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Estimation of Temperature Conductivity Coefficient Impact upon Fatigue Damage of Material

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Abstract. In the paper we consider the peculiarities of adhesive wear of cutting tools. Simulation of heat flows in the cutting zone showed that, as thermal conduction and heat conductivity of tool material grow, the heat flows from the front and back surfaces to tool holder will increase and so, the temperature of the contact areas of the tool will lower. When estimating the adhesive wear rate of cemented-carbide tool under the cutting rates corresponding to the cutting temperature of up to 900 °C, it is necessary to take the fatigue character of adhesive wear into consideration. The process of accumulation and development of fatigue damage is associated with micro- and macroplastic flowing of material, which is determined by the processes of initiation, motion, generation, and elimination of line defects – dislocations. Density of dislocations grows with increase of the loading cycles amount and increase of load amplitude. Growth of dislocations density leads to loosening of material, formation of micro- and macrocracks. The heat capacity of material grows as the loosening continues. In the given paper the authors prove theoretically that temperature conductivity coefficient which is associated with heat capacity of material, decreases as fatigue wear grows.

1. Introduction

One of the main factors affecting durability of cutting tools is temperature in the contact area [1, 2]. The thermal and physical characteristics of tool and machined material will influence the temperature in the cutting area [3-6]. Simulation of heat flows in the cutting area showed that, as thermal conduction and heat conductivity of tool material grow, the heat flows from the front and back surfaces to tool holder will increase and so, the temperature of the contact areas of the tool will lower [3]. The diagram of heat flows in the cutting tool is presented in Figure 1.

Analysis of cutting tool use under factory conditions showed that cemented-carbide tool is quite often used under the cutting rates which correspond to the temperatures of up to 900°C in the cutting area, i.e. under the cutting rates which are lower than the rate corresponding to the inflexion point of the curve showing the dependence of wear upon cutting rate [7]. At this segment of the curve the durability of the tool increases as the cutting temperature grows Figure 2. It is commonly accepted [8, 9] that this temperature region corresponds to adhesive wear of the tool. According to the current opinion [8, 10-12], adhesive wear is based upon the phenomenon of adhesive bond – developing strong temporary bonds between the contacting surfaces resulting from their mutual deformation under high temperature. The ability of materials for adhesive wear grows under recrystallization temperature. Plastic deformation is localized in the areas of actual contact of chip or machined surface with the tool where the protecting oxide and adsorbed films are destroyed, thus, the conditions for physical contact and formation of chemical bonds are created. As a result, we observe adhesive bonding of machined and tool material [13, 14]. It should be mentioned that formation and destruction of seizure bridges occurs with a certain periodicity. Destruction takes place in the surface or subsurface layer of less strong (machined) material. At the same time the crystal lattice in the surface layers of the tool is also damaged, as repeated seizure and breaking of adhesive bonds cause cyclic stress of the surface layer of tool material which is characterized by increased fragility (in comparison to the machined material) [13, 14]. Cyclic loading affecting the contact edges of the tool leads to formation of fatigue cracks resulting in separation of wear particles [7].

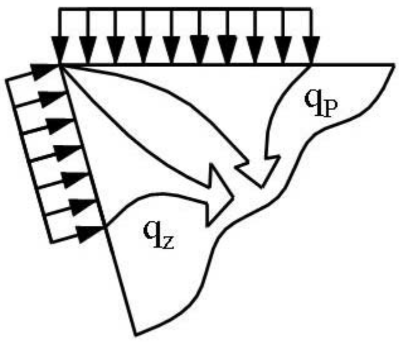

Figure 1. Cutting tool heat flows

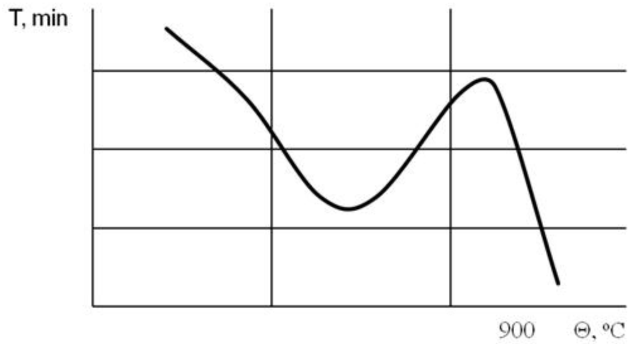

Figure 2. The curve of the temperature-tool life

The fatigue nature of adhesive wear was experimentally revealed in many works, such as [15, 16]. That is why estimation of wear rate of cemented-carbide tool under the temperatures below 900°C requires taking the fatigue nature of adhesive wear into account.

Results and Discussion

According to many researchers, the process of accumulation and development of fatigue damage is associated with micro- and macroplastic flowing of material, which is determined by the processes of initiation, motion, generation and elimination of line defects – dislocations [17-20]. Density of dislocations grows with increase of the loading cycles amount and increase of load amplitude. Growth of dislocations density leads to loosening of material, formation of micro- and macrocracks.
Temperature conductivity coefficient [21]

$$a = \frac{\lambda}{cp} \quad (1)$$

where c - specific thermal capacity;

ρ - density,

characterizes the rate of temperature distribution in space.

Basically, the temperature conductivity coefficient allows judging of the processes of accumulation and development of fatigue damage but reference literature does not provide any articulate information on this problem. Nevertheless, there is a number of data indicative of such dependence.

For metals, temperature conductivity is determined by the total of electron and phonon contribution (flat waves of deformation) [22, 23]

$$\lambda = \lambda_e + \lambda_p \quad (2)$$

The phonon component λ_p of heat-transfer resistance determined by dissipation (disappearing of one (or two) phonon and appearing of two (or one) phonons) at the dislocations, is directly associated with viscous drag of dislocations by phonons. We observed great changes of λ_p according to density of dislocations of LiF crystal [23] see Figure 3. Also in work [24] the authors describe decrease of thermal conduction for lead with addition of bismuth in comparison to pure metal.

In work [25] the authors note decrease of thermal conduction coefficient of KCl with addition of KNO_2 in comparison to pure metal as well as decrease of thermal conduction under deformation of KCl and CaF_2.

The electron component of thermal conduction λ_e is directly proportional to electrical conductivity [23, 26], i.e. they speak about correlation between these parameters.

Reference literature provides information on relation between electrical conductivity, level of peak voltage and number of load cycles for some metals (C1010, C1020, Armco iron) [19]. As an example in Figure 4 we provide one of such diagrams for C1010 under the number of load cycles $N=1{,}56\cdot10^6$ at every level of peak voltage σ.

Decrease of thermal conduction with growth of load cycles is associated with gradual accumulation of discontinuity in the metal, the tendency for higher rate of electrical conductivity decrease are more noticeable when submicroscopic cracks develop to become microcracks. Immediately before destruction of the sample electrical conductivity falls most abruptly [19].

Thus, the information in reference literature on relation between electrical conductivity coefficient and thermal conduction coefficient λ, correlating with it, and generation and accumulation of dislocations, allows making a conclusion that, as fatigue grows thermal conduction of material in the center of damage decreases.

As for temperature conductivity coefficient we did not find any direct information conserning its relation with fatigue in reference literature.

In the process of fatigue damage accumulation the crystal lattice also accumulates defects and loosening of material, resulting from it, occurs [18, 19]. Thermal capacity of material (c) increases in the course of material loosening [21]. That is why it is possible to suppose that temperature conductivity coefficient which is associated with thermal capacity of material (1), to a greater extent (than λ) will decrease as fatigue damage grows.

One of important parameters of dislocation structure is density of dislocations ρ'. Density of dislocations is total length of dislocation lines in the unit of volume of materials and it is determined by the following correlation [23]

$$\rho' = \frac{1}{A\Lambda}, \quad (3)$$

where Λ - mean free path of phonons;

A - scattering cross-section of phonons per unit of dislocation length.

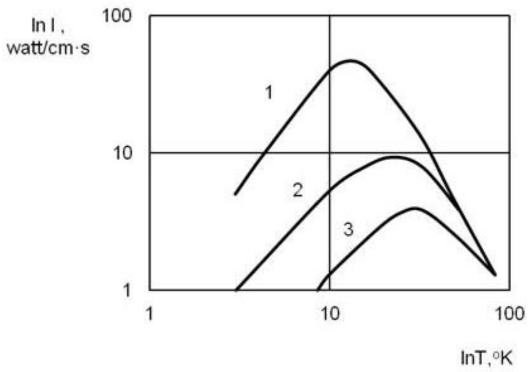

Figure 3. Dependence of temperature conductivity of LiF crystal upon absolute temperature under various degree of deformation:1 – after keeping during 2 hours under 830° C (ρ' =3·104 cm-2), 2 – after deformation of 2,4% under room temperature , (ρ' =1,8·107 cm-2),3 – after deformation of 4% under 180° C (ρ' =4,6·107 cm-2)

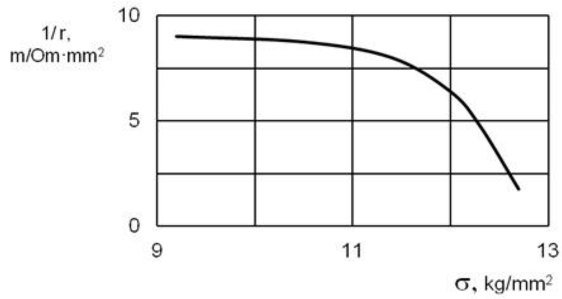

Figure 4. Influence of cyclic stress amplitude upon electric conductivity change

Scattering cross-section of phonons per unit of dislocation length can be determined as [23]

$$A = \frac{\gamma^2 b^2}{S} 2\pi\nu , \qquad (4)$$

where S - sound velocity;
b - Burgers vector;
γ - Gruneisen constant;
ν - oscillation frequency of dislocations.

Gruneisen constant is determined by the expression [27]

$$\gamma = \frac{\alpha E a_0{}^3}{C_a} , \qquad (5)$$

where a_0 - atomic size;
E - elasticity modulus;
C_a - atomic heat capacity;
α - coefficient of linear expansion.

free path of phonons can be found from equation from Debye equation [28]

$$\lambda = \frac{1}{3} cS\Lambda\rho , \tag{6}$$

where λ - thermal conduction;
c - specific heat capacity;
ρ - density.

Thus

$$\Lambda = \frac{3\lambda}{cS\rho} . \tag{7}$$

Thermal conduction is expressed through temperature conductivity (a) [21]

$$\lambda = c\rho a . \tag{8}$$

After combining (8) and (7) we obtain

$$\Lambda = \frac{3a}{S} . \tag{9}$$

From equation (9) it follows that the free path of phonons is directly proportional to temperature conductivity of material which is proved by the works of A.A. Kusov [29].

Thus, using (9) and (4) in (3) we determine dislocation density as function of temperature conductivity

$$\rho' = f(a) \tag{10}$$

or

$$\rho' = \frac{S^2}{6\pi a \gamma^2 b^2 \nu} , \tag{11}$$

Taking

$$\frac{S^2}{6\pi \gamma^2 b^2 \nu} = m , \tag{12}$$

we obtain the formula to calculate the density of dislocations

$$\rho' = \frac{m}{a} \tag{13}$$

Conclusion

When estimating the rate of adhesive wear of cemented-carbide cutting tool under the cutting speeds corresponding to the cutting temperature of up to 900 C, it is necessary to take the fatigue nature of adhesive wear into account. Accumulation of fatigue damage causes change of thermal and physical characteristics of material. Analysis of formula (13) allows saying that, under accumulation of fatigue damage, i.e. under growth of dislocation density, temperature conductivity coefficient decreases, thus, proving the suggested hypothesis that the temperature conductivity coefficient which is associated with thermal capacity of material, decreases due to the growth of fatigue damage. So, temperature conductivity coefficient can be considered a structurally-sensitive characteristics of material and used as information parameter for forecasting the durability of cemented-carbide cutting tools.

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