Journal of Achievements in Materials and Manufacturing Engineering

VOLUME 23
ISSUE 1
July
2007

Machining M42 tool steel using nanostructured coated cutting tools

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Received 03.04.2007; published in revised form 01.07.2007

Manufacturing and processing

ABSTRACT

Purpose: This paper discusses improvements associated with the life of cutting tools used to machine M42 tool steel. To achieve this in an efficient way, 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 existing machining operations; this provides a standard for tool life and surface finish.

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

Research limitations/implications: The implications of the paper tend to indicate that machining M42 tool steels without lubricant can be optimized using coated cutting tools. The limitations of the paper include machining at one specific cutting speed 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 certain circumstances. Further research is needed to explain how the wear mechanism changes with varying machining conditions.

Originality/value: The paper presents original information on the characteristics of dry machining of M42 tool steel under specific machining operations. The paper is of interest to manufacturing engineers and materials scientists.

Keywords: Machining; Tool steel; Nanostructured coatings

1. Introduction

The factors that lead to tool wear are mechanical, thermal, chemical, and abrasive [1-3]. Owing to chip formation a significant amount of heat is generated. Owing to the cyclic nature of the cutting operation these thermal loads pulsate leading to thermal fatigue of the cutting tool. The typical wear zones on the cutting tool edge are shown in Figure 1. The wear zones are characterized by the type of wear that occurs 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 machining. These mechanisms include:

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

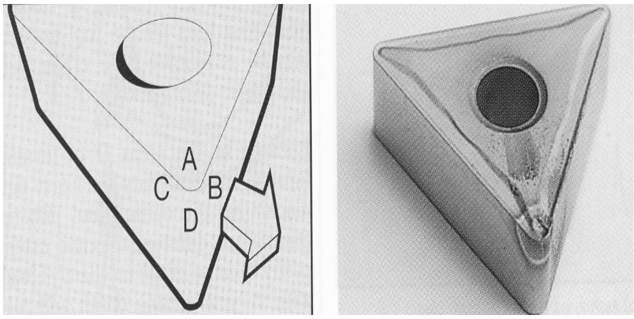

Fig. 1. Wear zones on the cutting tool caused by chip formation [3]

2. Experimental procedures

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

$$VT^{-1/k} = C \qquad (1)$$

Where V is the cutting speed in meters per minute (m/min), T is the tool life in minutes (mins.), k is an exponent dependent upon the machining conditions and the tool and workpiece compositions, and C is a constant. For each tool life equation, 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 measured and used in the calculation. For the machining of M42 tool steel, a computer numerically controlled lathe was used to vary the cutting speeds. An Emco Maier computer numerically controlled milling machine was used to mill bars of M42 tool steel that were one inch diameter bars with a measured surface roughness of 25 μm and a hardness of approximately 58-63 HRC. The type of machining regime used was a roughing cut using the parameters shown in Table 1. A maximum depth of cut was used of 2.54mm in order to produce a thick chip. Water coolant was applied to the chips as they collected in the chip tray. This was conducted in order to machine the metal 'dry'. The uncoated cutting tool inserts were composed of 94wt.% tungsten carbide bonded with a 6wt.% cobalt binder. The coated cutting tools were supplied with a superlattice coating composed of up tp 1000 deposited layers to form a coating thickness of 3-4µm. The maximum feed rate was used in these experiments was set at 0.2 mm per revolution of the machine tool spindle. The tools were initially sharp and were not previously used in any other applications. The coatings were developed for dry machining operations and research on the thin film coatings are described in references [4-10]. The initial cutting speed used for the experiments was set at 28 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 8688-3685 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 using multilayer nanocrystalline coatings on cutting tools [15].

3. Experimental work

Over 200 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.

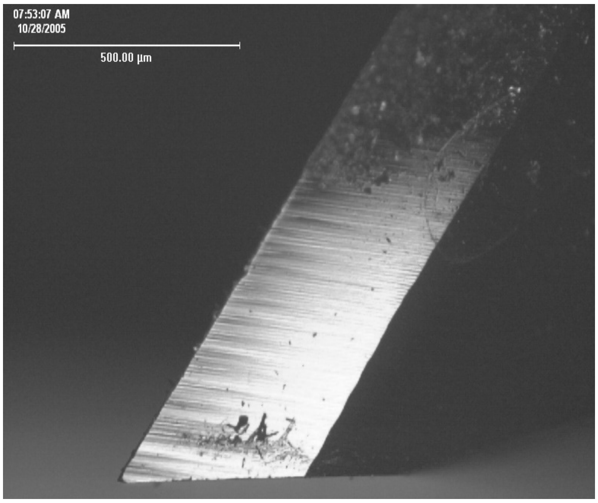

Fig. 2. New coated tool showing sharp cutting edge

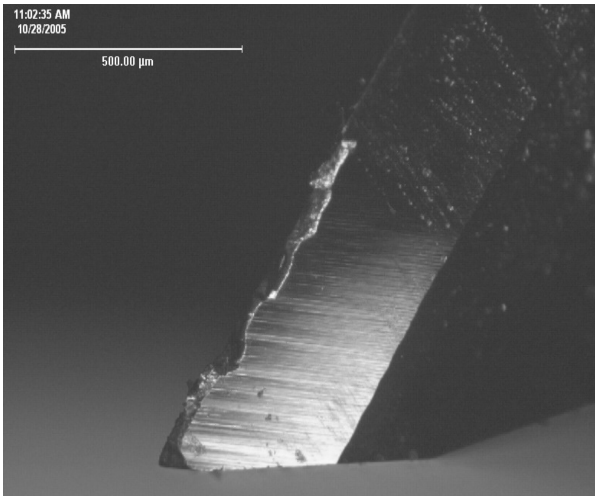

Fig. 3. Worn coated tool edge

It is 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 engaged during machining, 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 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 mechanism 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. TiN coated WC-Co $VT^{0.3} = 33$
2. $Ti_{0.46}Al_{0.54}N$ coated WC-Co $VT^{0.35} = 38$
3. $Ti_{0.44}Al_{0.53}Cr_{0.03}N$ coated WC-Co $VT^{0.37} = 43$
4. $Ti_{0.43}Al_{0.52}Cr_{0.03}Y_{0.02}N$ coated WC-Co $VT^{0.39} = 50$

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 a low tool life compared to more commonly used engineering steels.

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. Tool life equations related to finish machining operations are currently in progress and will be reported on in a subsequent paper.

Table 1.
Cutting tool life experimental results for coated tools

Cutting Tool	Spindle speed (m/min)	Cutting tool life (minutes/seconds)
	30	91.2s
TiN coated WC-Co	50	16.54s
	70	6s
	30	144s
$Ti_{0.46}Al_{0.54}N$ coated WC-Co	50	28s
	70	11.2s
	30	156s
$Ti_{0.44}Al_{0.53}Cr_{0.03}N$ coated WC-Co	50	39s
	70	17s
	30	236.4s
$Ti_{0.43}Al_{0.52}Cr_{0.03}Y_{0.02}N$ coated WC-Co	50	64.5s
	70	28.1s

4. Discussion

Coated cutting 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 reductions in dissolution wear. As a result of machining, large portions of the tool are retained because there are mechanically robust regions. This is not the case for uncoated tools as noted in a previous study because high temperatures are generated that encourages dissolution wear. This leads to the formation of mechanically weaker regions, which become prone to chipping.

The incorporation of 3 mol% CrN in $Ti_{1-x}Al_xN$ alloys did not change film hardness or microstructure [7]. 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 has showed [7] that the start 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 pathway 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 oxidation with cation out-diffusion, giving rise to void formation and under-dense columnar 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. In 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 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 thin film. The machining characteristics of coated cutting tools did have some benefit to extending the life of the cutting tool when machining M42 tool steel. The benefits associated with using titanium based coated tools was further enhanced by using a superlattice layer thin film cutting tool. This ensured that thermal fatigue cracking of the coating did not interfere with the normal operation of the cutting insert when machining M42 tool steel.

5. Conclusion

During the machining of hardened M42 tool steel, TiAlCrYN coatings are effective at reducing tool wear due to chipping and tend to improve tool life. This was observed during rough machining operations and has not yet been observed in finish machining opeartions.

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