ISSN 1068-798X, Russian Engineering Research, 2018, Vol. 38, No. 6, pp. 457–461. © Allerton Press, Inc., 2018.
Original Russian Text © E.E. Ashkinazi, V.G. Ral'chenko, V.I. Konov, D.V. Vinogradov, P.A. Tsygankov, E.A. Dryzhak, A.V. Khomich, 2018, published in Vestnik Mashinostroeniya, 2018, No. 3, pp. 77–81.

Frictional Coefficients between Aluminum–Silicon Alloy and Cutting Inserts with MPCVD Diamond Coatings

E. E. Ashkinazi[a], V. G. Ral'chenko[a], V. I. Konov[a], D. V. Vinogradov[b], *, P. A. Tsygankov[b], E. A. Dryzhak[c], and A. V. Khomich[d]

[a]Prokhorov Institute of General Physics, Russian Academy of Sciences, Moscow, Russia
[b]Bauman Moscow State Technical University, Moscow, Russia
[c]OOO MVS GRUP, Moscow, Russia
[d]Fryazino Branch, Kotelnikov Institute of Radioengineering and Electronics, Russian Academy of Sciences, Fryazino, Russia
**e-mail: vdv2010@bk.ru*

Abstract—The frictional coefficients at the front and rear surfaces of a VK6 hard-alloy cutter with experimental nano- and microcrystalline CVD diamond coatings applied in microwave plasma are determined by extrapolation to zero cut-layer thickness. It is found that, for diamond coatings with a single microcrystalline layer and those with both a microcrystalline layer and a nanocrystalline layer, the frictional coefficients are less than for an uncoated hard-alloy cutter and also for a cutter with a Sandvik diamond coating.

Keywords: cutter life, diamond coatings, two-layer coatings, plasma chemical synthesis, hard alloy, aluminum–silicon alloy, frictional coefficient, cutting force

DOI: 10.3103/S1068798X18060047

The surface properties of cutters greatly affect tool deterioration: cutter wear, buildup of workpiece material on the cutter, and the heat liberation in friction between the chip and the cutter's front surface and between the workpiece and the cutter's rear surface. These processes largely depend on the frictional coefficients at the cutter's front and rear surfaces.

The application of diamond coatings directly to hard-alloy cutters is of great interest on account of the extremely low frictional coefficient and high strength and wear resistance of thin diamond layers [1]. Today, diamond coatings are usually applied to cutting tools by chemical vapor deposition (CVD) [2]. This method relies on the activation of a hydrocarbon mixture, most often in microwave plasma (MPCVD) or by means of a hot filament (HFCVD). Diamond coatings obtained by CVD on tungsten-carbide (WC–Co) cutters greatly improve the wear resistance and life of hard-alloy tools, significantly reduce the frictional coefficient between the chip and coating, prevent tool erosion and corrosion, reduce heating and buildup, and result in higher quality of the machined surface [3]. This is especially important in the high-precision machining of metal-matrix and carbon composites for the aerospace, defense, and nuclear industries.

The application of two-layer and multilayer diamond coatings may improve adhesion to the substrate and also the tool's cutting properties. For example, the deposition and properties of two-layer diamond coatings with a microcrystalline base and a nanocrystalline upper layer were considered in [1–3]. In such coatings, the microcrystalline layer provides hardness and adhesion to the substrate, while the nanocrystalline layer provides reduced roughness and greater elasticity. Multilayer diamond coatings may also be used to prevent cracking and increase the thermal conductivity [4].

The frictional coefficient of tools with diamond coatings is also important in the machining of aluminum–silicon alloys, which tend to adhere to the cutter, on the one hand, and are highly abrasive on account of their silicon content, on the other. Tools that ensure a lower frictional coefficient are less subject to adhesion and more resistant to abrasive wear [5]. By investigating the frictional coefficient at the surface of tools with such diamond coatings, we may predict their wear resistance, optimize their application, and select the best cutting conditions.

If grown on substrates other than diamond, diamond coatings are polycrystalline and generally have columnar texture, associated with the competitive growth of individual crystallites. Depending on their grain size, diamond coatings may be classified as microcrystalline (crystallites larger than 500 nm) and nanocrystalline (crystallites smaller than 100–200 nm). For nanocrystalline coatings with a smooth surface, the frictional coefficient is lower than for microcrystalline coatings. However, tests show that, with normal loads, the threshold at which microcrystalline coatings peel away (160 N) is markedly higher than for nano-

Table 1. Geometric parameters of experimental cutting inserts

Insert	γ, deg	α, deg	ρ, μm	*r*, mm
Uncoated	5	0	30	0.8
Microcrystalline coating	5	0	45	0.8
Microcrystalline + nanocrystalline coating	5	0	35	0.8
Sandvik coating	12	7	20	0.8

crystalline coatings (90 N), on account of the difference in adhesion [6].

The frictional coefficients are measured on a diagnostic system developed at Bauman Moscow State Technical University and installed in the tool-technology laboratory for assessment of the wear resistance and cutting forces in turning [7]. The tests are conducted on a 1K62 lathe with a Kistler dynamometer. A390 Al–Si alloy workpieces (diameter 85 mm) are employed. The measurement results are analyzed by means of Kistler DynoWare software.

Triangular turning inserts of VK6 hard alloy are used, as well as a rhombic insert with a Sandvik diamond coating, The VK6 alloy inserts are tested with no coating, with a microcrystalline coating of thickness up to 5 μm, and with a two-layer coating (microcrystalline layer + nanocrystalline layer) of thickness up to 12 μm [8]. Table 1 presents the rounding radii of the cutting edge and the radii at the cutter tip of those inserts. We see that all the inserts have similar characteristics and may be used for comparative research. Note that the rounding radius of the Sandvik insert is smaller than for the triangular inserts by a factor of 1.5–2. All the inserts are placed in appropriate holders. The geometric parameters of the cutting section for the triangular insert are as follows: rear angle $\alpha = 5°$, front angle $\gamma = 0°$, and primary plane angle $\varphi = 90°$. For the rhombic insert, $\alpha = 12°$, $\gamma = 7°$, and $\varphi = 96°$.

Currently, CVD diamond coatings are applied to most cutting tools [9]. An important coating characteristic is the adhesion to the substrate. In the deposition of diamond coatings on a hard-alloy substrate with cobalt binder, the influence of adhesion on the tool life is a key consideration. Adhesion is disrupted on account of the catalytic action of cobalt, which facilitates the formation of sp^2 carbon in place of diamond. It is important here that cobalt is present both at the growth surface of the diamond coatings and in the gas phase and also that the cobalt diffuses out of the substrate in the course of chemical vapor deposition. To limit the action of cobalt on this process, we use a hard-alloy substrate preliminarily subjected to selective etching of tungsten-carbide subgrains and the boundaries of the cobalt binder by means of Murakami reagent (10 g $K_3[Fe(CN)_6]$ + 10 g KOH + 100 mL H_2O) for 5 min, with subsequent etching by Caro's acid (3 mL 96% H_2SO_4 + 88 mL 30% H_2O_2) for 15 s.

To eliminate the mobility of the binder and prevent clustering of cobalt at the stage of diamond nucleation, tungsten barrier layers are also applied. To prevent cracking during the growth of the diamond layer, ion-plasma heating of the substrate to 700°C is replaced by cold magnetron heating with substrate temperature no higher than 50°C. To reduce the internal stress, a two-stage technology is developed for the application of a tungsten film:

(1) application of a thin (10–30 nm) tungsten sublayer on a substrate activated by an ion beam, when the working pressure of the magnetron discharge is less than 0.25 Pa:

(2) further film growth at optimal pressures of 0.5–0.7 Pa.

The hardness of the diamond coating after application of the tungsten layer is 77.1 *HRC*, which is 2.5 *HRC* greater than for the etched surface. The Vickers microhardness is 1600 HV_{100} for a maximum indenter depth of 0.59 μm and a loading rate of 13.3 mN/s. The ratio of the inverse elastic deformation to the total mechanical work of indentation is decreased to 37%.

Samples of one- and two-layer diamond coatings on VK6 hard-alloy substrates (cutting inserts) are produced in a microwave plasma chemical reactor with a methane–hydrogen (CH_4–H_2) atmosphere. In the experiments, diamond is synthesized on VK6 substrates in an ARDIS-100 microwave plasma chemical reactor developed at the Natural-Science Research Center, Prokhorov Institute of General Physics, Russian Academy of Sciences, in collaboration with OOO Optosystemy (http://www.cvd-diamond.ru). The conditions of synthesis are as follows: microwave power 2.5–2.9 kW; substrate temperature 750–800°C, pressure in chamber 9.3–10.6 kPa; mixture of H_2 (purity 99.99999%) and CH_4 (purity 99.9995%); methane concentration 4 and 15% in the growth of microcyrystalline and nanocrystalline coatings, respectively; gas flow rate 1 dm^3/min. To increase the nucleation density, detonation diamond powder and high-pressure and high-temperature (HPHT) diamond from suspensions of 5- and 50-nm particles, respectively. That ensures a nucleation density of ~109 particle/cm^3.

As a rule, the frictional coefficient is determined in the simulation of friction in various systems, using an indenter of the tool material and a counterbody of the workpiece material [10, 11]. In some studies, the frictional coefficient is determined by computational and experimental methods. However, it is difficult to use such methods in determining the frictional coefficients in cutting, since the friction at the tools' contact surfaces is heterogeneous and the characteristics of the material required for the calculations cannot be obtained in practice.

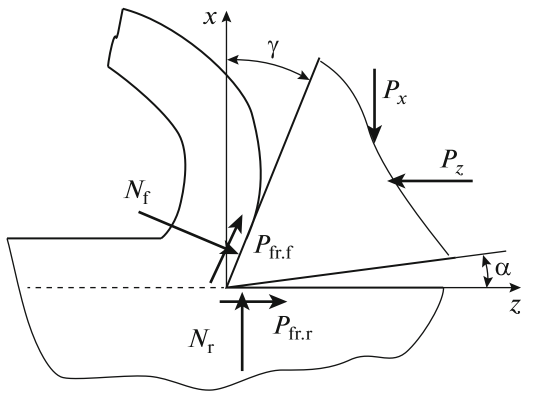

Fig. 1. Forces in the primary secant plane.

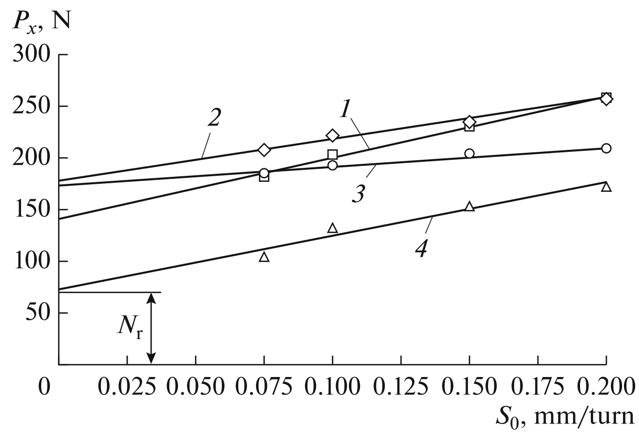

Fig. 2. Dependence of the axial cutting force P_x on the supply S_0 for VK6 alloy inserts with no coating (*1*), with a single-layer microcrystalline diamond coating (*2*), with a two-layer (microcrystalline + nanocrystalline) diamond coating (*3*), and with a Sandvik diamond coating (*4*).

To obtain reliable results, the frictional coefficient must be measured directly in cutting, but that poses methodological difficulties. In particular, it is difficult to determine the forces on the cutter's front and rear surfaces. To that end, we calculate the frictional coefficients at the cutter's front and rear surfaces by extrapolation of the cutting force to zero cut-layer thickness [12, 13]. According to the extrapolation method, the force on the rear surface does not depend on the cutting force at the rear surface, the cut-layer thickness (the supply), the front angle, and the chip deformation. Therefore, the forces at the rear surfaces are equal to the forces with zero cut-layer thickness, corresponding to $S_0 = 0$.

The normal pressure and the frictional force act on the cutter during its operation (Fig. 1). Since the plane angle of the cutters used in the experiments is 90°, we may write

$$P_z = P_{fr.r} + P_{fr.f}\sin\gamma + N_f\cos\gamma;$$

$$P_x = N_r + P_{fr.f}\cos\gamma + N_f\sin\gamma,$$

where P_z and P_x are the primary and axial components of the cutting force; $P_{fr.f}$ and $P_{fr.r}$ are the frictional forces at the cutter's front and rear surfaces; N_f and N_r are the normal forces at the cutter's front and rear surfaces; and γ is the rake angle.

In the experiment, we use cutters with $\gamma = 0$. In that case

$$P_z = P_{fr.r} + N_f;$$

$$P_x = N_r + P_{fr.f}.$$

Hence, the frictional coefficients at the cutter's front and rear surfaces may be calculated from the formulas

$$K_{fr.r} = \frac{P_{fr.r}}{N_r}; \quad (1)$$

$$K_{fr.f} = \frac{P_{fr.f}}{N_f} = \frac{P_x - N_r}{P_z - P_{fr.r}}. \quad (2)$$

The frictional force $P_{fr.r}$ and normal force N_r are determined by interpolation of the dependence of the cutting force on the cut-layer thickness according to the formula

$$P_{fr.r} = P_z \text{ when } S = 0; \quad N_r = P_x \text{ when } S = 0.$$

Note that this method permits the calculation of the frictional coefficient at the cutter's front and rear surfaces. By contrast, only the frictional coefficient at the rear surface may be calculated by the method in [14, 15].

To determine the frictional coefficients, three measurements of the projections of the cutting force are made at each of the values $S_0 = 0.075$, 0.15, 0.1, and 0.2 mm/turn. On that basis, the forces P_z and P_x are plotted as a function of the supply (the cut-layer thickness). The curves obtained are approximated by linear functions (Figs. 2 and 3). Table 2 summarizes the results.

The equations in Eq. (2) permit the determination of the forces $P_{fr.r}$ and N_r on the insert at zero cut-layer thickness. The frictional coefficients may then be calculated from Eqs. (1) and (2). Table 3 presents the experimental results and the calculated frictional coefficient at the rear surface in the turning of A390 alloy.

Table 2. Approximate equations for the cutting forces P_x and P_z

Insert	P_x	P_z
Uncoated	$141 + 589S_0$	$106 + 1083S_0$
Microcrystalline coating	$178 + 402S_0$	$103 + 1170S_0$
Microcrystalline + nanocrystalline coating	$174 + 184S_0$	$99 + 1134S_0$
Sandvik coating	$73 + 516S_0$	$69 + 1173S_0$

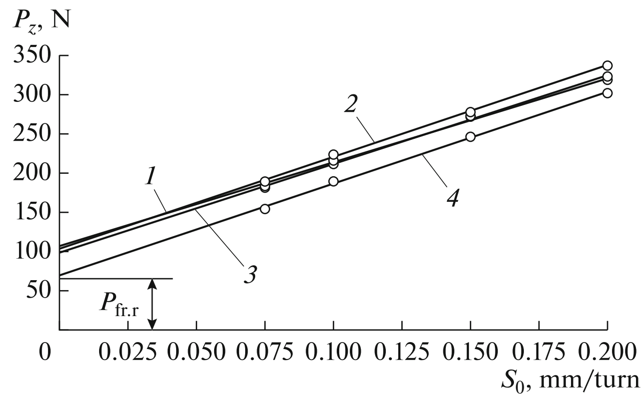

Fig. 3. Dependence of the primary cutting force P_z on the supply S_0 for VK6 alloy inserts with no coating (*1*), with a single-layer microcrystalline diamond coating (*2*), with a two-layer (microcrystalline + nanocrystalline) diamond coating (*3*), and with a Sandvik diamond coating (*4*).

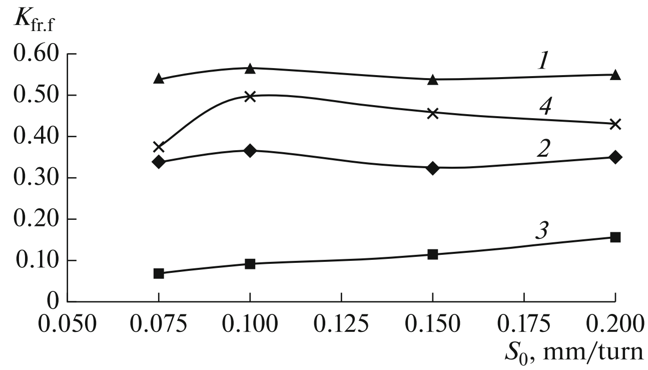

Fig. 4. Dependence of the frictional coefficient $K_{fr.f}$ at the front surface on the supply S_0 for VK6 alloy inserts with no coating (*1*), with a single-layer microcrystalline diamond coating (*2*), with a two-layer (microcrystalline + nanocrystalline) diamond coating (*3*), and with a Sandvik diamond coating (*4*).

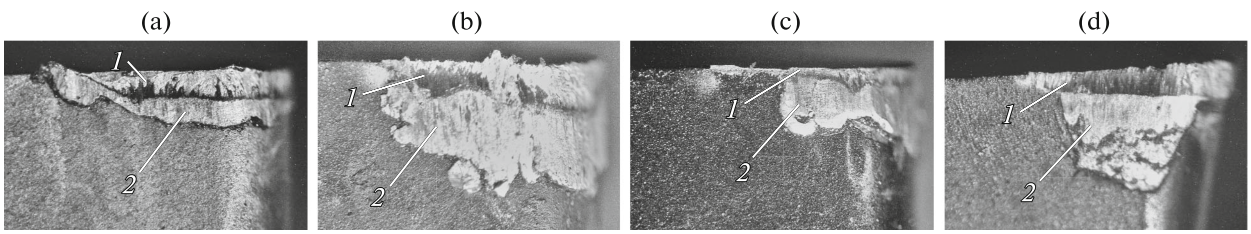

Fig. 5. Wear at the rear surface of inserts with no coating (a), with a single-layer diamond coating (b), with a two-layer diamond coating (c), and with a Sandvik diamond coating (d): (*1*) wear area; (*2*) buildup.

We see that single-layer (microcrystalline) and double-layer (microcrystalline + nanocrystalline) diamond coatings ensure the lowest frictional coefficient; it is about the same in both cases. The difference between the frictional forces and normal forces at the rear surface for inserts with diamond coatings and the inserts with a Sandvik coating may be attributed to the different rounding radii of the cutting edges: a smaller force acts at the Sandvik insert, with a smaller rounding radius, on account of the smaller deformation of the insert.

Table 3. Frictional force $P_{fr.r}$, normal force N_r, and frictional coefficient $K_{fr.r}$ at rear surface

Insert	$P_{fr.r}$, N	N_r, N	$K_{fr.r}$
Uncoated	106	141	0.75
Microcrystalline coating	103	178	0.58
Microcrystalline + nanocrystalline coating	98	173	0.57
Sandvik coating	69	73	0.95

On the basis of Eq. (2), the frictional coefficient $K_{fr.f}$ at the front surface may be calculated when S_0 = 0.075, 0.15, 0.1, and 0.2 mm/turn (Fig. 4). The difference in the results is small. Therefore, we calculate mean values: $K_{fr.f}$ = 0.55 with no coating; 0.34 with a single-layer (microcrystalline) diamond coating; 0.11 with double-layer (microcrystalline + nanocrystalline) diamond coating; and 0.44 with a Sandvik coating. We see that, when using the double-layer diamond coating, the frictional coefficient is a third of that observed with a single-layer coating and a fifth of that observed for VK6 alloy with no coating. We may understand why the frictional coefficient at the rear surface is several times that at the front surface on the basis of the following reasoning.

In cutting A390 alloy, we note intense buildup of material from the workpiece on the cutter (Fig. 5). The material adhering to the rear surface fills the gap between the cutter and the machined surface (Fig. 6). Then friction with the machined material is observed not only at the rear surface but also at the buildup. In other words, the frictional force consists of two components $P_{fr.t}$ and $P_{fr.b}$. Since the buildup consists of the machined material, the frictional force $P_{fr.b}$ will considerably exceed $P_{fr.t}$ and hence the frictional coeffi-

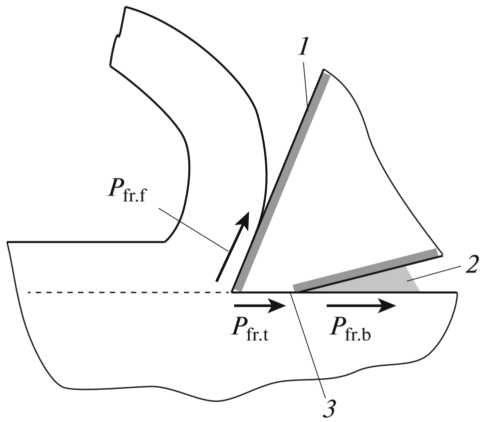

Fig. 6. Forces on a cutter with wear at the rear surface.

cient at the rear surface will exceed that at the front surface, where there is no buildup.

CONCLUSIONS

By extrapolation of the cutting force to zero cut-layer thickness, we may determine the frictional coefficients of nano- and microcrystalline CVD diamond coatings at the front and rear surfaces of a VK6 hard-alloy cutter in the turning of A390 aluminum–silicon alloy.

The frictional coefficients at the front and rear surfaces of the diamond-coated inserts are less than those for the Sandvik diamond coating.

For the double-layer (microcrystalline + nanocrystalline) diamond coating, the frictional coefficient is a third as much as with a single-layer diamond coating; and a fifth as much as with uncoated VK6 hard alloy.

The new CVD coatings are promising for use on hard-alloy tools. They offer the prospect of considerably reducing the cutting force and increasing the tool life.

ACKNOWLEDGMENTS

Financial support was provided by the Russian Scientific Fund (project 15-19-00279).

REFERENCES

1. Polini, R., Chemically vapor deposited diamond coatings on cemented tungsten carbides: substrate pretreatments, adhesion and cutting performance, *Thin Solid Films*, 2006, vol. 515, no. 1, pp. 4–13.
2. Settineri, L., Bucciotti, F., Cesano, F., and Faga, M.G., Surface properties of diamond coatings for cutting tools, *CIRP Ann.*, 2007, vol. 56, no. 1, pp. 573–576. doi 10.1016/j.cirp.2007.05.137
3. Dumpala, R., Chandran, M., and Ramachandra Rao, M.S., Engineered CVD diamond coating for machining and tribological applications, *JOM*, 20015, vol. 67, no. 7, pp. 1565–1577. doi 10.1007/s11837-015-1428-2
4. Catledge, S.A., Baker, P., Tarvin, J.T., and Vohra, Y.K., Multilayer nanocrystalline/microcrystalline diamond films studied by laser reflectance interferometry, *Diamond Relat. Mater.*, 2000, vol. 9, no. 8, pp. 1512–1517. doi 10.1016/S0925-9635(00)00279-X
5. Ashkinazi, E.E., Sedov, V.S., Petrzhik, M.I., Sovyk, D.N., Khomich, A.A., Ralchenko, V.G., Vinogradov, D.V., Tsygankov, P.A., Ushakova, I.N., and Khomich, A.V., Effect of crystal structure on the tribological properties of diamond coatings on hard-alloy cutting tools, *J. Frict. Wear*, 2017, vol. 38, no. 3, pp. 252–258.
6. Abreu, C.S., Amaral, M., Oliveira, F.J., et al., HFCVD nanocrystalline diamond coatings for tribo-applications in the presence of water, *Diamond Relat. Mater.*, 2009, vol. 18, nos. 2–3, pp. 271–275. doi 10.1016/j.diamond.2008.08.016
7. Vinogradov, D.V., Dreval', A.E., and Vasil'ev, S.G., Complex for evaluation of the wear resistance of materials and cutting forces during turning, *Inzh. Vestn. Mosk. Gos. Tekh. Univ. im. N.E. Baumana*, 2014, no. 9, pp. 33–42. http://engbul.bmstu.ru/doc/727928.html. Accessed November 20, 2016.
8. Ashkinazi, E.E., Sedov, V.S., Sovyk, D.N., et al., CVD-diamond hardening of the surface of a carbide tool in a microwave plasma, *Materialy Desyatoi mezhdunarodnoi konferentsii "Uglerod: fundamental'nye problemy nauki, materialovedenie, tekhnologiya," Troitsk, Tezisy dokladov* (Proc. Tenth Int. Conf. "Carbon: Fundamental Problems in Science, Material Science, and Technology," Troitsk, Abstracts of Papers), Moscow, 2016, pp. 43–45.
9. Sergeichev, K.F., Diamond CVD-coatings of cutting tolls: a review, *Usp. Prikl. Fiz.*, 2015, vol. 3, no. 4, pp. 342–376.
10. Kuksenova, L.I., Lapteva, V.G., Kolmakov, A.G., et al., *Metody ispytaniya na trenie i iznos: Spravochnik* (Testing Methods for Friction and Wear: Handbook), Moscow: Intermet Inzhiniring, 2001.
11. Vinogradov, D.V., Quality evaluation of fast-cutting tool, *Izv. Vyssh. Uchebn. Zaved., Mashinostr.*, 1993, nos. 10–12, pp. 121–125.
12. Rozenberg, A.M. and Eremin, A.N., *Elementy teorii protsessa rezaniya metallov* (Elements of the Theory of Metal Cutting), Sverdlovsk: Mashgiz, 1956.
13. Vinogradov, D.V., Analysis and development of methods for evaluation of efficiency of fast-cutting tools, *Cand. Sci. (Eng.) Dissertation*, Moscow, 1995.
14. Lipatov, A.A., Chigirinskii, Yu.L., and Kormilitsyn, S.I., Determining the cutting forces at the tool's rear wear area, *Russ. Eng. Res.*, 2010, vol. 30, no. 11, pp. 1158–1160.
15. Lipatov, A.A., Chigirinskii, Yu.L., and Kormilitsyn, S.I., Temperature-force characteristics of the contact interaction at the wear surface of the tool's rear surface during the turning of austenitic steel, *Obrab. Met. (Tekhnol., Oborud., Instrum.)*, 2012, no. 2, pp. 38–42.

Translated by Bernard Gilbert