The influence of tool diameter on wear during milling of titanium alloy Ti6Al4V

Wpływ średnicy frezu na jego zużycie podczas obróbki stopu tytanu Ti6Al4V

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One of the main problems associated with machining of difficult-to-cut materials is tool wear. Tool wear may comprise a large proportion of production costs. Titanium alloys due to its properties – low thermal conductivity, high durability and a large coefficient of friction belong to difficult-to-cut materials. The paper presents the results of research on the impact of cutter diameter on tool wear during the milling process of titanium alloy Ti6Al4V.

KEYWORDS: tool wear, titanium alloys, milling

In the aerospace industry, structural solutions capable of providing a light weight camera flying are used. One of these solutions are integral elements, which are constructed in such a way that they can replace the work of teams composed of many parts. Integral elements are of complex construction, and their implementation requires the formation of recesses, grooves, thin ribs, etc. In the manufacture of these items, it is necessary to remove a large volume of semi-finished product, sometimes even more than 90%, and the main method of machining is milling.

Integral elements used in aviation are generally made of light metal alloys, including alloys of titanium. Extensive use of titanium alloys for aviation is related to their properties such as high strength in relation to the specific mass, high resilience and resistance to corrosion and oxidation [7]. However, the properties of titanium alloys (such as high strength, high coefficient of friction, high chemical activity at elevated temperatures, low elasticity, and especially low thermal conductivity) make these materials very difficult to cut [1, 2]. The low coefficient of thermal conductivity of the workpiece (for titanium, it is 21 Wm-1K-1) causes a rapid heating of the tool cutting edges, which leads to accelerated wear. Cutting speed has, among others, a significant impact on the temperature of the blade. Therefore, titanium alloys are machined at a much slower speed than aluminum or steel alloys (the coefficient of thermal conductivity of these materials is much higher for aluminum 226 Wm-1K-1 and for iron 73.3 Wm-1K-1). Rapid tool wear, especially catastrophic, can cause damage to the workpiece, therefore, the diagnostic tooling system [6] is of great importance in the treatment of titanium alloys.

Up to date, titanium alloy wear testing was performed mainly during turning [2, 5, 6] and surface milling [1, 3, 4]. Execution of intricate integral components involves the need for milling ribs, grooves and recesses of different geometries, often with small transitions between successive surfaces, which require the use of mandrel cutters of different diameters. Large depth of the milled depressions imposes a large milling cutoff. In this situation, reducing the diameter of the cutter leads to reduced stiffness and worsening of heat dissipation. The aim of this study was to evaluate the use of the blade end mills of different diameters when milling the titanium alloy Ti6Al4V.

Methodology of research

Titanium alloy Ti6Al4V samples were used in the study, which, due to its high specific strength (strength to density ratio), is used in structures where mass reduction is important. Tab. I shows the chemical composition and mechanical properties of the inspection certificate.

The milling process used cutters of different diameter: D = 6, 12, 16, 20 mm, made of cemented carbide. Tool parameters are shown in tab. II. An example of a series of tools is shown in fig. 1. The tools are fastened in clamping sleeve holders. The research was carried out on the machining center VMC-Avia 800HSE equipped with Heidenhain control.

To maintain comparable conditions (same number of inputs and outputs of the tools from the cutting zone), the dimensions of the samples were chosen so that the length of the transition represented 2.5 times the diameter of the cutter. Tab. II summarizes dimensions of the samples in relation to the milling cutter diameter.

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In order to maintain comparable cutter load, the cutting width was set at 0.7 the diameter for each tool. Fixed cutting parameters were adopted: v_c = 40 m/min, f_z = 0.1 mm/blade, a_p = 2 mm. Concurrent milling was applied.

Tool wear was observed using an workshop optical microscope and Keyence VHX 5000 digital microscope.

Forms of wear on the working surfaces of the tool were analyzed according to the standard ISO 8688:1996.

TABLE I. Chemical composition and physical properties of titanium alloy Ti6Al4V

Chemical composition %	Al	6,25÷6,31
	V	4,09÷4,12
	O_2	0,184÷0,19
	Fe	0,18÷0,21
	C	0,026÷0,027
	N_2	0,007÷0,009
	H_2	0,002
	Ti	balance
Mechanical properties	*Rm*, MPa	1014
	$Rp_{0,2}$, MPa	954
	A, %	13
	Z, %	35,8
Explanations: *Rm* - tensile strength, $Rp_{0,2}$ - plasticity limit, *A* - elongation, *Z* - constriction.		

TABLE II. Dimensions of the samples and the cutting path with respect to the diameter of the cutter

Dimensions of Ti6Al4V alloy samples, mm *L*×*B*×*H*			
15×150×50	30×150×50	40×150×50	50×150×50
Cutter diameter *D*, mm			
6	12	16	20
Number of blades *z*			
4	4	4	5
Type of coating			
(Ti,Al)N2	(Ti,Al)N2	AlTiN	AlTiN
Length of single passage *L* = 2,5*D*, mm			
15	30	40	50
Milling width *B*, mm			
4,2	8,4	11,2	14

Fig. 1. Sample series of tools used for testing

Test results

There were three forms of milling wear that were identified by the digital microscope based on the standard:

- VB3 - local flank wear, understood as the confrontation area of a local nature,
- CH3 - local chipping (referred to as a small local loss in the form of chipping).
- CT - catastrophic wear.

Forms of wear are presented in fig. 2.

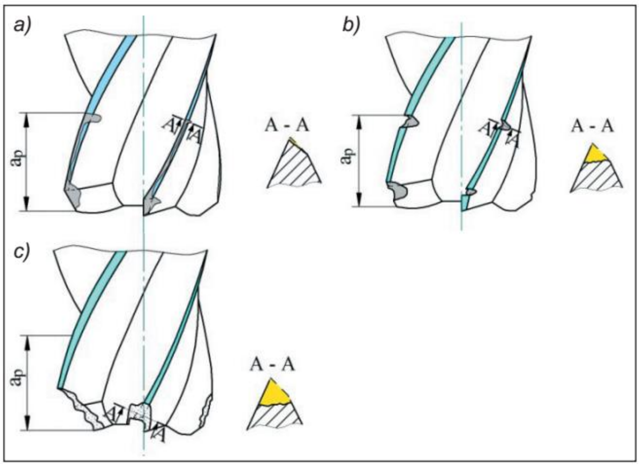


Fig. 2. Forms of wear. Symbols of wear according to ISO: *a)* local wear VB3, *b)* local chipping CH3, *c)* catastrophic wear CT

For 6 mm diameter mills, catastrophic wear has occurred on all blades in the first minute of cutting. Example blades wear CT was shown in fig. 3. The extensive loss of the blade is visible providing additional start of the cutting process to continue after the time at which there is a loss. The CT wear shows a total loss of milling properties by the tool.

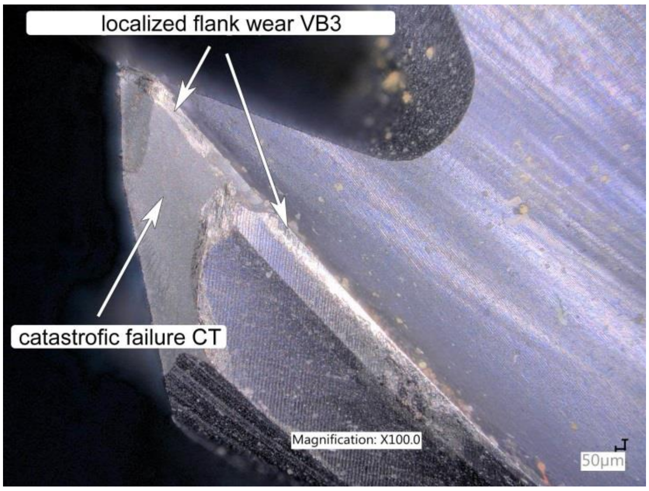


Fig. 3. View of CT catastrophic wear

The catastrophic wear of D = 6 mm diameter milling cutters probably resulted from the small stiffness that could have caused vibration during machining.

Tools with a diameter of D = 12 mm retained the cutting capacity until the cutting time t = 15 min, but after 10 min, the appearance of local CH3 was observed. After a time t = 15.3 min on the next blades, local CH3 was observed. The development of the wear of exemplary blade in consecutive time intervals is shown in tab. III.

In the process of cutting, chips flow down on the rake surface. The flow direction of the chip determines the plane of the largest drop of the rake surface. The position of this plane in the working system is dependent on the angle of attack and angle of helix. In the tested combination of the two cutter corners, it meant that the chips hit flowing into the free surface above the work surface. Characteristic wipes above the cut-off - caused by striking chips – are shown in fig. 4.

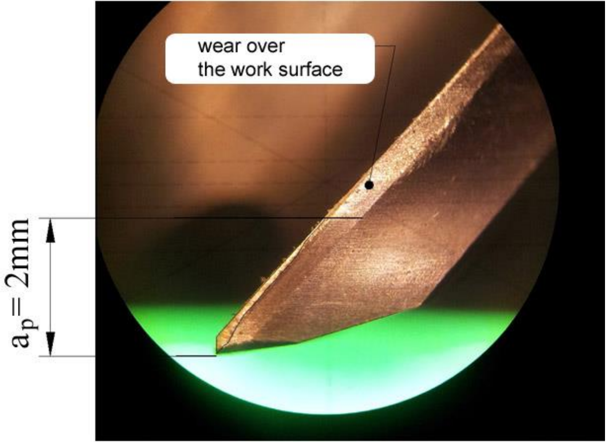
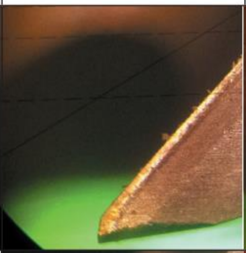
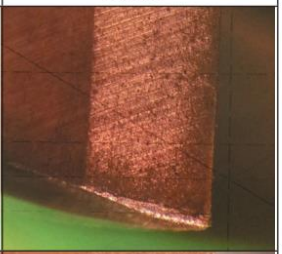
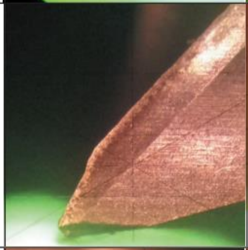
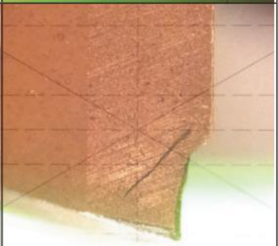
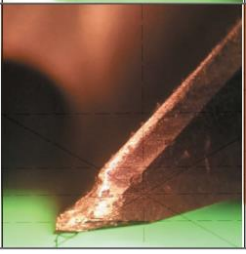
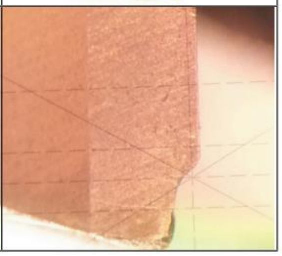


Fig. 4. Wipe over the work surface

Wipe over the machined surface

TABLE III. Development of wear in subsequent time intervals of tool diameter D = 12 mm

Time	Main application area	Auxiliary application surface
t = 5 min		
t = 10 min		
t = 15 min		

In the case of tools with diameter D = 16 mm and 20 mm, there was no catastrophic wear on cutting time t = 15 min. However, there was localized chipping CH3. An exemplary condition of the blades after 15 min of cutting for tools having a diameter D = 20 mm is shown in fig. 5. This shows the typical development of wear.

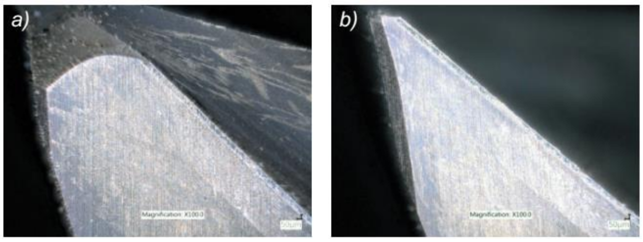


Fig. 5. Example of tool blades diameter D = 20 mm after cutting time t = 15 min: a) local chipping CH3, *b)* local wipe over VB3

Conclusions

On the basis of studies upon influence of the cutter diameter on the stability of blades during milling the titanium alloy Ti6Al4V, it can be concluded:

For cutters with a diameter of 6 mm, the catastrophic wear CF of all blades occurred in the first minute of cutting.

For the remaining tools tested, a characteristic scratch on the main application surface above the cutting line appeared, caused by chip shaking during machining and striking or pressing on the main application surface.

In the case of a milling cutter with a diameter of 12 mm, abrasive wear prevailed to 5 min. After 10 minutes of work, the abrasive wear has continued to grow; catastrophic wear CF occurred on blade No. 1, while the blade 3 revealed chipping flank CH3. By t = 15 min, local chipping CH3 occurred on all blades.

Tools with diameter D = 16 mm and D = 20 mm, in spite of local CH3 shifts, have retained the cutting capacity for t = 15 min.

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