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Influence of the Machining Conditions in Rotary Turning by Multifaceted Cutters on the Shaping Temperature and Forces

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Abstract—The influence of technological and design factors on rotary turning by multifaceted cutters is investigated. Semiempirical formulas are proposed to determine the best machining conditions. By optimizing the duration and conditions of machining, the cutting force and temperature in the cutting zone may be decreased, and disintegration of the chip may be improved.

Keywords: rotary turning, multifaceted rotary cutter, machining conditions, chip, productivity, quality

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Traditional shaping methods are often ineffective in the turning of complex steel that is hard to machine, nonferrous metals (aluminum, titanium, magnesium), and the corresponding alloys. The formation of continuous chip, corresponding to considerable frictional drag and high temperature in the deformation zone, shortens tool life and impairs the surface quality of the product [1, 2]. That limits the permissible primary cutting speed, with loss in productivity and greater machining costs.

The quality of traditional turning depends on the shape and size of the workpiece. In particular, the quality is lower in machining long shafts and the surfaces of castings with considerable shape deviations and margins. For such workpieces, it is more effective to use end milling on multipurpose CNC machines, where the tool drive permits high cutting speeds.

Chip fracture is facilitated by the discontinuity of the process in end milling. However, microimpacts on the cutting inserts produce accelerated wear, as well as vibration in the machine. That considerably impairs the final surface quality [3, 4].

These problems may be eliminated by combining single-edge oblique turning (in which the cut layer moves along the cutting edge) and rotary turning [2, 5–9].

Rotary turning by multifaceted cutters (Fig. 1) is a new method with specific advantages; its shaping kinematics was described in detail in [10–12]. In this cutting process, the chip runs along the cutting edge. The working sections are constantly renewed as a result of rotation of the multifaceted cutter. The result is guaranteed chip disintegration and improved heat extraction from the cutting zone. There is also no need for a working fluid. In this process, the working temperature is lower, and the quality of the process is improved. In many cases, it is possible to dispense with additional finishing operations (fine turning and grinding) [13–16]. Rotary turning by multifaceted cutters significantly increases the productivity (by a factor of 2.5), since the cutting speed is increased to 900 m/min, without loss of product quality or tool life [13].

If rotary turning by multifaceted cutters is to be effective, we must thoroughly study the influence of geometric and kinematic factors and the cutting conditions on the temperature and forces in the machining zone. On that basis, optimal cutting conditions may be identified, with improvement in the machining quality.

To assess the effectiveness of rotary turning by multifaceted cutters, we study the temperature and forces in the machining zone experimentally in a high-precision IZh250ITVM.F1 screw-cutting lathe, equipped with a rotary-turning module and a composite mandrel. We consider workpieces of steel 45 (State Standard GOST 1050–2013) and D16 aluminum alloy (State Standard GOST 4784–97). The temperature distribution between the chip, tool, and workpiece is determined by a contactless method using a Testo 875-1 thermal-scanning system (working range from −20 to 200°C; absolute measurement error ±2% up to 100°C and relative error ±2% above 100°C). To determine the cutting force, we use a specially designed probe. The quality of surface machining is assessed in terms of the roughness on a MarSurf M300 instrument. The chip morphology is studied on a Hitachi TM 1000

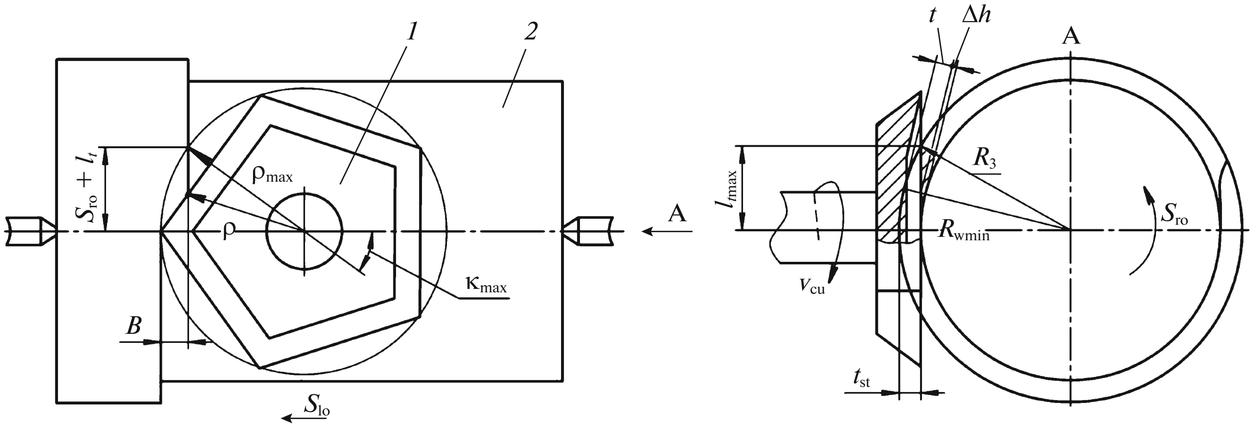

Fig. 1. Rotary turning by multifaceted cutters: (*1*) tool; (*2*) workpiece.

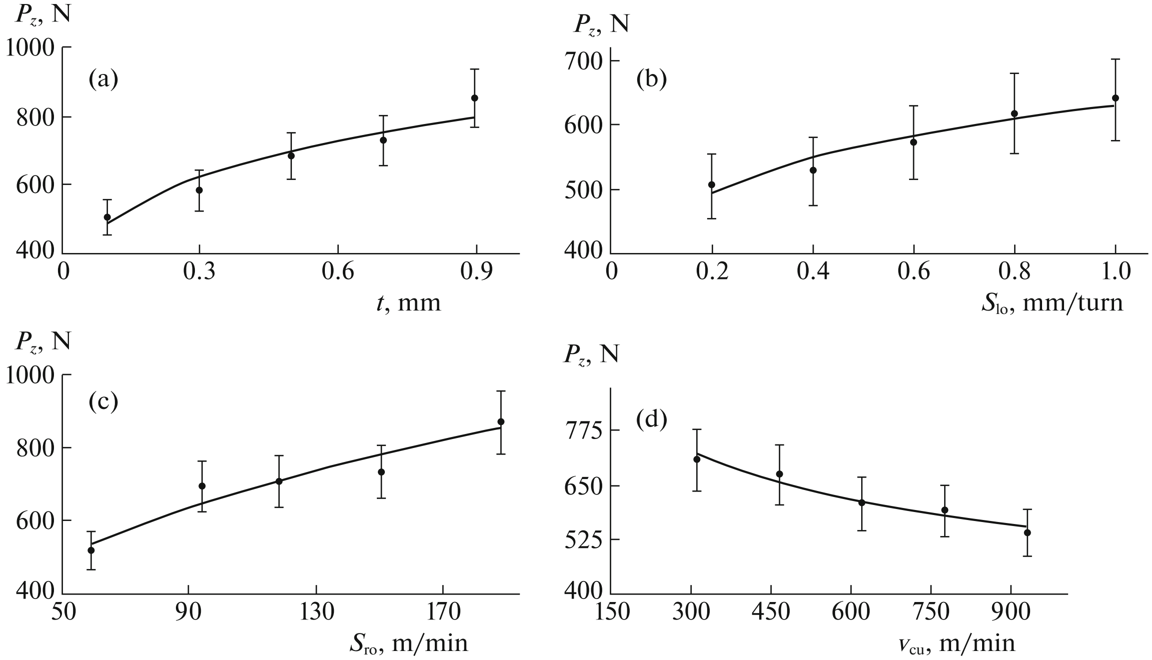

Fig. 2. Dependence of the cutting force component P_z on the cutting depth *t* (a), longitudinal supply S_{lo} (b), rotary supply S_{ro} (c), and cutting speed v_{cu} (d).

scanning electron microscope and a JEOL JSM-7001F scanning electron microscope.

We conduct a series of monofactorial experiments to determine the relation between the cutting parameters, the temperature in the machining zone, and the components of the cutting force. The independent variables selected are the longitudinal cutter supply in workpiece (shaft) rotation S_{lo} = 0.15–1.2 mm/turn; the rotary workpiece supply S_{ro} = 10–200 m/min; the workpiece speed n_w = 50–1000 rpm; the cutting speed v_{cu} = 310–933 m/min; the tool speed n_{cu} = 6000–18000 rpm; and the cutting depth t = 0.1–1.5 mm. Plates with six facets are used in the tool module.

In Fig. 2, we show the experimental results: the dependence of the cutting-force component P_z on the cutting parameters takes the form of parabolic or hyperbolic curves, which may be approximated by a power law: $y = Cx^k$.

Specifically, we find that $P_z = 813.92t^{0.2241}$ (R^2 = 0.9292); $P_z = 629.83S_{lo}^{0.1528}$ (R^2 = 0.9316); $P_z = 102.53S_{ro}^{0.4043}$ (R^2 = 0.9256); and $P_z = 2863.3v_{cu}^{-0.2402}$ (R^2 = 0.9497). On that basis, we may write the follow-

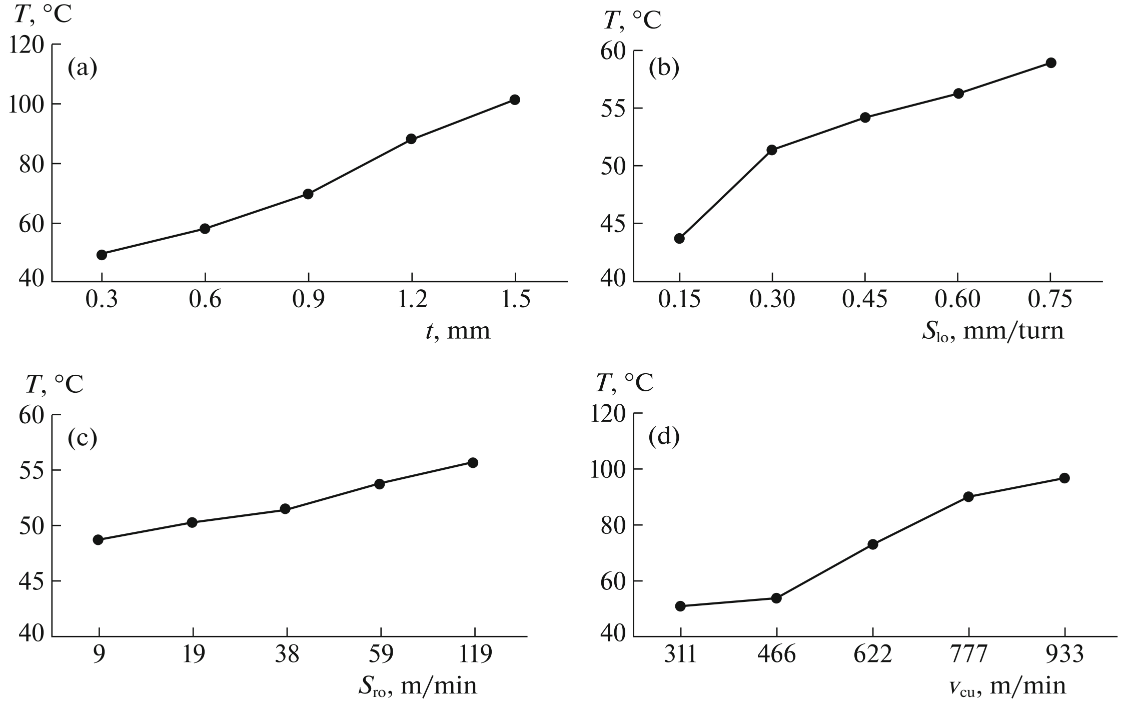

Fig. 3. Dependence of the temperature T in the machining zone on the cutting depth t when $S_{ro} = 38$ m/min, $S_{lo} = 0.3$ mm/turn, and $v_{cu} = 311$ m/min (a); on the longitudinal supply S_{lo} when $S_{ro} = 38$ m/min, $v_{cu} = 311$ m/min, and $t = 0.2$ mm (b); on the rotary supply S_{ro} when $S_{lo} = 0.3$ mm/turn, $v_{cu} = 311$ m/min, and $t = 0.2$ mm (c); and on the cutting speed v_{cu} when $S_{ro} = 38$ m/min, $S_{lo} = 0.3$ mm/turn, and $t = 0.2$ mm (d).

ing semiempirical expression for the primary component of the cutting force in rotary turning by multifaceted cutters [17]

$$P_z = 662.12\frac{S_{lo}^{0.1528}S_{ro}^{0.4043}t^{0.2241}}{v_{cu}^{0.2402}}. \qquad (1)$$

We find that, in rotary turning by multifaceted cutters, the experimental cutting force (up to 900 N) is significantly less than in traditional turning (up to 4000 N) for comparable t and S_{lo} values.

We also investigate the influence of t, S_{lo}, S_{ro}, and v_{cu} on the surface roughness Ra and Rz of the machined surface [18, 19]. The resulting formulas may be used, together with those for the cutting force, to determine the optimal conditions of rotary turning by multifaceted cutters: that is, the maximum productivity corresponding to the required surface quality. The temperature distribution at the surface of the multicutter tool, chip, and workpiece is determined by a contactless method using a Testo 875-1 thermal-scanning system (Fig. 3).

Computer analysis of the thermal images shows that the temperature in the machining zone is no more than 100°C: the cutter temperature is 30–40°C on entering the machining zone and 40–60°C on leaving the machining zone. The temperature distribution indicates that most of the heat passes to the chip, since the local working sections of the cutting edge are constantly renewed and cooled in rotation. Thus, there is no need for expensive and toxic working fluids to cool the machining zone. In addition, the constant renewal of the working sections of the cutting edge in long-term cutting permits stabilization of the temperature. Thus, the extremely low temperatures at the tool sur-

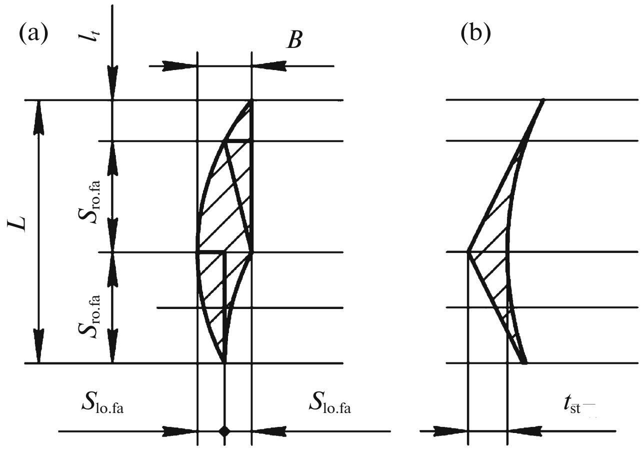

Fig. 4. Calculated chip cross sections in rotary turning by multifaceted cutters: (a) primary view; (b) side view.

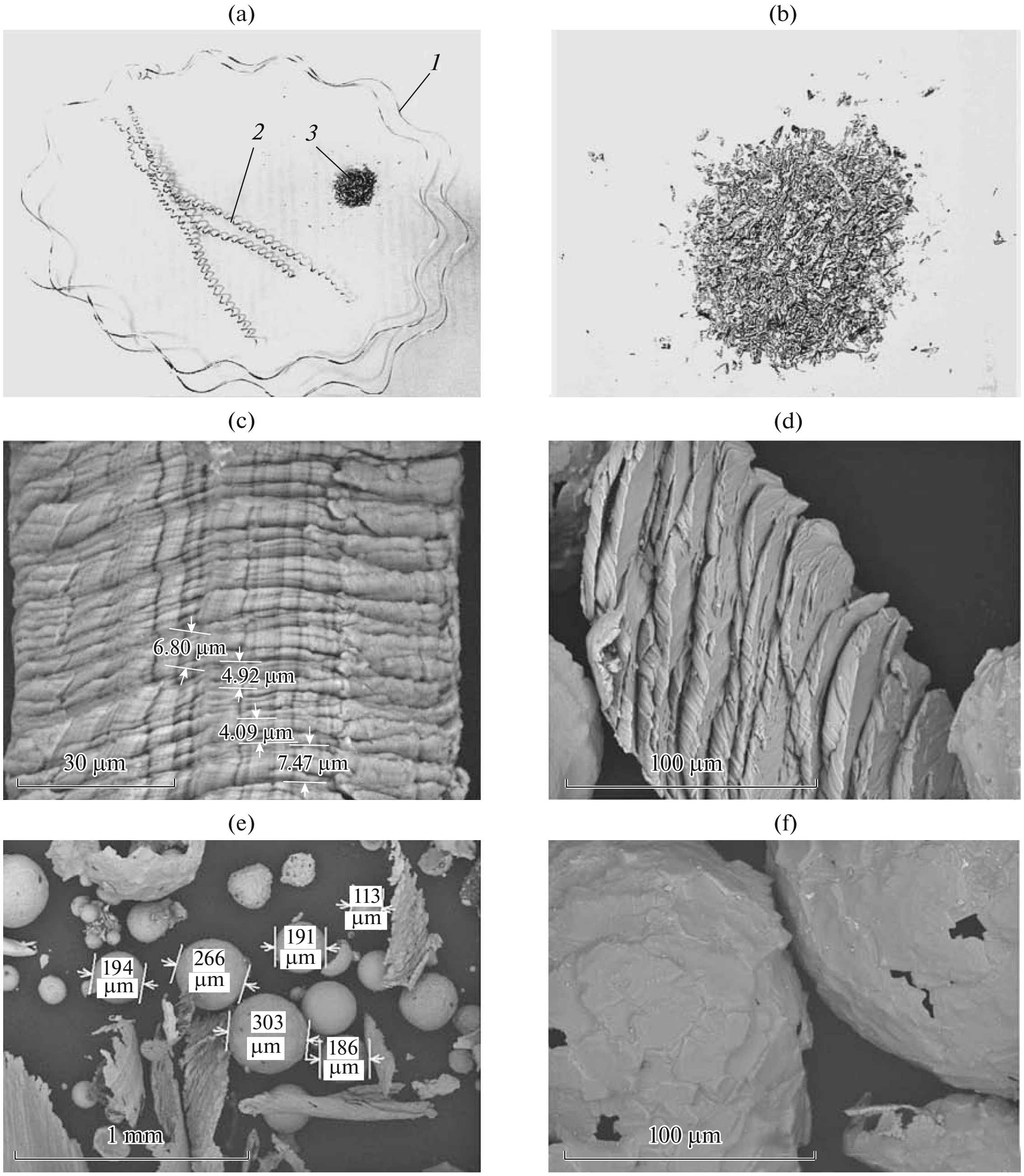

Fig. 5. Chip in machining D16 aluminum alloy (a–c) and steel 45 (d–f): (a) in machining by a pass-through cutter with (*2*) and without (*1*) a chip-breaking channel and by a multifaceted cutter (*3*); (b) in rotary turning by multifaceted cutters; (c, d) chip with shear elements; (e, f) chip in the form of hollow spheres.

face may be explained by the discontinuity of rotary turning by multifaceted cutters and the specifics of chip formation.

The shape and size of the cut-layer cross section in rotary turning by multifaceted cutters are determined on the basis of graphical analysis. The dimensions of the elementary chip fragments are determined by three parameters that depend on the machining conditions (Fig. 4a) [16–19]: the width $B = 2S_{\text{lo.fa}}$, where $S_{\text{lo.fa}}$ is the longitudinal supply at the cutter face; the length $L = 2S_{\text{ro.fa}} + l_t$, where $S_{\text{ro.fa}}$ is the rotary supply at the cutter face and l_t is the length of the section, which depends on the cutting depth; and the thickness $t = t_{\text{st}} - \Delta h = t_{\text{st}} - \sqrt{\rho^2 \sin \kappa^2 + R^2_{\text{w min}}} + R_{\text{w max}}$, where t_{st} is the cutting depth in the plane of the center axis; Δh is the possible height of the residual irregularities; $R_{\text{w min}}$ and $R_{\text{w max}}$ are the minimum and maximum radii of the workpiece; κ is the angle between the center axis and the contact point between the cutting edge and the workpiece surface; and ρ is the radius vector of the cutting-edge contour.

We find that the cut-layer thickness varies in the range from zero to the cutting depth. The cut-layer width behaves analogously. On the basis of this model of the process, the dimensions and shape of elementary cut surfaces may be predicted (Fig. 4a). The results are in good agreement with the actual layer cross sections of the chip (Fig. 4b). Kinematically, the proposed machining process is characterized by constant change in the cut-layer cross section. That results in more intense deformation. The height of the residual irregularities on the machined surface is lower on account of the discontinuous cutting process and the extremely rapid formation of chip elements.

In the experiments, we optimize the cutting conditions for rotary turning by multifaceted cutters and propose a new tool design and the best hard alloys for use in practical tool modules [20, 21].

The chip shape and size (Fig. 5) confirm that the chip is fragmented and then ejected from the cutting zone in rotary turning by multifaceted cutters. In machining aluminum by traditional cutters, long continuous chip is formed (Fig. 5a). In rotary turning by multifaceted cutters, by contrast, fine chip fragments (0.05–1.5 mm) are formed in comparable conditions (Fig. 5b).

The structure and morphology of aluminum and steel chip indicate considerable shear deformation in rotary turning by multifaceted cutters (Figs. 5c and 5d). Electron microscopy shows that the elementary shear surfaces of the chip fragments are no more than 1–2 μm, but they may bind together in relatively stable layers of thickness up to 5 μm.

In addition, the distance between the shear surfaces in rotary turning by multifaceted cutters corresponds to the intensity of deformation at frequencies of 36000–120000 s^{-1}. Experimental data indicate that the bulk fracture coefficient ω is 2 and 3 for steel 45 and aluminum chip, respectively.

Accordingly, in specific conditions, chip of different types is formed. This indicates intense deformation in the machining zone, discontinuous cutting, change in the mechanism of chip formation, and local heating along the junctions of individual shear elements. The outcome is the formation of chip with a new structure: hollow spheres (diameter 100–300 μm, wall thickness 0.5–2 μm), as seen in Figs. 5e and 5f. That confirms the anomalously high strain rates in rotary turning by multifaceted cutters.

CONCLUSIONS

We have established the influence of the cutting conditions on the primary component of the cutting force, which is considerably less (no more than 900 N) than in traditional turning. We have established semiempirical formulas to determine the cutting force as a function of the machining conditions. On that basis, rotary turning by multifaceted cutters may be efficiently used, with means of controlling the final surface quality. The temperature in the machining zone is significantly lower than within the chip. (The surface temperature of the tool's cutting section is no more than 120°C). That permits increase in tool life without the need for working fluid. Correspondingly, the quality of the process is improved. In rotary turning by multifaceted cutters, according to our experiments, fragmentation produces fine chip (between 100 μm and 3 mm), which is ejected from the machining zone. Morphological analysis of the chip confirms the theoretical assessments of the cut-layer shape and dimensions, taking account of the machining kinematics.

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CONFLICT OF INTEREST

The authors declare that they has no conflict of interest.

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