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CIRP Secrétariat
10, rue Mansart
75009 Paris
Tél. (1) 45 26 21 80, Fax (1) 40 16 40 75

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Thermostrength of Carbide Tools

V. A. Ostafiev (1), A. N. Noshchenko — Kiev Polytechnic Institute
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ABSTRACT:

The tool volume thermal-stressed state has been investigated. Due attention is paid to estimating the role of thermal and mechanical loads and adequately selecting the criteria of sizing-up the tool's strength. The data obtained as a result of the performed investigations are used so as to explain the experimentally established characteristics of the tool's wear and fracturing in the process of continuous and interrupted machining.

KEY WORDS:

Tool, strength, FEM.

I. Introduction

In the process of machining, the cutting tool takes up considerable thermal and mechanical loads. The investigation of temperature and/or stress distribution in the tool's cutting area is, therefore, an important issue both for the theory and practice of machining.

There are quite a few studies dealing with the temperature variation in machining, as well as those tackling the temperature-wear problems. As for the tool's strength, it was paid attention to by fewer authors. It is attributable, on the one hand, to the lack of reliable experimental methods of determining the stressed state under conditions of a more significant dynamic pattern or thermal and mechanical loads, particularly, during the interrupted cutting, and on the other hand, to the sophisticated nature of the theoretical study of stresses in the cutting tool.

Analysis of the available literature [1,2,3,4,9] indicates that the majority of strength studies ignore the combined influence of the thermal and mechanical loads, as well as the three-dimensional nature of the tool's stressed state. The strength analysis in these studies was based on comparing the stress tensor elements and the principal stresses with the strength characteristics of the instrumental material. Such an approach is far from being correct for the tool in the complex stressed state.

Invalid assumptions adopted for calculating strength parameters produced the results that did not match the experimental data and precluded the derivation of relationships demonstrating the interaction between the stressed state and the fracturing or the wear of the tool. Similar discrepancies between the theory and practice gave rise to a number of hypotheses and assumptions concerning the causes of the tool's failure.

The present paper is concerned largely with the analysis of the three-dimensional distribution of temperature and stresses inside the tool. Due attention is paid to estimating the role of thermal and mechanical loads and adequately selecting the criteria of sizing-up the tool's strength.

The data obtained as a result of the performed investigations are used so as to explain the experimentally established characteristics of the tool's wear and fracturing in the process of continuous and interrupted machining.

It should be noted that in this paper by the thermally stressed state we denote the state resulting both from the thermal load and the mechanical loads, if any.

2. Investigation method

The heat exchange parameters and the high-temperature strength of cutting tools in a three-dimensional formulation can be calculated only using the numerical methods.

The procedure of determining the three-dimensional transient temperature fields in the cutting zone based on the finite element method has been presented by the authors in [5].

The features of the above procedure that permitted the solution of the three-dimensional problem for the transient temperature field and the heat exchange in the cutting og metals can be listed as follows: automatic generation of all initial data on the mechanic parameters of cutting, as well as the data used for finite element calculations; automatic printout of all calculated distributions of temperature in the cross(nodal) planes and on the face with the complete or the partial data visualization; employment of explicit schemes of the temporal integration with the diagonal matrix of the heat capacity; characterization of the chip's movement and the movement of the material being machined according to the combined Euler-Lagrange procedure. The above characteristics, that the authors deem worthy of note, made it possible to reduce the time for data preparation, calculation and the analysis of the obtained results by several orders of magnitude.

The three-dimensional stressed state of the tool's cutting area was determined using the finite element method in the form of the displacement method. The tool's cutting area was digitized by means o of the tetrahedral elements. High temperature gradients in the tool's contact layers necessitate the use of a dense non-uniform net of finite elements. The number of nodes for the standard conditions of calculating the strength was equal to 1000-2500. For a three-dimensional problem this led to a set of 3000 to 7500 linear algebraic equations. In addition, the allowance for the influence of the thermal load produces the appreciable non-uniformity of vector elements in the right-hand side of the equation. Solution of these simultaneous equations is fairly difficult. As far as the accuracy and computation time were concerned, excellent results were obtained using the variation-gradient method [7] of solving the simultaneous linear algebraic equations.

The tool's cutting area strength was estimated

considering the distribution of principal stresses $\sigma_1, \sigma_2, \sigma_3$, the stress intensity σ_i and the equivalent stress σ_ℓ which is determined by the following relationship [1]:

$$\sigma_\ell = \gamma\sigma_i + (1-\gamma)\sigma_i A^{1-\frac{\sigma_1+\sigma_2+\sigma_3}{\sigma_i}} \quad (1)$$

The parameter $\gamma = \frac{\sigma_t}{\sigma_c}$ determines the fraction of the shear strain in fracturing, σ_c is the ultimate compression strength, σ_t is the ultimate tensile strength, while A characterizes the static factor of the development of fracturing and is equal to 0.8 for the alloys of the WC-Co group or 0.7 for the alloys of the WC-TiC-Co group. Fracturing is believed to occur if $\sigma_\ell > \sigma_b$. The safety assurance factor in the present investigations was found from the relation $K = \frac{\sigma_b}{\sigma_\ell}$.

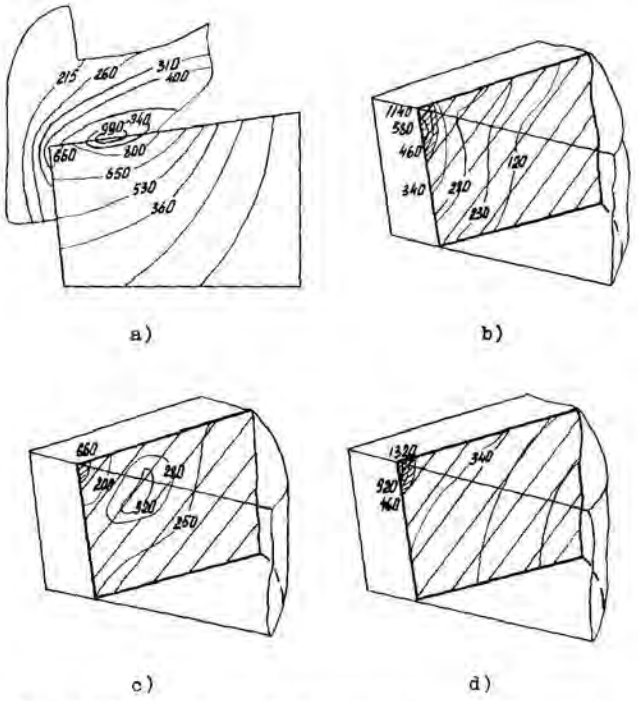
The obtained data on the empirical values of cutting forces, contact surfaces, chip ratio combined with the calculated distributions of contact loads [8], cutting thermal parameters, cutting tool geometry, thermal and physical and physico-mechanical properties of the tool material and the material being machined, were used as a source information for the finite element analysis of the three-dimensional distribution of transient temperature and stresses in the instrument's cutting area.

3. Analysis of the Results

The conducted cutting experiments and the numerical experiments lead us to believe that there exists an acceptable correlation between the stressed states of the tool's cutting area and the zones of fracturing and cutting. Of particular importance is the fact that when determining the stressed state it is necessary to take into account the combined action of mechanical and thermal loads. Ignoring the thermal factor while calculating the tool's strength parameters produces the results that do not fit the fracturing zones of contact surfaces observed during the experiment. Thus, Fig. I,a presents the distribution of temperature in the central section of the cutting zone at the moment of its actual stabilization in the tool's cutting area. The zone of the maximum temperature values of 990 °C is located in the beginning of the second half of the contact area and it is very depth-localised.

Fig. I,b,c, and d show the distributions of stress in the central section respectively for the cases of exclusively mechanical, thermal and combined loading of the tool's cutting area. The mechanical stress creates a stress field, whose peak equals 1140 MPa, on the rear surface below the cutting edge. The temperature gradients produce two zones of stress localization (I) a zone in the vicinity of the cutting edge (σ_ℓ =660 MPa) due to the flow of the heated metal, and (2) a zone below the frontal surface in the second half of the contact with the chip (σ_ℓ =320 MPa)

Dominating in the case study were the mechanical stresses. Their distribution, however, does not fit the zones of fracturing or wear either in form, or in dimensions. If allowance is made for the combined action of thermal and mechanical loads in the calculations undertaken, then there occurs the variation of both the values and the character of stress distributions.



a) b) c) d)

Fig. 1. Distribution of temperature and stresses in the turning of steel 40X by the tool made of alloy TI5K6 (V =200 m/min, S=0.1 $\frac{mm}{rev}$, t=0.5 mm, $\alpha=-8^\circ$, $\gamma=6^\circ$, $\varphi=53^\circ$, $\varphi_1=14^\circ$) :
a) - temperature in the central section;
b) - σ_ℓ as a function of mechanical load;
c) - σ_ℓ as a function of thermal load;
d) - σ_ℓ as a function of a combination of mechanical and thermal loads.

The largest values of σ_ℓ are related to the cutting edge and the region with the stresses $\sigma_\ell > \sigma_b$ (σ_b =450 MPa) protracts along the rear surface reaching the frontal surface, the phenomenon unobserved in the case of mechanical stresses. The extent of this region along the rear surface of the zone with a safety assurance factor below I was equal to 0.17 mm, while the measured wear of the rear surface was 0.16 mm. The high value of σ_i=5910 MPa in this zone is a special indicator of the predominantly ductile fracturing going on in this zone.

The available results testify to the fact that the distribution of stresses σ_ℓ gives the best correlation with the fracturing zones of contact surfaces, whereas the remaining stress invariants can be used in analysing the fracturing mode.

Fig. 2 shows the temperature field in the cutting zone along with the distribution σ_ℓ in the tool's cutting area when the cutting speed is brought down to 124 m/min (other machining conditions are indicated in Fig. 1). The reduction of cutting speed resulted in the chip ratio by 15%, while the contact length and the cutting force components were reduced respectively by 25 and 10%. When the cutting speed is decreased from 200 to 124 m/min, the maximum temperature values fall from 990 to 797 °C. The distribution σ_ℓ remained the same, while the maximum values of σ_ℓ decreased from 1320 to 920 MPa. The most overloaded tool parts are as usual the vicinity of the cutting edge and the rear surface, but the reduction of stresses diminishes in a fairly appreciable way the probability of the coloration and the wear rate. This regularity is confirmed by the experimental results.

The study was also investigating the thermally stressed state of the tool made of the alloy BK8 in the machining of stainless steel IXI8H9T and the titanium alloy BTI-0.

The distribution of temperature and stresses σ_i in the machining of steel IXI8H9T is shown in Fig.3. This example is a convincing illustration of the thermal load's contribution. The distribution σ_i calculated considering just the mechanical load, does not coincide with the fracturing zone of a single-point tool on the rear surface and does not suggest a possibility of the appearance of a wear crater on the frontal surface, which was, none the less, detected during the experiment. The maximum values of σ_i related to mechanical loads were localized in the narrow layer on the frontal surface and their values (σ_i = = 470 MPa with σ_b = 800 MPa for BK8) should not be alarming. If considered in the experiment is the combined action of mechanical and thermal loads, then there occurs the variation of both the values and the character of stress distribution σ_i .

According to the analysis data, there form two zones of fracturing on the tool's cutting planes: one on the rear surface, and the other on the frontal surface, which yields a good agreement with the experimental data. In this case the maximum values of σ_i increase 2.5 -fold reaching 1230 MPa and they are 1.5 times the ultimate strength σ_b of the alloy BK8. The highest values of the stress intensity pertain to the cutting edge equalling 2890 MPa, this fact testifying to the plastic character of edge fracturing. In the crater's thin surface layer the stress intensity σ_i is equal to 2310 MPa, exceeding

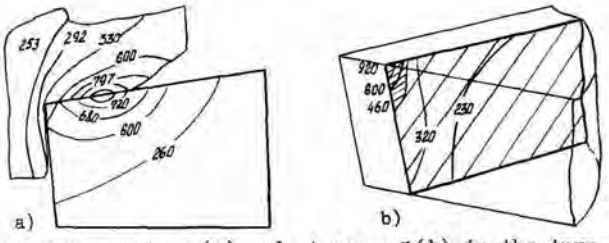


Fig.2. Temperature (a) and stresses σ_i (b) in the turning of steel 40X by the tool made of alloy TI5K6 (V =124 m/min, other parameters same as those shown in Fig.I).

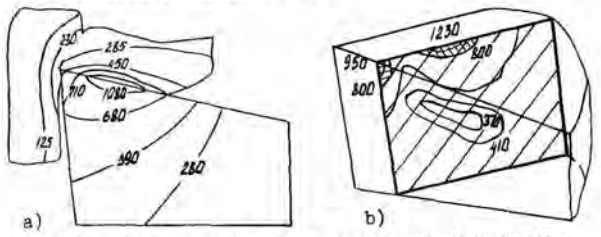


Fig.3. Temperature (a) and stresses σ_i (b) in the turning the steel IXI8H9T using a tool made of the alloy BK8(V = 60 m/min; S=0.44 mm/rev, t=2.8 mm, α=15°, γ=7°, φ = φ_1=45°, λ = 0°).

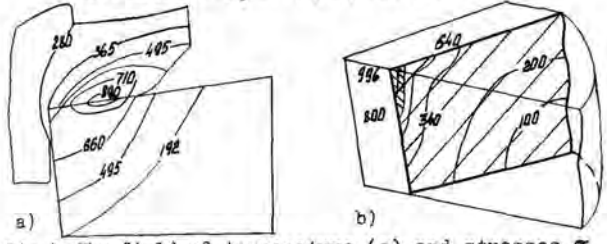


Fig.4. The field of temperature (a) and stresses σ_i (b) in the turning the titanium alloy BTI-0 using the tool made of the alloy BK8(V=73m/min S=0.15 mm/rev, t=0.5 mm, α =-6°, φ=58°, φ_1=14°, λ= 0°).

the yield limit, as well. However, it is highly probable that the fracturing character on this site is determined by the principal stress σ_1 reaching 1200 MPa. With such values of σ_1 the brittle fracturing becomes possible.

Temperature and stress distributions σ_i in the tool made of alloy BK8 while machining the titanium alloy BTI-0 are shown in Fig.4. In machining the titanium, plastic fracturing of the cutting edge and the rear plane is the main cause of the tool's failure. This conclusion is supported by the results of the calculations performed. The most stressed parts of the tool are the cutting edge and the rear surface. The stresses here reach 996 MPa and are in excess of σ_t . High values of σ_i = 3240 MPa indicate the plastic character of the tool's destruction.

This computation technique was also employed for analysing the fracturing processes when the tool is used for the interrupted machining with the cooling aqueous liquid. Considering the great difficulty of obtaining all data, necessary for calculating the fracturing parameters under the real conditions of intermittent machining, the tool's heating was simulated based on the data of continuous cutting of the steel 40X using the tool made of the alloy T15K6 with the cutting speed of 200 m/min. These data were presented above. If the mechanical conditions are assumed constant, the variation of the stressed state will be determined by the transient temperature. With this assumption in mind, the study was focused on investigating stresses in the tool's cutting area during the cutting-in and quitting the machining zone (the moment of mechanical stress relaxation), as well as the stresses occuring when the tool is cooled with the different time intervals.

While the tool's cutting area cuts into the machined surface, the sudden heating of the contact surfaces causes a very unfavourable set of mechanical and thermal stresses in the vicinity of the cutting edge (see Fig.5). After 2 ms the maximum values of σ_i become equal to 1700 MPa, while at an almost steady-state temperature they reach 1320 MPa after a passage of 40 ms. When the tool's cutting area leaves the machining zone there occurs the restructuring of the stressed state in accordance with the temperature distribution at the moment of stress relaxation. Under the contact site, there forms a centre of stresses, whose value σ_i = 465 MPa exceeds the boundary strength σ_b for the alloy TI5K6, while the stresses on the peak abruptly fall to 116 MPa. Fig.5 presents the dynamic pattern of the variation of the variation of stresses σ_i as a result of cooling. 0.34 ms after the beginning of the cooling the maximum values of temperature drop to 751°C (the decrease is 240°C), whereas the stresses σ_i drop to 309 MPa. After a passage of 0.68 s, the maximum values of the temperature are equal to 643°C, and the stresses σ_i amount to 274°C, although in this case there exists the variation of the character of distribution of these parameters. The area of the maximum values of σ_i has migrated to the end of the contact site and reached the frontal surface. In 2.04 s the temperature drops to 437°C, and the stress to 182 MPa. The maximum stresses in these localization zones occur in the rear auxiliary plane subject to active cooling. When the instrument reaches the depth of 0.295 in-

side the material machined, the stresses decrease to 128 MPa. From the viewpoint of statistic strength, such stress values should pose no danger. However, under conditions of the cyclic loading similar stresses may cause thermal cracks.

The investigations performed show that the dynamic pattern of the temperature variation exerts pronounced influence on the formation of the tool's stressed state. Very high heating rate (10^5 to 10^6 deg/s) of the contact surfaces when the tool penetrates the blank leads to the deterioration of strength pattern in the vicinity of the cutting edge. The deterioration in question manifests itself differently on the brand of a high alloy tool. For instance, when machining the steel 40X by the tool made of the alloy T15K6, in the initial period of cutting-in one can observe the increase of the stress level σ_t by 30-40% compared to the period in which the tool's cutting area temperature had virtually stabilized. Equilibration of temperature is accompanied by the decrease of the values of σ_1, σ_2, σ_3 by one third and the increase of the σ_1 level by 30%. Under comparable conditions of machining using the BK8 tool no higher level of stresses σ_t in the initial cutting stage has been detected. However, the dimensions of a zone with a safety assurance factor below unity are almost twice those of a similar zone existing under the steady-state temperature. The safety assurance factor in the vicinity of the TI5K6 tool's top amounted to 0.25, while the similar index for the BK8 tool was equal to 0.4. These results are in agreement with a greater wear resistance of the tool made of BK8 operated during the heavy-duty interrupted machining under conditions of the variable thermal and mechanical loading. Considering the fact that forces grow to their rated values in a much quicker way than does the temperature equilibration in the cutting part, one can infer that the dynamic pattern of the tool's stressed state variation in penetrating the blank controls, to a great extent, the temperature distribution character. The resulting stress level jeopardizes strength and produces fracturing or pays the way for the subsequent fracturing and/or wear. The further period of the tool's operation is characterized by the accelerated growth of the contact's length on the frontal surface as compared to the cutting forces. This alleviates the specific contact loads, and, therefore, reduces the temperature of the cutting lip. Making allowance for the thermal stress in design calculations of the tool's strength in this stage of its operation increases the general level of stresses, whose distribution is in good agreement with the zones of fracturing and wear.

When the instrument leaves the machining zone and upon the relaxation of stress load, the stress field σ_1 in the tool is formed entirely by the temperature gradients. These stresses are continuously decreased in the process of cooling and their magnitude is much lower than that characteristic of stresses during the cutting-in and the continuous cutting. However, for the alloy TI5K6, whose thermal conductivity and the values of σ_b are two times those for an alloy BK8, stresses can achieve critical levels. In this case the region of maximum values of stress is located below the frontal surface in the contact zone adjacent to the rear auxiliary surface (Fig.5).

The presented analysis of the tool's operation, based on the investigation of its strength parameters, is by no means complete. The multiplicity of processes underlying the wear and fracturing of the tool prevents the formulation of a tractable theory. However, the satisfactory agreement between the three-dimensional thermally stressed state of the tool and the experimentally observed fracturing and wear of contact surfaces testifies to the particular importance of all thermal stress problems to be elucidated when designing machine tools and selecting the optimized operating conditions.

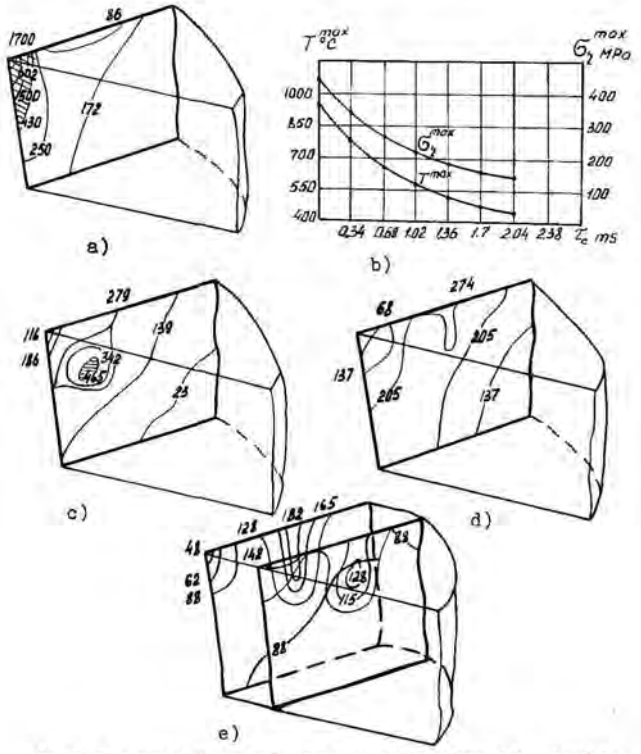


Fig.5. Temperature and stresses σ_1 during the tool's penetration of the material, leaving the material and cooling (machining parameters are listed in Fig.1) :
a) - stresses σ_1 2 ms after the penetration;
b) - variation of the maximum values of temperature and stresses σ_1 during the tool's cooling;
c) - stresses σ_1 at the moment of relaxation of the mechanical load;
d) - stresses σ_1 in the cooling during 0.68 ms;
e) - stresses σ_1 in the cooling during 2.04 ms.

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