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Selection of Machining Conditions in Terms of the Temperature Dependence of Chip Formation

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Abstract—The formation of elementary chip in the cutting of difficult machines is investigated. A method is developed for determining the optimal cutting conditions on the basis of the temperature of best tool performance with elementary-chip formation.

Keywords: cutting, elementary chip, hard-to-machine material, chip continuity, optimal tool temperature
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Many engineering components operate in challenging conditions: at high temperature pressure, in aggressive media, and so on. Therefore, they are made from materials with special properties: high strength, low density, and high corrosion resistance. As a rule, such materials are difficult to cut and likely to form elementary chip. Intense tool wear may be expected. In such cases, safe chip extraction is a serious concern, especially when using numerically controlled machine tools and robot systems.

Optimal machining conditions are required for efficient use of tools and machine tools and increased productivity. To this end, the formation of elementary chip in the high-speed cutting of structural materials and in the cutting of most plastic materials was studied in [1]. The formation of elementary chip was regarded as similar to the formation of continuous chip in [2].

We study the formation of elementary chip in the machining of high-temperature KhN73MBTYu alloy and VT1 and VT3-1 titanium alloys in external longitudinal turning by hard-alloy VK8 cutters of different geometry. In the tests, the cutting speed, supply S, and front angle γ of the tool are varied; this is facilitated by means of a special tool-holder design.

The main characteristics of chip formation are the chip shrinkage ζ_a, inclination β_1 of a chip element, chip height a_1, height a_2 of the continuous section, increment m of the elements, and chip continuity a_2/a_1. These characteristics correspond to the final deformation of the chip elements (Fig. 1).

The parameters of elementary chip were considered as a function of the cutting speed in [3]; this dependence is very complex. As a rule, in the machining of high-temperature alloys and titanium alloys, increase in cutting speed facilitates the formation of elementary chip. This contrasts with the results for structural steel and many nonferrous metals and alloys.

The chip formation is also affected by factors such as the temperature, physicochemical transformations, and contact processes.

In the present work, we investigate the influence of the cutting temperature on the chip formation.

The temperatures at the cutter's front face and in the zone of chip formation are the most significant [4]. They affect the contact processes at the front plane and, in particular, determine the frictional coefficient between the cutter and chip, which, in turn, determines the direction of the resultant force at the cutter's front face. This affects the position of the fracture plane—that is, the plane of maximum tangential stress. These factors help determine the tool's wear rate.

The temperature field of a chip element is characterized by high gradients close to the shear plane [5]. That is associated with adiabatic shear, which results in cyclic chip at high cutting speeds [6–8].

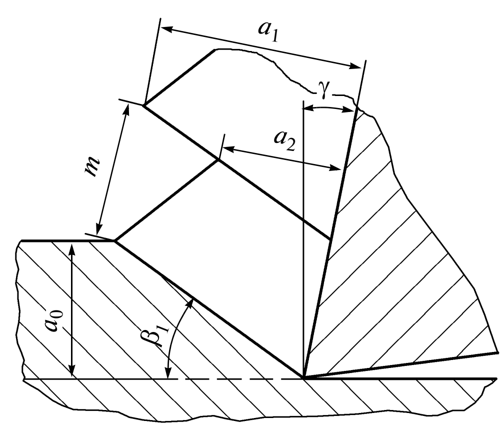

Fig. 1. Parameters of elementary chip.

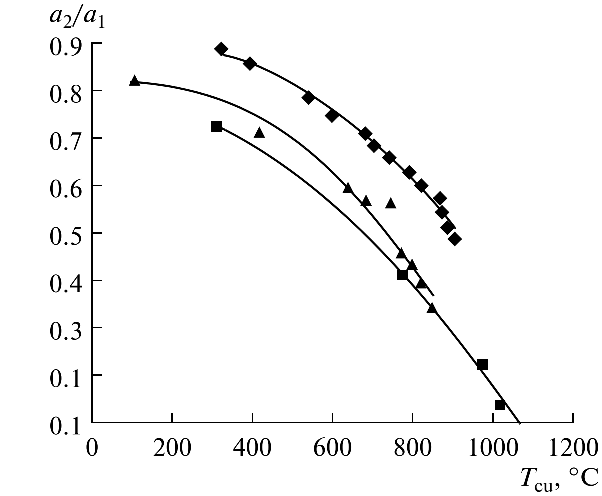

Fig. 2. Dependence of the chip continuity a_2/a_1 on the cutting temperature for VT1 (◆), KhN73MBTYu (▲), and VT3-1 (■) alloys.

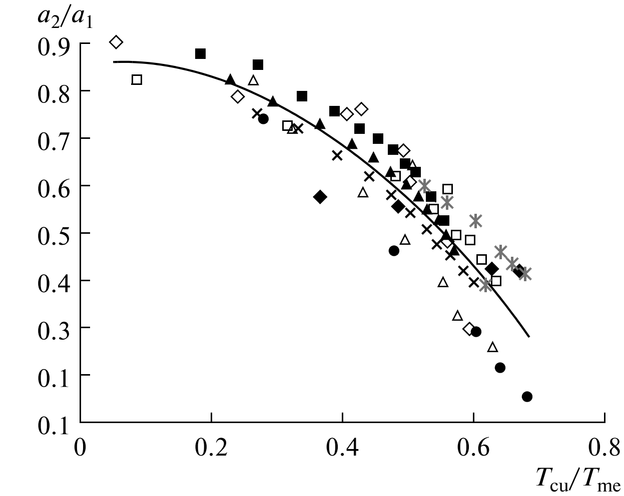

Fig. 3. Curve of the chip continuity a_2/a_1 as a function of the homological temperature T_h according to experimental data (shown by the points).

With increase in strain rate and decrease in the thermal conductivity and specific heat of the machined material, the influence of the temperature and cutting speed on the chip formation grows.

The chip formation may be characterized by the chip continuity a_2/a_1, which depends on the type of chip: $a_2/a_1 \approx 1$ for continuous chip; and $a_2/a_1 < 1$ for elementary chip. Thermocouples are used to measure the cutting temperature. In high-speed machining, high temperatures are observed in the chip-formation zone. It might seem that, at 800–1000°C, the plasticity of the machined materials should increase, with corresponding increase in the chip increment and a_2/a_1 and decrease in the shear angle. However, experiments show the opposite.

In Fig. 2, we plot a_2/a_1 as a function of the mean cutting temperature in the case where $S = 0.26$ mm/turn and $\gamma = 7°$, when cutting various materials differing in thermal conductivity: $\lambda = 18.85$ W/(m °C) for VT1 alloy; $\lambda = 11.7$ W/(m °C) for KhN73MBTYu alloy; and $\lambda = 7.95$ W/(m °C) for VT3-1 alloy. With low thermal conductivity of the blank and high cutting speed, the chip is heated to high temperature within a narrow shear zone and the contact-surface microprojections. That facilitates shear deformation only within the corresponding zones.

For example, for hard-to-machine materials, the resistance to plastic deformation after preliminary heating of the blank is less than in the same conditions without preliminary heating [9, 10]. In some cases, the cut-layer thickness is increased so as to boost the productivity in roughing [10].

To rule out the influence of the blanks' physical properties, we plot the results in terms of the homological temperature $T_h = T_{cu}/T_{me}$ for VT1, KhN73MBTYu, and VT3-1 alloys in Fig. 3. (Here T_{cu} is the cutting temperature and T_{me} is the melting point of the alloy.) In the experiments, $S = 0.1$–0.47 mm/turn and $\gamma = 8°$–17°; different cutting speed s are employed. The results show that the curves are of the same form in all cases. This confirms that the temperature has the dominant influence on the type of chip. The spread of the data may be attributed to imprecision in measuring the mean cutting temperature.

In optimal cutting conditions at high speeds, elementary chip is formed; the elements are connected by a thin contact layer, which provides some bond strength. Like the chip continuity, this strength depends on the cutting temperature.

As already noted, elementary chip may be safely and simply removed from the cutting zone. The type of chip determines the tool wear. However, researchers do not agree on this topic: reduction in tool life was observed on switching to elementary chip in [7, 11]; but tool life increased, by contrast, in [12]. However, some increase in tool life arises because buildup appearing in the case of continuous chip protects the cutter from contact with the chip.

The performance of a hard-alloy tool in machining high-temperature steel and alloys was studied in [13, 14]. The results indicated that the properties of the machined material have no significant influence on the optimal tool temperature, but simply determine the optimal cutting speed. In turning blanks with various levels of resistance to machining, the temperature in the cutting zone is constant at the optimal speeds of the hard-alloy tools. Therefore, we may select cutting conditions corresponding to the temperature of maximum tool performance and the creation of chip of the required form.

On the basis of research regarding the temperature at which the chip switches from one type to another, we may develop a method of determining the best cutting conditions on the basis of the temperature of maximum tool performance.

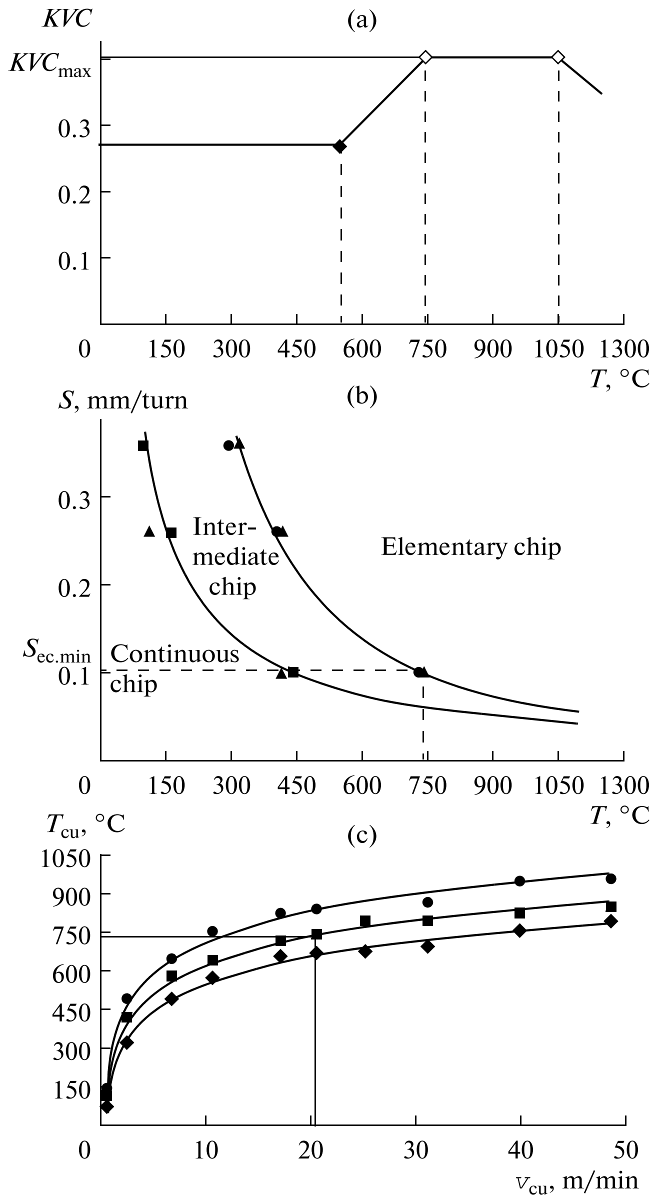

Fig. 4. Selecting the cutting parameters: (a) temperature dependence of the tool's impact strength *KVC* for VK8 alloy; (b) temperature dependence of the supply S, with regions corresponding to different types of chip for EI698 alloy; (c) dependence of the cutting temperature T_{cu} on the cutting speed v_{cu} when $S = 0.36$ (●), 0.26 (■), and 0.10 (◆) mm/turn.

The temperature of maximum tool performance may be determined from the temperature dependence of the tool's impact strength *KVC* (Fig. 4a) [13, 14]. In other words, we may determine the temperature corresponding to KVC_{max} for the given hard alloy. From the experimental data, we plot the temperature dependence of the supply corresponding to different types of chip: continuous, intermediate, or elementary (Fig. 4b). For the temperature corresponding to KVC_{max}, we identify the range $S > S_{ec.min}$ where elementary chip is formed. Then, from the dependence of T_{cu} on v_{cu}, we determine the cutting speed for selected S values (Fig. 4c).

Thus, if maximum tool performance is ensured, we may produce elementary chip, which is easily removed from the cutting zone. In addition, the use of optimal cutting conditions reduces the machining costs.

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