short tool life and tool failures were attributed to edge rounding and the clustering of crystals into supercrystals leading to point loading of cutting force rather than line loading along the cutting edge.

In this study, drilling tests were further extended to include a softer workmaterial, examine diamond film coverage on the drills, and analyze tool failure causes. This paper presents the findings on film morphology, drill surface coverage, and tool life. Tool fracture studies will be published separately.

## 3. Experimental procedures

Commercially available drills were coated with diamond films using the hot-filament chemical vapor deposition method. Scanning electron microscopy (SEM), Raman Spectroscopy, and X-ray diffraction were used to characterize the quality of the coatings. A horizontal machining center was used for drilling various workpieces with the coated drills. SEM was also used to determine the nature of drill fracture. The details of the experimental procedures follow.

### 3.1. Drill specifications and preparation

Commercially available WC drills (94%WC-6% Co), 0.125 inch in diameter, 118° point angle, and 25° helix angle were used in this study. The as-received drills were ultrasonically cleaned in reagent grade acetone to remove surface organics.

Two different surface preparation methods were used to remove surface cobalt. In the NA (nitric acid) method the drills were first ultrasonically cleaned with acetone. They were then ultrasonically treated in an initial 1 : 1 v/v mixture of $HNO_3 + H_2O$ for fifteen minutes, rinsed, and ultrasonically treated again for five minutes in ultra-pure water. The PT method, was a proprietary chemical treatment for surface cobalt removal [12]. After both the NT and PT treatments for cobalt removal the drills were ultrasonically cleaned again for 5 minutes each in acetone and methanol.

### 3.2. Scanning electron microscopy

A Cambridge Instruments SEM was used for microscopic evaluation of all predeposited and diamond deposited drills. The SEM used a 2.57 A filament current, a 107 pA probe current, and an excitation voltage of 20 kV.

### 3.3. Diamond deposition conditions

Diamond films were deposited using a Hot Filament CVD (HFCVD) reactor constructed from a high vacuum six-way cross. The arrangement for the depositions is described in [9–11]. Growths were performed for sixteen hours with a 1% methane/hydrogen gaseous mixture at a 100 sccm flow rate, 15–20 Torr chamber pressure, and substrate and filament temperatures of 1050 K and 2120 K, respectively. Substrate and filament temperatures were measured with a disappearing filament type optical pyrometer and are reported without correction for emissivity or temperature correction for the glass window effects. Previous research on temperature correction for similar glass material indicated a correction range between 50–100 K.

### 3.4. Raman spectroscopy

The diamond films were analyzed using a Dilor XY Raman spectrometer with a microscope attachment and CCD detector. Spectra were recorded using 100 mW of 514.5 nm excitation focused on the samples through a ×80 objective of the microscope. No degradation of the samples was observed under these conditions. The Raman shifts reported in this paper are based upon calibrating the instrument using the 1332 $cm^{-1}$ line from a single crystal diamond sample.

### 3.5. XRD conditions

The films were step-scanned on WC [102] and Diamond [111] with a chromium radiation of 2.2897 angstroms wavelength. A rectangular collimator of 5 mm aperture was used during scanning. The scanning positions on the drills are shown in Fig. 1. Extreme care was taken in drill set-up to avoid shielding problems due to nature of the drill geometry. The residual stresses were automatically calculated from the scans.

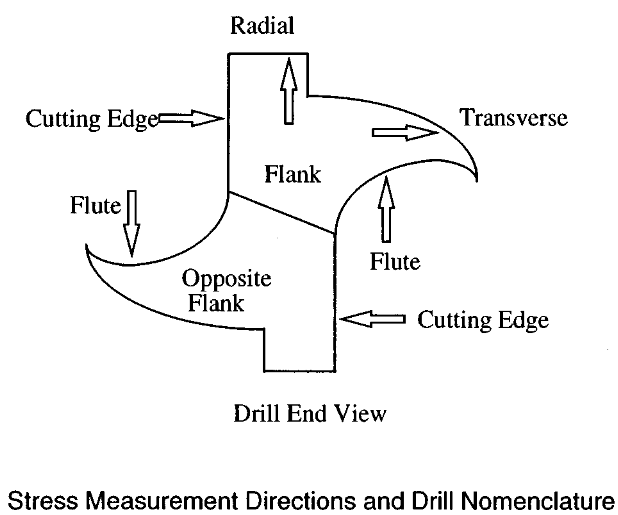



*Figure 1* Scanning positions for stress measurement on drills.

### 3.6. Machining conditions

Drilling tests were performed with two uncoated and four diamond-coated WC drills (two each of NA and PT treatments, respectively) on a Magnum 800 Horizontal Machining Center rated at 50 hp with a maximum spindle speed of 10,000 rpm. The maximum attainable cutting velocity was limited by the available rpm and drill

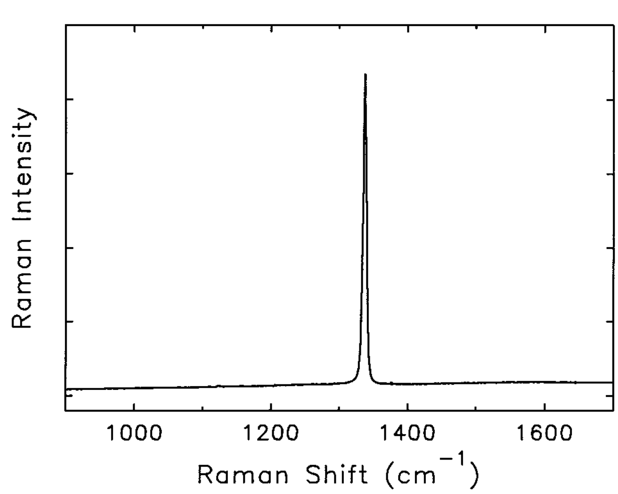



*Figure 2* A typical Raman spectrograph for the coated drills.

diameter. Lanxide (40% aluminum oxide composite) brake rotors and 6061-T6 Aluminum were used as work materials. All holes were drilled 0.5″ deep. Table I lists the drilling conditions for the work and tool material combinations.

Force and torque data were collected on-line via a calibrated dynamometer and data acquisition software.

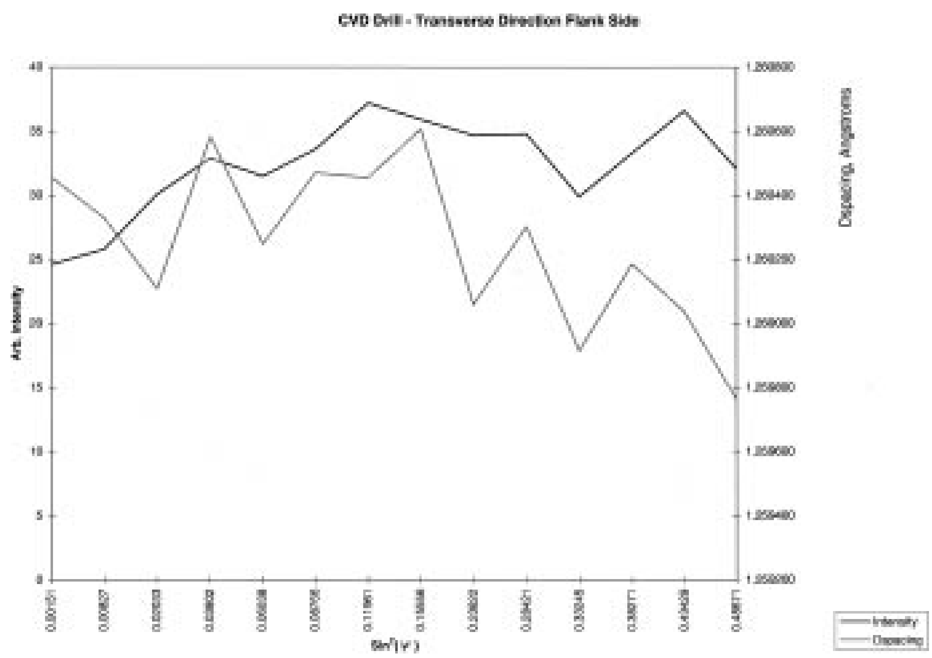
TABLE I Drilling conditions

| | Aluminum oxide workmaterial | Aluminum workmaterial |
|---|---|---|
| Diamond coated drills | 300 fpm (9167 rpm) velocity, 0.001″/cutting edge feed | 300 fpm (9167 rpm) velocity, 0.001″/cutting edge feed |
| High speed drills | 147 fpm (4500 rpm) velocity, 0.001″/cutting edge feed | Not done |

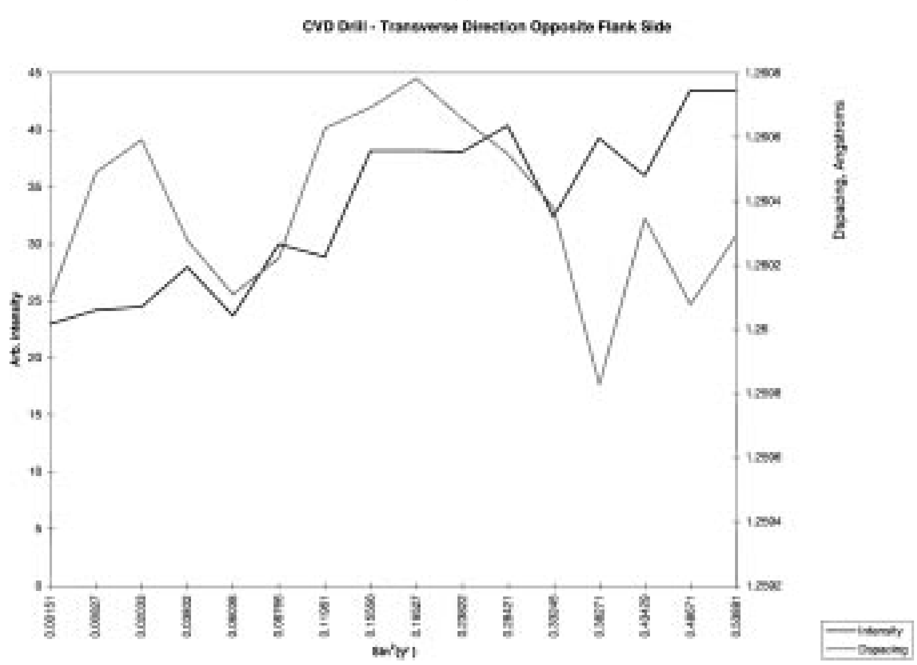
## 4. Results

### 4.1. Diamond film quality

The quality of the deposited diamond film evaluated from Raman spectroscopy is shown in Fig. 2. The sharp peak at wavenumber position close to that of natural diamond (1332 $cm^{-1}$) indicates high film purity with negligible graphitic and cobalt components. Positive shifts (wavenumber lines greater than the 1332 $cm^{-1}$ wavenumber calibration line of natural diamond) were recorded for all films deposited on drills. The positive

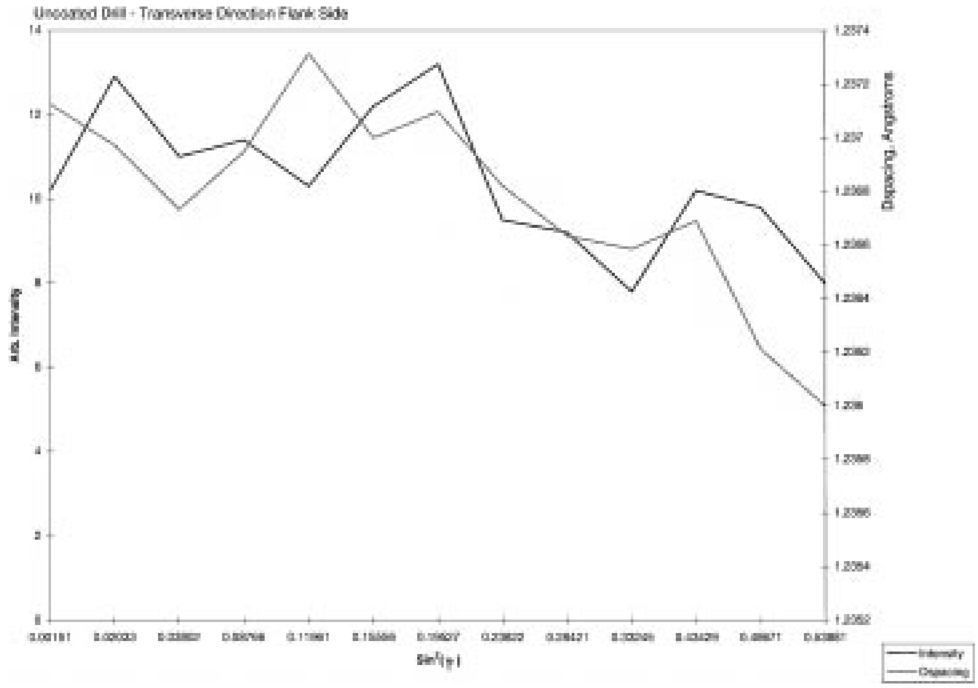



(a)




(b)

*Figure 3* (a) Intensity and Interplanar spacing vs. $\mathrm{Sin}^2\psi$ plot for coated drills-flank side; (b) Intensity and Interplanar spacing vs. $\mathrm{Sin}^2\psi$ plot for coated drills-opposite flank side; (c) Intensity and Interplanar spacing vs. $\mathrm{Sin}^2\psi$ for uncoated drills.




(c)

*Figure 3* (*Continued.*)

shifts indicate the presence of compressive stresses in the film and interface [13, 14]. Diamond has a smaller coefficient of thermal expansion than WC; compressive stresses therefore, develop when the sample is cooled from the deposition temperature (1050 K) to room temperature. These thermal compressive stresses have been shown to predominate any intrinsic growth stresses [11].

### 4.2. Film stresses and interpretations

The x-ray diffraction measurements enabled the estimation of intensity, the atomic planar spacing variations with the angle of x-ray diffraction tilt for the film, and the overall stresses in the film. The well-known "$\mathrm{Sin}^2\psi$" technique was used for the determination of film characteristics and stresses [15]. These measures indicate the roughness of the film surface, film uniformity, preferred crystal orientation, qualitative grain size, and the presence of stresses [15]. Fig. 3a–c show the Intensity and inter-planar spacing (Dspacing) versus $\mathrm{Sin}^2\psi$ plots for coated (Diamond hkl) and uncoated (WC hkl) drills. From Fig. 3a, it is evident that the Intensity is relatively uniform for all $\mathrm{Sin}^2\psi$ values. This indicates a roughened surface. The undulating nature of the Dspacing plot is indicative of a preferred orientation of the film. SEM images presented in the next section show that these films do appear to have a net [110] orientation. Additionally, the significant cycling of Dspacing values at points close to $\psi = 0^\circ$ implies shear stresses in the film. Shear stresses might be expected due to the typical columnar growth for diamond films. Similar trends are observed in the XRD data shown in Fig. 3b for the opposite flank side of the coated drill. However, the intensity values are significantly different between Fig. 3a and b indicating variations in film morphology, roughness, and grain size at two opposite drill flanks.

The intensity plot in Fig. 3c for the uncoated drills show a lower intensity in comparison to Fig. 3a and b. This is expected because of significant differences in emitted intensity and intensity loss due to scattering from a roughly ground drill surface. The Dspacing for the uncoated drills are also lower and there is also some variation between values calculated for the two rake faces. This is expected because of variable residual stresses due to drill grinding.

The overall stresses for coated drills are seen in Fig. 4 to be compressive except in one case. The stress values are varying between radial and transverse directions and are lower for coated drills. This is due to stress relaxation occurring at coating temperatures. Variations in stress levels are also observed in orthogonal directions for each cutting edge as well as, between the diamond film and WC with the film exhibiting higher film stresses. Original surface defects, growth

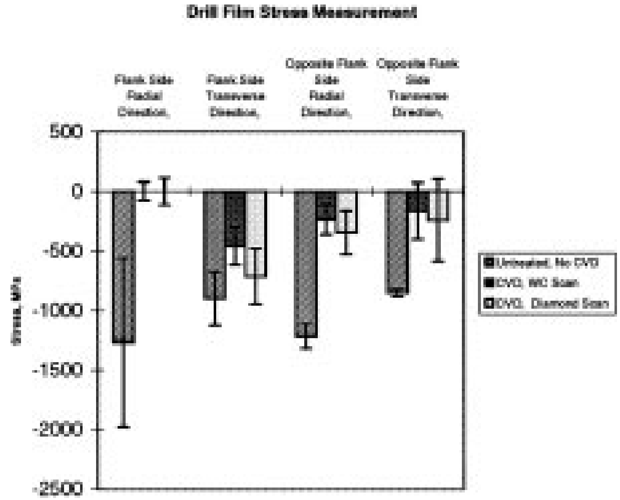
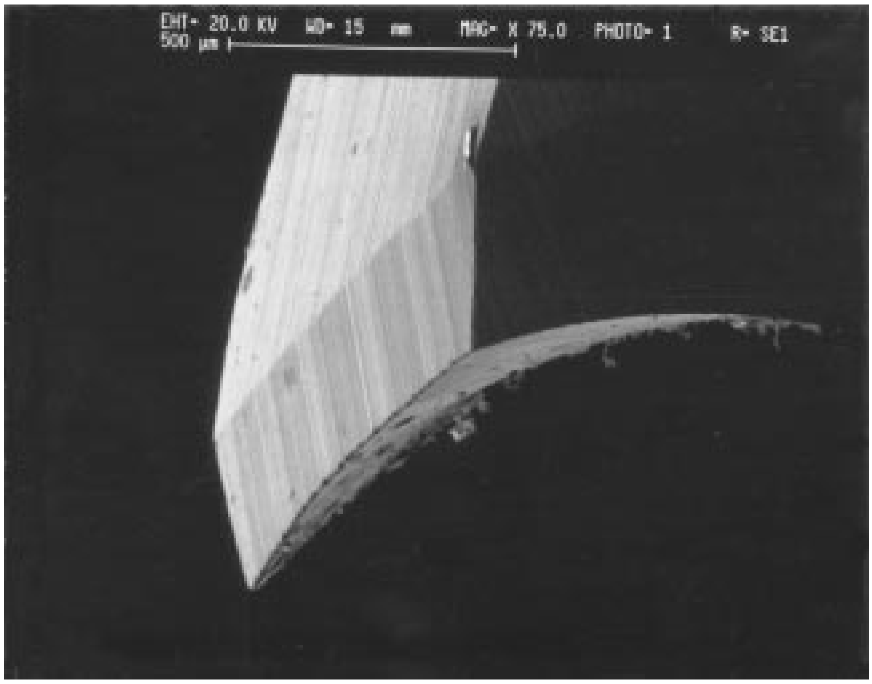
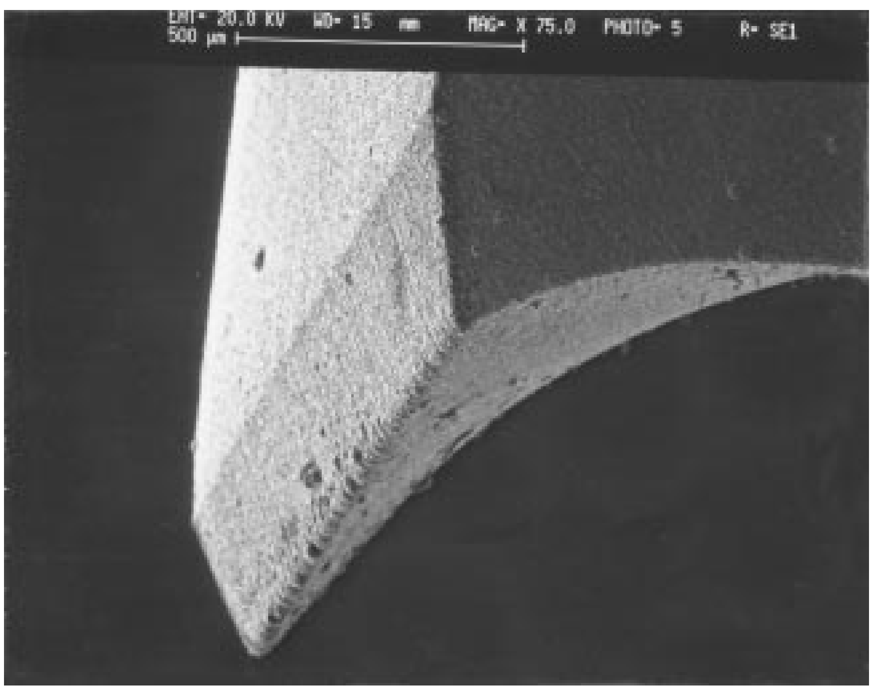



*Figure 4* Stress measurements for drills.




(a)




(b)

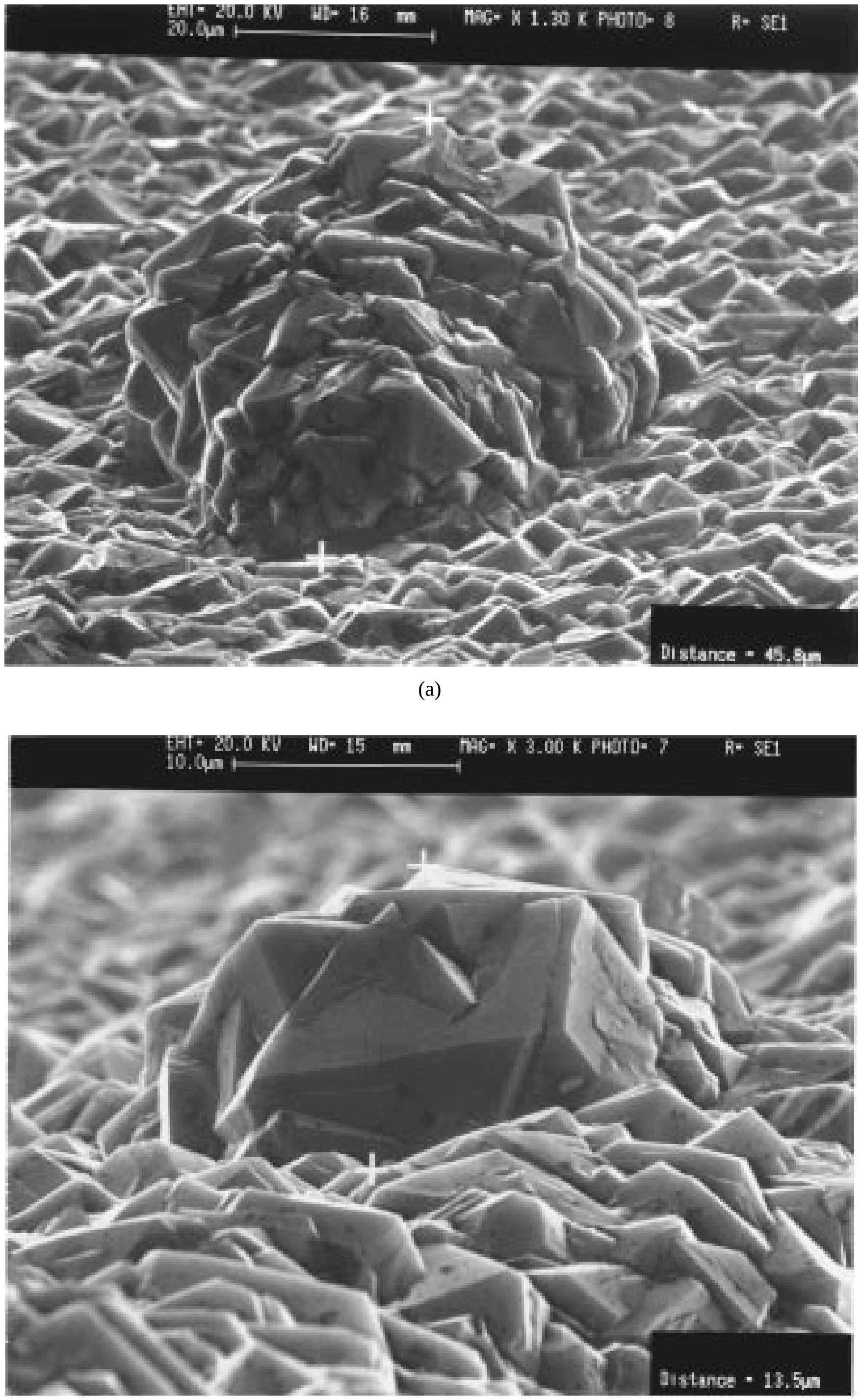
*Figure 5* (a) Uncoated drill scanning electron micrograph—Magnification 75×; (b) Coated drill scanning electron micrograph—Magnification 75×.

related film defects, and higher expansion coefficient of WC may be the main factors contributing to the variations.

In summary, the films exhibit preferred orientation, roughness, shear stresses, and varying levels of compressive stresses. The stresses also vary significantly between opposite cutting edges and directions. While some fluctuations in stresses are natural, large variations may lead to load fluctuations during drilling with premature drill failure. An important unanswered question in this study is the allowable stress variability for acceptable machining performance. This is discussed later in relation to the drill size effects.

### 4.3. Film morphology

The morphology of the films was investigated using SEM and is seen in Figs 5–7. In Fig. 5a an uncoated drill SEM image is shown. The drill surface is clearly seen to contain many deformities and gouges; the drill grinding striations are also evident. The corresponding deposited drill SEM image is shown in Fig. 5b. The film thickness was about 10 microns and it is evident that cutting edge rounding occurs. Fig. 6a and b show select areas of the film at a higher magnification. Here the individual crystals are clearly cubo-octahedron with preferred orientation. The film, although uniform overall, also shows supercrystal formation (as protrusions) at




(a)

(b)

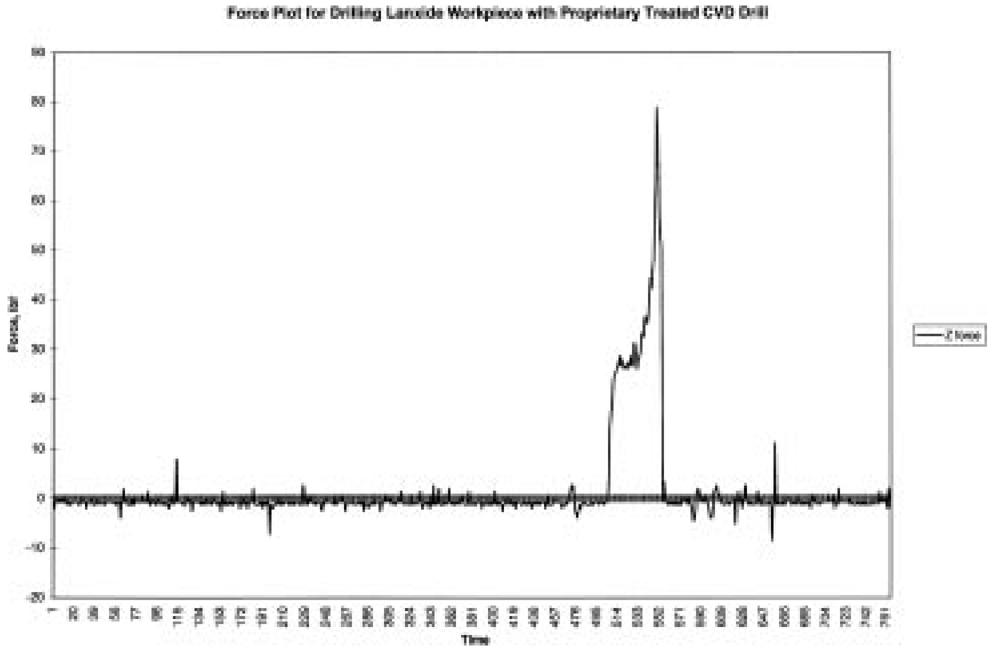
*Figure 6* (a) Diamond crystal formation—Magnification 1300×; (b) Magnified view of diamond clusters—Magnification 3000×.

sites with pre-existing gouges (seen in Fig. 5a). The crystals are also fairly large; total supercrystal size is 45.8 microns with one individual crystal measuring 13.5 microns. It is possible that these supercrystals project out of the cutting edge and are initial work-piece contact points with concentrated loading during drilling. This could very easily lead to catastrophic cutting edge failure.

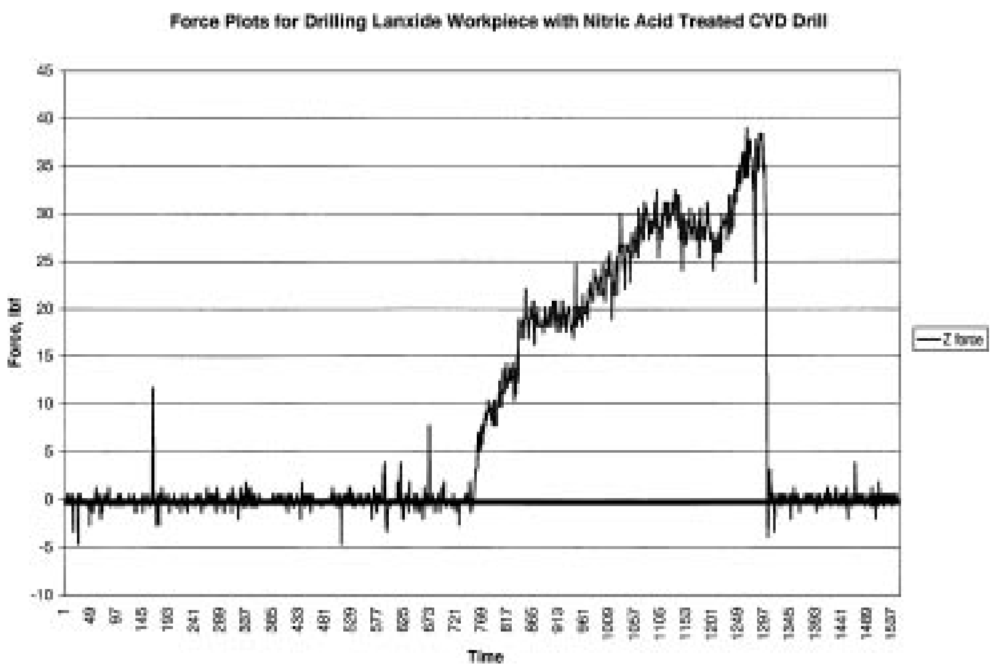
Fig. 6a and b also show that once a supercrystal formation starts, growth multiplication occurs with crystal build-up. As seen in these figures, the sizes of the individual component crystals also vary and some crystals seem to stop growing (because they are not as large) while others do not. The causes of these build-ups, the growth mechanisms, and the growth inhibitors are unknown at this point.

### 4.4. Machining tests

The machining tests were performed according to the conditions in Table I and the equipment specified earlier. SEM was done on drills to assess wear. The coated drills all failed catastrophically with fractures at the drill shank with short tool life for both aluminum and Lanxide workmaterials without any coating delamination. The uncoated drills lasted for about fifteen holes when




(a)



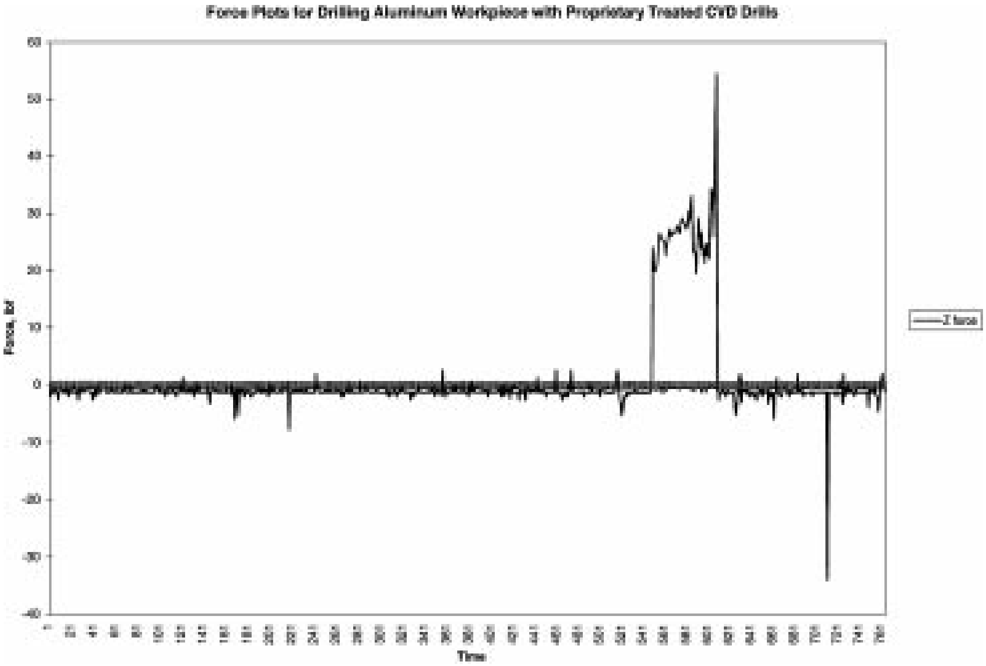

(b)

*Figure 7* (a) Force plots for drilling Lanxide with proprietary treated CVD drill; (b) Force plots for drilling Lanxide with nitric acid treated CVD drill; (c) Force plots for drilling Aluminum with proprietary treated CVD drill; (d) Force plots for drilling Aluminum with nitric acid treated CVD drill; (e) Force plots for drilling Lanxide with untreated HSS drill. (f) Force plots for drilling Aluminum with untreated HSS drill.

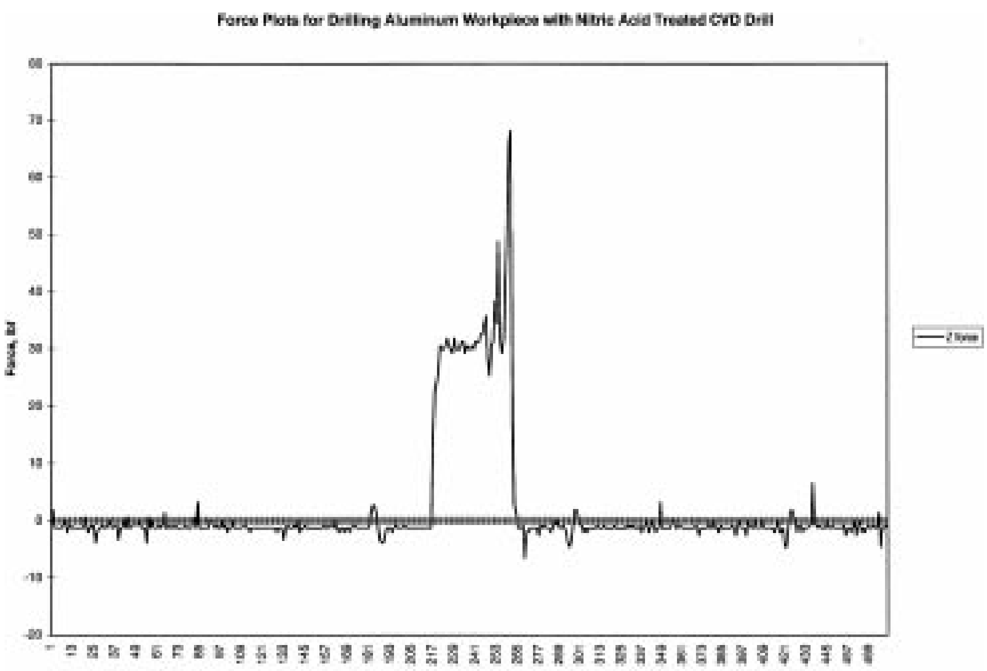
machining Lanxide. Fig. 7a–e show the force plots for drilling Lanxide and aluminum with proprietary treated and coated, nitric acid treated and coated, and uncoated drills, respectively. The axial force plots for the coated drills all exhibit a step-rise followed immediately by a steep rise in cutting force. The drills failed catastrophically synchronously with the steep rise in the force. The axial force plots for uncoated drills on both workmaterials do not show this steep rise. Also, the peak axial force amplitudes are smaller for uncoated drills when machining aluminum. For Lanxide, the axial forces for coated drills are lower than uncoated drills; however, coated drill failure was catastrophic at the shank. The HSS drills exhibited higher forces than the coated and uncoated tungsten carbide drills for the same feed because of lower drill material hardness and related temperature effects.

The SEM image of an uncoated drill wear after drilling fifteen holes in Lanxide is presented in Fig. 8 and crater wear is evident. The length of the crater is 430 microns. Also, seen is the loss of sharpness of the cutting edge due to its gradual abrasion and rounding.

The steep rise in axial force indicates that cutting edge rounding, leading to ploughing, may be a cause for tool failure. Another probable cause may be point loading of the supercrystals leading to stress concentrations




(c)




(d)

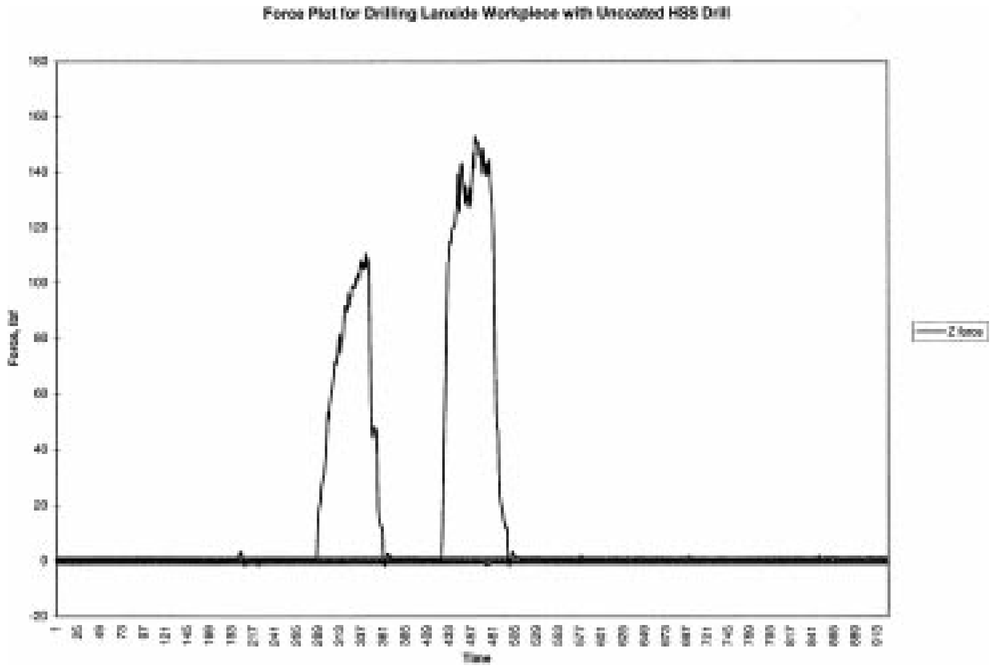
*Figure 7* (*Continued.*)

and shear failure of the tool. The rigidity of the drills is low for the given diameter; thus, high stress concentrations are likely to lead to catastrophic failures. This is further exacerbated by the amount of cobalt loss from the surface. The failure types also raise the issues of drill sizes limitations for workmaterial types, growth parameter selection for film robustness in performance, and growth morphology. These are discussed below.

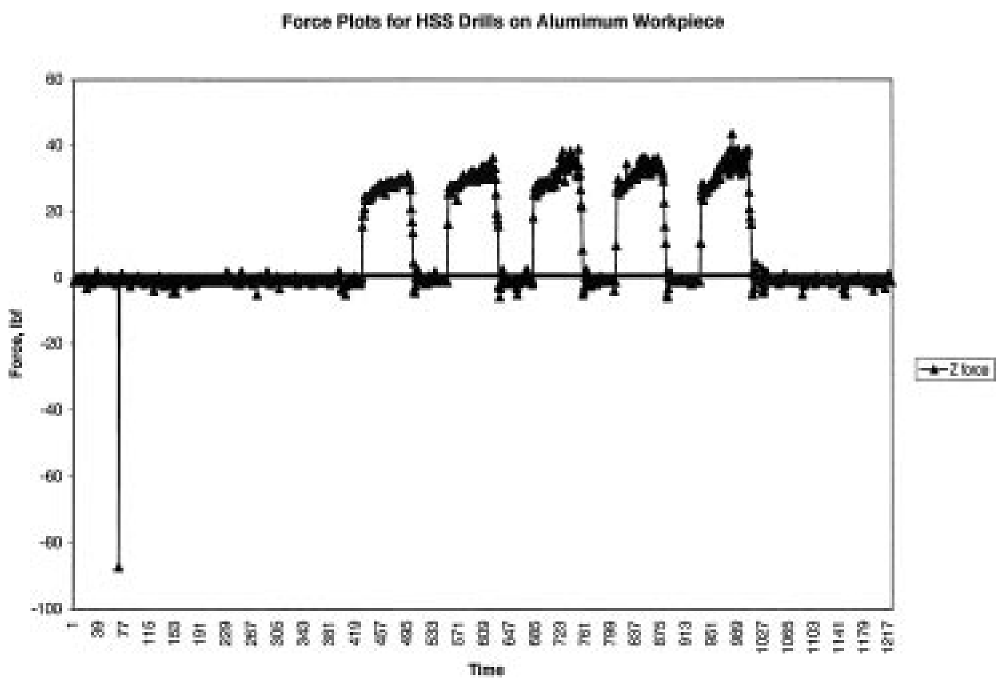
## 5. Discussions

### 5.1. Drill size effects

It may be possible that drill rigidity limits the usable drill diameter for particular workmaterial-drill combination. Catastrophic drill failure at shank was noted for both Lanxide (an abrasive and hard material) and Aluminum (a soft material). While, this may initially imply that for the coated drills, the chosen drill size (0.125″ diameter) is unsuitable for machining these materials, further experimentation should be done to determine the effect of materials, cutting speeds, and drill sizes on diamond coated drills. A selected diameter set with identical drill specifications should be coated and tested across a range of workmaterials, hole types, and speeds to determine economic effectiveness of the drills. The results will indicate useful size ranges. Additionally, the allowable stress variability for acceptable drill performance is also an important issue and should




(e)




(f)

*Figure 7* (*Continued.*)

be studied. In other words, what is the limit of allowable variation in cutting edge stresses before performance degrades? This may be a difficult problem to solve.

## 5.2. Coating process robustness

It has been observed from this study that there are significant variabilities in film stresses at various points on the coated surface. Whether such variations arise from the coating process and cause drill failures is unknown at this point; further experimentation in necessary to test this hypothesis. One approach is through a designed statistical experiment where drill sets are coated at set coating parameters, the stresses measured, and the drills tested. This approach follows from the determination of size limitations discussed above. The results will correlate stress variations with drill performance and can be used for setting appropriate growth parameters and workmaterials.

## 5.3. Growth morphology

The SEMs clearly show continuous film growth but undesirable (and unavoidable) cutting edge rounding and crystal clustering. The reasons for such clustering is unknown. It is important to study these clustering mechanisms on set levels of surface deformities in the form of voids and gouges. Additionally, the effect of

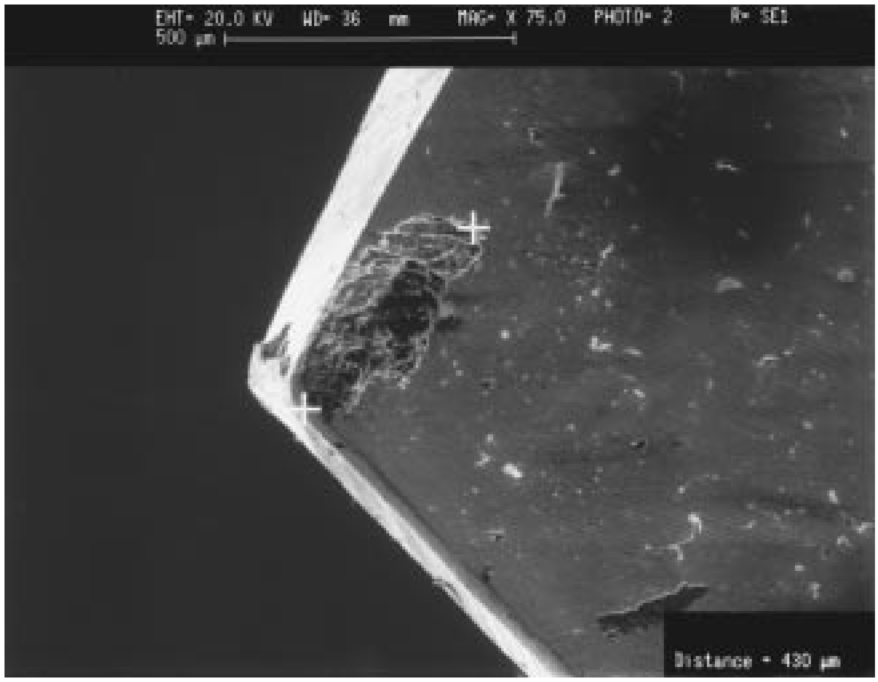



*Figure 8* Scanning electron micrograph of uncoated drill cutting edge wear—Magnification 75× .

these clusters on the machining performance of coated drills should also be studied. These studies may indicate what levels of surface quality are necessary for acceptable film growth and performance, and if such levels of surface quality are economically feasible. Additionally, drill size effects and coating process robustness studies might also influence the perceived need for this work.

In summary, a comprehensive empirical approach is necessary to establish the underpinnings of a scientific database for the effectiveness of diamond coated drills. As a start the fundamental relationships between growth parameters and morphologies, drill sizes, and drilling performance should be established.

## 6. Conclusions

The effectiveness of diamond coated tungsten carbide drills in drilling various workmaterials was examined in this work. Catastrophic coated drill failure with steep rise in axial (thrust) force was observed for all workmaterials drilled. Prior drill and coating stress and morphology characterizations indicated significant variations in drill stresses along the flank and flute surfaces, and the formation of diamond supercrystals. This study stresses the need for further research in the following areas:

- mechanisms for reduction of supercrystal formation,
- the extent of allowable stress variations for acceptable cutting tool performance,
- the effect of cutting edge imperfections on film nucleation, further growth, and adhesion,
- dependence of surface preparation methods, substrate grain size, deposition parameters, work material properties, and machining parameters on machining performance,
- geometry effects of tools, such as, taps and end mills, on films stresses.

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