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High speed end milling of AISI 304 stainless steel using new geometrically developed carbide inserts

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Abstract: AISI 304 stainless steel possesses some properties, such as low thermal conductivity and high ductility that make them be classified under materials of poor machinability that exhibit a lot of difficulties during cutting. This work reports an experimental study on the performance of multilayered (TiN/TiCN/TiN) carbide inserts recently developed for end-milling of AISI 304 stainless steels. The length of chip-tool contact is small for these inserts as they contain a chip breaker that restricts the chip-tool contact area. In this study, the possible failure modes of tool wear were discussed and the effect of cutting speed and feed rate variation on tool life and tool wear modes was investigated. An increase in tool wear was noticed with increasing the cutting speed, while at the same time, a decrease in tool wear was observed with increasing the cutting feed. The most optimum cutting parameter for end milling operation using a single end mill was established in terms of maximum productivity and maximum tool life.

Keywords: Flank wear, Tool life, TiN coated carbide, 304 stainless steel

1. INTRODUCTION

Austenitic stainless steels are grades of chromium-nickel steels exhibiting a very high corrosion resistance in addition to a wide range of excellent mechanical properties not offered by any other alloy. Austenitic stainless steels cannot be hardened by traditional heat treatment processes but they can be strengthened by cold working [1].

AISI 304 steel is hard to machine. Machining operations of austenitic stainless steels are usually accompanied by a number of difficulties such as irregular wear and built-up-edge (BUE) on the tool flank face and crater face, respectively [2]. The present of BUE will cause an increase in tool wear rate and deterioration of the surface integrity of the work.

The poor machinability of this material is usually accounted for some reasons such as having very low heat conductivity, high ductility, high tensile strength, high fracture toughness and high work hardening rate [2, 3]. Work hardening of stainless steels is caused after a previous severe cutting operation by a worn tool. Work hardening will cause increased rates of tool wear and damage. One way employed to reduce work hardening effect on tool life is to conduct end-milling operations at high feed rates with a sharp tool [4].

Several studies on machining of austenitic stainless steels have been conducted in order to evaluate the performance of different tool materials when cutting different grades of stainless steels.

Jukka Paro et. al. [5] studied tool wear characteristics of TiN and Al_2O_3 coated carbide inserts when turning of X5 CrMnN 18 18 stainless steels. It was found that tool failure at tool nose was the dominant wear mechanism which was due to high cutting forces. Agrawal et. al. [6] reported that the composition of stainless steel grades influenced the tool wear and tool–chip adherence. M. Nordin et. al. [7] found that a multilayered TiN / TaN coating outperformed single layered TiN and TaN inserts due to its lower tool–chip interaction. Jie Gu et. al. [8] reported that TiAlN coated inserts produced high wear resistance than TiN and ZrN coated tools. D. O'Sulliran and M. Cotterell [9] studied the machinability of AISI 304 stainless steels with an emphasis on work hardening effect during machining using on–line techniques. Some studies indicated that the machinability of stainless steels can be improved by adding oxide forming elements, such as sulphide and calcium [10, 11].

The purpose of this paper is to present the results of a study that has been done on tool wear of multilayered (TiN/TiCN/TiN) carbide inserts, recently developed for cutting stainless steels, when end-milling of AISI 304 stainless steel using a single-insert end-milling cutter.

2. EXPERIMENTAL DETAILS

2.1. Workpiece Material

The AISI 304 stainless steel workpieces were provided in fully annealed condition in sizes of 50.8×50.8×120 mm. The yield and tensile strengths are 296 MPa and 600 MPa, respectively. The workpiece was checked for its hardness with an average value of HRB 88. The chemical composition of the machined workpiece material is shown in Table 1.

Table 1.
Chemical composition (wt. %) of AISA 304

Element	C	Si	Mn	Cr	Mo	P	S	Ni
wt %	0.02	0.32	1.31	16.38	2.03	0.30	0.20	12.17

2.2. Tool Material

The tools used in this study are carbide inserts PVD coated with a multilayer of TiN/ TiCN/ TiN. The employed inserts possess a clearance angle and a rake face angle of 7º of 15º, respectively, with a lightly honed T-land at the cutting edge. Some geometrical specifications of this insert are shown in Figs. 1

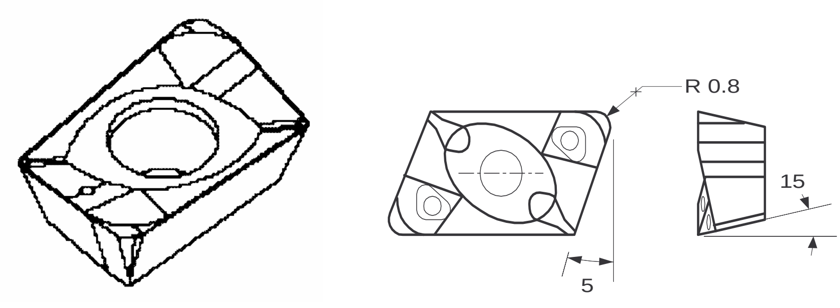

Figure 1. Geometrical elements of insert ADKT 1035 PDSRLC

The inserts, equipped with a chip breaker, are manufactured by Kennametal with an ISO designation of ADKT 1035 PDSRLC (KC725M). They are specially developed for milling applications where stainless steel is the major machined material. The tool holder used in the experiments is a single insert holder with a diameter of 12 mm.

2.3. End-Milling Cutting Tests

The end-milling tests were conducted on Okuma CNC machining centre MX-45VA with maximum spindle rotary speed of 7000 rpm and maximum power of 10 hp. The cutting tests were carried out according to ISO standard. The tests were performed using a coolant at surface cutting speeds of 150, 190, 225 and 260 m/min and constant axial and radial depths of cut of 10 mm and 2 mm, respectively. Four cutting feeds of 0.025, 0.050, 0.075 and 0.100 mm/rev were used. The cutting experiments were repeated three times in order to have accurate readings of the flank wear. Cutting speeds were chosen higher than the recommended speeds in order to move the experiment into the “high cutting speed” category.

The workpiece was prepared by chamfering one edge where the tool entered so that the depth of cut increased gradually. Every two passes (one pass is equal to 115 mm), the cutting test was stopped to observe the flank wear VB using an optical microscope with an image analyser. The tests then were continued until the flank wear VB had exceeded 0.3 mm in accordance with ISO 8688.

3. RESULTS AND DISCUSSION

In the current work, it was observed that the increase in cutting speed at a constant feed caused a noticeable reduction in tool life. At the highest cutting speeds (260 m/min),the variation of feed values between 0.05 and 0.1 mm/rev had little effect on tool life. At these values of feeds, tool life ranged between 3 to 4 min. However, at the lowest value of feed (0.025 mm/rev), tool life increased to double (7.4 min).

From Fig. 2, it is noticed that, for most cutting experiments, the flank wear developed in three stages: rapid initial wear, gradual uniform wear and accelerating wear. Observing Fig. 2b, one can notice that at the feed 0.05 mm/rev for cutting speeds 225 and 260 m/min, the initial flank wear started at a larger value (120 and 100 μm, respectively) compared to the average flank wear of other cutting speeds and feeds. Although the initial wear for these two speeds, at feed of 0.05 mm/rev, was the highest in all cutting tests, their flank wear limit (0.3 mm) was reached after a cutting length longer than that of feed of 0.025 mm/rev for the same cutting speeds. Notch wear was the dominant mode of failure observed during the cutting experiments. This mode was noticeable at the highest cutting speed (225 m/min) with the lowest feed value (0.025 mm/rev) used in this study.

During machining ductile materials such as austenitic stainless steels, built-up edge chip can easily be formed at certain cutting conditions. In this study, it was found that BUE occurred mostly at 190 m/min-speed and 0.075 mm/rev-feed. BUE was absent at higher or lower cutting speeds and feeds. The insert used at these cutting conditions was sectioned and polished to be investigated by a scanning electron microscope equipped with EDX. Fig 4 shows an SEM image of this insert. It is clearly seen that that 304 stainless steel chips welded to the tool edge at these cutting conditions forming a BUE. The formation of BUE led to a dramatic increase in the load exerted on the tool edge. This caused micochipping and cracks of the tool. As it is shown, not far from the chip-tool contact, a narrow crack of 30-μm depth

(Fig. 2a, c). Fig. 2b shows small tool material particles embedded into the chip body and moving away with chip leaving the tool body.

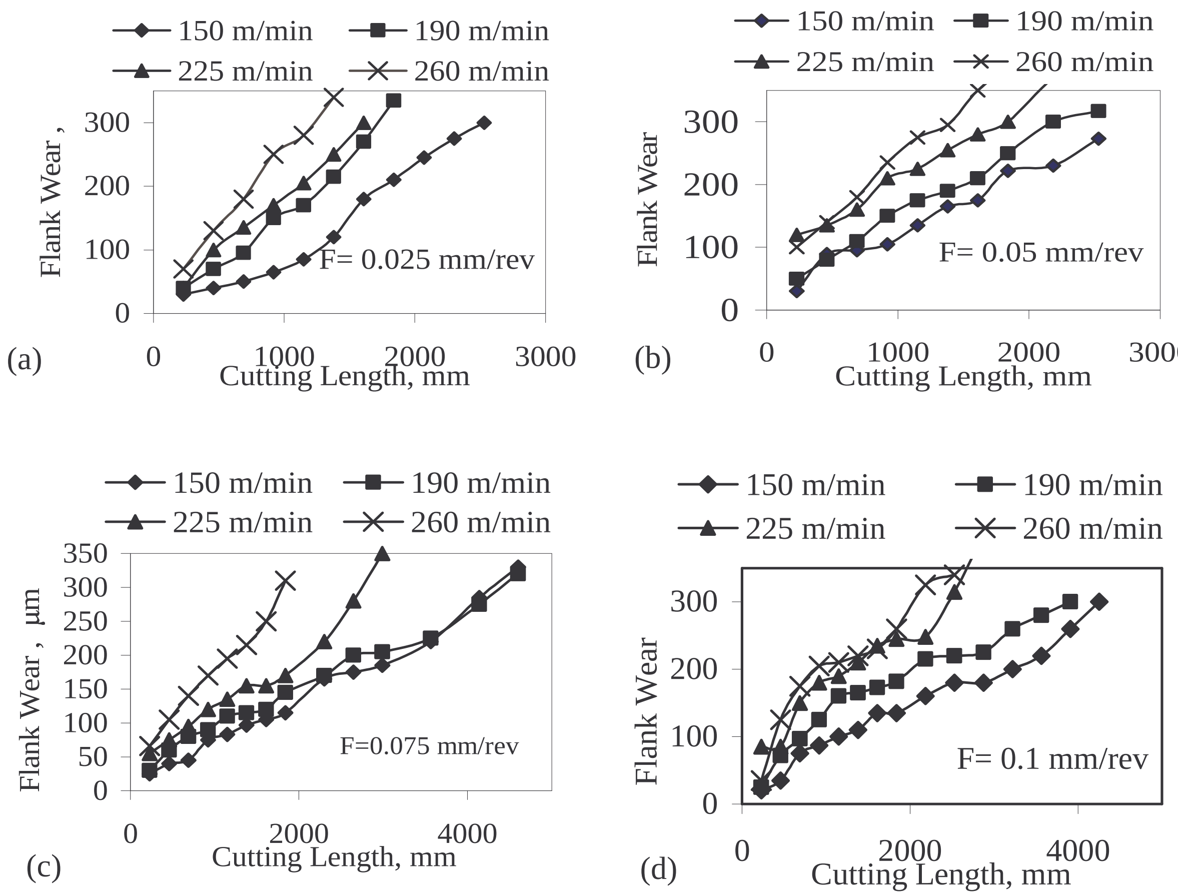

Figure 2. Cutting length vs. flank wear: (a) F=0.025, (b) F=0.05, (c) F=0.075, (d) F=0.1mm/rev

Another mode of tool failure, which is diffusion wear, occurred. The EDX analysis of a point taken in the tool body (Point A) (Fig 3b) proved the occurrence of this kind of wear. The tool body contained some elements such as Fe, Cr and Ni found in AISI 304 steel. Table 2 shows the chemical composition of the tool at point A after reaching wear limit.

4. CONCLUSION

The main conclusions drawn from this study are as follows:

1. The increase in cutting speed caused a dramatic reduction in tool life. The tool lives of the highest three cutting speeds used in this study (190, 225 and 260 m/min) were close to each other while the tool life at V_c = 150 m/min was almost doubled.
2. Feed variation at high cutting speeds has small affect on tool life. Varying feed at cutting speed of 260 m/min yielded nearly the same tool life.
3. It was found that BUE occurred at high values of feeds and medium cutting speeds (190 and 225 m/min).

4. The most optimum cutting conditions that yielded good productivity at maximum possible tool life were at V_c=150 m/min and F = 0.075 mm/rev.
5. The dominant tool failure mode was notch wear at the flank face.

Table 2.
Chemical composition of tool at point A

Element	W	Co	C	Cr	Fe	Ni
wt %	78.94	11.87	5.96	0.91	1.61	0.71

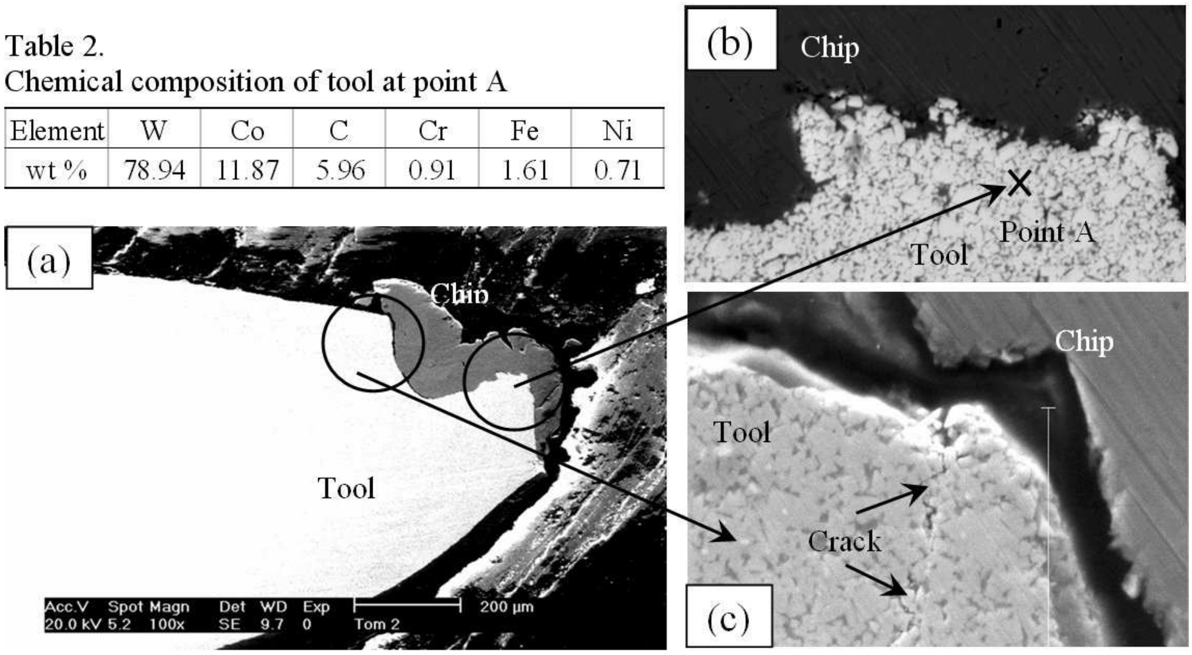

Figure 3. (a) SEM-image of insert (V_c = 190 m/min and F= 0.075) revealing BUE (b) Narrow deep micro crack near the tool-chip boundary. (c) Micro particles leaving tool body

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