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# Tool–Workpiece Interaction in Deformational Cutting

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**Abstract**—A method is developed for the comparison of deformational cutting and traditional cutting in terms of the force and energy consumption. The force required is less in deformational cutting than in traditional cutting.

*Keywords*: turning, cutting force, cutting tool, deformational cutting, cutting edge, chip, machining precision, energy consumption

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In machining, the force on the tool is an important consideration. The influence of the tool geometry and operating conditions on the cutting forces in traditional machining has been thoroughly studied [1–3]. The geometry of the working part of tools for deforming cutting differs significantly from that of lathe cutters [4]. In deformational cutting, the shaping process differs in the following respects from traditional cutting: the chip is not separated from the workpiece; the influence of plastic deformation is considerable; and frictional forces are increased on account of the large contact area between the tool's front surface and the fin that forms (Fig. 1) [5].

This aspect of deformational cutting means that the formulas derived for the forces in traditional cutting are inapplicable. In Fig. 2, we show the components of the cutting force at the tool's working surface for deformational cutting with fins formation.

In the general case, the components of the cutting force for deformational cutting are as follows

$$P_z = P_{z\,\mathrm{fs}} + P_{z\,\mathrm{rs}} + P_{z\,\mathrm{ars}};$$

$$P_x = P_{x\,\mathrm{rs}} - P_{x\,\mathrm{fs}} - P_{x\,\mathrm{ars}}; \quad P_y = P_{y\,\mathrm{rs}} - P_{y\,\mathrm{fs}},$$

where $P_{z\,\mathrm{fs}}$, $P_{x\,\mathrm{fs}}$, $P_{y\,\mathrm{fs}}$ are the components of the cutting force at the front surface; $P_{z\,\mathrm{rs}}$, $P_{x\,\mathrm{rs}}$, $P_{y\,\mathrm{rs}}$ are the components of the cutting force at the rear surface; and $P_{z\,\mathrm{ars}}$, $P_{x\,\mathrm{ars}}$ are the components of the cutting force at the auxiliary rear surface.

The tool for deformational cutting may operate both with fin formation and with its separation as chip. The result of tool operation is determined by the ratio of the cutting depth $t$ and the tool feed $S_0$. At large cutting depths and small tool feed deformational cutting is converted to traditional cutting. The ratio of $t$ and $S_0$ ensuring stable fin formation is the region of existence of deformational cutting [6].

To determine the forces between the tool and the workpiece in deformational cutting with fin formation and with its separation as chip, we conduct experiments with a VK8 cemented carbide cutter: primary plane angle $\varphi = 30°$; secondary plane angle $\varphi_1 = 90°$; front angle $\gamma = 51°$; rear angles $\alpha = \alpha_1 = 6°$; and inclination of cutting edge $\lambda = 41°$. We also compare the energy efficiency when using a deformational cutting tool with chip separation and a regular cutter with the recommended geometry for the specific machined material. The experiment is conducted with machining parameters corresponding to the lower boundary of the region of deformational cutting—in other words, in the zone where both fin formation and its separation as chip are possible.

In the experiments, the tool feed $S_0$ is increased in increments at specified cutting depth $t$, with transition from cutting with chip separation to cutting with fin

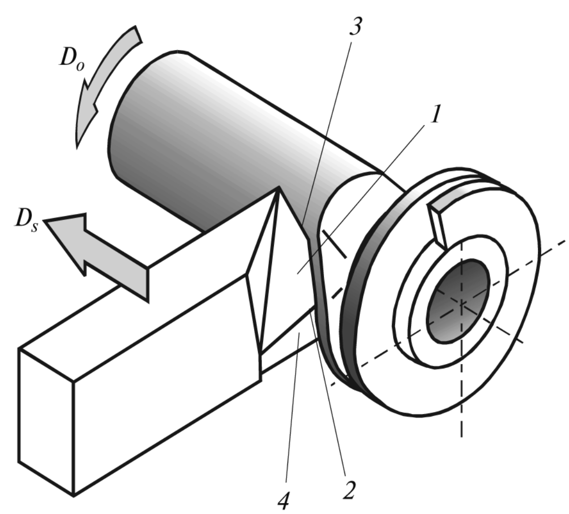


**Fig. 1.** Deformational cutting: (*1*) primary cutting edge; (*2*) deforming (secondary) edge; (*3*) front surface; (*4*) auxiliary rear surface.

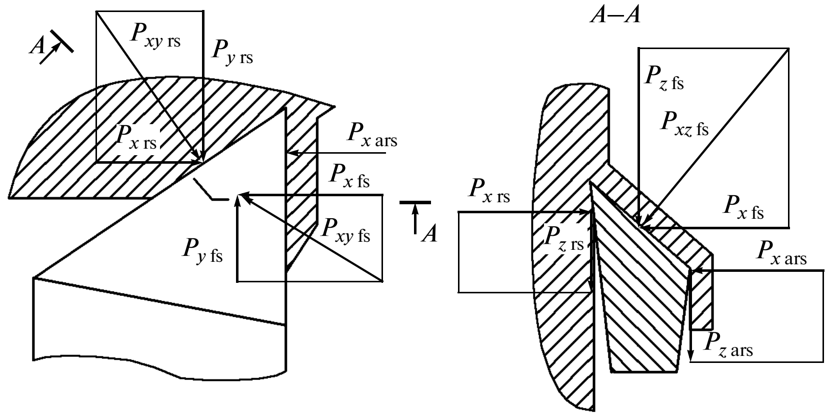


**Fig. 2.** Components of the cutting force in deformational cutting.

formation. With increase in $S_0$, traditional cutting is first transformed to partial fin formation and then to stable deformational cutting. Experiments are also conducted for a different cutting depth. In all the experiments, we consider longitudinal turning of M1 copper workpieces (diameter 80 mm) on a 16K20 screw-cutting lathe, at a cutting speed $v_{\mathrm{cu}} = 25$ m/min. The components of the cutting force are measured by means of a Kistler (Switzerland) 9257 three-component dynamometer, with data output to a PC. With increase in $S_0$, we observe chip formation, the transition zone, or fin formation.

The zones of unstable fin formation (the transition zones) are shaded in Fig. 3. To the left of the transition zone, we see the dependence $P_z = f(S_0)$ in chip formation; to the right, we see the dependence $P_z = f(S_0)$ in fin formation. In analysis of the experimental data, these two curves of $P_z = f(S_0)$ are extrapolated into the transition zones, so that we may compare them. On transition from chip formation to stable deformational cutting, the components of the cutting force markedly change without change in cutter geometry (Figs. 3 and 4).

We find that, in machining with chip removal, $P_z$ is less than in deformational cutting. In other words, the

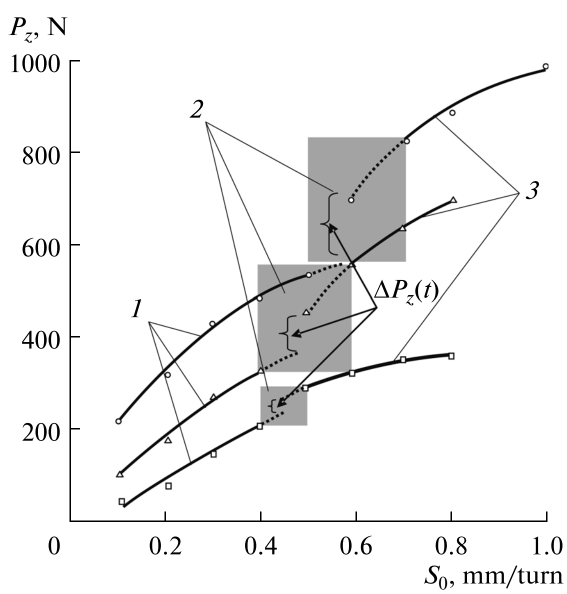


**Fig. 3.** Dependence of the primary component $P_z$ of the cutting force on the tool feed $S_0$ when $t = 0.5$ (□), 1 (△), and 1.5 (○) mm: (*1*) cutting with chip separation; (*2*) transition zones with different cutting depth $t$; (*3*) deformational cutting with fin formation.

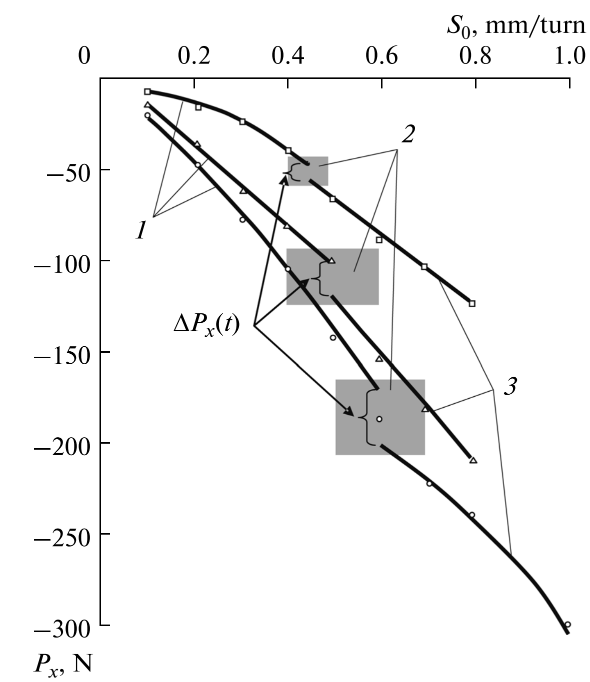


**Fig. 4.** Dependence of the axial component $P_x$ of the cutting force on the tool feed $S_0$ when $t = 0.5$ (□), 1 (△), and 1.5 (○) mm: (*1*) cutting with chip separation; (*2*) transition zones with different cutting depth $t$; (*3*) deformational cutting with fin formation.

energy consumption is greater in deformational cutting than in traditional cutting. The decrease in $P_z$ may be explained in that chip separation is associated with significantly smaller tool–workpiece contact area at the front surface (decrease in $P_{z\,\mathrm{fs}}$) and the auxiliary rear surface (decrease in $P_{z\,\mathrm{ars}}$). Note that, on transition to traditional cutting, the auxiliary deforming edge becomes an auxiliary cutting edge.

On account of the configuration of the tool's front surface in deformational cutting, the sum of $P_{x\,\mathrm{fs}}$ and $P_{x\,\mathrm{ars}}$ in deformational cutting is always greater than the reaction $P_{x\,\mathrm{rs}}$ at the primary rear surface of the tool. Therefore, when using a tool designed for deformational cutting, $P_x$ is negative both with fin formation and with chip formation. The decrease in absolute magnitude of $P_x$ with chip formation when using a tool designed for deformational cutting is explained in that the reaction $P_{x\,\mathrm{fs}}$ of the front surface is reduced, while the force $P_{x\,\mathrm{ars}}$ from the bent fin ceases to act at the auxiliary edge (Fig. 2).

In traditional cutting and deformational cutting, $P_y$ is very small (no more than 22 N). Accordingly, the curves for $P_y$ are not shown here. However, they are taken into account in comparing the total cutting forces. On account of the configuration of the tool's front surface in deformational cutting, the tool is drawn not only in the feed direction but also in the radial direction. In specific machining conditions, that results in approximately equal absolute values of $P_{y\,\mathrm{rs}}$ and $P_{y\,\mathrm{fs}}$, but opposite signs. That minimizes the influence of $P_y$ on the machining precision and offers the prospect, in principle, of turning flexible or thin-walled parts by means of a tool designed for deformational cutting, without radial deformation.

We now determine the difference between the components $P_x$, $P_y$, $P_z$ (Fig. 2) in deformational cutting and traditional cutting and then the total difference

$$\Delta P = \sqrt{\Delta P_x^2 + \Delta P_y^2 + \Delta P_z^2}.$$

We also calculate the force $P_{\mathrm{cu}}$ at the end of the zone with chip separation

$$P_{\mathrm{cu}} = \sqrt{\Delta P_{x\,\mathrm{rez}}^2 + \Delta P_{y\,\mathrm{rez}}^2 + \Delta P_{z\,\mathrm{rez}}^2}.$$

In Fig. 5, we plot $\Delta P/P_{\mathrm{cu}}$ for different values of the cutting depth $t$. We see that the cutting force in deformational cutting is 1–26% greater than in the case of chip separation. With increase in cutting depth, this difference increases. The greater cutting force in deformational cutting may be attributed not only to the increase in $P_z$ (Fig. 3) but also to the additional action of forces $P_{x\,\mathrm{ars}}$ and $P_{z\,\mathrm{ars}}$ on the auxiliary rear surface from the fin that is formed (Fig. 2). Thus, it is energetically preferable to remove the chip by the auxiliary edge than to deform it in fin formation.

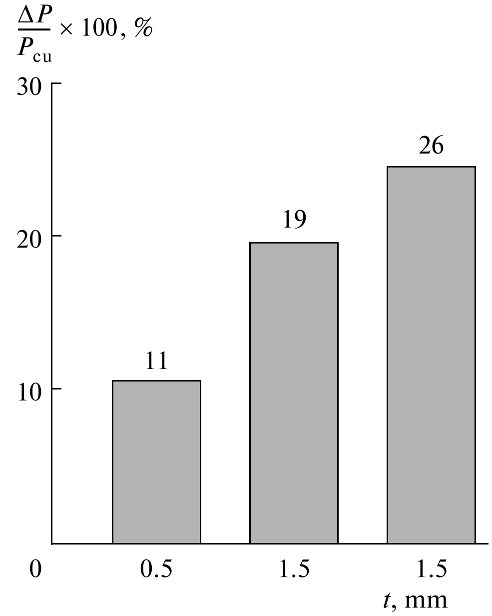


**Fig. 5.** Dependence of $\Delta P/P_{\mathrm{cu}}$ on the cutting depth $t$: $\Delta P$ is the increase in the force on deformational cutting; $P_{\mathrm{cu}}$ is the cutting force in the case of chip separation.

Since we know that the radial cutting force is minimized if a tool designed for deformational cutting is used for turning with chip separation, it is of interest to compare the forces observed in machining M2 copper by a cutter with standard geometry for traditional cutting [7] and a VK8 cemented carbide cutter designed for deformational cutting, other conditions being equal. The geometric parameters of the standard cutter are

$$\varphi = \varphi_1 = 45°, \quad \gamma = 15°,$$
$$\alpha = \alpha_1 = 6°, \quad \lambda = 0.$$

The table presents the experimental data.

Analysis of these data leads to the following conclusions.

(1) In chip removal by a tool designed for deformational cutting, the cutting force is less than for a traditional cutter by a factor of 3.4–4.8.

(2) The component $P_x$ of the cutting force is negative when using a tool designed for deformational cutting, in contrast to traditional cutting.

Cutting forces for turning by tools designed for traditional/deformational cutting with chip removal, when $t$ = 0.5 mm

| $S_0$, mm/turn | $P_z$, N | $P_x$, N | $P_y$, N | $P$, N |
|---|---|---|---|---|
| 0.1 | 220/43 | 25/–6 | 70/20 | 232/48 |
| 0.2 | 370/77 | 50/–16 | 130/22 | 395/82 |
| 0.3 | 560/150 | 73/–24 | 185/21 | 594/153 |
| 0.4 | 700/213 | 85/–39 | 240/3 | 745/217 |

(3) The component $P_y$ of the cutting force is very small (no more than 22 N). That permits optimal positioning of the front surface of the tool designed for deformational cutting, so as to minimize $P_y$ in the machining of flexible parts with chip removal.

Deformational cutting may be used not only for nonferrous metals but for steels of hardness up to 220 *HB*. By the experimental method already described, we study the deformational cutting forces for 40X steel (hardness 160 *HB*) on transition from cutting with chip separation to deformational cutting. The parameters of the tool designed for deformational cutting are as follows:

$$\varphi = 42°, \quad \varphi_1 = 90°, \quad \gamma = 47°,$$
$$\alpha = \alpha_1 = 3°, \quad \lambda = 53°.$$

The other machining parameters are unchanged. The cutting depth $t = 0.5$ mm; the cutting speed $v_{cu} =$ 60 m/min.

Comparison of the results for 40X steel with the earlier findings for copper permits the following conclusions.

(1) The basic pattern is the same: deformational cutting consumes 8% more energy than cutting with chip separation.

(2) The cutting force is 1.5–5.5 times greater for steel than for copper. The difference declines with increase in the tool feed.

(3) Unstable fin formation sets in sooner for steel than for copper and corresponds to a much narrow feed range.

(4) In contrast to the machining of copper, $P_x$ has a small positive value in the cutting of 40X steel with chip separation; it is only negative in cutting with fin formation.

## ACKNOWLEDGMENTS

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