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Mechanics of Chip Formation in Cutting

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Abstract—The stress–strain state in chip is investigated by the finite-element method. In addition, the cutting process and the mechanics of chip formation are studied experimentally over the whole temperature range of metal cutting.

Keywords: machinability, chip formation, stress–strain state

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With a view to import substitution, we need effective means of cutting new hard and temperature-stable materials, which are difficult to machine.

Extensive experimental data are now available in handbooks regarding the machining of parts made from various materials. However, manufacturers must still identify the best machining conditions for hard materials and the best tool life attainable in the production of new parts [1–4]. Determination of the best machining conditions for tough materials entails expensive, challenging, and lengthy endurance tests in the laboratory. That implies significant expenditures of time and money.

Analysis of literature data has shown how the type of chip depends on the machining temperature and cutting speed over the whole of the practical temperature range, for any particular material [5–9]. The chip passes through the following sequence of types: elementary, articulated, continuous, articulated, and elementary [5–9]. This pattern is observed for materials in different machinability groups. However, no explanation for such behavior has been offered.

In the present work, we attempt to account for the changes in chip structure over the whole of the practical temperature range, on the basis of the mechanics of failure, as the machined material is converted to chip.

Analysis of the photographs in Fig. 1 shows that, in metal cutting, cracks form at the contact and free surfaces of the chip [8].

To explain this behavior, chip formation is simulated by the finite-element method. In addition, the mechanics of the cutting process and chip formation is investigated experimentally over the whole of the practical temperature range.

Graphic modeling of turning results in a clear picture of the workpiece and chip formation. That permits tracking of all the deformation processes in the chip [4].

Kompas V15 and ANSYS software is used for simulation; the results are entered in Excel tables.

The loading conditions are analogous to rough turning: the cutting section consists of VK8 hard alloy; the rake angle $\gamma = 0°$; the primary plane angle $\varphi = 90°$;

(a) (b) (c) (d)

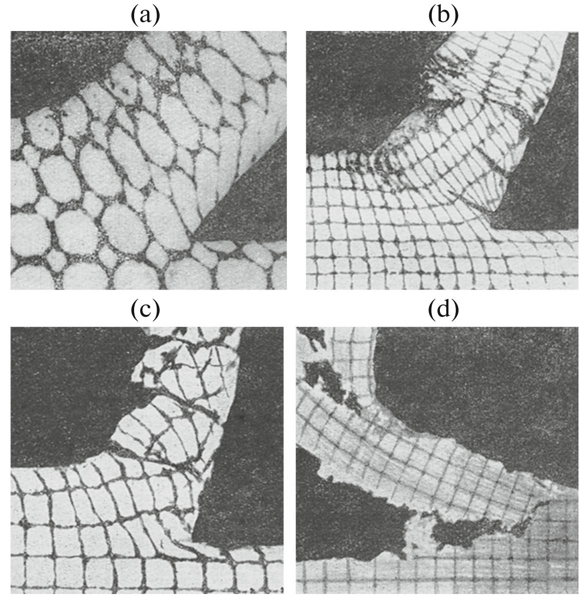


Fig. 1. Chip roots with coordinate grid [8]: (a) continuous chip (KhN77TYuR alloy); (b) segmented chip (KhN77TYuR alloy); (c) elementary chip (VT2 alloy); (d) broken chip (cast iron).

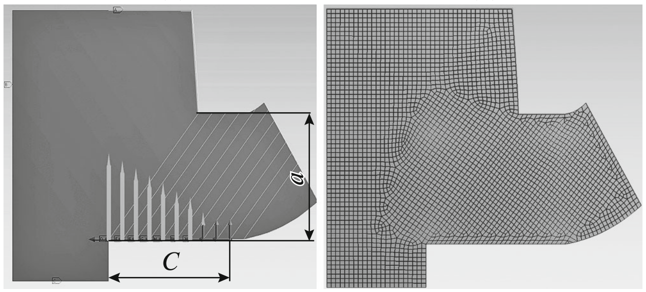


Fig. 2. Boundary conditions for chip formation (a) and finite-element grid in a longitudinal section of the chip (b).

the machined material is 10X11H23T3MP steel; the cutting depth $t = 1.5$ mm; the supply $s = 0.42$ mm/turn; the cutting speed $v = 50$ m/min [10–14].

The mechanical characteristics of the 10X11H23T3MP steel used in ANSYS calculations of the stress isolines are the Poisson's ratio μ and elastic modulus *E*.

The boundary conditions of chip formation are specified in terms of the reactions to the cutting forces P_{Zi} and frictional forces F_i at the chip's contact surface (length *C*) in the cross section being considered (Fig. 2a).

The stress is calculated by the finite-element method (Fig. 2a), which is applied to a solid body. In the general case, this is the region occupied by a continuum or a field, which is divided into finite elements. The boundaries of the elements form a grid. At intersection, the boundaries form node points. Additional nodes may be created at the boundaries and within the elements. The ensemble of all the finite elements and nodes constitutes the basic finite-element model of the deformed body. This model must cover the region occupied by the object as completely as possible [15].

ANSYS software automatically divides the three-dimensional model of the chip into a finite-element grid (Fig. 2b).

To verify the applicability of the finite-element method, we compare the isolines of the maximum tangential stress τ_{max} obtained by simulation and the isochromatic lines obtained experimentally by a photoelastic method [16].

We find good agreement of the isochromatic τ_{max} lines and the results of simulation (Fig. 3).

The stress–strain state of the chip is calculated by the finite-element method in three cross sections:

(1) *A–B*, which is the conventional shear plane (*1*);

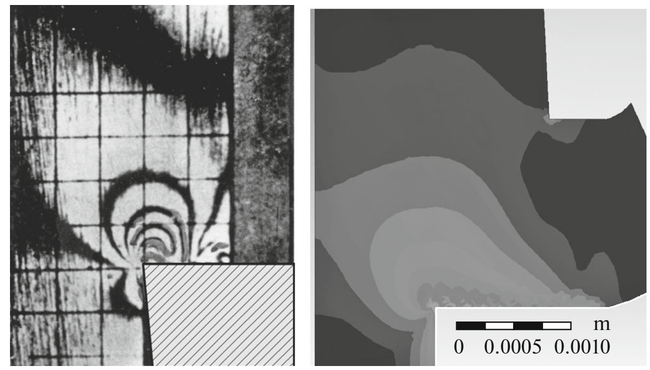


Fig. 3. Isolines of the maximum tangential stress τ_{max} in free cutting ($\gamma = 0°$): according to a model based on optically active material [16] (a); and according to simulation (b).

(2) *A–C*, which is a plane perpendicular to the direction of chip departure from the contact zone with the tool's front surface (*2*);

(3) *A–D*, which is the plane passing through point *A* on the free chip surface, where the direction of chip departure changes; and point *D*, where the chip breaks away from the tool's front surface (*3*).

Analysis of the stress–strain state in cross sections *A–B*, *A–C*, and *A–D* indicates that the hazardous tensile stress σ_1 is a maximum at points *A*, *B*, and *D*. At other points, including points where the chip is in contact with the tool's front surface, σ_1 tends to zero.

The tensile stress σ_1 is greatest at point *D* in cross section *A–D* (Figs. 4a and 4b). The compressive stress σ_3 is greatest at point *B* in cross section *A–B*, as we see in Figs. 4c and 4d.

The Mises equivalent stress σ_{equ} in the longitudinal section of the chip is greatest in cross section *A–B* (the conventional shear plane), as we see in Figs. 4e and 4f. That is consistent with the idea of plastic shear failure in this plane.

Analysis of the chip's stress–strain state indicates that, in the chip-formation zone (Figs. 4a and 4b), tensile regions appear. Concentrations of tensile stress σ_1 are observed at the chip's free surface at point *A* and at the end of the contact line between the chip and the tool's front surface at point *D*. Note that, in cross section *A–D*, considerable hazardous tensile stress σ_1 is observed, on account of crack formation in the chip at its free and contact surfaces.

In Figs. 4e and 4f, we show isolines of the stress and its distribution in a longitudinal section of the chip corresponding to shear failure of the chip.

The table presents experimental data for the following parameters of chip formation as a function of

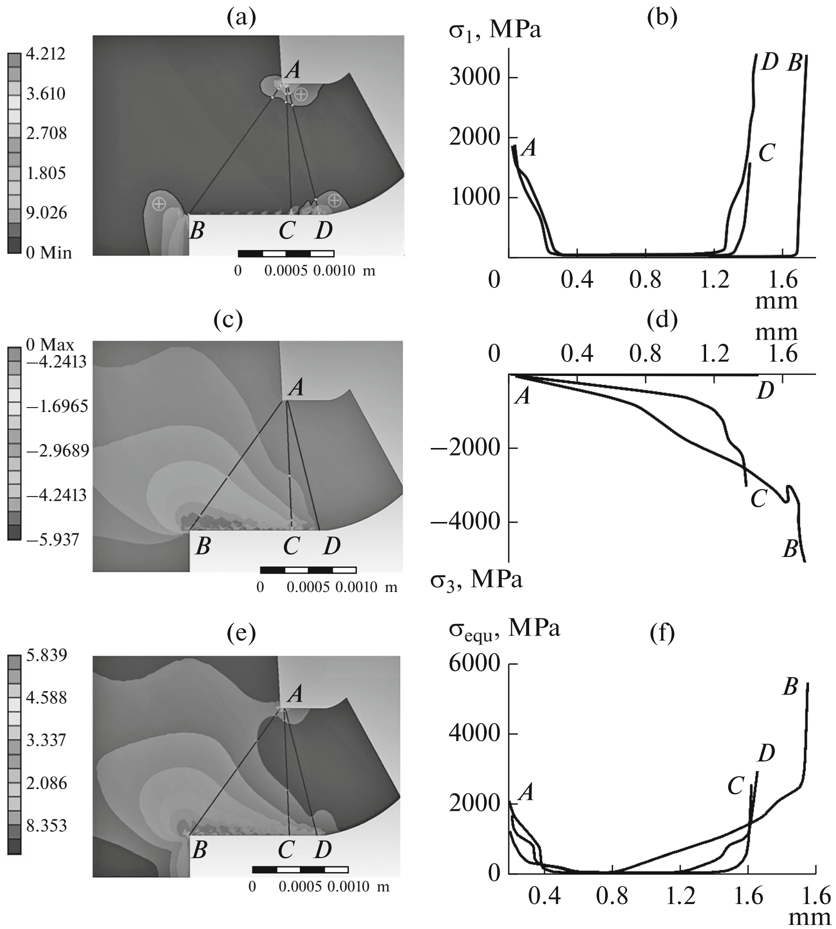


Fig. 4. Simulation of rough turning (10X11H23T3MP steel; v =10 m/min; t = 1 mm) in a longitudinal section of the chip: (a) isolines of the tensile stress σ_1; (b) curves of tensile stress σ_1; (c) isolines of compressive stress σ_1; (d) curves of compressive stress σ_1; (e) isolines of Mises equivalent stress σ_{equ}; (f) curves of Mises equivalent stress σ_{equ}.

the cutting temperature and speed: the type of chip [4]; the inclination of the fracture surface to the chip's contact surface; and the chip's continuity factor k [17].

In the light of the numerical data for the stress–strain state of the chip and the experimental data regarding the type of chip in different cutting conditions, we may draw some conclusions regarding the failure mechanics of the machined material in chip formation.

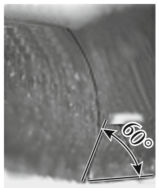
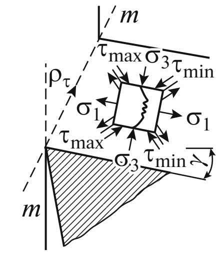
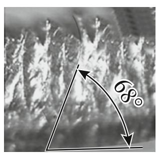
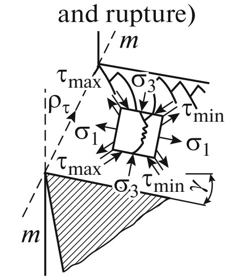
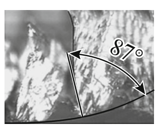
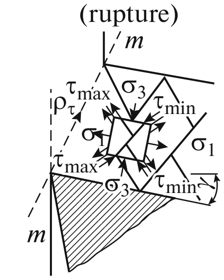
(1) In the case of continuous chip, at temperatures of 400–600°C, when the continuity factor $k \approx 0.96$ and the inclination of the fracture surface to the chip's contact surface is about 60°, failure corresponds to plastic shear in cross section A–B, in the zone with the maximum Mises equivalent stress σ_{equ}.

(2) In the case of segmented chip, at temperatures of 600–800°C, when $k \approx 0.87$ and the inclination of the fracture surface is about 68°, the plasticity declines. Mixed brittle–plastic failure (with rupture and shear) occurs under the action of tensile stress σ_1 and the Mises equivalent stress σ_{equ}.

(3) In the case of elementary chip (when he inclination of the fracture surface is about 90°), at temperatures of 800–1000°C, with high-temperature embrittlement of the machined material, further loss of plasticity is accompanied by weakening of the bonds between elements, and k tends to zero. Brittle failure is observed in cross section A–D, in the region with maximum tensile stress σ_1.

Thus, we have described the failure mechanics of machined material as it is converted to chip, on the basis of finite-element simulation of the chip's stress–strain state and experimental data on the type of chip produced over the whole of the practical temperature and cutting-speed range.

Experimental data regarding chip formation

No.	Chip type (inclination of failure surface)	v, m/min	θ, °C	k	Type of failure
1	 Continuous helical chip	5	560	0.96	Plastic failure (shear) 
2	 Segmented chip	50	760	0.87	Brittle–plastic failure (shear and rupture) 
3	 Elementary chip	148	1040	0.64	Brittle failure (rupture) 

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