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Ultra-precision machining of stainless steel using coated carbide tool

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ABSTRACT

Purpose: This paper discusses the experimental work carried out to investigate the performance of coated carbide tool in ultra-precision machining of stainless steel and evaluates whether this tool can be used to fabricate a cavity with high form accuracy and surface finish on a stainless steel mould insert.

Design/methodology/approach: The results obtained in the turning process and the machining of cavity on a mould insert under various conditions and parameters are examined.

Findings: The experimental results obtained in the turning tests gave an important insight of the appropriate parameters and the condition to be used in the machining of cavity on a mould insert. The cavity machined on the stainless steel mould insert with the coated carbide tool in the presence of natural oil has superior form accuracy and surface finish.

Research limitations/implications: Further research is needed to investigate the performance of the coated carbide tools in machining profiles of other shape and diameter.

Practical implications: Profile with a superior form accuracy and surface finish can be machined on a stainless steel mould insert using a coated carbide tool instead of using a PCBN tool, a much more expensive tool.

Originality/value: The paper presents original information on the ultra-precision machining of tool steels at low speeds. The paper is of interest to manufacturing engineers.

Keywords: Machining; Carbide tool; Lubricant; Stainless steel; Wear

MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Many mould inserts used for the injection moulding of optical lenses are fabricated from stainless steel with hardness of between 40 HRC and 55 HRC. Figure 1 shows the diagram of a stainless steel insert plated with electroless nickel (ENi). Mould inserts used for the injection moulding of CD and DVD optical lenses have aspherical profiles with diameter of less than 5 mm machined on their surfaces. The aspherical profile on the base material of the insert (stainless steel) can be generated on an ultra-precision machine using a low-speed spindle (which can be operated up to 3000 rpm) or a high-speed spindle (which can be operated up to 10000 rpm). When a profile with a diameter of 5 mm is machined using a low-speed spindle, say at the maximum speed of 3000 rpm, the cutting speed reduces significantly from 47 m/min to 0 m/min as the cutting tool is fed towards the centre of the profile. This underlines the need for investigating the wear behaviour of cutting tools at low cutting speeds. A change in the cutting speed can cause a change in both the strain hardening in the chip and the cutting temperature and hence the wear rate.

After an aspherical profile is generated, the stainless steel insert is usually plated with electroless nickel so that an aspherical profile with a much higher form accuracy can be diamond turned on the insert. In ultra-precision machining, wear on both the flank and rake faces have proven to be crucial to the surface finish and dimensional accuracy [1,2]. If the form accuracy of the aspherical profile generated on the stainless steel insert is low (due to tool wear), when a diamond tool is used to machine an aspherical profile on the ENi plating, it may machine through to the stainless steel, thus resulting in high tool wear [3,4]. To achieve a high accuracy of profile on the stainless steel insert, tool wear must be kept to a minimum by using the appropriate tool type and machining parameters.

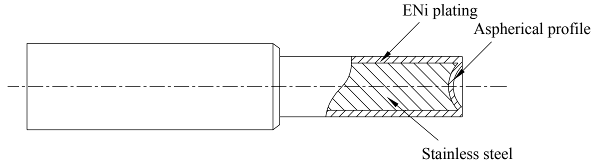


Fig. 1. Diagram of a mould insert

Precision brazed PCBN (polycrystalline cubic boron nitride) tips are widely used in the machining of mould inserts. It is not known whether carbide tools, cost much less than PCBN tools, can be used to machine mould insert to the required form accuracy and surface finish, suitable for ENi plating, on a mold insert. Not many papers have reported on the wear of tools during machining of stainless steel on an ultra-precision machine where the depth of cut, feed rate and cutting speed used are much lower than those used in conventional turning. Recently, Ding *et al.* [1] and Liew *et al*. [2,5] have investigated the wear of PCBN, and PVD-coated and uncoated carbide tools in the machining of STAVAX at low cutting speeds (below 44 m/min), depths of cut (3 μm and 20 μm) and feed rate (5 μm) using an ultra-precision machine. It was found that the tool wear controlled essentially by mechanical process. The PCBN tools were predominantly subjected to abrasion resulting in either fracture or groove wear depending on the hardness of the machined surface. In this study, experiments were carried out to study the performance of PVD carbide tools in the ultra-precision machining of STAVAX (specialized stainless steel) at low cutting speeds and evaluate whether this tool can be used to fabricate a cavity with high form accuracy and surface finish on a stainless steel mould insert.

2. Experimental procedure

2.1. Cutting test

Investigation on the wear of the uncoated and coated carbide tools in the machining of STAVAX with a hardness of 40 HRC (composition by wt% 0.38% C, 0.9% Si, 0.5% Mn, 13.6% Cr, 0.3% V, balance Fe) was carried out by turning on a Precitech CNC ultra-precision machine without and with lubricant. The depth of cut and the feed rate can be set to an accuracy of 0.1 μm and 0.1 μm/rev respectively. A sprayed mixture of compressed air and a solution containing 93vol% liquid paraffin oil and 7vol% cyclomethicone was used as lubricant. These chemicals can be found in Johnson's baby oil which is recommended by Precitech to be used as lubricant in the ultra-precision machining of alloys such as aluminium and stainless steel. The feed rate was kept constant for all the tests at 5 μm/rev. The tangential (F_t) and radial (F_r) forces acting on the tool during machining were continuously measured using a dynamometer. F_t and F_r are, respectively, in directions normal and parallel to the rake face of the tool. The machining process was monitored using a CCD camera.

2.2. Cutting tools

The machining tests were carried out with tool inserts grade ACZ310 (Carbide tool grade K20 PVD-coated with 2000 alternate layers of AlN and TiN, each layer 1.25 nm thick). These tool inserts were obtained from Sumitomoto Electric. The AlN/TiN superlattice film has a hardness of 3900 HV. The tool inserts conformed to ISO designation CCGT 060204 (nose radius = 0.4 mm, clearance angle = 7°). The inserts were mounted on a commercial tool holder conforming to ISO designation SCLCR.

3. Results and discussion

3.1. Flank wear

Figure 2 shows the change in the flank wear V_B with distnace at various depths of cut. The flank wear of the tool increased significantly in the initial stage of machining, after which it remained fairly steady, even with further increase in cutting distance.The lubricant was effective in reducing the flank wear. The flank wear V_B and the dominant wear modes observed on the rake face of the tools used to machine the workpiece at various cutting speeds for a distance of 440 m are summarized in Fig. 3. From this figure, it can be seen that in the absence of lubricant, a decrease in the cutting speed from 44 m/min to 8 m/min resulted in a slight increase in the flank wear but a significant change in the wear mode on the rake face.

3.2. Morphology of the tool surface

The tools used to machine the workpieces were examined using a SEM and an EDX spectrometer system. Figure 4(a) shows the tools used to cut the workpiece for a distance of 440 m without lubricant. A layer of coating was detected on the rake face adjacent to the cutting edge, suggesting that the coating on this region was not removed during machining. At some distance up the rake face, some coating material was removed. It is possible that the coating was removed by abrasion. Several researchers [6,7] had examined the friction condition at the chip-tool interface in the machining of steel. They found that at some distance from the tool edge where sliding took place or seizure was intermittent, abrasion was much more severe than that at the region adjacent to the immediate vicinity of the cutting edge where seizure occurred due to high stress concentration. Hard abrasive foreign particles in the work material can play a significant role in the wear of tools in which under conditions of sliding, these particles make a greater contribution to abrasive wear than under seizure condition. Over the seizure region where the normal stress is high, deformation occurs in the lower layer of the chip material. In other words, the contact area at this zone does not involve a severe rubbing of the coating material on the tool surface. This explains why the coating material at the tool edge is not removed when machining was carried out without lubricant. Similar friction behaviour was also found to occur on the rake face of the PCBN tool [1,2]. At some distance up the rake face, numerous amount of CBN particles were removed by abrasion. The cavities, formed due to the removal of the particles, acted like a chip breaker and thus as a preferential site for fracture to occur.

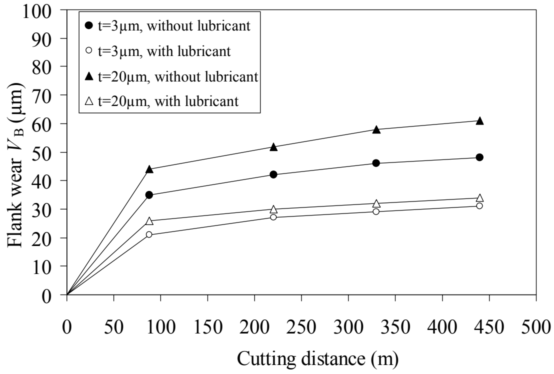


Fig. 2. Flank wear of PVD-coated tools in the machining of modified AISI 420 stainless steel at 44 m/min

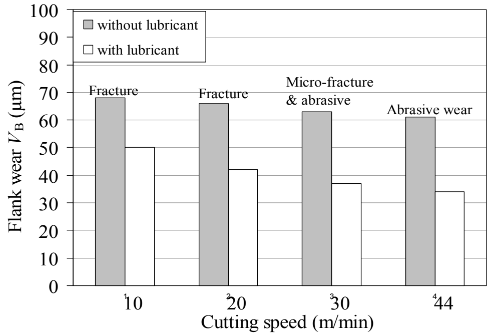


Fig. 3. Flank wear and the dominant wear mode at the rake face of the PVD-coated tool used to machine AISI 420 stainless steel for a distance of 440 m at a depth of cut of 20μm.

Reducing the cutting speed from 44 m/min to 30 m/min resulted in the coating material on the rake face being removed at a higher rate, suggesting that the abrasive wear increased with a reduction in the cutting speed. At 30 m/min, fine-scale fracture also occurred at the tool edge (Fig. 4(b)). This wear mechanism caused the tool edge becoming round. A change in the geometry of the tool edge also coincided with an increase in the vibration of the tool and the fluctuation of the cutting forces. Extensive fracture took place on the rake face during machining at speeds below 20 m/min (Fig. 4(c)). Figure 4(c) shows a large cavity formed at the tool tip due to fracture. The formation of cavity altered the geometry of the tool edge which in turn caused the fluctuation of the cutting forces becoming more erratic. It is clear that tool wear increases significantly as the cutting speed is reduced from 44 m/min to 10 m/min. This could be attributed to an increase in the severity of abrasion and stress acting on the tool edge due to an increase in the shear strength in the flow-zone as a result of a temperature drop in the work material [6]. This explanation is in accord with the observation made in out previous study that increasing the hardness of the work piece from 40 HRC to 55 HRC can cause fracture to take place on the rake face at 44 m/min. The lubricant was very effective in preventing the formation of surface fracture and reducing the abrasive wear. All the tools tested at all speeds in the presence of lubricant showed no evidence of fracture (Fig. 4(d)).

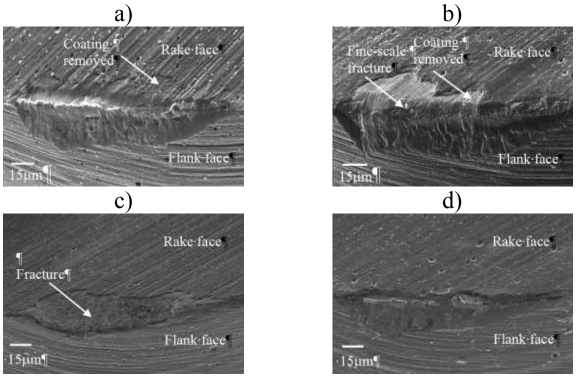
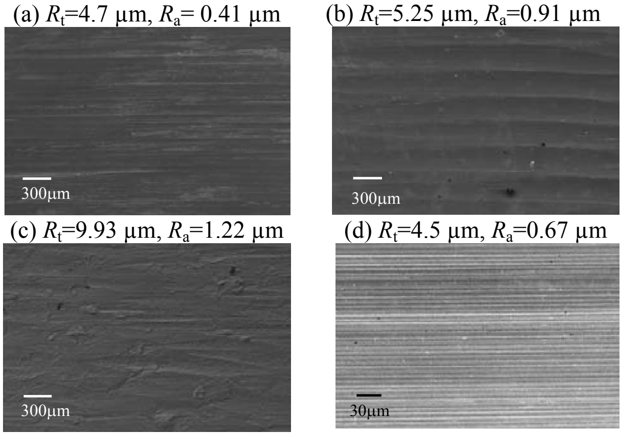


Fig. 4. SEM images of the PVD-coated tools used to machine the workpiece for 440 m at (a) 44 m/min without lubricant, (b) 30 m/min without lubricant, (c) 10 m/min without lubricant and (d) 10 m/min with lubricant

A notable feature of the cutting forces obtained during cutting under dry condition was the fluctuations of the F_t and F_r forces, which were in contrast to the less variable and lower forces obtained in the presence of lubricant. The prevailing low cutting forces obtained in the presence of lubricant reflects the presence of low shear-strength layers at the interfaces. The effectiveness of the lubricant in reducing the abrasive wear and surface fracture can therefore be attributed to the reduction in the cutting forces and the presence of a low shear-strength film at the interfaces.

3.3. Morphology of the workpiece surfaces

The R_t (peak-to-valley) and R_a (surface roughness) values of the workpieces (measured in a direction parallel to the feeding direction) increased with a reduction in the speed. Numerous grooves and scratch marks, mostly parallel to the cutting direction, are evident on the surface of the workpiece machined at 44 m/min under dry condition (Fig. 5(a)). Such features are characteristics of abrasion by the debris trapped at the chip-tool interface. At the cutting speeds of 30 mm/min and below under dry condition, fracture occuring at the tool edge changed the effective rake angle to negative. High forces generated by the flow of the chips on the negative rake angle tool caused vibration to take place which in turn resulted in the formation of undulating surface (Fig. 5(b)) with distinct ridges spaced at a distance of between 200-300 μm. This gave rise to high R_t value. When the sharpness of the tool edge was maintained by the application of lubricant, a much less undulating surface was generated. The surface of the workpiece machined at 10 m/min and 20 m/min in the absence of lubricant was covered extensively with metal debris (Fig. 5(c)). When fracture took place, the chip material strongly bonded to the tool and continuously ploughed into the surface of the workpiece. When it became unstable, it detached from the tool and adhered onto the workpiece [8]. In the case where the interfaces were lubricated and tool wear was reduced by lubricant, a superior finish was obtained (Fig. 5(d)).


(a) R_t=4.7 µm, R_a= 0.41 µm (b) R_t=5.25 µm, R_a=0.91 µm

(c) R_t=9.93 µm, R_a=1.22 µm (d) R_t=4.5 µm, R_a=0.67 µm

Fig. 5. SEM of the surfaces of the workpieces machined for a distance of 440 m at a depth of cut of 20µm at (a) 44 m/min without lubricant, (b) 30 m/min without lubricant, (c) 10 m/min without lubricant and (d) 10 m/min with lubricant.

3.4. Machining of spherical profile

A PVD-coated carbide tool was used to turn spherical profiles (with diameter of 5 mm) on stainless steel using a constant spindle speed of 3000 rpm. During machining of a profile, as the cutting tool is fed towards the centre of the profile, a change in the contact point on the tool nose (from point A to B) accompanied by a reduction in the cutting speed will take place as illustrated in Fig. 6. Point A of the tool cuts at a speed of 47 m/min. When the tool reaches to the centre of the profile, point B of the tool will do the cutting at a speed of close to 0 m/min. Cutting at low speed caused this part of the tool to fracture and the flank wear increased significantly. Fracture at the tool edge would then cause the material at the center of the profile uncut, resulting in the formation of a large protrusion (with a height and diameter of up to 30 µm and 15 µm) at the centre of the profile as illustrated in Fig. 7. Fracture also caused the work material strongly bonded to the tool and continuously ploughed into the surface of the workpiece and vibration to take place, resulting in the formation of undulating surface.

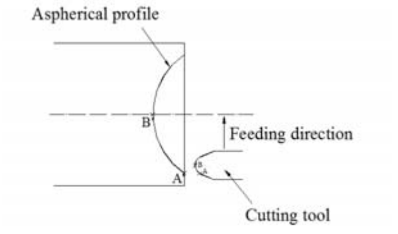


Fig. 6. Schematic diagram showing the change in the contact point along the tool nose during machining a spherical profile

The form accuracy of the profiles measured using a Zygo measurement interferometric system were found to be lower than 25 µm. The profiles machined in the presence of lubricant had superior surface finish (R_a=0.7 µm) and small protrusions (with a height and diameter of less to 9 µm and 7 µm respectively) with form accuracy of higher than 12 µm. This allows the same spherical profile to be turned on the ENi plating with a thickness of 50 µm using a diamond tool without machining through to the stainless steel.

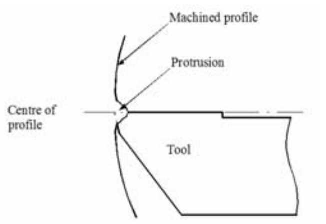


Fig. 7. A protrusion is created at the centre of the machined profile as a result of fracture at the tool edge

4. Conclusions

The experimental results obtained in the turning tests gave an important insight of the appropriate parameters and the condition to be used in the machining of cavity on a mould insert. The profile machined on the stainless steel mould insert with the coated carbide tool in the presence of natural oil has superior form accuracy and surface finish. This allows the same profile to be turned on the ENi plating using a diamond tool without machining through to the stainless steel.

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