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Improved Hard Alloys for Efficient Milling

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Abstract—Milling efficiency is improved by aerodynamic modification of the surface structure of hard-alloy tools. A physical interpretation of this method is outlined. Test results for the proposed tool and a standard tool are compared.

Keywords: milling, hard alloy, structure, aerodynamic modification, sound, strength, productivity

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Improving the efficiency of cutting and, in particular, milling is of great practical interest [1–5]. Milling involves the removal of material from the blank by multicutter tools as a result of brief discontinuous contact [6]. The azimuthal cutting force fluctuates widely on account of the variable cut-layer thickness, dynamic impacts, and vibration. With decrease in the number of mill teeth and increase in machining parameters such as the cut-layer thickness, the milling width, the supply per tooth, and the cutting speed, we see broader variation in the azimuthal cutting force. In addition, its variation increases with increase in basing error of the replaceable polyhedral plates in the mill housing and tooth wobble due to nonaxial insertion of the mill in the machine tool [7].

In milling with large cyclical impact loads, we note fatigue damage to the mill and disintegration of the cutting-plate surface. This may be prevented if the tool's wear resistance is increased by increasing its strength and by modification of the working surface (the application of wear-resistant coatings and ion implantation) [8–10].

Today, we still lack a mill material that is characterized by hardness, wear resistance, and impact strength, and we need methods of boosting the impact strength of the material without impairing its hardness and wear resistance.

THE MILLING PROCESS

Milling tools are made of hard alloys, which are heterogeneous composites: brittle and refractory grains of tungsten, titanium, and tantalum carbides are cemented by cobalt binder. Thus, the heterogeneous large-grain structure of the hard alloy consists of faceted carbide grains (crystals) in cobalt binder. The lattice dimension is 0.2–0.7 nm. The deficiencies of hard alloys include brittleness, which increases with decrease in cobalt (Co) content; low flexural strength (0.9–2.1 GPa); and low impact strength (25–75 kJ/m^2) [11].

In milling with large variable vibrational and impact loads, various kinds of wear are observed. Damage accumulates in the surface layer of the replaceable polyhedral plates, which may disintegrate. The tool wear depends greatly on the cutting temperature: adhesive and abrasive wear occurs up to 600°C; at 600–900°C, abrasive wear increases as a result of surface oxidation, and diffusional wear is observed; above 900°C, besides those types of wear, the stability of the cutting edge declines and high-temperature creep develops.

The wear rate of the hard alloys depends on the heat conduction—that is, on the rate of heat transfer from the tool's cutting edge to the blank in the contact zone. Such heat transfer reduces the contact temperature. The heterogeneous alloy microstructure reduces its thermal conductivity. The total thermal conductivity of the tool consists of the conductivity of the crystal lattice and the thermal vibrations of the free electrons.

For T15K6 hard alloy, we investigate the total thermal conductivity with increase in the cutting temperature θ to 500°C and beyond. In Fig. 1, we show the thermal conductivity λ and linear expansion coefficient α as a function of θ for the components of the replaceable polyhedral plate and the blank. For Co, λ is 1.76 times higher than for T15K6 alloy; that increases the heat transfer from the tool's cutting edge to the blank. For W, however, λ is 1.35 times that of T15K6 alloy. In that case, the total heat conduction in the contact zone is reduced by a factor of 1.3, and the wear resistance of the tool is improved [12].

At a cutting speed $v = 180$ m/min, the temperature in the cutting zone is 850°C. The thermal conductivity

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of the machined material—say, steel 45—and the hard alloy components changes as follows with increase in temperature from 500 to 850°C: λ falls by a factor of 1.54 for steel 45 (Fig. 1), 1.23 for cobalt, and 1.3 for tungsten. The total thermal conductivity of T15K6 hard alloy falls by a factor of 1.3 with increase in temperature from 500 to 850°C. That results in sharp temperature rise of the replaceable polyhedral plate and increase in the wear rate. As a result, the cobalt binder in the contact zone has a higher temperature than the other alloy components; that reduces its hardness. The carbide grains experience tensile stress, while the binder is subject to compressive stress.

On heating to 850°C, the expansion is 3.4 times greater for the cobalt binder than for the tungsten-carbide (WC) grains and twice that for the titanium-carbide (TiC) grains.

Suppose that the carbide grain at the plate surface is retained by a hemispherical cobalt shell. Then wear may be explained in that, with decrease in adhesion of the TiC and WC grains on interaction with the blank and the chip, they are ripped out of the cobalt binder and entrained from the contact zone more intensely than at cutting speeds below 100 m/min.

Thus, milling efficiency may be improved not only by improving the microstructure of the tool surface but also by increasing its thermal conductivity—specifically, by creating a uniform small-grain structure at the surface of the hard-alloy plate, with smaller carbide grains, and ensuring strong adhesion to the cobalt binder. That boosts the thermal conductivity from the rear surface of the cutter to the blank and lowers the cutting temperature.

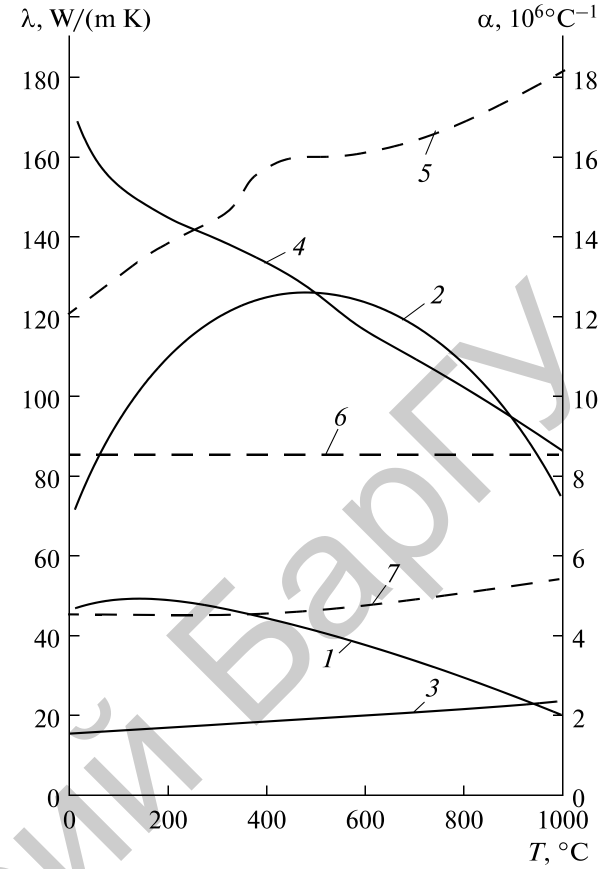

Fig. 1. Dependence of the thermal conductivity λ (—) and linear expansion coefficient α (---) on the temperature θ of the hard-alloy plate and the blank: (*1*) steel 45; (*2*, *5*) Co; (*3*, *6*) Ti; (*4*, *7*) W.

AERODYNAMIC MODIFICATION OF THE SURFACE STRUCTURE

The wear resistance of standard replaceable polyhedral plates may be improved by aerodynamic modification [13]. A T15K6 alloy plate with a cutting-edge length of 12.7 mm is subjected to aerodynamic modification in two cycles. Each cycle consists of heating to 840°C, 20-min holding, and aerodynamic treatment: vibration of industrial-grade air at a frequency of 8 kHz for 6–8 min. The air is supplied at a pressure of $1.5–2 \times 10^5$ Pa. The air flow rate is 2.7 m^3/h in the first cycle and 4.9 m^3/h in the second cycle. Aerodynamic treatment is followed by two cycles of stress removal at 150–170°C for 20 min, with subsequent complete cooling in air.

In aerodynamic treatment of standard T15K6 alloy plates, the grain size of the carbide phases in the surface structure is reduced and redistributed: the number of WC grains of area <2 μm^2 increases from 48 to 82, while grains of area >10 μm^2 disappear. Before aerodynamic modification, grains of area up to 14 μm^2 are seen.

We investigate the structure and phase state of T15K6 alloy samples on a DRON-2.0 X-ray diffraction system in monochromatized cobalt radiation, according to Bragg–Brentano geometry. X-ray recordings are made in scanning mode with a 0.1° increment at 30 kV, with an anode current of 15 mA [14]. The interplane distance *d* is determined from the Wulf–Bragg formula

$$a = d_{hkl}\sqrt{h^2 + k^2 + l^2} \text{ and } 2d\sin\theta = n\lambda$$

where λ is the radiation wavelength; θ is the diffraction angle; *a* is the lattice constant; *h*, *k*, *l* are the indices of the diffraction line. The physical broadening of the diffraction lines is determined by approximation; their integral intensity is determined by means of HS++ software (developed by PanAnalytical, the Netherlands).

Analysis of the X-ray diffraction patterns (Fig. 2) shows that broadening of the TiC diffraction lines is due to the small size of the grains and their high content of defects and dislocations. The broadening of the WC diffraction lines is also due to the small grain

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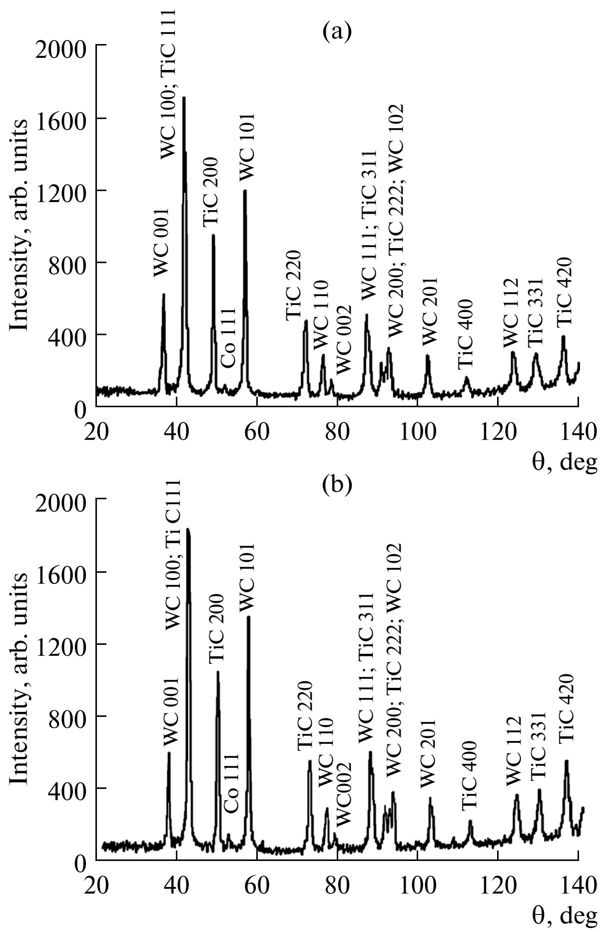

Fig. 2. Fragments of the X-ray diffraction patterns of standard (a) and aerodynamically modified (b) surfaces of T15K6 alloy plates.

size. The dislocation density is much higher in TiC than in WC.

Aerodynamic modification somewhat reduces the physical broadening of the diffraction lines from the carbide phases. Thus, for the WC 002 line, the broadening is slight. The ratio of the diffraction lines also changes. In particular, the broadening ratio of the TiC diffraction lines becomes closer to the secant ratio of the diffraction angles. That indicates the annihilation of dislocations and decrease in TiC grain size. For WC, the broadening ratio of diffraction lines 001 and 002 lies between the secant ratio and tangent ratio of the corresponding diffraction angles. That indicates some increase in dislocation density in the WC grains after aerodynamic modification.

In vibrational and pulsed treatment, the dislocations arriving at the surface enlarge the surface defects, which extend deeper into the volume of the material. Cracks begin to form; their development is accelerated by dynamic loads.

Most of the hard alloy consists of carbide phase, which, in turn, consists mainly of crystalline grains of tungsten carbide, a complex titanium carbide, and cobalt binder. The crystal lattices of the alloy have various defects, such as point defects (vacancies and interstitial defects, substitutional and interstitial atoms in the crystal lattice); linear defects (edge and screw dislocations); and surface and volume defects (twinning zones, grain boundaries, the crystal surface, packing defects, grain boundaries, and phase boundaries). Within the grains, ordered positioning and stability of the atoms must extend all the way to the grain boundaries.

Under the action of the external force, the distance between the atoms changes in the direction of the tension, and the crystal lattice is distorted. That creates stress, which significantly affects the deformation and failure of the alloy. In the presence of dislocations, even small stress produces considerable deformation of the crystals. Cracks are stress concentrators. They generate stresses that exceed by an order of magnitude the stresses created by the working loads.

Taking account of the pair configuration and the validity of Hooke's law for the hard alloys, we make the following assumption: the displacement of the atom may be described by a plane elastic wave propagating along the line that connects the atoms. The minimum vibration frequency of the atoms is determined by the maximum lattice dimension. The maximum vibration frequency is bounded by the distance between the closest lattice atoms. Calculations indicate that the normal vibration spectrum of the lattice includes acoustic vibration frequencies. That is the basis for the aerodynamic modification of hard alloys. In other words, aerodynamic modification involves the action of elastic waves such that self-organization is initiated. That leads to structural and phase transformations in view of the localized resonance with the crystal lattice. Self-organization ensures transition from disordered motion and a chaotic state of the fluctuations to a new order, with improvement in alloy structure for the given operating conditions.

PRODUCTION TESTS

We now investigate the cutting properties of T15K6 alloy polyhedral plates employed as the teeth of a 12-tooth end mill (diameter 200 mm). We determine the number of 25 × 16 × 140 mm steel 45 cutter handles that may be machined before critical tool wear is observed. The tests are conducted on a GF2120 turret-milling machine, in discontinuous conditions—that is, with repeated tooth insertion in the blank and its subsequent removal and consequently with repeated impacts. At 5-min intervals, the wear at the rear surface of all the plates is measured by means of a MWD microscope (Poland), and the roughness R_z of the machined surface is determined on a MIS-11 microscope. Milling continues until the plates are completely blunt, as indicated by squeaking, considerable vibration, and roughness of the machined surface cor-

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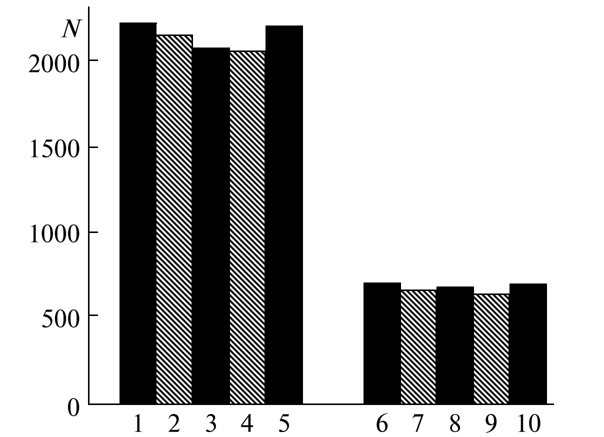

Fig. 3. Working life (the number N of blanks that may be machined) of aerodynamically modified (1–5) and standard (6–10) T15K6 hard-alloy plates in the milling of steel 45 blanks; cutting depth 1.5–2 mm; tool speed 325 rpm; supply 1250 mm/min.

responding to a vibrational grid [15]. Others indicators of bluntness are buildup on the front surface of the plates and even plate fracture. In Fig. 3, we plot the tool life (the number N of blanks that may be machined) in five experiments for standard and aerodynamically modified hard-alloy plates.

We find that, as a result of nonlinear resonant vibration of the atoms in the hard-alloy tool, aerodynamic modification reduces the grain size of the phases and induces self-organization of the crystal lattice and the grains, with consequent increase in the milling efficiency: the mean life of the polyhedral T15K6 alloy plates in an end mill is increased by a factor of 3.1, while the number of parts machined by a single set of plates is increased from 590 to 2140.

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