Tribology International 53 (2012) 115–123

Contents lists available at SciVerse ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Comparative wear behavior studies of coated inserts during milling of NiCrMoV steel

S. Oomen-Hurst, M.D. Abad, M. Khanna, S.C. Veldhuis*

Department of Mechanical Engineering, McMaster University, Hamilton, ON, Canada

ARTICLE INFO

Article history:
Received 2 December 2011
Received in revised form
16 February 2012
Accepted 22 February 2012
Available online 8 March 2012

Keywords:
NiCrMoV steel
Cutting tool materials
Tool wear
Raman analysis

ABSTRACT

This paper contains the results of a tool wear study conducted to compare the performance of three coated carbide inserts during milling of NiCrMoV steel. Wear behavior of CVD TiCN/Al_2O_3/TiN and PVD TiAlN/Al_2O_3/ZrN multilayer coatings was compared on the milling inserts with different designs (various chip breaker groove angles). To understand the wear process, detailed XRD and SEM/EDS analysis combined with Raman spectroscopy of the worn inserts have been performed. It was shown that the high chemical and thermal stability of the TiAlN layer in the PVD coating provides superior protection for the tool substrate after the outer coating layers have detached.

1. Introduction

The NiCrMoV steels are in the group of ultra-high strength low alloy martensitic steels and combine good hardenability with high ductility, high strength, high fatigue strength and creep resistance. Nowadays, the use of this kind of steel for aircraft and automotive applications has increased noticeably [1]. Many studies have been carried out with this kind of steel in order to see its structure and properties [1–3], and specially the fretting fatigue response [4,5]. Problems arise in machining of this steel due to its high hardness and toughness as well as its inhomogeneous microstructure, which contributes to accelerated tool wear and chipping. Despite having critical and wide ranging applications, the material is relatively new and few studies have been done to study its machinability [6,7].

Cemented carbide has been the dominant cutting tool material since it was invented in 1923 [8], and the use of wear-resistant hard coatings have dramatically improved their performance since 1971. There are two well established vapor processing routes for coating, namely chemical vapor deposition (CVD), which was the first to appear, and physical vapor deposition (PVD). TiC, TiN and Al_2O_3 were the first materials to be used for coating inserts by CVD, and showed excellent results due to their built up edge resistance, wear resistance and heat resistance, respectively. Varying combinations of these coating materials also showed considerable improvements in tool life. Years later, the PVD process offered unique advantages over CVD due to lower deposition temperatures ($\sim$500 °C as opposite to $\sim$800–1000 °C in CVD). TiAlN, due to its excellent speed capability and heat resistance, was one of the most used coatings for cutting tools deposited by PVD. Al_2O_3 coatings are typical obtained using CVD processes, and their mechanical properties have been substantially improved during the last decade by enhanced bonding, phase control and microstructural refinement [9]. Depositing this electrically insulating, oxide coating by PVD has been challenging, since achieving the correct coating structure has proven quite difficult [10]. However, it is possible to find information on the wear of Al_2O_3 coatings prepared by PVD [11]. Currently, there are some multilayer coatings that are produced by duplex processing techniques which combine both CVD and PVD methods [12,13]. These grades are excellent for machining most materials including cast irons, steels, stainless steels, and some superalloys/exotics in turning, boring, and milling operations ranging from heavy roughing to high speed finishing [14].

The design of cutting edge geometry and its influence on machining performance have been research topics in metal cutting for a long time [15–17]. Following Dogra et al. [17], the tool chip breaker geometry influences the specific cutting energy behavior of the tool. Even small modifications on cutting edge geometry affect the cutting force levels and specific cutting energy values.

In the presented study three different cemented carbide cutting tools have been used to machine NiCrMoV steel. They were: an insert with TiCN/Al_2O_3/TiN CVD coating (1), and two TiAlN/Al_2O_3/TiN PVD coated inserts with different chip breaker angles of 10° (2) and 16° (3). An exhaustive study by means of

* Corresponding author.
E-mail address: veldhu@mcmaster.ca (S.C. Veldhuis).

0301-679X/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.triboint.2012.02.020

x-ray diffraction (XRD), scanning electron microscopy (SEM), energy dispersive x-ray spectroscopy (EDX), and Raman spectroscopy have been used to understand the wear performance and the behavior of different tools.

2. Material and methods

2.1. Workpiece material and cutting tools

All experiments were performed with workpieces composed of NiCrMoV steel (chemical composition in weight %; Ni 2.8–3.0, Cr 1.40–1.70, Mo 0.30–0.45, V < 0.15, C 0.26–0.32, Cu < 0.12, Si < 0.07, Mn < 0.04, Al < 0.010, As 0.010, Sn < 0.010, P < 0.007, S < 0.005, Sb < 0.005, Fe balance). Three different inserts provided by Walter (Walter AG, Tübingen-Germany) were selected to compare machining performance and are summarized in Table 1. The WKP (C1) insert is a CVD coated insert (thickness ~10 μm) and the WSP (C2) and WSM (C3) inserts are PVD coated (thickness ~4 μm) [18]. C1 had: (i) an inner TiCN coated layer featuring thermal stability and wear resistance, (ii) a middle coated layer of Al_2O_3 featuring thermal stability and wear resistance, and (iii) an outer coated layer of TiN featuring low friction and welding resistance, and as a wear-indicating layer [9]. C2 and C3 had: (i) an inner layer of TiAlN, (ii) a middle layer of aluminum oxide, and (iii) an outer layer of ZrN. The geometries of the inserts are identical except for the chip breaker groove which, for the inserts being studied, also affects the rake angle. The C1 and C3 inserts have a more aggressive (positive) groove angle compared to the C2 insert. Further geometry specifications are shown in Table 1 [18].

2.2. Material characterization.

The crystalline phases of the coated inserts were examined by XRD using a Bruker Smart6000 CCD detector on a Bruker 3-circle D8 goniometer and a Rigaku Cu K_α RU200 rotating anode (50 kV/90 mA) with cross-coupled parallel focusing mirrors. Five 300 s frames of 360° φ-rotation at increasing detector swing angles were integrated into a 1D diffraction pattern for the analysis of each sample. A Renishaw Invia Laser Raman spectrometer was used for the characterization. The excitation wavelength used was a 514 nm, Ar^+ ion, 20 mW laser. An incident power of 2–3 mW was used on the sample in a 2 μm diameter spot through a standard ×20 microscope objective. The spectra were collected with a 30 s data point acquisition time, a spectral range of 100–1200 cm^{-1} and a spectral resolution of 2 cm^{-1}. Flank wear measurement and general observation by optical microscopy (OM) of tool wear and workpiece were done using a Mitutoyo tool-maker's microscope. The microscope was equipped with an optical crosshair and micrometer table adjustments, and lit using adjustable fiber optic direct lighting. Microstructure investigations of the cutting tools were carried out by means of SEM and EDX using a Phillips SEM 515 microscope.

2.3. Cutting parameters and procedure

Two characteristics of cutting were chosen to be studied to gauge the performance of the three inserts being tested; flank wear and cutting forces. Four trials of each insert type were completed to obtain a small sample set, for a total of 12 cutting tests. The testing was done on a Makino 40 hp 5-axis CNC mill and a 1¼″ single flute tool was used for all tests. The cutting parameters used for the tests are summarized in Table 2. Partial tool engagement (shoulder milling) was used for testing. A pass refers to a single cutting pass on the workpiece. A cutting pass in this case is 255 mm in length, 3 mm wide and 3 mm in depth. Therefore, a single cutting pass represents 2295 mm^3 of material removed. A single cutting pass required approximately 1 min 30 s to complete.

2.3.1. Flank wear

Flank wear was selected to characterize the tool life of the inserts. Repeated cutting passes were completed up to a flank wear of 300 μm, which is a widely accepted and used standard for failure criteria of milling tools.

2.3.2. Cutting forces

Cutting forces were recorded as a supplement to measurements of flank wear. A Kistler 3-axis dynamometer was used for force collection. It is also useful as an independent indicator of performance as it can be used to benchmark the average cutting forces which can be used to compare the efficiency of each insert type. Three axis of force were recorded during cutting, *X*, *Y*, and *Z* directions. *X* corresponds to the 'cutting force', which acts in the direction of the movement of the cutting tool, *Y* to the 'side force', which acts perpendicular to the cutting force and *Z* to the 'thrust force' which acts parallel to the axis of the tool.

3. Results

3.1. Material characterization

The microstructure of the NiCrMoV steel is shown in Fig. 1(a) by OM and Fig. 1(b) by SEM at different magnifications. The optical image of Fig. 1(a) shows a fine grain, needle-like structure

Table 2
Cutting parameters used in testing.

	Testing process
Type	Milling (interrupted cutting)
Cutting speed	75–90 Surface m/min
Cutting tool	1 ¼″ single flute end mill
Radial DOC	3 mm
Axial DOC	3 mm
Chip load	0.15 mm/tooth
Feed	200 mm/min
Coolant type	Semi-synthetic, Flood

Table 1
Comparison of the three cutting insert types [18].

Cutting tools	Description			
	Walter product ID	ADMT1204 08R-F56	ADMT1204 08R-D56	ADMT1204 08R-F56
	Grade	WKP 35	WSP 45	WSM 35
	Coating type	TiCN/Al_2O_3/TiN	TiAlN/Al_2O_3/ZrN	TiAlN/Al_2O_3/ZrN
	Coating method	CVD	PVD	PVD
	Chip breaker angle	16°	10°	16°
	Designation	C1	C2	C3