Ultra-high-speed sharpening and hardening the coating of carbide metal-cutting tools for finishing aircraft parts made of titanium alloys

D S Rechenko1, A Y Popov1, Yu V Titov1, D G Balova1, B P Gritsenko2

1Omsk State Technical University, 11, Mira Ave., Omsk, 644050, Russia
2Institute of Strength Physics and Materials Science of Siberian Branch of Russian Academy of Sciences, Omsk, Russia

Abstract. The work is devoted to the creation of a hard-alloy tool for finishing processing of heat-resistant and titanium alloys. Objective: to increase the efficiency of carbide blade tools for finishing machining of aircraft parts of heat-resistant and titanium alloys by means of ultrafast grinding, to determine the method of hardening the cutting part and the conditions of its operation. Subject of the research: the quality of the cutting wedge (conditional inscribed radius of the blade rounding, the presence of microchips, blockages and microhardness) obtained by ultrafast grinding and work-hardening of the cutting part and the determination of the conditions of its operation. Objectives: to implement the method of carbide tools ultrafast sharpening, providing the required quality of the cutting wedge, characterized by the conditional inscribed radius of rounding of the blade, the presence of microchips, blockages and microhardness, capable of producing blade processing of parts from heat-resistant and titanium alloys with an accuracy of 3…5 microns and roughness of Ra 0.2…0.4 microns; to investigate the process of superfast sharpening and to determine the effect of sharpening modes of carbide metal cutting tools on the quality of the sharpened tools cutting wedge; to investigate the reason for the reduction of the durability of the cutting tool while reducing the rounding radius of the blade and to determine the composition of the hardening coating, which slightly reduces the sharpness of the blade; to investigate the influence of cutting modes of finishing heat-resistant and titanium alloys with a tool blade sharpness up to 5 microns on its durability, as well as the surface roughness and accuracy of the part. Research methods: electron microscopy (Jeol JCM-5700, an energy-dispersive spectrometer attachment JED-2300; NTEGRA PRIMA (NT-MDT)); optical microscopy (MikroCad Premium, ODSCAD measurement program; Axio Observer.A1m); vibrodynamic analyzer (DIANA-2M); coating thickness measurement method (Calotest CAT-S-0000); microhardness measurement method (PMT-3 and DM 8 B AFFRI); determination of the characteristics of the tribotechnical properties by the method of testing for friction and wear (II5018); determination of cooling capacity (Compaton). Theoretical and calculation methods: simulation method; end element method; methods of mathematical statistics.

1. Introduction

In recent years, the requirements for dimensional accuracy of structural elements of aircraft parts are in the range of 3…5 microns, and the roughness of the machined surface is about Ra = 0.2…0.4 microns. Such requirements are being met at the moment with the use of grinding and finishing operations, which are inefficient, costly and cause the residual stresses in the surface layer of aviation parts, which reduces the life of these parts. Theoretically, such requirements can be met by modern
high-precision blade equipment, tools and processing strategies. However, blade processing providing a similar level of quality is a problem due to the fact that the tool must have the corresponding sharpness of the cutting edge, characterized by the conditional inscribed radius of rounding of the blade. Modern cutting tools for finishing operations, using interchangeable carbide plates (ICP) available on the market have the best sharpness of the blade from 15 to 40 microns. The carbide tools for finishing operations produce Sandvik Coromant, Seco, Mitsubishi, KZTS, Kennametal, ZCC and others, while the carbide grain size is in the range from 0.1 to 1 micron. To increase the productivity and accuracy of machining aviation parts today it is possible to replace abrasive operations with blade ones. At the same time, minimization of abrasive operations in the manufacture of aircraft parts is currently the main trend in the world. The sharpness of the tool ultimately determines dimensional accuracy and roughness of processing. Therefore, to obtain the required dimensional accuracy of 3…5 microns, the radius of rounding of the blade must have a corresponding sharpness. In this case, the tool must be operational, that is, the blade must remain sharp throughout the entire processing period.

Researchers and modeling of the cutting process presented in works [1, 2] found out that shavings formation is possible only at a ratio of the thickness of the cut layer to the rounding radius of the blade ρ, which characterizes sharpness, with values more than 0.26. At smaller values, shavings are not formed, i.e. cutting does not occur. In this case, these dependencies are valid only for sufficiently large radii of the blade rounding, as a rule, for semi-finishing plates having a blade edge about ρ = 50 μm. At small thicknesses of the layer being cut, a negative front angle is formed on the cutting part, which often reaches values up to -50°. This leads to the fact that cutting becomes difficult, shavings are not formed properly, so that the required parameters for the quality of processing with such a tool, is almost impossible to achieve.

2. Problem formulation

The force calculation of cutting of heat-resistant and titanium alloys made it possible to establish that obtaining a blade radius of less than one micrometer is impractical because it will not be workable from the strength point of view [3]. The formed requirements for turning and milling ICP come to the fact that the sharpness of the tool should be about 3…5 microns, chips, microcracks and debris should be comparable to the sharpness, and the defective layers that soften the cutting wedge should be minimal.

The implementation of such requirements is possible in several ways – sharpening in several operations with disks of different grain sizes; fine-tuning after sharpening operations; electro-diamond grinding and high-speed grinding. At the same time, by sharpening in several operations and high-speed sharpening, you can get the required sharpness, but these methods cause microchips and microcracks in the tool blade, therefore the blade will not be workable for finishing. Fine-tuning is an inefficient process and is possible only for fairly simple surfaces; complex surfaces are difficult to process. Preliminary experiments showed that superfast grinding allows to achieve the formed requirements for tool quality.

3. Task solution of implementation of the method of carbide tools ultra-high-speed sharpening

High-speed grinding studies are carried out at the Chinese Industrial Institute, some research results at speeds up to 160 m/s are presented in works [4–11]. A further increase in speed in the mentioned above works is limited to the design of the grinding wheel, which has a solid metal body with a diamond-bearing layer deposited on the periphery. The speed limit is associated with a significant increase in centrifugal forces leading to the separation of the diamond layer. In this work, to achieve a cutting speed of 400 m/s, we created a special grinding and sharpening wheel, designing which we solved the problems of the method of its fastening, of determining the rational profile of the wheel and the way of attaching diamond inserts, given that this place is the most objected to loads. The first two
problems were due to the experience in operating aviation disks, and the third problem was solved by modeling the sector of a circle - by calculating equivalent stresses, relocations and deformations. The proposed grinding wheel was tested in the armored chamber to break. According to calculations and field tests, the speed up to which the grinding wheel can perform processing was 668 m/s, which provided a safety factor of 1.5.

The creation of an efficient high-speed machine with wide technological capabilities was implemented on the basis of the VZ-326F4 grinding and sharpening machine, which provided the necessary working movements for sharpening carbide tools at peripheral speeds up to 400 m/s (Fig. 1).

![Ultra high speed grinding and sharpening machine](image-url)

**Figure 1.** Ultra high speed grinding and sharpening machine

4. Experimental results and discussions

On the basis of experimental studies, a rational diamond tool SD4, having a grain size of 28/14, on a Bakelite bond B01-1 was selected. Further studies made it possible to determine that carbide plates for finishing machining of heat-resistant and titanium alloys, as supplied, have a blade edge of $\rho = 37...43 \, \mu m$ (Fig. 2,a).

When the sharpening speed is $V = 30 \, m/s$, the sharpness of the ICP blade is $\rho = 16...30 \, \mu m$ (Fig. 2,b), with a further increase in the sharpening speed, the sharpness of the blade increases (Fig. 2,c,d,e) and at the sharpening speed of $V = 400 \, m/s$, the conditional radius of rounding of the blade is $\rho = 3...5 \, \mu m$ (Fig. 2,e). At the same time, with superfast sharpening, on the blade there are no obvious microchips, no obvious microcracks, which are present during classical sharpening at lower speeds.

The results of measurements of the sharpness of the ICP blade at various grinding speeds are summarized in Table 1.

| Machining speed $V$, m/s | Value type       | Average $\mu m$ | Minimal $\mu m$ | Maximal $\mu m$ | Deviation $\mu m$ |
|-------------------------|------------------|-----------------|-----------------|-----------------|------------------|
| As supplied             | Radius measurement| 40.4            | 37.4            | 42.7            | 1.09             |
|                         | Chipping         | 0.7             | 0.0             | 3.2             | -                |
| 30                      | Radius measurement| 20.1            | 15.5            | 29.87           | 3.08             |
|                         | Chipping         | 0.8             | 0.0             | 4.7             | -                |
| 60                      | Radius measurement| 10.8            | 8.6             | 15.7            | 1.92             |
|                         | Chipping         | 1.1             | 0.0             | 3.5             | -                |
| 160                     | Radius measurement| 5.5             | 4.5             | 6.8             | 0.5              |
|                         | Chipping         | 0.8             | 0.0             | 3.3             | -                |
| 240                     | Radius measurement| 7.4             | 6.4             | 10.7            | 0.79             |
|                         | Chipping         | 1.0             | 0.0             | 4.4             | -                |
| 400 | Radius measurement | 4.4 | 3.7 | 5.1 | 0.4 |
|-----|--------------------|-----|-----|-----|-----|
|     | Chipping           | 0.8 | 0.0 | 3.2 | -   |

![Figure 2](image_url)

**Figure 2.** The results of measuring the sharpness of the ICP blade for finishing difficult-to-work materials: a) as supplied; b) after sharpening at $V = 30$ m/s; c) after sharpening at $V = 60$ m/s; d) after sharpening at $V = 160$ m/s; e) after sharpening at $V = 240$ m/s; f) after sharpening at $V = 400$ m/s

The study of the process of ultra high speed grinding allowed to establish that with an increase in the speed of sharpening, the wear mechanism of diamond grains changes (Fig. 3). At speeds less than 120 m/s, the wear mechanism is dominated mainly by the complete removal of diamond grains from the surface of the wheel, as a result of the formation of an abrasion pad, and also due to the constant clogging of the grinding wheel, which as a result becomes inoperative.
Figure 3. The change in the mechanism of wear of diamond grains with an increase in the speed of sharpening

With an increase in the sharpening speed from 120 to 240 m/s, the mechanism of wear of diamond grains changes in the direction of wear at the macro level, as a result, each individual grain is removed in several parts. With a further increase in speed, the micro wear of grains begins to predominate and as a result, in this mode, the circle operates in the self-sharpening mode, that is, with a constantly aggressive part of the cutting surface.

**Study of the causes of reducing the stability of cutting tool when decreasing the blade radius of rounding and determining the composition of a strength coating**

In order to improve the performance of the ICP, the issues of applying a strengthening coating on the cutting wedge were considered. The most common coatings at the moment are TiN-based coatings, but they are able to withstand thermal stress up to 500 °C, with a further increase in temperature these coatings become inoperable due to their peeling and separation from the surface. At the same time, the best results in resistance to oxidation and to thermal loads were shown by coatings based on aluminum and silicon nitrides (Al-Si-N), which have a microhardness of about 25-30 GPa, and also, due to the developed deposition technology, they allow to obtain quite thin layers. In this work, we used a coating with a thickness in the range of 2...2.5 microns, which slightly reduced the sharpness. Moreover, this coating is able to withstand thermal loads up to 1500 °C.

The use of various processing methods affects the microhardness of the machined surfaces of the tool. It has been established that with classical honing, at speeds of the order of 30 m/s, the microhardness decreases along the front surface when approaching the tool blade. At superfast grinding, these indicators change slightly. About 15-17 GPA provides superfast grinding. The combined use of ultrafast sharpening and hardening coatings allowed us to obtain a microhardness of the front surface of the order of 24-27 GPa, which indicates an increase in the efficiency of the tool.

In the study of machined surfaces with superfast and classical sharpening, it was found out that increasing the speed of sharpening leads to a change in the elemental composition of the surface layers of the ICP. With an increase in the rate of grinding on the treated surface, a decrease in the oxygen content (in free form and in compounds) is observed. When the grinding speed is 30-40 m/s, the
oxygen content is in the range of 1.5…6 %, and when the speed increases to 300-400 m/s, the oxygen content does not exceed 1 %, which further confirms the theory of the effect of oxidation on reducing the microhardness of the treated surfaces, which affects the performance of the cutting wedge ICP (Fig. 4).

![Graph showing the effect of oxygen content on microhardness](image)

**Figure 4.** The effect of oxygen content on the change in microhardness

As a method of hardening ICP, a reinforcing negative chamfer on the front surface within $f = 3...5 \, \mu m$ and an angle $\gamma = -10^\circ$ was also used. Obtaining such elements on the cutting part of such dimensions at the moment is a technological problem, therefore several abrasive tools with different characteristics were tested in this work and the characteristic of the grinding wheel was determined, which made it possible to obtain stable negative chamfers – a circle with an SDN characteristic, 7/5 grit bakelite-based B2-01 (Fig. 5).

![Images of different ICP blades](image)

**Figure 5.** ICP blades obtained by blunting various abrasive materials:
- a) 47F2500 Norton (Brazil);
- b) SDM28/20 B2-01 (Russia);
- c) E532GT Luga (Russia);
- d) SDN7/5 B2-01 (Russia);
- e) suspension of submicropowder Masaper prep polishing suspension 0.05 microns (USA)

The described activities and the results of research in the complex allowed us to work out the technology for manufacturing ICP in batches.

**Research on the effect of the cutting modes of the heat-resistant and titanium alloys finishing processing with a tool blade sharpness up to 5 \( \mu m \) on its strength and quality of the parts**
To obtain experimental data on processing, a number of materials VT3-1, 3M, PT-3V, VT20, VT22, KhN77TYuR and 12KH18N10T were chosen as the brightest representatives of the titanium group.

When milling and turning titanium alloy VT20 and VT22, the best result was shown by sharpened ICP coated with Al-Si-N coating and implanted additionally in the Mo coating to reduce the friction coefficient. As a result of testing the ICP it was determined that it is possible to obtain either an increase in durability of the order of 5.5 times as compared to the ICP that we use for the moment, or a significant decrease in the roughness of the machined surface due to an increase in cutting conditions. Similar results were obtained with high-speed milling.

Comparative tests in turning and milling titanium alloys VT3-1, PT-3V and 3M were carried out on high-precision machines using modern tooling with a cut depth of 5, 10 and 50 microns. As a result, the microscopic irregularities of the machined surfaces decreased, according to dimensional values, by a factor of 5-10 and were Ra = 0.11…0.16 μm, at a cutting speed of 150 m/min while turning. During milling, the best roughness values were achieved at a cutting speed of 120 m/min Ra = 0.08…0.10 μm (Fig. 6).

![Figure 6. Roughness of machined surfaces during a) turning and b) milling of titanium alloys VT3-1, PT-3V and 3M](image)

Carbide plate wear was investigated. It has been established that the type of wear is similar to classical wear, that is, wear areas obtained by abrasion are observed on the back surface, and microchips are observed on the front surface. At the same time, even with significant wear on the back surface, the tool blade remains operational.

Experience in the use of carbide tools showed that the cutting ability during finishing is determined by the coefficient of the cutting ability Kc.a. – the ratio of the thickness of the cut layer of the processed material α to the conditional inscribed rounding radius of the tool blade ρ. It is established that when the ratio of the thickness of the layer being cut to the rounding radius of the blade is Kc.a. ≤ 0.25 cutting ability is absent, under these conditions of cutting there is a scratching and indentation of the processed material. When the coefficient of the cutting ability Kc.a. = 0.25…0.5, unstable cutting is observed, with further increase in the ratio value, the cutting ability becomes more stable. That is, the use of modern cutting tools having a blade edge of ρ = 15…25 μm, stable cutting ability occurs when the thickness of the cutting layer is in the range of more than α = 7.5…12.5 μm. At the same time, an increase in the ratio of the thickness of the layer being cut to the sharpness of the blade over
Kc.a. > 10 leads to unstable cutting ability, due to significant loads on the blade and the intensification of wear.

On the basis of the conducted research, it was established that for stable obtaining dimensional accuracy of 3...5 μm and roughness of the processed surface Ra = 0.1...0.2 μm of parts made of heat-resistant and titanium alloys during blade processing, it is necessary to ensure the smallest conditional entered rounding radius of the blade, i.e. maximum sharpness, as well as the absence of microchips and cracks on the cutting wedge, with a minimum level of oxidation.

It was established experimentally that by increasing the speed of sharpening the ICP and applying the coating based on Al-Si-N, it is possible to obtain a workable carbide tool with a blade sharpness of less than 5 microns, providing a dimensional accuracy of the order of 3...5 microns and a roughness of the treated surface Ra = 0.2...0.4 microns when finishing blade processing of aviation parts from heat-resistant and titanium alloys, which is equivalent to grinding and can be recommended instead of the latter.

5. Conclusion

Improving the efficiency of carbide blade tools for finishing aircraft parts made of heat-resistant and titanium alloys by ultra high speed sharpening and applying a hardening coating on the cutting part under certain conditions of its operation eliminates grinding and finishing operations, which reduces the defective layer and minimizes the cost of parts production. Thus, the problem of obtaining suitable parts is solved due to the guaranteed receipt of the required tolerance for the machined size and surface roughness.

Acknowledgments

The authors thank and dedicate this work to the Russian scientist-physicist, corresponding member of the Russian Academy of Sciences Sergey Grigorievich Psahie.

References

[1] Malekian M, Mostofa M G and Park S S 2012 J. Materials Processing Technology 212 pp 553–559.
[2] Woon K S, Rahman M and Fang F Z 2008 J. Materials Processing Technology 195 pp 204–211.
[3] Rechenko D S, Popov A Y, Babaev A S and Laptev N V 2018 J. Russian Engineering Research 38 pp 794–797.
[4] Li B, Ni J, Jianguo Y and Steven Y 2014 J. Advanced Manufacturing Technology 70 pp 813–819.
[5] Li Z, Ding W, Liu C and Su H 2016 J. Advanced Manufacturing Technology 34 pp 0–9.
[6] Mamalis A G, Horvath M and Grabchenko A I 2000 J. Materials Processing Technology 97 pp 120–125.
[7] Tian L, Fu Y, Xub J, Li H and Ding W 2015 J. Machine Tools & Manufacture 89 pp 192–201.
[8] Wang C, Fang Q, Chen J, Liu Y and Jin T 2016 J. Advanced Manufacturing Technology 83 pp 937–948.
[9] Zhao Z, Fu Y, Xu J and Zhang Z 2016 J. Advanced Manufacturing Technology 87 pp 3545–3555.
[10] Zhu Y, Lu W, Sun Y and Zuo D 2016 J. Advanced Manufacturing Technology 89 pp 0–9.
[11] Yang L, Fu Y, Xu J and Liu Y 2015 J. Materials and Design 88 pp 827–836.