JESTECH, 15(1), 21-26, (2012)

JESTECH

HARD MILLING OPERATION OF AISI O2 COLD WORK TOOL STEEL BY CARBIDE TOOLS PROTECTED WITH DIFFERENT HARD COATINGS

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Abstract

Milling of hard materials is an important operation in tool production. With the hard milling operations, a decrease in the production time and in the cost of products can be obtained by the elimination of some process steps and coolants. However, unpredictable tool life and premature failure of cemented carbide tools are major process restrictions in hard milling due to the higher cutting forces and temperatures compared to conventional machining. One of the methods used for tool life enhancement is the protection of the tools by hard coatings, therefore a selection of the cutting tool giving the longest lifetime is needed. In this study, the cutting performance tests were performed on AISI O2 (90MnCrV8) cold work tool steel (58 HRC) in order to determine the best cutting tool giving the longest tool life. Four types of tool were used during the tests for lifetime comparison, i.e. uncoated, nanolayer AlTiN/TiN, multilayer nanocomposite TiAlSiN/TiSiN/TiAlN and commercially available TiN/TiAlN coated tool. Wear mechanisms and chip formation were analyzed by optical microscope, SEM and EDS. The most suitable cutting tool for hard milling of AISI O2 cold work tool steel was determined as nanolayer AlTiN/TiN coated carbide tool.

Keywords: Machinability, AISI O2 steel, Nanolayer and nanocomposite coating, Tool life

1. Introduction

The world is experiencing an increase in demand for hard machining operations in terms of sustainable manufacturing. With the hard milling operations, a decrease in the production time and in the cost of products can be obtained by the elimination of some process steps and coolants [1]. However, unpredictable tool life and premature failure of cemented carbide tools are major process restrictions in hard milling due to the higher cutting forces and temperatures compared to conventional machining [2]. The most common way used by authors to increase tool life and to improve cutting performance is to protect the carbide cutting tools by hard coatings [3-5]. Especially nanolayer and nanocomposite coatings are of interest due to their high hardness, good adhesion to substrate, and high oxidation resistance [6-9]. The suitable coating should be selected according to workpiece material and hard cutting conditions. It is known that nanolayer AlTiN/TiN and multilayer nanocomposite TiAlSiN/TiSiN/TiAlN coatings have application temperature of 1100° [10]. Therefore, these types of coatings may be a candidate in hard milling operations. The goals of this study are to inspect the wear mechanisms of carbide cutting tools coated with nanolayer AlTiN/TiN, multilayer nanocomposite TiAlSiN/TiSiN/TiAlN and commercial TiN/TiAlN coatings and determine the best cutting tool giving the longest lifetime in hard milling of hardened AISI O2 cold work tool steel.

2. Experimental Details

The workpiece material was selected as AISI O2 (90MnCrV8) cold work tool steel, with an as-annealed hardness of ~58 HRC. The material is widely used in manufacturing of tools (punches) and dies for blanking, punching and similar operations; threading and wood working tools, machine knives for the pulp, paper and

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metalworking industries; measuring tools and plastic moulding dies [11]. The chemical composition of the material is presented in Table 1.

Table 1. Chemical composition of AISI O2 steel (wt. %)

C	Si	Mn	P	S	Cr	V
0.88	0.29	2.07	0.024	0.009	0.26	0.08

Cemented carbide cutting tools with triangular shape were used during the machining tests. The designation of the uncoated tools is 218.19-125T-T3-MD10, and the tools have a chamfer with the angle of 32º in order to strengthen the cutting edge. The tools were positioned on the cutter, supplied from SECO, with the code number of R217.21-2532.0-R125.2 with the cutting diameter of 21 mm and teeth number of 2 to provide radial rake angle of 0º, axial rake of 6º and flank angle of 6º. The machine tool used in the cutting tests was a three-axis Mori Seiki Frontier-M, CNC-vertical milling machine tool, with a peak power of 10 kW.

In order to compare the effect of coatings on tool life of cemented carbide cutting tools, two types of coating, i.e. nanolayer AlTiN/TiN and multilayer nanocomposite TiAlSiN/TiSiN/TiAlN, were deposited on uncoated carbide tools by industrial magnetron sputtering system CC800/9 sinOx ML (CemeCon). Commercially available TiN/TiAlN coated carbide tools (F15M), supplied from SECO, were used for tool life comparison. Some physical and mechanical properties of the coatings are presented in Table 2. SEM images of fracture cross-sections of the coatings are given in Figure 1. Nanolayer AlTiN/TiN and multilayer nanocomposite TiAlSiN/TiSiN/TiAlN coatings have dense and fine grained structure, while commercial TiN/TiAlN coating has columnar structure.

Table 2. Properties of the coatings

Coating	Structure	Thickness [μm]	Individual layer thickness [μm]	Hardness [HV]	Elastic modulus [GPa]
AlTiN/TiN	Nanolayered	~3.2	~0.02* (bilayer)	2996	369
TiAlSiN/TiSiN/TiAlN	Multilayered	~3.6	~0.2 / ~2.3 / ~1.1	3240	309
TiN/TiAlN**	Homogenous	~2.0	~2.0	-	-

* The bilayer thickness varies due to 3-fold rotation of the substrate during deposition of the coating [12].
** TiN is top layer and only for coloring.

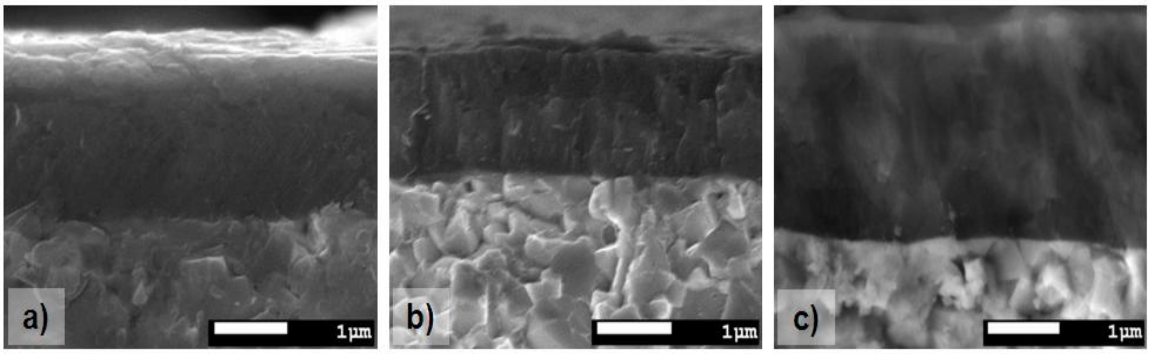


Figure 1. SEM images of fracture cross-sections of (a) nanolayer AlTiN/TiN, (b) multilayer nanocomposite TiAlSiN/TiSiN/TiAlN and (c) commercial TiN/TiAlN coatings deposited on carbide substrates

The cutting parameters used for the evaluation of coating performance were selected from the previous study [13] in which the optimal cutting parameters for high productivity, low cutting forces and low surface roughness were obtained by response surface methodology. The cutting parameters used in this study were given in Table 3. During machining tests, tool wear condition was evaluated using a CCD camera mounted on a Mitutoyo ToolMaker microscope aided with imaging software. After each cutting distance of 45 cm or 90 cm, the milling procedure was stopped, the tools were removed from the cutter and taken to the optical microscope by which the depth of the notch wear of the most damaged insert was measured. The flank wear of 0.3 mm was stipulated as the criterion for tool rejection. Wear images were taken from the flank and rake faces. Wear analysis was performed using optical microscope and scanning electron microscopy (SEM) from similar viewing angle by using a customized tool holder in combination with energy-dispersive X-ray spectroscopy (EDS) for flank and rake faces.

Table 3. Cutting conditions

cutting speed, V_c	150 m/min
feed rate, f_z	0.1 mm/tooth
depth of cut, a_p	1.0 mm
workpiece material	AISI O2, ~58 HRC
Lubricant	dry cutting

3. Results and Discussions

3.1. Cutting performance

The cutting tests were carried out in machining of AISI O2 cold work tool steel, with an as-annealed hardness of ~58 HRC. Four types of cutting tools were used during the tests in order to compare the effect of coatings on lifetime of carbide cutting tools, i.e. nanolayer AlTiN/TiN, multilayer nanocomposite TiAlSiN/TiSiN/TiAlN, commercial TiN/TiAlN coated and uncoated tool. The cutting tests were repeated at cutting parameters given in Table 3.

Notch wear was the dominant tool failure for all the cutting tools. Therefore, the depth of notch wear (VB_N) was measured in order to calculate the lifetime of the tools. A flank wear limit value of 0.3 mm was adopted in this study to mark the tools end of life. Fig. 2 presents lifetime of the all tools in cutting length. The number of stops was 5 for the AlTiN/TiN nanolayer coated tool, 3 for multilayer nanocomposite TiAlSiN/TiSiN/TiAlN coated tool and 4 for commercial TiN/TiAlN coated tool and 1 for the uncoated tool. All of the coatings increased the wear resistance and hence the lifetime of uncoated one. Nanolayer AlTiN/TiN coated tools showed longer lifetime than those TiN/TiAlN, multilayer nanocomposite TiAlSiN/TiSiN/TiAlN coated and uncoated. Nanolayer AlTiN/TiN coated cutting tools exhibited the longest lifetime with cutting length of ~3.7 m, leading to ~10 times longer lifetime over the uncoated tools. The coating sustained to protect the cutting edge until the cutting length of 2.7 m due to its high adhesion and wear resistance. However, after this cutting length the notch wear grew drastically as the substrate was exposed. As for the uncoated tool, it exceeded the wear criteria after one pass with the cutting length of 0.45 m.

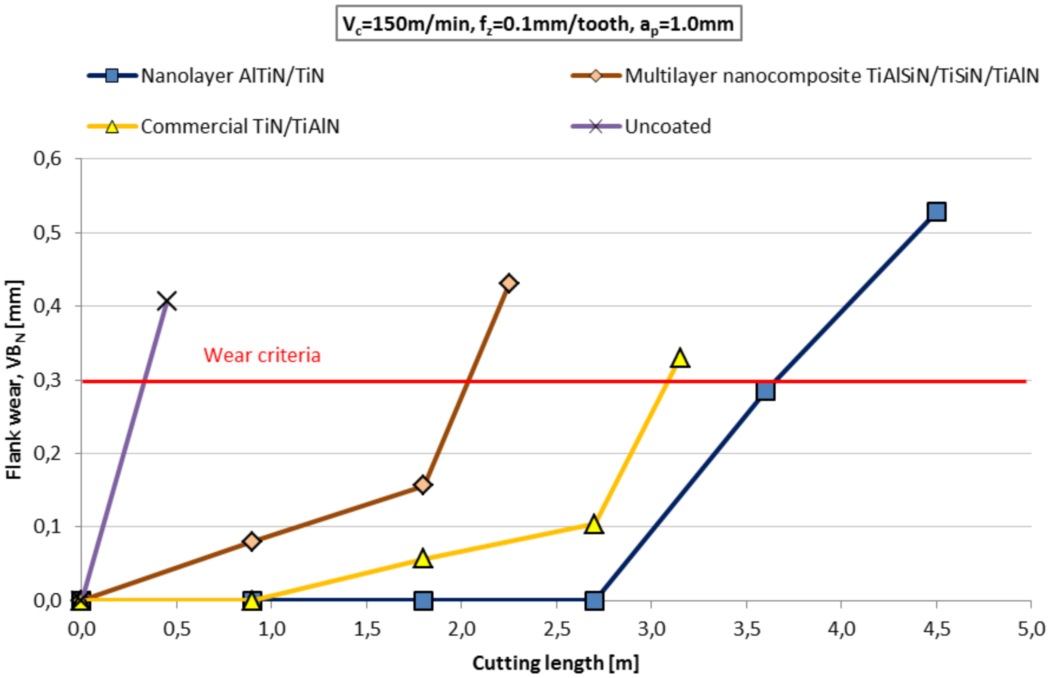
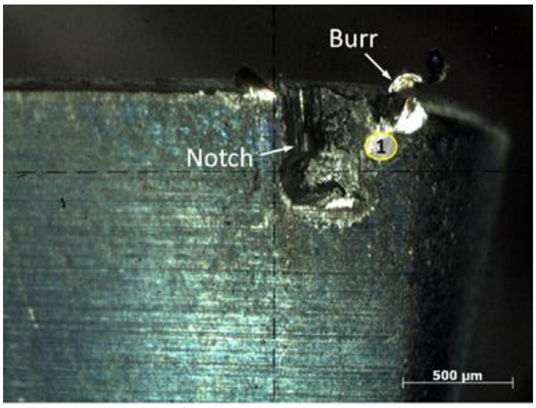


Figure 2. Comparison of lifetimes of coated and uncoated carbide cutting tools

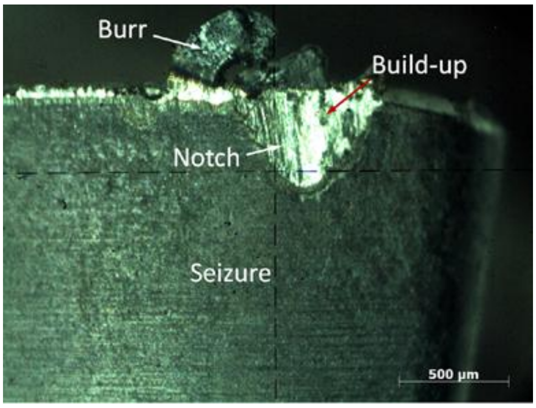
3.2. Tool wear analysis

During the cutting tests, it was observed that the main wear modes for all coated tools were abrasion and adhesion of workpiece on the cutting edge. Adhesion of workpiece on uncoated tool was quite low. Optical microscope images of the worn tools are shown in Fig. 3.

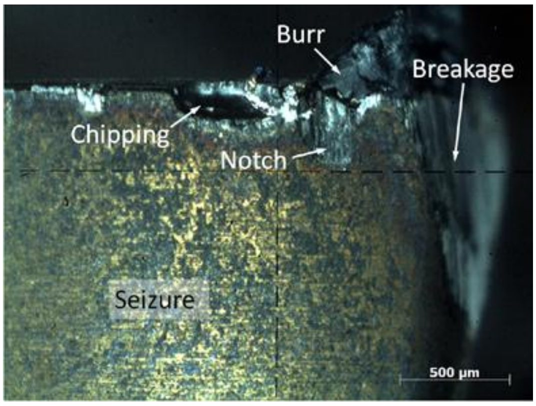
The dominant tool failure was abrasive wear for all the tools. After the protective coatings worn, the substrate was exposed. The exposed substrate material widened during machining. It was confirmed by elemental analysis that there is high sticking of the workpiece material onto the tools flank face and cutting edge except uncoated tool, causing the adhesion and the formation of seizure zones on the rake and flank faces of the tool (Fig. 4). The deterioration in cutting edge due to the abrasion of carbide substrate and the adhesion of workpiece resulted in an increase in cutting forces and temperatures. The maximum adhesion and seizure was observed with multilayer nanocomposite TiAlSiN/TiSiN/TiAlN coated tools (Fig. 3.b). It is thought that this was the primary reason of shorter tool life compared to other coated tools. It is well known that in dry high speed cutting operations TiAlN coatings develop permanently wearing and regrowing dense Al_2O_3 top layer formed at high temperatures (>800 ºC) [14, 15]. And also, the temperature coming out during cutting process can be estimated by the color of chips [16]. Therefore, in our study the temperature during dry cutting process was estimated to be around 1000 ºC due to blue and silver colors of the chips. The high amount of oxygen in weigth % on the worn area confirmed that such an Al_2O_3 formation exists on the coating (Fig. 3). Other tool wear types observed were chipping and thermal cracks due to the interrupted cutting process and the change in tool temperature. In addition, a breakage on the tip of commercial TiN/TiAlN coated tool occurred (Fig. 3.c). Uncoated tools showed regular flank wear instead of notch wear, as well as stair-formed face wear on the rake face (Fig. 3.d).



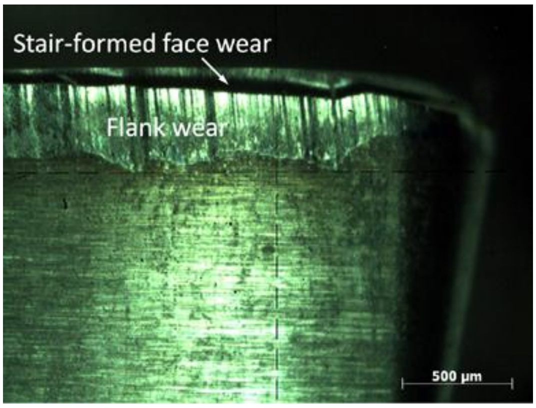
a) Nanolayer AlTiN/TiN



b) Multilayer nanocomposite TiAlSiN/TiSiN/TiAlN



c) TiN/TiAlN



d) Uncoated

Figure 3. Optical microscope images of worn carbide tools

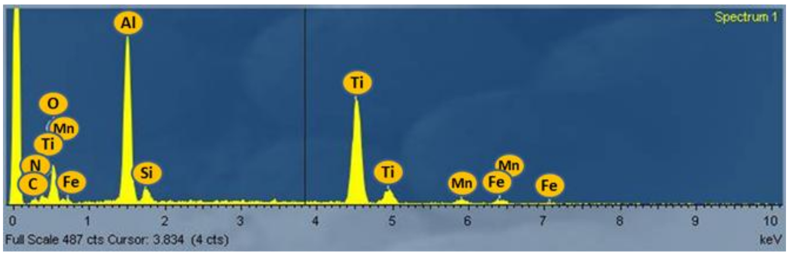


Figure 4. EDS spectrum of nanolayer AlTiN/TiN coated tool (from the point 1 in Fig. 2.a)

3.3. Chip formation

The shape of the chips is influenced by the hardness of the workpiece material and the formation of saw-tooth chips is a typical characteristic in hard machining [1]. In our study, the chips which have saw-tooth shape were obtained as a result of high hardness of the AISI O2 steel (58 HRC) as shown in Fig. 5.

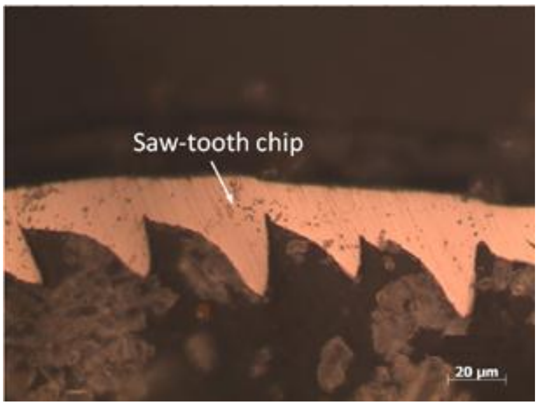


Figure 5. Image of the saw-tooth chip obtained from hard machining of AISI O2 steel

4. Conclusions

Wear mechanisms, tool life and chip formation were evaluated for four types of carbide cutting tools during machining process of hardened AISI O2 cold work tool steel (58 HRC). The tools coated with nanolayer AlTiN/TiN, multilayer nanocomposite TiAlSiN/TiSiN/TiAlN, commercial TiN/TiAlN coatings and uncoated cutting tools were used.

Nanolayer AlTiN/TiN coated cutting tools exhibited the longest lifetime with cutting length of ~3.7 m, leading to ~10 times longer lifetime over the uncoated tools. It was observed that the main wear modes for all coated tools were abrasion and adhesion of workpiece on the cutting edge. The dominant tool failure was abrasive wear for all the tools. The deterioration in cutting edge due to the abrasion of carbide substrate and the adhesion of workpiece caused to an increase in cutting forces and temperatures. Therefore, Al_2O_3 formation occurred on the worn area. Other wear types observed were chipping and thermal cracks due to the interrupted cutting process and the change in tool temperature. In addition, a breakage on the edge of commercial TiN/TiAlN coated tool occurred. Uncoated tools showed regular flank wear instead of notch wear, as well as stair-formed face wear on the rake face. The evidences of little adhesion and seizure formation and substantially extended tool lifetime makes the nanolayer AlTiN/TiN coating as a good candidate in dry cutting of hardened AISI O2 cold work tool steel.

Acknowledgements

This work was supported by Unit of Scientific Research Projects of Süleyman Demirel University, Turkey (project 2187-D-10) and the Slovenian Research Agency (project L2-2100).

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