Research on the high quality replacement carbide plates operability with Al-Si-N hardening coating

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Abstract. Quality requirements for the manufacturing parts made of hard-to-machine materials with cutting tools are quite high. At the same time, modern carbide cutting tools are not always able to maintain working capacity throughout the entire mechanical operation, providing these requirements. The article considers test results of replaceable carbide plates during finish processing of a heat resistant alloy. Carbide plates were sharpened with ultra high speed grinding, and then hardened with Al-Si-N coating, which made it possible to obtain tool blade sharpness \( \rho = 3...5 \mu m \) and to achieve resistance several times higher compared to a similar tool.

1. Introduction

The achievement of the required accuracy of parts made of hard-to-machine materials used in modern military engineering is often a very difficult task, and sometimes practically impossible without the use of finishing operations. It is known that any of the finishing operations are expensive, low-productive, demand highly skilled workers, special equipment and devices, which significantly increase manufacturing costs. The elimination of finishing operations from the technological process is possible only if the required quality of processing with a cutting tool is ensured. The problem is that a modern metal cutting tool is not able to provide the required quality of processing, due to its insufficient sharpness.

The quality of a processed surface defines the operation efficiency of a metal part and it is characterized by a number of criteria. Modern technological processes of high precision unit making for aviation, automobile, rocket production industries etc. cannot be performed without high quality carbide cutting tool. Often it forms the required surfaces of parts and determines the roughness and accuracy of processing. Therefore, creating a high quality cutting tool is an actual and a complex task. The quality of the cutting tool is a complex characteristic, including following parameters: blade sharpness, defined by a conditional inscribed rounding radius; lack of microchips and microcracks; roughness of the cutting wedge surfaces; geometric correspondence of the cutting wedge profile; the cutting wedge oxidation level. These parameters determine the operability of the cutting tool. The creation of a carbide tool with high parameters of quality makes it possible to exclude grinding operations from the technological process of manufacturing high precision parts from hard-to-machine materials, which of course reduces production costs.

At present, there are several basic technologies for grinding and obtaining high quality carbide cutting tools. The use of fine-grained diamond wheels, fine-tuning and electro-diamond sharpening makes it possible to obtain blade sharpness no less than 5 microns, but on the cutting wedge there can be formed microcracks, front and back surface backfalls and sometimes microchips. Meanwhile, the
surface roughness obtained by grinding can reach $Ra = 0.04 \, \mu m$. The main and essential disadvantage of all these sharpening methods is the oxidized surface layer formation on the treated surfaces and the volume near the cutting wedge blade. This happens as a result of thermal loads, while the use of cutting fluid does not exclude the occurrence of oxygen on the treated surfaces.

2. Problem formulation

The aim of the work is to obtain a high quality carbide tool with ultra high speed grinding followed by a hardening coating application to exclude finishing operations in precision parts manufacturing. In the present study the following tasks were solved: the creation of a high speed grinding machine VZ-326F4; sharpening of a carbide blade using various modes; determination of the sharpened tool quality using raster microscopy; and application of a hardening coating by deposition in an argon-nitrogen gas mixture using a vacuum machine "KVANT".

3. Theory

Some directive technological processes of manufacturing parts for military equipment do not allow grinding, polishing and finishing operations. It is possible to use only blade operations, while the quality requirements for the treated surfaces are quite high. The blade operations requirements for dimensional accuracy can reach $3...5 \, \mu m$, and for roughness $Ra = 0.1...0.2 \, \mu m$. Of course, to achieve such quality indicators for a blade tool is very problematic, primarily because of the quality of the carbide tool itself, e.g. the sharpness of the blade, the presence of microchips and microcracks and defective layers of the cutting wedge.

High quality cutting edge of the metal cutting tool is currently achieved by various methods - finishing, electro-diamond grinding, grinding with fine-grained wheels, etc., but these methods are low-productive and do not allow to obtain a stable result, namely, sharpness of the blade $- \rho = 3...5 \, \mu m$; absence of microchips and microcracks; the roughness of the cutting wedge surfaces $- Ra = 0.04...0.10 \, \mu m$; geometric correspondence of the cutting wedge profile; the cutting wedge condition.

The method of ultra high speed grinding with the use of traditional grinding and shaping movements combined with a reinforcing nanostructured coating makes it possible to produce a high quality carbide tool.

Classical sharpening methods and modes followed by finishing operations make it possible to obtain a blade with sharpness no less than $5...6 \, \mu m$. The sharpening of a replaceable carbide plate (RCP), made of hard alloy GC1105, was carried out at a speed $V = 30...40 \, m/s$, longitudinal feed $F = 1...1.5 \, m/min$ and a cutting depth $t = 10...20 \, \mu m/double \ stroke$. In this case, cobalt burns out from the cutting wedge surface layers, which indicates a low grinding quality.

The blade sharpness was measured by MikroCad Premium, manufacturer GF Messtechnik GmbH, using software for measuring ODSCAD in OOO PROMTEKH (St. Petersburg).

The elemental composition of the surface was determined by X-ray spectral analysis, the condition of the carbide plates cutting edge was examined by means of a scanning electron microscope EVO50 (Carl Zeiss, Germany) and a scanning electron microscope Jeol JCM-5700 (Japan), with an energy-dispersive spectrometer JED-2300 attachment. It was found that the WC content (tungsten carbide) is about 92%, and Co (cobalt) - about 5.5% and O (oxygen) - about 2.3%, which indicates the formation of oxides on the hard alloy surface (atomic percentages are used). Studies have shown, that the percentage of oxygen is in the range between 1.7...6.3%, depending on the grinding modes and the application of the cutting fluid. The change in the chemical composition indicates the occurrence of high contact temperatures during grinding.

Ultra high speed grinding method for grinding modes $V = 300...400 \, m/s$, $F = 1...1.5 \, m/min$ and $t = 3...5 \, \mu m/double \ stroke$ makes it possible to obtain a blade with a sharpness of $2...3 \, \mu m$. It was found that the WC content (tungsten carbide) is about 94%, and Co (cobalt) - about 6%, which corresponds to the initial composition and condition of the alloy GC1105 (Sandvik Coromant) for CNMG120404 type plates. At the same time, no detectable oxides are observed on the controlled surface, and no cobalt burning from the cutting wedge body is observed.
After superfast grinding and obtaining sharpness of the blade 2...3 μm, a hardening coating was applied to the front surface. Ensuring of the required carbide tool blade firmness during finishing operations is possible due to the use of selection of optimal processing modes and application of hardening coating on the cutting wedge surfaces [1-4]. Currently there are several basic methods for modifying tool surfaces. Of the total amount of surface modification operations, the share of strain hardening is about 10%; thermal hardening is 15%; surface alloying - 25%; coating application - 48% and combined methods - up to 2%.

The analysis of coatings applied to cutting tools revealed two groups that differ in their application technology and use features: chemical vapour deposition (CVD) and physical vapour deposition (PVD) (Table 1). High requirements are imposed on modern coatings: the coefficient of friction μ should be in the range from 0.1 to 0.35; heat resistance from 900 to 1200 °C; chemical stability; hardness 35-50 GPa; adhesion strength 50-150 N, etc. Many studies have been written on the application of these methods [5-9]. There are significant disadvantages that limit the use of the CVD method on the finishing tool. This is due to the rounding of the cutting edge during deposition, as well as to the uneven coating of tools with complex shapes.

The use of PVD coatings allows to coat sharp edges without causing significant dulling due to uniform deposition. With the help of the PVD process, coatings up to 5 microns thick are obtained, which do not require additional processing. The PVD method allows coatings to be applied without increasing the brittleness of the tool, since the application temperature is about 500 °C, in contrast to 900-1000 °C for the CVD method. The PVD method allows the use of coating compositions such as Ti-CN, Al-Si-N, Ti-Al-N and Al-Cr-N, oxides of Al₂O₃, (Al-Cr)₂O₃, Ti-Al-Si-Cr-N. According to the authors of the studies [8; 12], multilayer coatings have great prospects due to the increase in the specific loads on the cutting tool, caused by the wide spread of titanium and high temperature alloys. At the same time, optimal coating thicknesses are 4.0-12.0 μm, at which minimum residual stresses and maximum adhesion forces with the base are achieved in the coating [5; 6].

| Characteristic                                      | CVD                     | PVD                     |
|----------------------------------------------------|-------------------------|-------------------------|
| Heating temperature during application, °C          | 700-1100                | 200-500                 |
| Coating area                                       | External, internal open | Reversed to ion source  |
| Thickness of applied coating, microns               | 2-10                    | 0,1-6                   |
| Increases the rounding radius of the blade         |                         |                         |
| Composition of the applied coating                 | Ti-N, Ti-C, Ti-C-N, Al₂O₃| Ti-N, Ti-C, Ti-C-N, Al₂O₃, Ti-Al-N, Cr-N, Al-Si-N, Zr-C, Ti-Al-Si-N |
| Microhardness of coating, GPa                       | 20-24                   | 21-35                   |
| Coefficient of friction                             | 0,4-0,7                 | 0,07-0,5                |
| Oxidation temperature, °C                           | 400-600                 | 400-1100                |
| Residual stresses                                   | High tensile            | Tensile-compressive     |
| Heat treatment after coating application            | Required to remove      | Not required            |
| residual stresses                                   |                         |                         |

According to the data of study, the additional element introduction of silicon Si or boron B makes it possible to increase the hardness, as well as the stability of the coating while operating. In addition, it is also important to improve other properties of the coating, for example, improving heat resistance and oxidation resistance, reducing the coefficient of friction and wear, increasing endurance, etc. Current experiments show that nanocomposite coatings consisting of nanograins exhibit such properties. Such nanocomposites can be formed either by reactive sputtering, when the nanocrystalline phase is formed at a low deposition temperature or by nanocrystallizing from an amorphous material.
The unique properties of coatings are stipulated by their nanostructure. However, nanostructures remain stable only at temperatures below the recrystallization temperature, at which grain growth and the formation of new crystalline phases begin [6]. The thermal stability of most hard coatings lies at temperatures below 1000 °C, this is certainly enough for their use in many areas. However, cutting tools for processing heat-resistant and titanium alloys can experience extreme local temperatures (up to 2000 °C). Therefore, it is extremely important to use protective coatings that are thermally stable at temperatures $T > 1000$ °C and at the same time provide good protection against oxidation. These two requirements can only be met with amorphous composite nanostructured coatings, because amorphous materials do not contain grains.

An important characteristic of coatings is the elastic modulus of coating $E$, which shows the ability of the coating to be elastically deformed when a force is applied. According to the existing studies, the elastic modulus of Ti-N is 590 GPa, Ti-C is 460 GPa, Al-C is 350 GPa, Ti-Al-N is 350 GPa, Si-Ti-N is 350 GPa, Si-Al – 200 GPa, Si-BCN – 210 GPa [3]. Studies [6; 7; 9] show that the best results for resistance to oxidation have Si-Ti-N, Al-Si-N and Si-B-C-N coatings. The hardness of these coatings is in the range 25-30 GPa, and the modulus of elasticity is in the range of 200-350 GPa.

4. Experimental results
In order to clarify the effect of the hardening coating on the cutting properties of the tool, a study was made of the tool life with an Al-Si-N coating, and Mo ions were implanted in coatings of some samples. The coating thickness on the cutting wedge front surface was 2.3 μm, and a coating with a much worse adhesion of 0.26 μm thickness due to dusting was also formed on the rear surface. Resistance tests of the RCP with different geometry (Figure 1) were carried out when turning the steel XH77THOP on an Okuma ES-L8II lathe with BlasoCut 2000 cutting fluid. Machining conditions are as follows: cutting speed $V = 40$ m/min, longitudinal supply $F = 0.05$ mm/rev and cutting depth per diameter $t_d = 15$ μm.
**Figure 1.** Blades of carbide plates razor-sharpened and with chamfer: a) razor-sharp, coating Al-Si-N; b) razor-sharp, coating Al-Si-N + Mo; c) with chamfer, coating Al-Si-N; d) with chamfer, coating Al-Si-N + Mo

The razor-sharp plate (Figure 2, a) has a pronounced cut and a classic wear on the back surface. The razor-sharp plate with a coating and implanted molybdenum Mo (Figure 2, b) has a classic wear on the back surface. The plate with a chamfer and an Al-Si-N coating (Figure 2, c) has residual outgrowth traces (stagnant zone) with coating remained, and the plate with a chamfer and implanted molybdenum Mo (Figure 2, d) has a pronounced wear on the front surface with a peeling coating and residual outgrowth traces. Meanwhile, this plate has chipping on the blade. The best result for resistance and quality of processing was shown by a plate with negative chamfer and coating. According to the test results, the plates had different wear.
Tool resistance in the processing of the high temperature alloy XH77TIOP was evaluated by changing the quality parameters of the workpiece, namely, when the roughness of the machined workpiece surface $Ra = 0.2 \mu m$ was increased, after which the RCP was replaced.

5. Results discussion

The obtained stability results in comparison with the initial RCP are given in Table 2.

| Plate                      | Resistance T, min | Cutting path L, m | Processed area S, cm² |
|----------------------------|-------------------|-------------------|-----------------------|
| Razor-sharp, coating Al-Si-N | 42.4              | 1696              | 847.8                 |
| Razor-sharp, coating Al-Si-N + Mo | 59.5              | 2379              | 1189.7                |
| With chamfer, coating Al-Si-N | 169.6             | 6782              | 3391.2                |
| With chamfer, coating Al-Si-N + Mo | 43.5               | 1741              | 870.4                 |
| Initial                    | 31.3              | 1252              | 626.1                 |

Obtained results of processing alloy XH77TIOP, presented in Table 2, show that the best result for resistance and quality of processing has a plate with chamfer and Al-Si-N coating. The resistance is 169.6 minutes, which is 3.9 times higher than the standard RCP (initial).

6. Conclusion

The carried out researches have shown, that high speed sharpening provides much higher quality of the RCP blade and of the cutting wedge processed surfaces. Classical grinding modes provide the sharpness of the blade at 5...10 µm, and high speed grinding - at 2...3 µm, meanwhile the treated surfaces do not have traces of oxides. The operation efficiency of the tested RCP, evaluated by the resistance when turning the heat resistant alloy XH77TIOP, is 3-4 times higher than with the standard RCP.

The application of thin Al-Si-N type coatings results in an effective increase in the RCP resistance, without deterioration of the machined parts quality.
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References
[1] Sinopalnikov V A and Tereshin M V 1987 Monitoring the state of high-speed drills to limit their temperature Soviet engineering research (vol 7 Issue 6) pp 59–62
[2] Filimonov L N 1979 High-speed grinding (Leningrad: Machine building) p 248
[3] Wang C, Fang Q, Chen J, Liu Y and Jin T 2016 Subsurface damage in high-speed grinding of brittle materials considering the kinematic characteristics of the grinding process International Journal of Advanced Manufacturing Technology (vol 83) pp 937–948
[4] Zhu Y, Lu W, Sun Y and Zuo D 2016 Grinding characteristics in high-speed grinding of boron-diffusion-hardened TC21-DT titanium alloy with vitrified CBN wheel The International Journal of Advanced Manufacturing Technology pp 0–9
[5] Gribkov V A, Grigoriev F I, Kalin B A and Yakushin V L 2001 Perspective radiation-beam technologies of material processing (Moscow: All the year round) ed Kalina B A p 528
[6] Gribkov V A, Demina E V, Dubrovsky A V, Maslyaev S A, Pimenov V N, Sasinovskaya I P, Miklaszewski R and Scholz M 2009 Application of a plasma accelerator of the dense plasma focus type in simulation of radiation damage and testing of materials for nuclear systems International Topical Meeting on Nuclear Research Applications and Utilization of Accelerators p 8
[7] Korotaev A D, Borisov B D, Moshkov Yu V, Ovchinnikov S V, Pinzhin Yu P and Tyumentsev A N 2009 Elastic stress state in superhard multielement coatings Physical Mesomechanics (vol 12 (5-6)) pp 269–279
[8] Rechenko D S, Popov A Y, Gritsenko B P, Sungatulin A R, Titov Y V, Sergeev V P, Voronov A V, Deev K A and Pupchin V A 2016 Formation of wear-resistant structures on solid alloy for superfinish processing AIP Conference Proceedings (vol 1783 part 020191 (1-4))
[9] Mitterer C, Mayrhofer P H and Musil J 2003 Thermal stability of PVD hard coatings Vacuum (vol 71 (1)) pp 279–284