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Wear performance of different PVD coatings during hard wet end milling of H13 tool steel

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ABSTRACT

Wear performance of end mill tools with different PVD coatings has been studied under the condition of hard wet machining of H13 tool steel. It was shown that tool life of the coated tools could be improved by around 100% due to the application of AlCrN–TiAlN bilayer as compared to AlTiN monolayer PVD coating. Failure mechanisms of the coated tools were evaluated by SEM. The micro-mechanical characteristics of the coated tools were studied. It was shown that to achieve a better tool life under heavy loaded hard wet end milling conditions the coating should possess an improved fatigue fracture resistance combined with stronger load support shown by a higher H^3/E_r^2 ratio. In this study we discuss the use of nanoindentation, nano-impact and micro-scratch testing to predict the wear behaviour of studied coated tools.

1. Introduction

Moulds and dies are increasingly demanded in different engineering fields. The hardened tool steels are widely used in the fabrication of moulds and dies due to their high performance under operating conditions. However, mould and die machining is a time consuming and costly process [1,2]. Traditionally electrical discharge machining (EDM) and grinding processes are mainly used to manufacture the moulds. However, the material removal rate of EDM is relatively low and both methods can create surface damaged layers [3]. Furthermore, the drawbacks above result in high manufacturing cost. In addition, the moulds and dies usually contain various types of 3-D freeform face at the cavity and core, which are difficult to machine with EDM and grinding processes. Therefore, there is a need to develop alternative technologies to overcome these drawbacks [3]. Lately, direct milling of H13 in hardened state has been started to be used as a competitive finish and semi-finish process [4–7]. This is due to the development of tool materials capable of milling hardened tool steels [8]. Machining of dies and moulds in hardened state could be cheaper and faster than traditional methods [9,10]. It also has other advantages, such as elimination of part distortion caused by heat treatment [11,12].

AISI H13 tool steel has combination of high-temperature strength and wear resistance [13]. It has been widely applied in extrusion mandrels; hot forging and pressure die casting. However, high performance machining of dies and moulds made of H13 tool steel in a hardened state is a challenge. Under high performance machining conditions of the hardened tool steel, the mechanical characteristics of the cutting tool are strongly diminished by the elevated temperature in the cutting zone [14]. The tool wear rates grow dramatically, resulting in the short tool life and impaired surface integrity [14]. Therefore, optimization of machining operations is fundamental when low production costs of dies and moulds are essential. It could result in enhancement of machining efficiency. One of the most efficient ways to improve the efficiency of the machining process is an application of surface engineered tooling, in particular carbide tools with PVD coatings.

Coatings used for surface engineering of cutting tools play substantial role in the recent advancement in high performance machining of hard to cut materials, specifically hardened H13 tool steel. End milling of 3-D parts is a most frequently used operation. Wet machining conditions are most widely used on production floor due to a variety of reasons. With introduction of hard to cut materials to manufacturing practice cutting tool requires efficient protection from thermal and mechanical loads in the cutting zone [15–18]. This is especially important for wet conditions where thermal fatigue is a major contributing factor to the tool life. By means of the coatings applications overall wear resistance of cutting tools and, what is even more important, productivity of the machining process could be significantly improved [19,20]. Thus, it is of significant importance to study coated tool life and evaluate failure mechanisms for these severe machining conditions. A number of PVD coatings have been developed for end milling of hardened steels [21–23]. Most promising for this application are AlTiN [24] with high fatigue fracture resistance [25,26] and AlCrN-based coatings [27,28] with high hardness, improved micro-mechanical properties [28–30] and reduced thermal conductivity [27]. The goal of this paper is twofold: 1) to identify failure mechanisms (wear and chipping) for end mills

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Table 1
Cutting conditions.

Machine	Tool	Workpiece material and hardness	Cutting parameters				
			Speed, m/min	Feed, mm/min	Depth of cut, mm	Width of cut, mm	Coolant
Makino MC56-5XA milling centre	Kennametal carbide high feed end mills KMDA 1000A6ANA, D = 10 mm	H13, hardness 46–48	160	15,275	0.3	4	Wet machining

with advanced coatings under conditions of wet high performance machining of hardened H13 tool steel and 2) to identify which set of micro-mechanical characteristics is responsible for wear behaviour of cutting tools under heavy loaded conditions of interrupted cutting which is typical for end milling of hardened H13. In this way it would be possible to justify coatings selection for specific applications.

2. Experimental

The hard coatings investigated in this research were synthesized using Oerlikon Balzers Rapid Coating System (RCS) in the cathodic arc ion platting mode [30]. The following coatings were employed: AlCrN-based [31] coatings (AlCrN monolayer [32] and AlCrN–TiAlN bilayer [33]) as well as AlTiN PVD coating. AlCrN–TiAlN bilayer coating has an AlCrN functional layer deposited on the TiAlN supporting layer. TiAlN layer endures good adhesion and mechanical strength whereas AlCrN layer exhibits good oxidation resistance, hot hardness and low thermal conductivity [33]. A pure reactive nitrogen atmosphere was used during the deposition of all the coatings. The pressure during deposition was 3.5 Pa and the substrate temperature was held at 450 °C. With the exception of the AlN coating, the DC-substrate bias voltage was held at −40 V during the deposition. Due to the insulating character of AlN, for this coating a unipolar pulsed bias voltage of −40 V and 10 kHz was applied. Targets were operated with ~3.5 kW. The thicknesses of the coatings were in the range of 1.5 to 3.6 μm [31]. The micro-mechanical characteristics of the coatings were measured on WC–Co substrates using a Micro Materials NanoTest system. Nanoindentation was performed in a load controlled mode with a Berkovich diamond indenter calibrated for load, displacement, frame compliance and indenter shape according to an ISO14577-4 procedure. The area function for the indenter was determined by indentations to 0.5–500 mN into a fused silica reference sample. For the nanoindentation of the coatings, the peak load was 40 mN and 40 indentations were performed for each coating. This load was chosen to minimize any influence of surface roughness on the data whilst ensuring that the indentation contact depth was under 1/10 film thickness so that a coating-only (load-invariant) hardness could be measured in combination with coating-dominated elastic modulus. Nanoindentation was performed at room temperature. Nano-impact testing was performed with a NanoTest fitted with a cube corner indenter as an impact probe. The indenter was accelerated from 12 μm above the coating surface with 20 mN coil force to produce an impact every 4 s for a total test duration of 300 s. Tests were performed with 20 and 30 mN coil force. The tests were repeated 10 times at both forces. The coatings' nano-impact fatigue fracture resistance was assessed by the final measured impact depth and confirmed by microscopic analysis of impact craters. Four repeat micro-scratch tests to 5 N were run for each coating as three-scan topography-scratch-topography experiments using a $R = 25$ μm probe. In the scratch scan after 250 μm the load was linearly ramped at 150 mN/s to reach a peak load of 5 N at 420 μm and then kept constant at this value until the end of the scratch track after 600 μm. Analysis of the on-load depth and residual depth data after correction for frame compliance, topography and slope allows true depth data to be displayed and the location of first coating failure to be determined.

Cutting tests were performed according to the requirements of the ISO 8688. Machining parameters used are shown in Table 1. A tool dynamometer (9255B, Kistler) was used to measure the cutting forces. Comprehensive data on wear performance including flank wear, rake wear, average cutting forces and chipping intensity was reported. The coated tool wear and chipping was measured using a Mitutoyo optical microscope and a magnification of 30×. The worn end mills with a collet were fitted in a special holder for measurement. The accuracy of measurement was ±5 microns. End mills were coated by suppliers to provide the coatings used for testing. The coatings were pre-examined for surface irregularities using optical and scanning electron microscopy. Wear behaviour of worn tools was analyzed using SEM/EDS. EDS analysis was employed as well for studying chemical composition of the coatings.

A Bruker D8 DISCOVER with DAVINCI.DESIGN diffractometer with a CoKα tube was used to perform XRD analysis and identify the phases formed. 2D frames were collected with DIFFRAC. Measurement Centre Version 3.0 software was integrated to 1D using DIFFRAC.EVA Version 4.0 (all from Bruker-AXS). A pattern search/match was then executed using the integrated ICDD PDF-2 2011 powder database.

3. Results

Table 2 shows the chemical, phase composition [31–33], thickness and surface roughness of the coatings tested.

XRD data on coating tested is presented in Fig. 1. The data shown confirms information on phase composition of the coatings presented in Table 2.

Table 3 shows the micro-mechanical characteristics of the coatings studied measured by nanoindentation. The hardness of the coatings was similar within a range of 29–33 GPa. Plasticity index (= plastic work/total work in indentation) is higher and correspondingly H/E ratio is lower for AlTiN coating indicating its better ductility. However, the load bearing support (H^3/E_r^2 ratio) is noticeably higher for AlCrN–TiAlN bilayer coating. Impact fatigue fracture resistance at 30 mN is shown in Fig. 2. Imprints are very small and hardly visible by SEM at

Table 2
Characteristics of the coatings tested.

Coating	Architecture	Chemical composition (EDX data)	Phase composition [31]	Thickness, μm	Surface roughness, μm
AlTiN	Monolayer [24,26]	$Al_{67}Ti_{33}N$	Fcc $Al_{1-x}Ti_xN$	1.3 ± 0.2	0.08 ± 0.02
Alnova	Monolayer [32]	$Al_{70}Cr_{30}N$	Fcc $Al_{1-x}Cr_xN$	3.6 ± 0.2	0.06 ± 0.02
Aldura	Bi-layer with TiAlN supporting layer [33]	$Al_{65}Cr_{35}N$	Fcc $Al_{1-x}Cr_xN$	2.0 ± 0.2 Outer layer 1.1 ± 0.2	0.013 ± 0.02