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Experimental investigation on hard milling of high strength steel using PVD-AlTiN coated cemented carbide tool

Qinglong An [a,*], Changying Wang [a], Jinyang Xu [a], Pulin Liu [b], Ming Chen [a]

[a] School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China
[b] Shanghai Aerospace Precision Machinery Research Institute, Shanghai 200240, PR China

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ABSTRACT

High strength steel 30Cr3SiNiMoVA (30Cr3) is usually used to manufacture the key parts in aviation industry owing to its outstanding mechanical properties. However, 30Cr3 has poor machinability due to its high strength and high hardness. Hard milling is an efficient way in machining high strength steels. This paper investigated hard milling of 30Cr3 using a PVD-AlTiN coated cemented carbide tool with regard to cutting forces, surface roughness, chip formation and tool wear, respectively. The experimental results indicated that the increase of cutting speed from 70 to 110 m/min leads to direct reduction of cutting forces and improvement of surface finish, while both feed rate and depth of cut have negative effect on surface finish. The occurrence of oxidation on chip surfaces under high cutting temperature makes the chips show different colors which are strongly influenced by cutting speed. Saw-toothed chips were observed with the occurrence of the thermo-plastic instability within the primary shear zone. Micro-chipping and coating peeling were confirmed to be the primary tool failure modes. Serious abrasion wear and adhesive wear with some oxidative wear were confimed to be the main wear mode in hard milling of 30Cr3.

1. Introduction

Demand for high strength steel 30Cr3SiNiMoVA (30Cr3) is growing in the aerospace and aviation industry due to its superior mechanical properties, such as high strength, strong corrosion resistance, and high hardness. High strength steel contains different amounts of various alloying elements such as Si, Mo, and Ni. Those alloying elements provide solid solution strengthening, resulting in the formation of numerous martensites with high strength and high hardness. 30Cr3 can achieve an ultimate tensile strength of 1800 MPa and a high hardness of HRC 50–55 after an appropriate quenching process.

Although 30Cr3 has excellent mechanical properties, it is a typical difficult-to-cut material. The poor machinability of 30Cr3 can be summarized as follows. (1) Serious tool wear: 30Cr not only has high tensile strength, but also has good toughness. During the machining process, the contact length of the tool–chip interface is small and the stress and heat are concentrated in the cutting area which easily lead to crater wear and flank wear and in turn tool life reduces. (2) High cutting forces: Ultra-high shear strength leads to the direct rise of cutting forces and high level tool vibration in the machining process. Under the same cutting condition, the main cutting force is 120%–150% higher than that for 45 steel [1,2]. (3) High cutting temperature: The thermal conductivity of AISI 1045 steel is 50.2 W $(m\cdot k)^{-1}$, while the thermal conductivity of 30Cr3 is only 29.3 W $(m\cdot k)^{-1}$ [3]. Low heat conduction of 30Cr3 may lead to a high cutting temperature in the cutting zone during the machining process and accelerate tool wear [4].

Traditionally, grinding processes are always the final finishing operations of hardened steels. In recent years, hard cutting operations have been considered an attractive alternative to traditional finish grinding operations [5,6]. Firstly, hard cutting can achieve the same surface quality as grinding processes when appropriate cutting parameters are employed [7]. Secondly, hard cutting operations have become a profitable alternative instead of grinding for hardened steel, because it can reduce manufacturing costs, improve production efficiency and eliminate the environmental impact of coolant [8,9]. However, the reliability of hard cutting processes is often unpredictable [10]. The main factors affecting the reliability of hard machining are surface integrity and tool wear.

Surface roughness is one of the important indicators of surface integrity and cutting forces are the indispensable variables to monitor the hard cutting process. Numerous research works have been done with regard to surface roughness and cutting forces in hard machining. Paulo Davim and Figueira [11] investigated the machinability of cold work tool steel with ceramic tools using statistical techniques. The results showed that it is possible to obtain a surface roughness ($Ra < 0.8$ μm) with appropriate cutting parameters and the primary factors affecting the surface roughness were tool wear and feed rate. Ebrahimi and Moshksar [12] studied the machinability in hard turning of microalloyed and quenched-tempered steels at different cutting

* Corresponding author at: Building B-327, School of Mechanical Engineering, Shaihai Jiao Tong University (No. 800 Dongchuan Road, Minhang District), Shanghai 200240, PR China. Tel.: +86 34206824.
E-mail address: qlan@sjtu.edu.cn (Q. An).

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conditions. It was found that each of the materials showed high cutting forces at low cutting speeds ascribed to the low temperature and formation of the build-up edges on the contact zone. According to some other studies [13,14], better surface quality and lower cutting forces could be obtained with higher cutting speeds, but machining at too high of a speed may accelerate tool wear.

In the machining process, tool wear is an important factor directly affecting the surface quality of the machined parts and an important parameter in evaluating the performance of the cutting tools [15]. The exploring of tool wear mechanisms in hard machining is beneficial to understand the metal removal, revealing important friction phenomena occurring during the cutting process, and determining optimal cutting conditions [7,16]. Conventional cutting tools usually suffer rapid wear rates because of high temperature and strong adhesive wear between the tool and the work material during the machining process of hardened steels [17]. In order to tackle these problems, coated tools are applied to reduce tool wear and improve cutting condition [9,18]. It is reported that PVD (Ti, Al)N-TiN coatings outperform CVD Ti(C, N)–Al_2O_3 coatings at the same cutting condition for machining high strength steel 30CrMnSiNi2A [19]. Halil Çalışkan et al. [20] investigated the influence of three different coatings (nanolayer AlTiN/TiN, commercial TiN/TiAlN and multilayer nanocomposite TiAlSiN/TiSiN/TiAlN) on the cutting forces and surface roughness during face milling of AISI D2 cold work tool steel. It was found that the coating has no significant effect on cutting forces and surface roughness. Chinchanikar and Choudhury [21] carried out experiments of hard turning of hardened AISI 4340 steel with coated carbide cemented inserts. They observed that PVD coated inserts could achieve better surface roughness, indicated by the polished and bright back surface of the chip, compared to the rough surface showing some parallel strips with CVD coated inserts. Paulo Davim and Figueira [11] found that the tool wear is highly influenced by the cutting velocity (54.7%) followed by cutting time (13.4%) in hard turning of cold work tool steel with ceramic tools.

This present work concerns the fundamental cutting characteristics of hard milling of high strength steel 30Cr3 with a PVD-AlTiN coated tool. The cutting force, surface roughness, chip morphology and tool wear were experimentally investigated. The objective of the present paper is to explore the hard milling mechanisms of high strength steels.

2. Material and methods

2.1. Workpiece material

A 30Cr3 block with the dimensions of 100 mm × 100 mm × 50 mm was used in the milling experiments. Through improving the chemical composition, applying advanced smelting and heat treatment processes, 30Cr3 has outstanding mechanical properties. The chemical composition of 30Cr3 is shown in Table 1. The content of alloying elements Cr, Ni, Mn and Mo is beneficial for the improvement of the strength and hardness of 30Cr3. Fig. 1 shows the metallographic microstructure of 30Cr3 after a heat treatment of 15 min normalizing at 930 °C, 15 min oil quenching at 910 °C and 2 h tempering at 250 °C. As shown in Fig. 1, various needle-shaped martensites were observed in the material matrix. The presence of these martensites makes the strength and hardness of 30Cr3 higher than most other materials. In addition, these martensites were surrounded by several small black particles which were carbide materials obtained after quenching process. These carbide materials usually have small grain size effect which could improve the mechanical properties of 30Cr3. Table 2 presents the comparison of room temperature mechanical properties of 30Cr3 after oil quenching at 900 °C, compared with Inconel718 and Ti-6Al-4V [22]. It is evident that 30Cr3 has the highest tensile strength and hardness. On the contrary, these martensites with high strength and high hardness cause severe mechanical and thermal shock to the cutting tool, which would lead to the worst machinability compared with Inconel718 and Ti-6Al-4V.

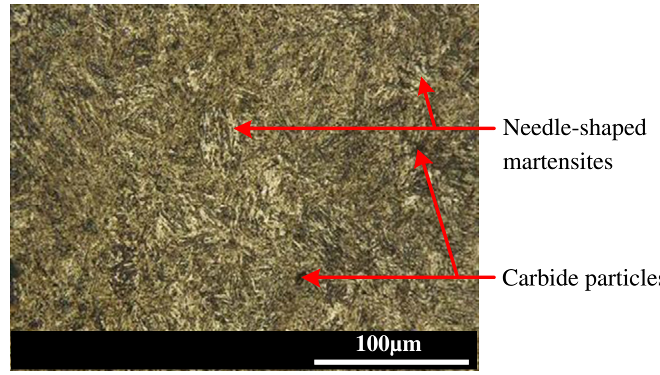

Fig. 1. Metallographic microstructure of 30Cr3 (after 15 min normalizing at 930 °C, 15 min oil quenching at 910 °C and 2 h tempering at 250 °C).

Table 1
Chemical composition of high strength steel 30Cr3 (wt.%).

Element	C	Cr	Si	Ni	Mn	Mo	V	Fe
Content	0.34	3.2	1.2	1.2	0.8	0.8	0.15	Balance

2.2. Cutting tool

Coated cemented carbide end mill type JABRO-JS522 from Seco Tools was used in the experiments. The tool edges of the end mill experienced special strengthening treatment which can greatly meet the cutting performance requirements of high-speed hard milling of high strength steels. Geometry parameters of the end mill used in the experiments were listed in Table 3. The tool features a rigid 0.9-degree tapered neck design which can reduce tool deflection in the milling operation, reduce milling vibration and improve surface finish. It also features a wear-resistant polished physical vapor deposition (PVD) aluminum titanium nitride (AlTiN) with Al content of 60 at.% and WC–8 wt.% Co carbide substrate.

The AlTiN coating has the same structure as titanium aluminum nitride (TiAlN) coating and both of them belong to a kind of multi-layer coated materials composed of TiN, Al_2O_3 and TiCN materials. The only difference between them is that AlTiN coatings have an Al content higher than 50 at.%, while, TiAlN coatings contain less than 50% Al. Al content is one of the key parameters which influence the critical properties of a coating. The optimal Al content is 60–70 at.% [16]. The higher Al content will change the crystal structure and lattice distortion of the coatings and the increase of the aluminum element will enhance the performance of high hardness and high oxidation resistance under high temperature conditions. In AlTiN crystal film, Al atoms replace part of Ti atoms in TiN, which lead to lattice distortion. As we all know, when lattice distortion increases, on the one hand, grain boundaries increase, and on the other hand, dislocation density increases, therefore, the deformation of the crystal will be more difficult resulting in an increase of coating hardness. When the Al content of AlTiN coating changes, the hardness of the coating also changes. Researches have shown that when the Al and Ti content ratio reaches 1.5, the hardness of AlTiN can obtain a maximum hardness of 3200 HV [23].

Table 2
Mechanical properties of 30Cr3, Inconel718 and Ti-6Al-4V.

Material	Tensile strength σ_b (MPa)	Yield strength $\sigma_{0.2}$ (MPa)	Ductility δ (%)	Hardness (HRC)
30Cr3 (normalized and oil quenched)	1854	1640	12.8	50–55
Inconel718 (solution treated and aged)	1350	1170	16	38–44
Ti-6Al-4V (annealed)	950	880	14	30–36