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Dry face milling of titanium alloys

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Abstract: In machining titanium alloys, cutting tools generally wear out very rapidly because of the high cutting temperature resulted from the low thermal conductivity and density of the work material. In order to increase the tool life, it is necessary to suppress the cutting heat as much as possible by applying an abundant amount of coolant, but this will entail serious techno-environmental and biological problems. To study the performance and avoid these limitations, a PVD-coated insert was used to the dry face mill of (α + β) titanium alloys. As a result it was found that the inserts exhibit an excellent cutting performance at low cutting speeds and feed rates, and there is no significant difference in the dominant insert failure mode between the wet and dry cutting in discontinuous cutting.

Key words: carbide tool; face milling; titanium alloy

1 Introduction

Titanium alloys are extremely difficult to machine. The machinability of titanium and its alloys is generally considered to be poor owing to several inherent material properties. The machining of titanium alloys has been hindered by their high-temperature strength, very low thermal conductivity, and relatively low elastic modulus and chemical reactivity [1]. The heat affected zone is very small when cutting titanium alloys, it is mainly for this reason that the cutting speeds remain very low when using straight-grade cemented carbides [1, 2], and large quantities of chemically active cutting fluids are needed to cool the cutting area during machining, but this will entail serious techno-environmental and biological problems to the operators. The National Institute of Occupational Safety and Health, USA has drafted a document calling for a reduction of metalworking fluid mist to 0.05 mg/m^3 [3].

Titanium alloys are generally used for the components that require the greatest reliability, and therefore the surface integrity must be maintained. According to Kahles [4], when machining any component it is essential to satisfy the surface integrity requirement.

Most machining studies of titanium and its alloys have focused on the turning process, which involves continuous cutting. These results are not applicable to the milling process, where interrupted cutting takes place, subjecting the tools to a variety of hostile conditions. Investigations on the face milling of the alloys using uncoated carbide tools have been carried out by only a few researchers [5, 6], chipping and flaking of the cutting edge have been reported to be the main deterioration modes when milling titanium alloys using carbide tools. These types of deterioration modes are a result of a combination of various factors such as high thermo-mechanical and cyclic stresses, as well as the adhesion to, and breaking off from the tool faces or workpiece materials.

To enable a better understanding of the milling of titanium and its alloys, more experiments are required. Thus, this research aims to investigate the cutting performance of PVD-coated inserts with respect to tool failure deteriorations, surface hardness and surface roughness, and analyze chips formed in the face milling of Ti-6Al-4V titanium alloy during dry cutting under various cutting conditions.

2 Experimental techniques

2.1 Workpiece material

The machining tests involved the face mill of Ti-6Al-4V bars with a dimension of 36 mm×125 mm×44 mm and a hardness of HRC 37.7. The nominal composition, mechanical and physical properties are presented in **tables 1** and **2**.

2.2 Cutting tool

A Sandvik set of holder 392.14005-40 22 050, arbor R245-050Q22-12M, PVD-coated insert R245-12 T3 K-MM was used as the cutting tool. Although four

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inserts can be use in this milling cutter, only one was used in our experiments. The milling cutter was positioned at the center of the workpiece to avoid the occurrence of "foot formation" as a result of unfavorable exit angles [7].

Table 1 Mechanical and physical properties of the workpiece material

Tensile Strength / MPa	960-1270
0.2% proof stress / MPa	885
Density / (g·cm^{-3})	4.42
Elongation / %	≥ 8
Reduction in area / %	≥25
Elastic modulus / GPa	100-130
Hardness (Hv)	330-370
Thermal conductivity / (W·m^{-1}·k^{-1})	7

Table 2 Nominal composition of the workpiece material (wt%)

Al	5.5-6.75
V	3.5-4.5
Fe	0.03 (max)
H_2	0.0125 (max)
$O_2 + N_2$	0.25 (max)
Ti	Balance

2.3 Machining tests

All the machining tests were carried out on a DECKEL MAHO (DMU 70 V) universal milling and drilling machine of standard 1200 r/min with a 10 kW motor drive. Throughout the tests, different axial depths of cut (DOC) 0.5, 1, 1.5, 2, and 2.5 mm were used with a 36 mm radial depth of cut; the feed rates were set at 0.1, 0.12, and 0.125 mm/tooth respectively, and the cutting speed employed during the machining tests was 48, 55 m/min respectively.

All trials were carried out under dry cutting conditions. Inserts were examined after each predetermined cutting action. The flank wear land was measured using a tool makers' microscope; tool deterioration and the chips formed were observed using a Keyence scanning electron microscope (SEM) of 25-3000 in magnification; the surface finish measured using a stylus type surface stylus roughometer (JB-3C), and the hardness measured using a Rockwell 'C' scale.

3 Results and discussion

3.1 Tool deterioration modes

Tool deterioration modes were recorded under various cutting conditions and investigated after each face milling operation as shown in **table 3**. Generally, notching at the tool face and flank face was suppressed throughout the machining tests, but under most of the cutting conditions flank wear was the dominant failure mode.

Table 3 Tool failure modes

Test No.	Speed / (m·min^{-1})	Feed / (mm·tooth^{-1})	DOC / mm	Failure mode	Flank wear / mm
1	48	0.100	0.5	VB, PD	0.100
2	48	0.100	1.0	VB, CH	0.113
3	48	0.100	1.5	—	—
4	48	0.100	2.0	KT	—
5	48	0.120	1.5	VB	0.150
6	55	0.100	2.0	VB & FL	0.080
7	48	0.125	2.5	VB & CR	0.451
8	55	0.120	1.5	VB	0.100

Note: VB—flank wear; CH—chipping; PD—plastic deformation; KT—crater; FL—flaking; CR—cracks.

According to Sandvik, a cutting speed of 48 m/min was used in the first set of tests. At low feed rates and depth of cuts, the width of flank wear was increased in proportion to the DOC used in the first two tests, but plastic deformation was observed in test 1; this failure mode is normally detected at low cutting speeds when machining titanium alloys [8]. When the depth of cut increased to 1.5 mm, the insert surface does not appear to have any deterioration; this can indicate that we are about to reach the optimal parameters for this insert in dry cutting. More increased in DOC changed the deterioration mode to 0.122 mm crater wear. To study the effect of feed rate, it was increased from 0.1 to 0.12 mm/tooth and DOC was kept at the optimum value that was achieved in test 3. This change caused flank wear to increase 0.15 mm. A set of high cutting rates of the feed rate and DOC recommended by ISO, were used in test 7, these high cutting rates entailed a drastic flank wear of 0.451 mm, as shown in **figure 1**, with comb cracks detected in the cutting surface. These deterioration modes produced indicate that a cutting speed of 48 m/min is not compatible with other parameters and must be increased.

The cutting speed was increased from 48 to 55 m/min. For comparison we repeated the test carried out by Jawaid [9]; he used a 0.1 mm/tooth feed when face milling the same material in wet cutting. This test carried out in dry cutting resulted in a very small amount of flank wear (0.08 mm), the same as that concluded by the reference above. Flaking was also observed on the rake surface; this phenomenon is most frequently observed when the coated tool inserts are used but may also be observed with other tool materials. The flank wear of 0.1 mm was detected when the feed rate increased to 0.12 mm/tooth.

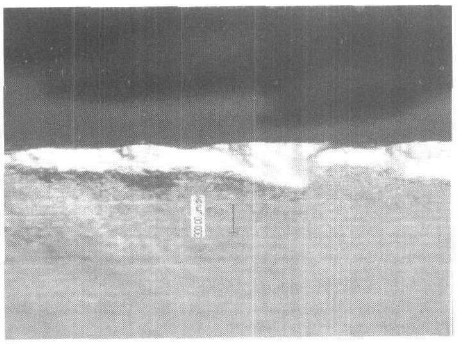

Figure 1 Drastic flank wear in test 7.

3.2 Surface hardness

The surface hardness under various cutting conditions was measured and is shown in **figure 2**. The range of the harnesses is between HRC 43.8 and 48.1. This can be ascribed to the work-hardened layer resulting from the cutting action. Except in test 1 a hardness of HRC 26.5 less than the hardness of the original workpiece was measured. The softening effect of the material at this level was probably due to the low DOC used in this test that machined only the hardened layer produced by the previous cutting and due to the over-aging of titanium alloys as a result of very high temperature produced at the local surface in previous cutting, the low thermal conductivity also caused the temperature below that of the machined surface to be retained.

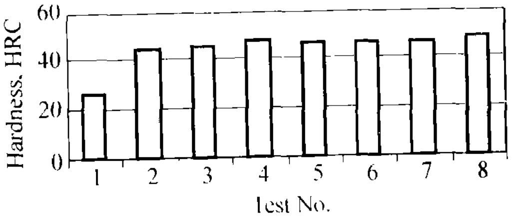

Figure 2 Variations of surface hardness.

3.3 Surface roughness

The roughness values recorded were unstable during the cutting processes as shown in **figure 3**. Lower surface roughness values were recorded at high cutting speeds, where the highest value was recorded at the low cutting speed and 0.1 mm/tooth in feed rate; the small chipping observed during this test probably caused this drastic increase in surface roughness.

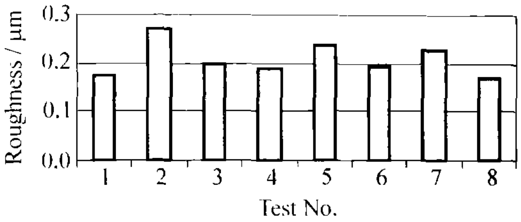

Figure 3 Variation sof surface roughness.

3.4 Chip formation

Generally, chips collected at low cutting speed rates are short and curlier than those collected at high speeds as shown in **figure 4**. This can be attributed to the low temperature generated during cutting. Serrations were noticed on the edge of the chips collected from last three tests; these indicate that they are prone to high stress as shown in the SEM photograph in **figure 5**(a). This may be attributed to the high speed or high cutting conditions used and most of the heat generated is concentrated in a very narrow area of the primary cutting band, during the formation of the chip, the new segment generated makes the later segment slide through the tool rake face. Additionally, the low elastic modulus of titanium alloys and their high strength at elevated temperatures further impair their machinability.

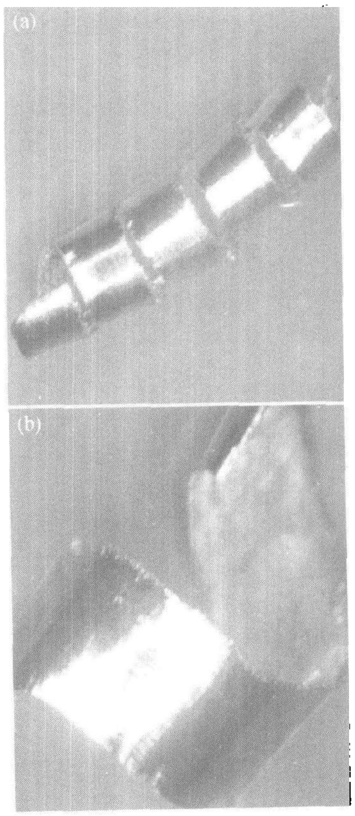

Figure 4 Typical chip shapes at low speeds (a) and high speeds (b).

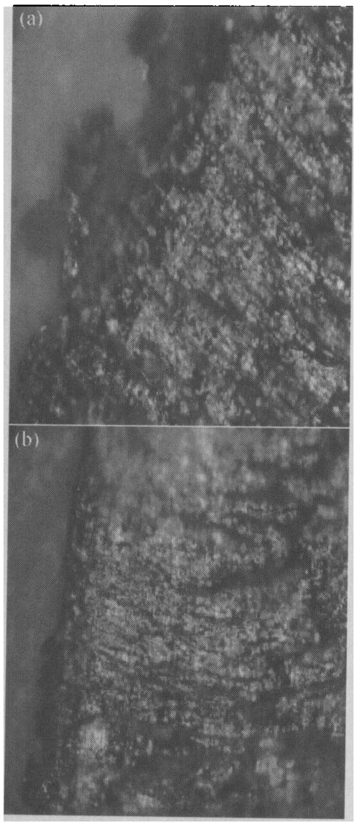

Figure 5 SEM photographys of chips at high speeds (a) and low speeds (b).

4 Conclusions

(1) Dry milling of titanium is very effective at low speeds, low feed rates and low depths of cut with respect to tool wears.

(2) The best cutting conditions with respect to the highest tool life were achieved at a cutting speed of 48 m/min, a feed rate of 0.1 mm/tooth, and a cut depth of 1.5 mm.

(3) Flank wear is the dominant insert failure mode in dry cutting.

(4) No significant difference in flank wear was observed between the wet and dry cutting in discontinuous cutting.

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