WEAR MECHANISMS OF CERAMIC CUTTING TOOLS WHEN MACHINING HARDENED STEEL AISI D2 COLD WORK TOOL STEEL OF 60 HRC

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Abstract

Wear mechanisms of mixed ceramic (AI_2O_3 + TiCN) cutting tool when machining hardened steel AISI D2 cold work tool steel was investigated. The machining test was performed on a CNC lathe using three different speeds, namely 120, 180 and 220 m/min, while feed and depth of cut were held constant at 0.06 mm/rev and 0.4 mm based on feedback and suggestion from the manufacturers. Flank and rake face of the cutting tools was monitored at selected time intervals; furthermore, characterization and morphologies of various wears formed at the surface of tool insets after cutting operation are analyzed in detail with a Scanning Electron Microscope (SEM) observation. It was found that the mixed ceramic cutting tools wear mechanism is subjected to not only abrasion, adhesion but also to chipping, especially when machining at high cutting speed of 220 m/min.

Keywords: Hardened Steel; Cold work tool Steel; Mixed ceramic cutting tools; Wear mechanisms

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1. Introduction

Hard turning is a topic of great interest in today's industrial production and scientific research. The hard turning technology has the potential for improving productivity against grinding in the manufacturing process. Hard turning has certain potential process advantages over a grinding process which can improve the fatigue strength of the machined parts, increased productivity and reduced energy consumption [1, 2]. The other benefit includes a short process cycle time, process flexibility, part longevity, and less environmental impact [3]. Hard turning is a machining operation that involved with complex nonlinear and coupled thermo mechanical process. The complexities are due to large strain and high strain-rate in the primary shear zone and due to the contact and friction between the chip and cutting tool along the secondary shear zone. Therefore, tools used in hard turning are required to have properties such as high strength, high abrasive wear resistance and chemical stability at the high elevated temperatures.

There are two kinds of well known super hard materials over the past which are diamond and cubic boron nitride (CBN). Man made diamond, and CBN was manufactured by the middle of the 20th century. The commercialization of cubic boron nitride tools, start since 1970s, has resulted in a rapid advanced in hard turning technology. From 1990, CBN has received considerable attention in manufacturing industries. Finished hard turning by CBN cutting tools has attracted great interest, since it potentially provides an alternative to conventional grinding on machining of hardened steel. In particular, CBN inserts have been proven to produce as good or better tolerances than conventional grinding processes [4].

Hard turning has proven to be effective in reducing costs and lead times. The reduction in costs is since the turning can incorporate more operations into a single setup. Hard turning can dramatically reduce these production lead times by reducing the number of required production steps significantly. Currently, CBN cutting tools are still relatively expensive compared to ordinary carbide and ceramic cutting tools. In order to attain sufficiently high production rates at minimum cost, the uses of cheaper cutting tools at the same performance are necessary.

Among the earliest who reports on the machining of hardened steels up to 61 HRC with geometrically defined alumina cutting tools is by [5]. As a class of materials, ceramics possess high melting point, excellent hardness and good wear resistance. Unlike most metals, hardness levels in ceramics generally remain high at the elevated temperatures [6]. Major failure forms of ceramic tools such wear and tool fracture. Usually, tool wear is the dominant failure form in continuous machining, while the tool fracture is the main failure form in intermittent machining [7, 8]. An understanding about the wear mechanisms by coated mixed ceramic cutting tools will give an alternative to the manufacturing industries to exploit low costs cutting tools in hard turning of AISI D2 (60 HRC). It is therefore; of practical importance to understand and characterize the wear mechanisms in finish cutting of hardened AISI D2 cold work tool steel (60 HRC).

2. Experimental Setup

2.1 Workpiece

The work piece material is commercially available AISI D2 steel bars of diameter 90 mm and 250 mm long, which is being widely used as a material for the molding process. The typical composition of this special alloy steel is: 1.55% C, 0.4% Mn, 11.6% Cr, 0.8% Mo, 0.9% V and 0.3% Si. The AISI D2 cold work tool steel is a high carbon; high chromium tool steel alloyed with molybdenum and vanadium. It is characterized by: high wear resistance, high compressive strength, and high hardness after hardening. The work piece has a Vickers hardness of 60 HRC and elastic modulus of about 173 000 N/mm^2, and thermal conductivity of 13.4 x 10^{-6}/^{0}C.

2.2 Cutting tools

The tool material used in this study is a commercially available PVD TiN coating over an Aluminium Oxide and Titanium Carbonitride Ceramic ($Al_2 O_3$/TiCN). The flank and rake face of the cutting tools is observed using a low-power microscope and in order to enable further analysis of surface profiles, the Scanning Electron Microscope (SEM) is used. Table 1 shows the specifications of the cutting tool, cutting conditions and tool holders.

2.3 Machining setup

The machining operations were carried out with a HAAS VF series machining center, CNC slant bed lathe machine with a 432T control unit under dry cutting conditions. Before conducting the machining tests, a thin layer of 0.5 mm was machined with a new cutting edge in order to remove the uneven surfaces due to the previous operation and to ensure consistency. The machining test was carried out at three different speeds 120, 180 and 220 m/min, while feed and depth of cut were held constant at a reasonable value of 0.06 mm/rev and 0.4 mm based on feedback from the manufacturers.

Table 1.

The specifications of the cutting tool, cutting conditions and tool holders.

Tool holder	: MCLNL 1616H 12
Insert	: CNGA120408T01020
Nose radius	: 0.8 mm
Chamfer angle	: 20^0
End cutting edge angle	: 5^0
Side rake angle	: -5^0
Rake angle	: -5^0
Inclination angle	: 5^0
Cutting speeds	: 120, 180, 220 m/min
Feed	: 0.06 mm/rev
Coolant	: None (Dry)

3. Results and Discussion

3.1 Tool wear

Many attempts have been made to describe the tool wear for tool materials which bring a great number of suggestions to explain the connection between the cutting parameters and the tool wear. Today, high-quality ceramics are competing with uncoated and coated CBN in the field of steel machining. The life of cutting tools is generally assessed upon the basis of flank wear. In this study, typical flank wear profiles were observed. The growth of tool wear with time for various cutting speeds at a feed rate of 0.06 mm/rev and depths of cut 0.4 mm are observed (Fig. 1).

The wear pattern for all the cutting tools indicates the abrasive characteristics, which result from rubbing of the tool cutting edge and flank with the work-piece material (mainly the carbide) during cutting (Fig. 2). At low cutting speed of 120 m/min and 180 m/min, the flank wear increased gradually. Rapid increase is observed in cutting speed of 220 m/min. It only took about 9 min to reach $V_{B\ max}$ = 300 µm at 220 m/min. Generally, flank wear is uniform and regular along the major cutting edge. Most cutting tools experience a rapid rate of flank wear near the beginning of the machining cycle and reach at the steady state after a considerable cutting time.

Figure 1.

Tool flank wear propagation chart for mixed ceramic coated with PVD TiN at cutting feed, f =0.06 mm/rev and depth of cut = 0.4 mm

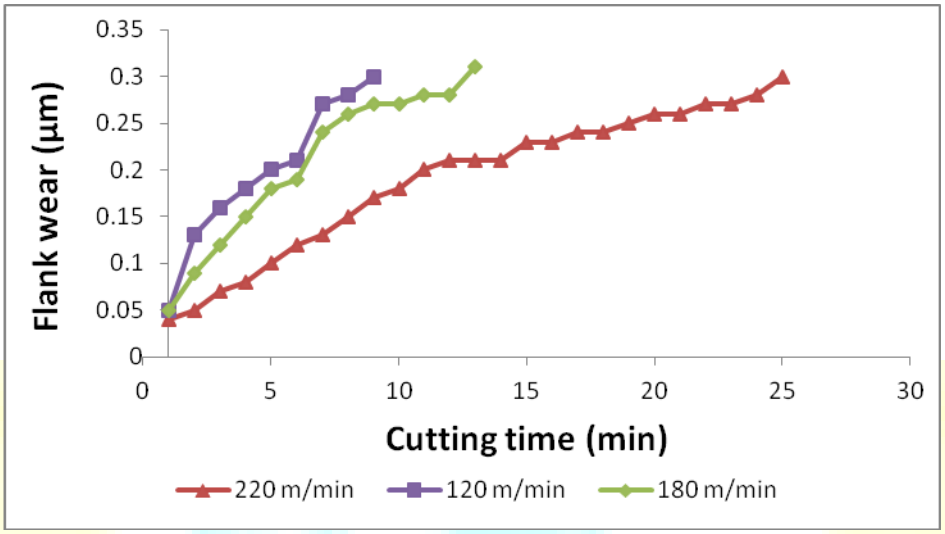
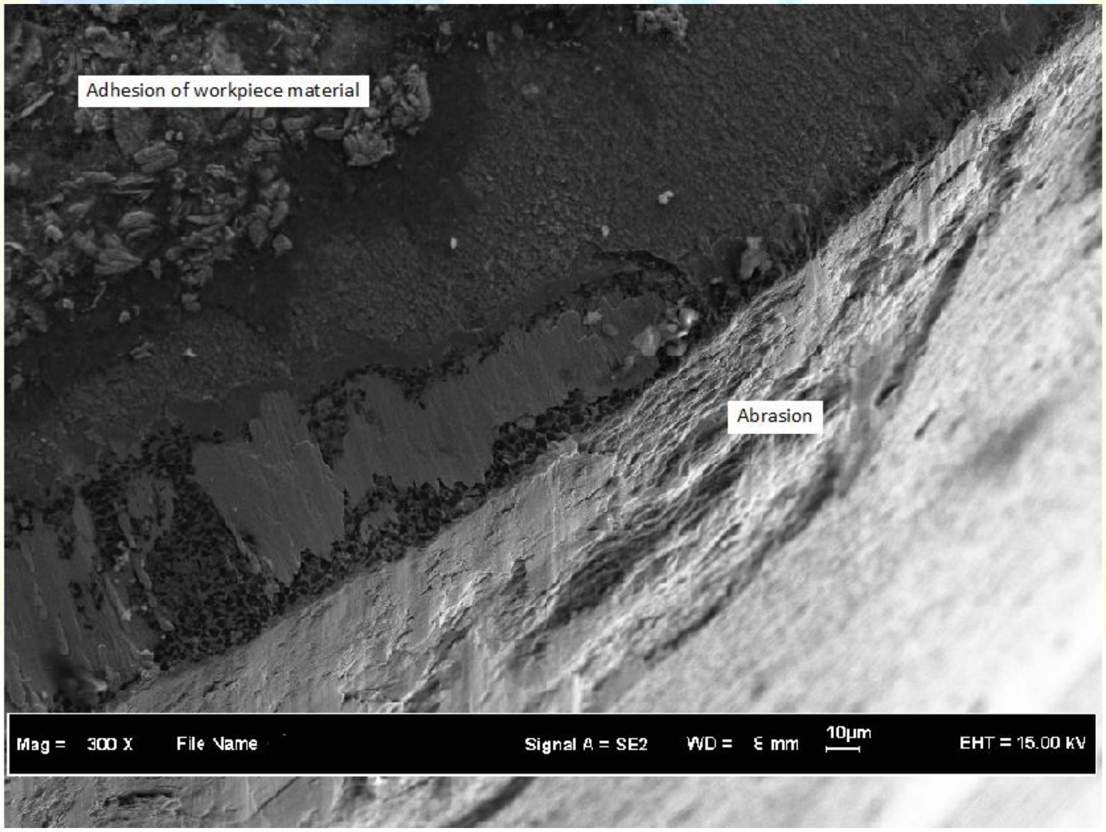


Figure 2.

The edge rounding is observed at early stage of cutting



Under the present experimental conditions, wear resistance of mixed ceramic is considered high. As expected, the experimental results showed that the application of coating prolonged the tool wear. Coating system impressively offers better tribological properties [9], improved cutting tool performance [10], and reduced tooling cost in many machining applications, which are often applied as multiple layers and produce a significant increase in tool life [11]. Previous researchers have examined the problem of ceramic tool wear, and the results are numerous [12, 13, 14]. Resistance to tool wear is related to coating material, grain size, binder material, tool geometry, cutting edge, cutting tool geometry (sharp, honed, wiper or chamfered), work-piece properties, and cutting conditions. The tool wear process consisted more than one wear mechanism.

3.2 Wear Mechanisms

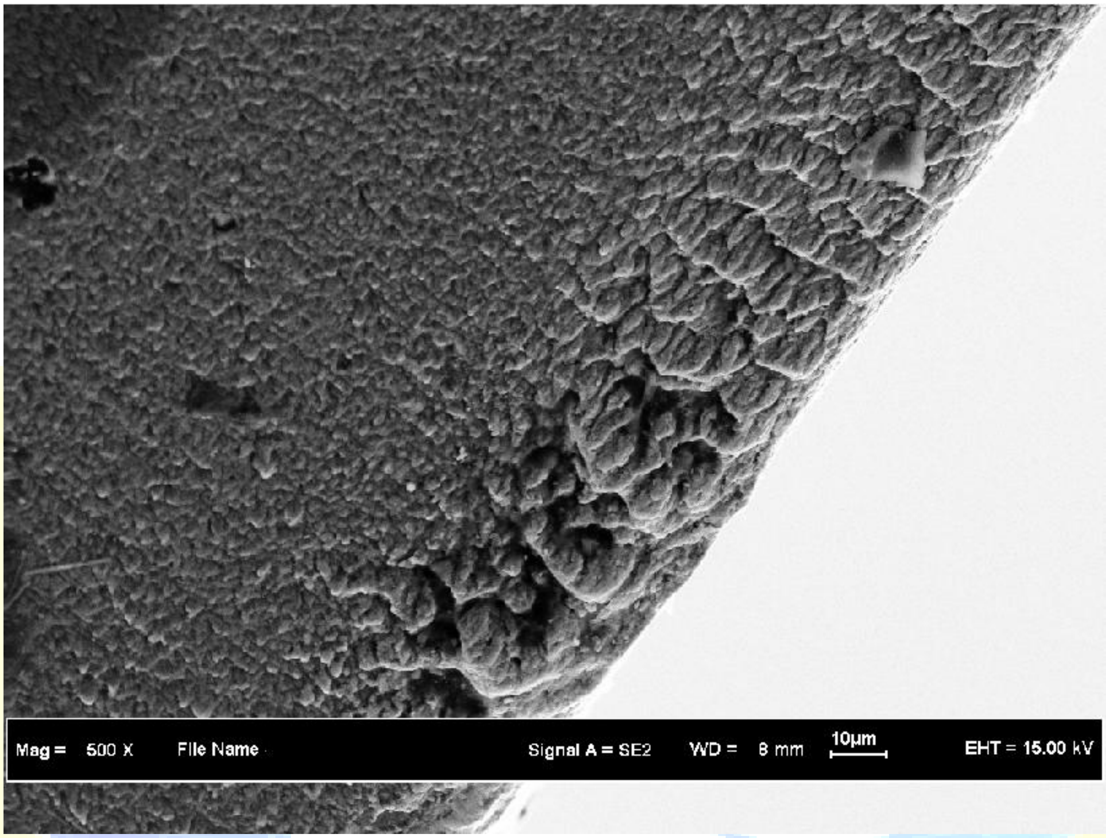
The appearance of worn surfaces of the cutting tool may indicate which mechanism had the greatest effect. The worn ceramic inserts were frequently examined under the low power microscope with magnification ranging from 200 to 500. Morphologies of various wears formed on the surface of tool insets after cutting operation are analyzed in detail with SEM observation. The SEM photographs showed clear different wear patterns and microstructures on the worn surfaces of the cutting tools. As we know that the contact areas of tool/chip and tool/work-piece are very small, and are subjected to both high cutting forces and high temperature. At all cutting speeds tested the early stage of cutting, initial breakdown in cutting edge with the edge rounding is observed with only a flank wear which increases rapidly. Then the flank wear becomes stable and stays constant, while a crater wear appears upon the rake face which is typical of abrasive wear. Under lower speed, cracks propagation perpendicular to the chip flow direction was observed. If the cutting operation continues further on, tool fracture will possibly occur.

The mechanical fatigue cracks and thermal cracks resulted from the combined action of both mechanical and thermal stresses are the dominant reasons for the late fracture of ceramic cutting tools. Thermal shock cracks, often associated with nose or flank wear, and are caused by large temperature gradients at the cutting edge. Chong et al. [15] in their study of the cutting behavior and related cracks in wear and fracture of ceramic tool materials concluded that wear and fracture of ceramic tools are significantly affected by cracks or micro cracks that formed in the cutting process.

The forms of fracture for ceramic tools vary with cutting conditions. Similar observation is also present by [16]; microcracks or crack-like defects inside the tool material were initiated and propagate continuously under the action of thermal tensile stresses at the lower temperatures. The evidence of abrasion of the hard carbide particles in AISI D2 microstructure and adhesion of work-piece material in the rake face was also observed. The adhered work-piece particles often remain attached to the cutting tool edge. This is believed due to the chemical reaction between the work-piece chip material and the ceramic tool material, and the process is activated by high temperatures at the tool-chip interface. Chemical wear (defined as the adhesion to the work-piece material on the tool face) is one of the main causes of tool failure. The adhered work-piece material always removes small particles of the tool when it breaks away and causes tool chipping [17]. The application of coating possibly provides a 'break-away' layer that delayed the exposure and wear of ceramic cutting tools. It was obvious that the coating fails by plastic deformation (Fig. 3).

Figure 3.

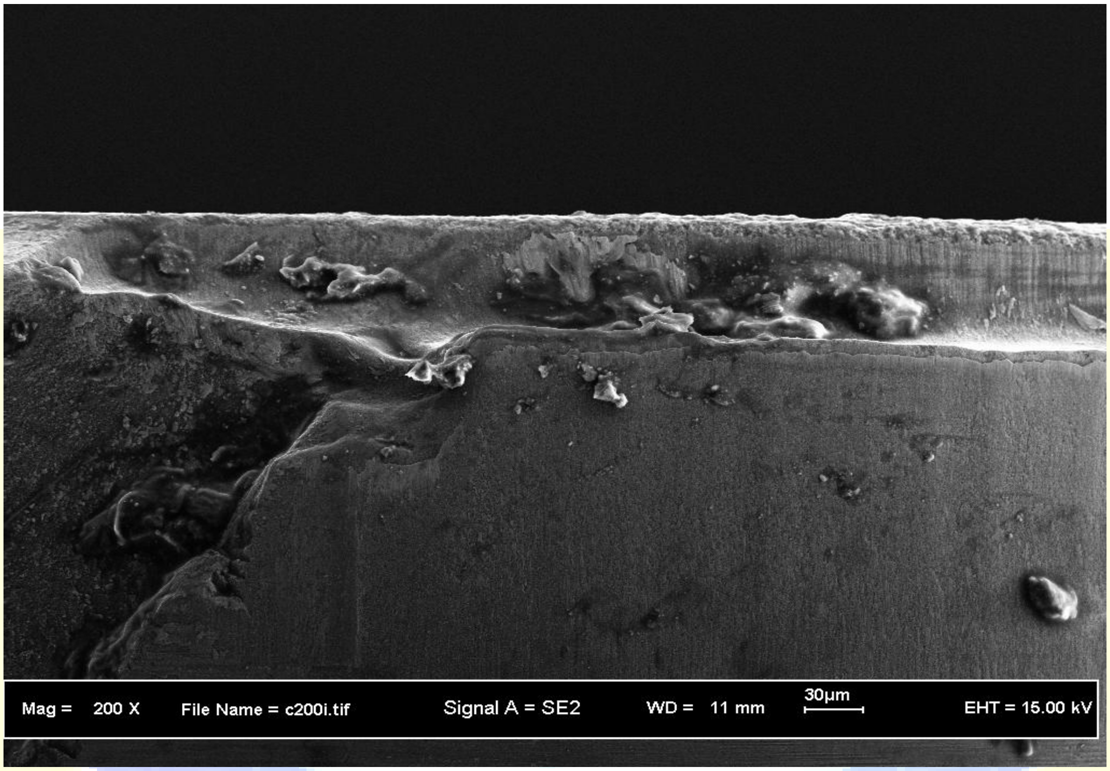
Plastic deformation of the coating material on the rake face



The flank wear of the mixed alumina tool increased with cutting speed and presenting a considerably higher tool wear rate when using a cutting speed of 220 m/min. Abrasion wear occurs on the tool flank, and it is generally attributed to rub on the cutting tool edge with the work-piece at the interface. It was observed that the flank wear plays a larger role at lower speeds, and notch wear is significant at the higher speeds (Fig. 4). According to [18] in their study of the effect of tool wear on tool life of Alumina-based ceramic cutting tools while machining hardened martensitic stainless steel (60 HRC), notch wear occurs by the rubbing process on the machined surface with the cutting tool at the boundary where the chip is no longer in contact of the tool. A machined surface may develop a thin work hardened layer which is hard and abrasive. This contact could contribute to notch wear.

Figure 4.

Notch wear at cutting speed of 220 m/min



4. Conclusion

The mixed ceramic cutting tools wear mechanism is subjected to not only abrasion, adhesion but also to chipping, especially when machining at high cutting speed. Chipping was ever observed in the mixed ceramic tools when machining at the higher speeds of $V_C = 220$ m/min. All ceramic tools undergo slow crater wear at their rake surface, mainly by plastic deformation and pull out of the deformed grains in addition to abrasion. It was observed that the flank wear played a larger role at lower speeds, and notch wear is significant at the higher speeds.

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