Study of the effect of sharpness of cutting tools on the formation of defects in the surface finish in micro cutting titanium alloys

D S Rechenko, D G Balova, A K Aubakirova, R U Kamenov, V G Churankin
Omsk State Technical University, 11, Mira Ave., Omsk, 644050, Russia

Abstract. The quality of machining of titanium alloys in the aviation and medical fields, characterized by the presence of micro vias, scales and surfacing on the treated surface, as well as the level of roughness is important in the manufacture of key parts. The quality parameters of the treated surface are influenced by many factors - cutting modes (cutting speed, depth and feed), cutting tool parameters (geometry of the cutting part, hardening coating, sharpness of the cutting wedge, etc.), technological equipment parameters (rigidity and accuracy), etc. The aim of the work was investigation of treated surface of titanium alloy VT1-00 when milling with small thicknesses of the shear layer, commensurate with the sharpness of the cutting wedge of the cutter. Method. The method of investigation of the treated surface during milling of titanium alloy on the micro level with the use of standard and high-quality carbide cutting tools is proposed. Results. Operating experience of the received carbide tool has shown that sharpness of a cutting wedge influences quality of the processed surface characterized by microwaves, scales and burrs, also by the roughness of the treated surface. On the basis of carried out researches it is established that for maintenance of conditions of normal cutting and chip formation it is necessary to provide sharpness of the cutting wedge characterized by the conditional entered radius of a blade rounding having values less than values of the sizes of grains of a processed material, that is \( r_e < 5 \mu m \). Field of application. The obtained results of work allow to substantiate the recommendations on the required sharpness of carbide cutting tools used for milling of titanium alloys at the micro level. Conclusions. Experiments on the study of the process of cutting of titanium alloy VT1-00 at the micro level to determine the effect of cutting tool sharpness on the quality of the treated surface (microwaves, scales and burrs), allow to form recommendations on its initial state and determine performance.

1. Introduction
The wide application of titanium alloys in aerospace, medical, automotive and electronics industries is due to their physical and mechanical properties. High quality requirements are placed on the parts, particularly in terms of dimensional accuracy, shape accuracy and roughness of the machined surface. The existing world experience in machining of titanium alloys covers a wide range of issues related to requirements to metal cutting equipment and tools, machining modes, etc. [1; 2]. This paper presents research of peculiarities of milling at the micro level. In foreign works [3; 4] the concept of "micromachining" is connected with the process of manufacturing miniature parts with high accuracy. According to the authors, this concept is associated with obtaining surfaces at the micro level, that is, it is determined by the processes of chip formation and surface layers of the treated part, the size of which varies within a few tens of micrometers.

2. Problem formulation
The task of the work is to study the treated surface of titanium alloy VT1-00 when milling with small thicknesses of the cut layer, commensurate with the sharpness of the cutting edge of the milling cutter.

3. Formatting the text
There are several non-traditional processing methods that can perform micro-level processing: ion-beam cutting, micro laser processing, micro forming and microelectrodischarge processing, but these machining processes have limitations either because of the creation of a two-dimensional (2-D) microstructure or because of high production costs. In addition to these machining methods, micro cutting is another unconventional machining method that is capable of forming miniature complex parts and individual elements [5-10].

Micro-level machining is considered better than other non-conventional machining methods because it has high productivity, process flexibility, low set-up costs and production of complex parts, but is also accompanied by some problems such as burrs, poor surface quality, breakages and rapid tool wear [1; 9]. Therefore, many factors such as tool vibration [1; 11], plastic deformation under the surface [1] and microstructure of the material [11] that are not taken into account, become significant at the micro level [10]. At the same time this process becomes more complicated when processing hard-to-machine materials, in particular titanium alloys VT6, VT1-00, VT3-1, etc., used for medical implants, turbine blades, aerospace fasteners, rods, valves, etc. because of its ratio of high strength per weight, ability to withstand high temperatures, biocompatibility and corrosion resistance [12].

Micro-level milling differs from classical milling mainly due to the ratio of cutting edge sharpness of the tool, characterized by a conventional inscribed blade rounding radius $r_e$, to the thickness of the cut layer $f_z$, which leads to rapid wear and breakage (Figure 1). In this case, unfavorable chip formation conditions occur, which is reflected in a decrease in the quality of treatment.

![Figure 1. Cutting pattern at cutting layer thickness: a) more sharpness of the cutting wedge $f_z > r_e$; b) less sharpness of the cutting wedge $f_z < r_e$.](image)

Reducing the thickness of the layer to be cut to values less than the sharpness of the tool blade makes it difficult to form chips and the treated surface. On the treated surface, there are defects such as microwaves, scales and burrs (Figure 2), the size of which often exceeds the size of titanium alloy grains. It is known that grains of titanium alloys have the size of 5...30 microns.
Figure 2. Finished specimen surface in titanium alloy with a standard end milling cutter.

This effect is due to the formation of a negative front angle, which leads to a lower cutting rate, higher squeezing and scratching rates. In this case, the material being processed is deformed due to shear and the cutting depth increases due to deformed shear, which at some point becomes larger than the blade-rounding radius, resulting in chips formation [3]. Therefore, in order to create conditions for normal cutting during milling, it is necessary to use carbide-cutting tools that have a sharpness of the blade much smaller than the grain size of the processed titanium alloys, i.e. the blade radius should be less than 5 µm. Such sharpness of the milling tool can be obtained due to a set of measures related to the superfast sharpening and subsequent application of hardening coating [11].

4. Experimental results and discussions

A review of the literature has shown that the formation of defects (microwaves, scales and burrs) depends on the cutting and feed rate [2, 12-19], but according to the authors this dependence is greater than the blade rounding radius. Figures 3 and 4 show the tool blade and the material being processed at the initial time and output.

As a result of superfast sharpening at cutting speed of 300-400 m/s and application of hardening coating Al-Si-N having microhardness of the order 24-27 GPa the milling cutter for milling at microlevel having sharpness of a blade of cutting edges $r_e = 3.7...5.1$ µm is made. Subsequent tests of the obtained milling tools were carried out on a high precision coordinate boring machine 2431SF10 at
cutting speed \( V = 56 \, \text{m/min} \), feed tooth \( S_z = 4.6 \, \mu\text{m} \). The resulting treated surface is shown in Figure 5, from which you can see the absence of microwaves, scales and burrs.

![Figure 5. Titanium alloy specimen surface treated with an end milling cutter for micro-level machining.](image)

On the researches carried out it is established that roughness of the processed surface on similar modes, at processing by the standard milling tool \( (r_e = 15...40 \, \text{microns}) \) is within the limits: in the transverse direction \( R_{a_t} = 3.34...5.59 \, \mu\text{m} \) and in the longitudinal direction \( R_{a_l} = 2.61...4.85 \, \mu\text{m} \), and when milling the resulting milling tool \( (r_e = 3...5 \, \mu\text{m}) \) – \( R_{a_t} = 0.86...0.90 \, \mu\text{m} \) and in the longitudinal direction \( R_{a_l} = 0.23...0.38 \, \mu\text{m} \) respectively.

5. Discussion of results

Researches of the treated surface of the titanium alloy VT1-00 at milling with small thicknesses of the cut layer, commensurate with the sharpness of the cutting edge of the milling cutter allowed to establish the influence of the rounding radius on the quality of the treated surface, characterized by microwaves, scales and burrs, also roughness of the treated surface. It is established that reduction of blade rounding radius in 5-6 times allows proportionally reducing the roughness level and size of defects.

6. Conclusions and conclusion

1. The operating experience of the obtained carbide tool has shown that the sharpness of the cutting wedge affects the quality of the treated surface, characterized by microwaves, scales and burrs, and the roughness of the treated surface. It is established that when machining with a standard milling tool \( (r_e = 15 \ldots 40 \, \text{microns}) \) the roughness of the machined surface is within the limits: in the transverse direction \( R_{a_t} = 3.34...5.59 \, \mu\text{m} \) and in the longitudinal direction \( R_{a_l} = 2.61...4.85 \, \mu\text{m} \), and when milling with the obtained milling tool \( (r_e = 3...5 \, \mu\text{m}) \) – \( R_{a_t} = 0.86...0.90 \, \mu\text{m} \) and in the longitudinal direction \( R_{a_l} = 0.23...0.38 \, \mu\text{m} \) respectively.

2. On the basis of the carried out researches it is established that for maintenance of conditions of normal cutting and chip formation it is necessary to provide sharpness of the cutting wedge characterized by the conditional entered radius of a blade rounding having values less than values of the sizes of grains of the processed material, that is \( r_e < 5 \, \mu\text{m} \).

References

[1] Ucun I, Aslantas K, and Bedir F 2013 An experimental investigation of the effect of coating material on tool wear in micro milling of Inconel 718 super alloy Wear 300 p 8–19

[2] Jaffery S I and Mativenga P T 2009 Assessment of the machinability of Ti-6Al-4V alloy using the wear map approach Int. J. Adv. Manuf. Tech. 40 p 687–696

[3] Ali M Y, Khan A A, Banu A and Asharaf M 2012 Prediction of Minimum Chip Thickness in Tool Based Micro End Milling Int. J. Integr. Eng. 4 p 6–10
[4] Kumar S P L, Jerald J, Kumanan S and Prabakaran R 2014 A review on current research aspect in tool-based micromachining processes *Materials and Manufacturing Processes* 29 p 1291-1337

[5] Jaffery S H I, Khan M, Ali L and Mativenga P T 2016 Statistical analysis of process parameters in micromachining of Ti-6Al-4V alloy *Proc. Inst. Mech. Eng. S* 230 p 1017–1034

[6] Kuram E and Ozcelik B 2013 Multi-objective optimization using Taguchi based grey relational analysis for micro-milling of Al 7075 material with ball nose end mill *Meas. J. Int. Meas. Confed.*, 46 p 1849–1864

[7] Camara M A, Rubio J C C, Abrao A M and Davim J P 2012 State of the art on micromilling of materials *Journal of Materials Science & Technology* 29 p 1291–1337

[8] Mamedov A and Lazoglu I 2015 Micro ball-end milling of freeform titanium parts *Advances in Manufacturing* 3(4) p 263–268

[9] Thepsonthi T and Özel T 2013 Experimental and finite element simulation based investigations on micro-milling Ti-6Al-4V alloy: Effects of CBN coating on tool wear *J. Mater. Process. Tech.* 213 p 532–542

[10] Thepsonthi T and Özel T 2012 Multi-objective process optimization for micro-end milling of Ti-6Al-4V titanium alloy *Int. J. Adv. Manuf. Tech.* 63 p 903–914

[11] Rechenko D S, Popov A Y, Titov Yu V, Balova D G, Gritsenko B P 2019 Ultra-high-speed sharpening and hardening the coating of carbide metalcutting tools for finishing aircraft parts made of titanium alloys *Journal of Physics: Conference Series* 1260 p 062020

[12] Rehman G Ul, Jaffery S H I, Khan M, Ali L, Khan A and Butt S I 2018 Analysis of Burr Formation in Low Speed Micro-milling of Titanium Alloy (Ti-6Al-4V) *Mech. Sci.* 9 p 231–243

[13] Bajpai V, Kushwaha A K and Singh R K 2013 Burr Formation and Surface Quality in High Speed Micromilling of Titanium Alloy (Ti6Al4V) Systems; *Micro and Nano Technologies; Sustainable Manufacturing* 2 V002T03A017

[14] Chen M J, Ni H B, Wang Z J and Jiang Y 2012 Research on the modeling of burr formation process in micro-ball end milling operation on Ti-6Al-4V *Int. J. Adv. Manuf. Tech.* 62 p 901–912

[15] Kim D H, Lee P-H and Lee S W 2014 Experimental Study on Machinability of Ti-6Al-4V in Micro End-Milling *Proc. World Congr. Eng.* II p 1–4

[16] Özel T, Thepsonthi T, Ulutan D and Kaftanolu B 2011 Experiments and finite element simulations on micromilling of Ti-6Al-4V alloy with uncoated and CBN coated micro-tools *CIRP Ann.-Manuf. Technol.* 60 p 85–88

[17] Özel T and Liu X 2009 Investigations on mechanics-based process planning of micro-end milling in machining mold cavities *Materials and Manufacturing Processes* 24(12) p 1274-1281

[18] Pratap T, Patra K 2017 Micro-fabrication Lab, Department of Mechanical Engineering *India IOP Conf. Series: Materials Science and Engineering* 229 p 012011

[19] Malekian M, Mostofa M G and Park S S 2012 Modeling of minimum uncut chip thickness in micro machining of aluminum *M.B.G. Jun Journal of Materials Processing Technology* 212 p 553–559

**Source of funding. Gratitude**

The work was carried out with the financial support of the Grant Council of the President of the Russian Federation for state support of young Russian scientists and for state support of leading scientific schools of the Russian Federation, grant number MD-345.2020.8.