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Machining strain hardening metals using nanostructured thin film end mills

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ABSTRACT

Purpose: This paper discusses improvements associated with the tool life of cutting tools used to machine alloy steels. To achieve this in an efficient manner, experiments on a variety of tool coatings are conducted on AISI M42 tool steel (58-63 HRC).

Design/methodology/approach: In order to assess the impact of different tool coatings on the machining process, initial experiments simulate current machining operations; this provides a benchmark standard for tool life and surface finish.

Findings: The findings in the paper show that TiAlCrN and TiAlCrYN coated WC-Co cutting tools perform better than uncoated and TiN coated cutting tools.

Research limitations/implications: The implications of the paper tend to indicate that dry machining of M42 tool steels can be optimized using coated cutting tools. The limitations of the paper include machining at specific cutting speeds and the employment of a short-time tool wear method.

Practical implications: The practical implications of the paper show that dry machining of hardened tool steels can be achieved under specific circumstances. Further research is needed to explain how the wear mechanism changes under various machining conditions.

Originality/value: The paper presents original information on the characteristics of dry machining of tool steels under specific machining operations. The paper is of interest to manufacturing engineers.

Keywords: Machining; Strain hardening materials; Nanostructured coatings

1. Introduction

The factors that lead to tool wear are mechanical, thermal, chemical, and abrasive [1-3]. During chip formation a significant amount of heat is generated, particularly on the flank of the tool. Due to the cyclical nature of the cutting operation these thermal loads pulsate leading to thermal fatigue of the tool material. The typical wear zones on the cutting edge are shown in Figure 1. The wear zones are characterized by the type of wear that occurs on certain parts on the tip of the tool and around the cutting edge. As a result of load factors exerted on the cutting tool edge, a few basic mechanisms dominate metal cutting. These mechanisms are:

1. Diffusion wear – affected by chemical loading on the tool and is controlled by the metallurgical composition of the tool and coating material.
2. Abrasive wear – affected by the hardness of the tool material and is controlled by the carbide content of the cutting tool material.
3. Oxidation wear – causes gaps to occur in coated films and results in a loss of the coating at elevated temperatures.
4. Fatigue wear (static or dynamic) – this is a thermo-mechanical effect and leads to the break down of the edges of the cutting tool.

5. Adhesion wear – occurs at low machining temperatures on the chip face of the tool and leads to the formation of a built-up-edge, and the continual breakdown of the built-up edge and the tool edge itself.

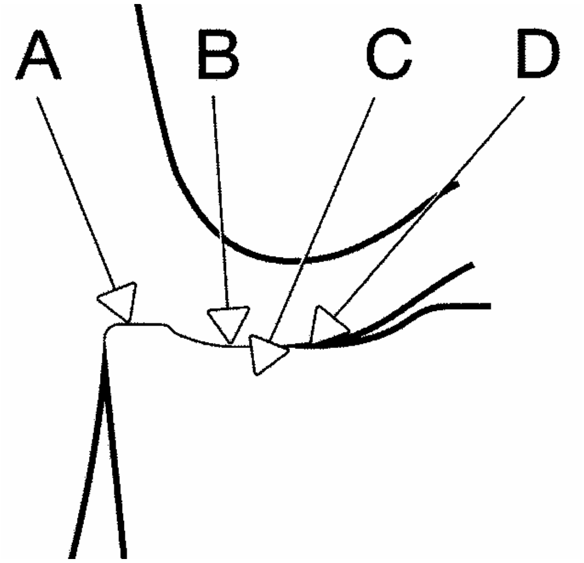

Fig. 1. Wear zones on the cutting tool caused by chip formation [3]

2. Experimental Procedure

Machining experiments were performed to assess the life of newly developed titanium based coated tools. The assessment of machinability used in these experiments pertains to the development of Taylor's tool life equations for uncoated and coated cutting tools. Taylor's tool life equation is stated as:

$$VT^{n} = C \tag{1}$$

where V is the cutting speed in meters per minute (m/min), T is the tool life in minutes (mins.), n is an exponent dependent upon the machining conditions and the tool and workpiece compositions, and C is a constant. For each tool life equation generated, a sample of the metal is turned at a specific cutting speed and the time it takes to wear 0.3mm of the flank face of the insert away from the cutting tool is noted and used in the calculation. For the machining of M42 tool steel in this study, a computer numerically controlled lathe was used to vary the cutting speed. An Emco Maier CNC mill was used to mill bars of M42 tool steel that were one inch square bars with a measured surface roughness of 25 µm. The type of cut used was a roughing cut using the parameters shown in Table 1. A maximum cut was used of 2.54 mm in order to produce a thick chip. Water coolant was applied to the chips as they collected in the chip tray. This was performed so as not to ignite the chips after they were deposited into the chip tray. This was conducted in order to machine the metal 'dry' in order to confirm or refute the effectiveness of the coated end mills. The uncoated cutting tool inserts were composed of 94wt.% tungsten carbide bonded with a 6 wt.% cobalt binder. The coated cutting tools were supplied with a superlattice coating composed of 1000 deposited layers to form a coating thickness of 3 µm. The alloy used for machining experiments was an M42 tool steel. The maximum feed rate was used in these experiments was set at 0.2 mm per revolution of the spindle. The tools were initially sharp and were not previously used in any other application. The end mills were coated at the Bodycote-SHU facility housed within the Materials Research Institute at Sheffield Hallam University. The coatings were developed for dry machining operations and the research on the thin film coatings are described in references [4-10]. The initial cutting speed used for the experiments was set at 30 m/min. The tool life was measured by inspecting the cutting tool until 0.3mm of the flank had worn away, which is in accordance with ISO 8688 standard. Further increments of cutting speed were made until a maximum cutting speed of 70m/min had been achieved. The improvement in cutting ability of coated tools using nanostructured PVD and CVD coatings has recently been reported by Dobrzanski et al. [11-13], and the simulation of stresses in titanium based coatings has been demonstrated by Dobrzanski et al. [14]. Dobrzanski also comments on the effectiveness of multilayer nanocrystalline coatings in a recent paper [15].

3. Experimental Results

Over 250 images have been taken of the cutting edges of the uncoated tools used to machine M42 workpiece material. A selection of images is shown in Figures 2 and 3.

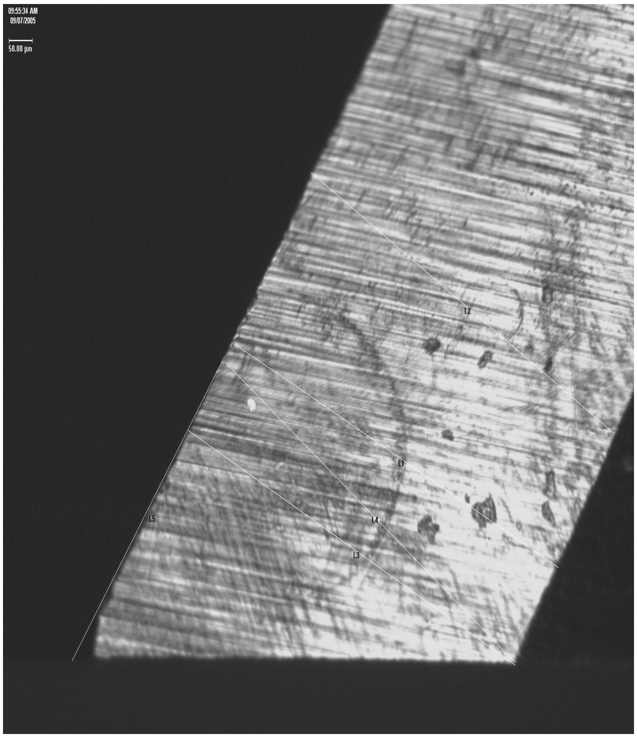

Fig. 2. New tool showing sharp cutting edge

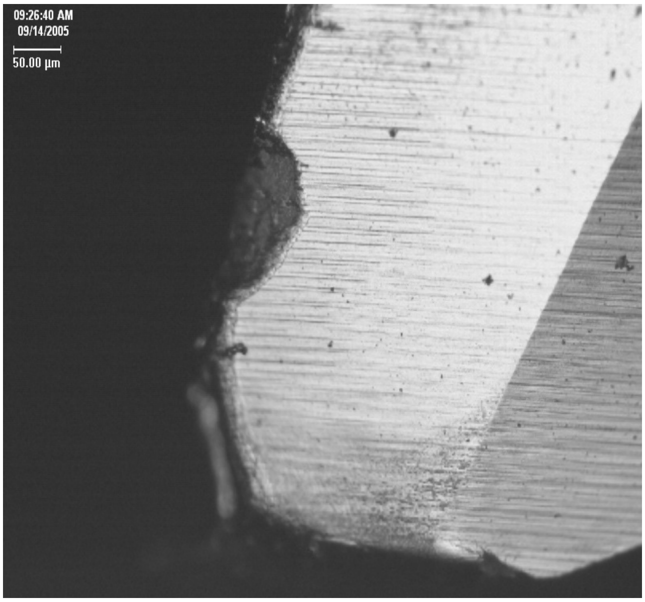

Fig. 3. Worn uncoated tool edge

It is usually observed that vibrations are worse when the tool first enters the workpiece, the reason for this could be due to the elastic restoring forces in the tool. As the tool enters the workpiece the tool begins to act as a cantilever beam, as the tool rotates the workpiece advances and applies a force to the tool. When the tool is fully engaged with the workpiece each tooth removes an identical amount of material and the resistive force experienced by the tool is constant and an equilibrium position is reached between the resistive forces and the elastic restoring forces. However, upon entry each tooth removes a different amount of material (since the arc lengths cut by each tooth are different) until the point of full engagement is reached. In this scenario the resistive forces cannot reach an equilibrium position with the elastic restoring forces (since the resistive forces are changing), hence the tool is continually bending back and forth at different rates and this results in the generation of vibrations. At the point of full engagement the equilibrium position is reached and no vibrations are produced until the tool exits the workpiece where again there is no equilibrium. The vibrations cause a problem because they contribute to chipping tool wear.

The life of the uncoated and coated cutting tools was compared after measuring the progression of flank wear of the cutting tool inserts after machining at different cutting speeds under the conditions. The results of the tool life experiments are presented in Table 1. Under the machining conditions stated, the dominant wear behaviour observed during the machining experiments was flank wear. The data provided above allows us to calculate the Taylor tool life equation for each cutting tool type for the experimental conditions stated. The following equations relate to the cutting tool types described:

1. Uncoated WC-Co $VT^{0.28} = 30$
2. TiN coated WC-Co $VT^{0.3} = 34$
3. $Ti_{0.46}Al_{0.54}N$ coated WC-Co $VT^{0.35} = 38$
4. $Ti_{0.44}Al_{0.53}Cr_{0.03}N$ coated WC-Co $VT^{0.37} = 42$
5. $Ti_{0.43}Al_{0.52}Cr_{0.03}Y_{0.02}N$ coated WC-Co $VT^{0.39} = 51$

The results presented show that the tool life is increased as the coating is improved with small additions of elemental chromium and yttrium. This effect coincides with the observations made regarding the oxidation behaviour of the coatings treated with various elemental concentrations of chromium and yttrium. Compared to other materials, the tool life equations presented appear to show that machining M42 tool steel results in an extremely low tool life compared to more commonly used engineering steels with microstructures that tend to favour good machinability.

The machinability of M42 tool steel appears to be similar to that of austenitic stainless steels, i.e., very low tool life even at moderately high cutting speeds. The observations of wear behaviour tend to show that the normal mode of wear during machining is progressive flank wear. However, it must be noted that cutting tool life experiments were based on roughing machining operating conditions and did not include experimental determination of tool life during finish machining operations.

Table 1.
Cutting tool life experimental results

Cutting Tool	Spindle speed (m/min)	Cutting tool life (minutes/seconds)
Uncoated Tool (WC-Co)	30	1 minute
	50	9s
	70	3s
TiN coated WC-Co	30	1.5 minutes
	50	16.5s
	70	5s
$Ti_{0.46}Al_{0.54}N$ coated WC-Co	30	2 minutes
	50	27s
	70	10.5s
$Ti_{0.44}Al_{0.53}Cr_{0.03}N$ coated WC-Co	30	2.5 minutes
	50	37s
	70	15s
$Ti_{0.43}Al_{0.52}Cr_{0.03}Y_{0.02}N$ coated WC-Co	30	3.9 minutes
	50	63s
	70	27s

4. Discussion

It can be seen that when comparing wear between the coated and uncoated tools, uncoated tools loose bulk tool material behind the wear front; whereas coated tools tend to retain a greater proportion of the bulk tool material. A possible reason for this could be due to the presence of the coating; at the tool-chip interface the coating suppresses high temperature generation, this leads to a reduction in dissolution wear. As a result of machining, large portions of the tool are retained because there are less mechanically weak regions. This is not the case for the uncoated tool because high temperatures are generated that encourages dissolution wear. This leads to the formation of mechanically weaker regions, which then become susceptible to chipping.

The incorporation of 3 mol% CrN in $Ti_{l-x}Al_xN$ alloys did not significantly change film hardness or microstructure. The latter remained columnar with individual columns consisting of single grains over extended vertical distances. Adding an additional 2 mol% YN increased the film hardness by $HK_{0.025}$ $\approx$300 kg mm^{-2} while Y segregation during growth promoted continuous re-nucleation which resulted in a considerable grain refinement and a more equi-axed structure.

Thermo-gravimetric analysis in oxidizing ambient atmospheres showed that the onset of rapid oxidation was increased from ≈ 600°C for TiN to 950°C for $Ti_{0.43}Al_{0.52}Cr_{0.03}Y_{0.02}N$, compared to 870°C for $Ti_{0.46}Al_{0.54}N$ and 920°C for $Ti_{0.44}Al_{0.53}Cr_{0.03}N$. The initial oxidation reaction path was found to be similar for the three alloys with the formation of an Al-rich surface oxide and Ti-rich oxide under-layer. Annealing $Ti_{0.44}Al_{0.53}Cr_{0.03}N$ layers on steel substrates for 1 h at 950°C results in massive oxidation with cation out-diffusion, giving rise to void formation and under-dense column boundaries extending nearly to the film-substrate interface. Voids are also observed on the substrate side of the film-substrate interface due to rapid out-diffusion of Cr, which is rejected by Ti-rich sub-layers in the oxidized film and accumulates at adjacent boundaries, and Fe. In stark contrast, the addition of only 2 mol% YN to form $Ti_{0.43}Al_{0.52}Cr_{0.03}Y_{0.02}N$ reduces the oxide thickness from >3 µm to ≈ 0.4 µm while significantly inhibiting out-diffusion of substrate species. STEM-EDX profiles, obtained after annealing, show that Y segregates to the nitride grain boundaries. This may explain the enhanced high-temperature oxidation resistance of $Ti_{0.43}Al_{0.52}Cr_{0.03}Y_{0.02}N$ alloy as Y and YO_x inhibit grain-boundary diffusion of both cation species toward the free surface and oxygen penetration into the film. The machining characteristics of coated cutting tools did have some benefit to extending the life of the cutting tool when machining uranium alloys. The benefits associated with using titanium based coated tools was further enhanced by using a superlattice coated cutting tool. This ensured that thermal fatigue cracking of the coating did not interfere with the normal operation of the cutting insert when machining uranium alloys. The use of coated tools appeared to have a similar tool life compared to austenitic stainless steels. However, further experiments are required to determine the life of the tools when finish machining operations are involved.

5. Conclusion

During the machining of hardened M42 tool steel, TiAlCrN and TiAlCrYN coatings are effective at reducing tool wear due to chipping and improve tool life.

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