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Journal of Materials Processing Technology 170 (2005) 121–126

Journal of Materials Processing Technology

www.elsevier.com/locate/jmatprotec

A comparative study on cutting tool performance in end milling of AISI D3 tool steel

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Received 10 December 2003; received in revised form 15 April 2005; accepted 19 April 2005

Abstract

In this work, high speed end milling of AISI D3 cold-work tool steel hardened to 35 HRC was investigated using coated carbide, coated cermet, alumina (Al_2O_3) based mixed ceramic and cubic boron nitride (CBN) cutting tools. Performances of the cutting tools were compared with respect to tool life and surface finish of the workpiece. The results were also discussed in terms of tool cost. The best cutting performance was obtained with CBN tool. TiCN mixed Al_2O_3 ceramic tool also proved to be suitable for high speed end milling of AISI D3 steel with 35 HRC. Coated carbide and coated cermet tools, on the other hand, did not exhibit good performance in high speed cutting operations. They should rather be used at low or moderate cutting speeds.

Keywords: High speed end milling; Tool steels; Flank wear; Surface roughness

1. Introduction

High speed machining (HSM) of tool steels in their hardened state reduces the machining costs compared with the traditional manufacturing route in which workpiece is first machined in annealed state, then hardening, grinding/electrical discharge machining and finally hand finishing operations are carried out in sequence [1]. HSM usually results in a very good surface finish so that the need for final finishing operations is considerably reduced [2].

The range of cutting tools for the HSM of hardened steels includes cemented carbides, cermets, Al_2O_3 based ceramics and CBN. Polycrystalline diamond (PCD) is not suitable for steel cutting as it reacts with iron, and also diamond turns into graphite above ∼750 °C, which can be easily attained in HSM operations [3].

Cemented carbide is the most commonly used cutting tool material for the machining of steels. Despite their high toughness, cemented carbide tools have low hardness values, which restrict their use in the HSM of hardened steels. In order to improve the machining performance of carbide cutting tools, they are usually coated with single or multi-layers of hard, wear resistant TiN, TiCN and TiAlN coatings by chemical vapour deposition (CVD) or physical vapour deposition (PVD) techniques [4–9]. TiN/TiCN coated carbide tools are suitable for steels with less than 42 HRC, while TiAlN coatings are used for materials with 42 HRC and over [10]. An investigation on machining of AISI D2 tool steel having a hardness of 60 HRC with TiAlN and TiCN coated carbide end mills revealed that the wear on the TiAlN coated tool was less than half of that observed on the tool with TiCN coating [11]. In another work it was shown that TiAlN coated carbide tool exhibited two to five times longer tool life (depending on cutting speed) than TiCN + Al_2O_3 + TiN coated carbide and uncoated cermet tools in high speed end milling of AISI D2 with 58 HRC, while the latter two showed a similar performance [12].

Cermet tools have high wear resistance, high chemical stability and hot hardness, but unfortunately have a lower degree of toughness compared to carbides [13], which renders them more suitable for finishing cuts. Increasing the binder content of cermets improves their performance in HSM operations [14]. It was reported that PVD TiZrN and TiCN coatings improved tool life of cermets in the machining of tempered

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doi:10.1016/j.jmatprotec.2005.04.111

steel [15] and the (Ti,Al)N-coated cermet tools demonstrated significantly enhanced wear resistance [16]. Kopac et al. [17] report that PVD TiN coatings on cermets have a positive influence on the surface finish when turning cold formed C15 E4 (ISO) steel bars.

Al_2O_3 and Si_3N_4 ceramics are promising materials for HSM applications. However, Si_3N_4 is not suitable for the machining of steels because of its chemical incompatibility with steel at elevated temperatures [18]. Al_2O_3 can be used in steel cutting, but it is very brittle. Therefore, Al_2O_3 based ceramic cutting tools are reinforced with TiC, TiN, ZrO_2, (W,Ti)C, Ti(C,N), SiC_p, SiC_w, TiB_2 additions [19–22]. A recent survey indicated that Ti[C, N] mixed Al_2O_3 ceramic and zirconia toughened Al_2O_3 ceramic tools both exhibited good performance in machining of hardened EN 24 steel (45 HRC) [23]. Another research showed that the tool life of Al_2O_3/TiC composite inserts in face milling of hardened carbon steel was higher when free carbon was incorporated into the ceramic matrix [24].

CBN tools generally have greater wear resistance than other tool materials due to their high degree of hardness. They have successfully been used in the high speed milling of hardened tool steels [12,25–29]. Despite their superior tool life, the cost of CBN cutting tools restricts their more widespread use in industry. Cutting performance of CBN tools is highly affected by the CBN content in the tool. In contrast to common expectation, low CBN content tool (50–70 vol.% CBN) with a ceramic binder phase based on titanium nitride (TiN) performs better than high CBN content tool (∼90 vol.% CBN) with a metallic binder despite the high hardness and toughness of the latter. For example, in finish hard turning of AISI 52100 steel (63 HRC), it was reported that the flank wear on the low CBN content tool was nearly half of that on the high CBN content tool under the same cutting conditions ($V_c = 120$ m/min, $f = 12.5$ µm/rev, $a_p = 50$ µm) [30]. There have been many explanations toward this interesting phenomenon [31–35]. Chou et al. [30] explain this in terms of high affinity of metallic binder of high CBN content tool to steel, as a result of which more severe adhesion occurs and consequently, CBN particles are plucked out due to loss of binder resulting in increased abrasive wear.

In this research, the performance of different cutting tool materials and coatings in high speed end milling of hardened AISI D3 steel (∼35 HRC) were investigated. AISI D3 is a cold-work tool steel with high carbon and chromium content (2% C, ∼12% Cr) and used in applications such as cold extrusion dies, blanking dies, die bases (impact extrusion), powder metal tooling, ceramic mouldings, cold punches, etc. Cutting tool performance was evaluated according to flank wear of the tool and surface finish of the workpiece.

2. Experimental work

Five different commercially available cutting tools were used in this research, the details of which are given in Table 1.

Table 1
Details of the cutting tools used in this study

Tools	Details
(1) TiCN coated cemented carbide (ISO P25–P50)	Coating process: PVD; coating thickness: ∼7 µm
(2) TiCN + TiAlN coated cemented carbide (ISO P15–P35)	Coating process: CVD; coating thickness: ∼10 µm; outer layer: TiAlN
(3) TiAlN coated cermet (ISO P25)	Coating process: PVD; coating thickness: ∼5 µm
(4) Al_2O_3 based ceramic (ISO P10)	TiCN mixed Al_2O_3 ceramic
(5) Cubic boron nitride (CBN) ISO (P10–P20)	Low CBN content tool with ceramic binder

Cutting tools used throughout the milling experiments were in the form of indexable inserts. The inserts were triangular with 16 mm edge length, 3 mm thickness and 25° × 0.1 mm chamfered cutting edge. The inserts were screw-clamped to an end milling tool holder with a 35 mm nominal diameter, which had the provision to hold two inserts, see Fig. 1. However, only one insert was used in milling tests in order to keep the removed volume of workpiece material at minimum. Combination of the insert and the tool holder resulted in a 0° axial rake angle, 0° radial rake angle and an 11° clearance angle. The overhang of the tools was 60 mm. Workpiece was a rectangular block of through hardened AISI D3 steel with dimensions 300 mm × 200 mm × 40 mm and a hardness of 35 HRC. The milling tests were conducted on a Mazak VTC-20B vertical machining centre. Flank wear was measured with Scherr Tumico 98/0001 toolmaker's microscope. Tool life was evaluated according to a maximum flank wear of 0.3 mm. Workpiece surface roughness R_a was measured using Mitutoyo MetuSurf 310 equipment (0.8 mm cut-off length).

Milling tests were carried out in dry conditions with a cutting speed in the range $V_c = 100$–200 m/min, a feed rate $f = 0.1$ mm/tooth, an axial depth of cut $a_p = 0.4$ mm and a radial depth of cut $a_r = 30$ mm. During milling tests, the cutter

Fig. 1. End milling tool holder used in this study.