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SOME REGULARITIES OF THE HEAT TRANSFER IN THE PROCESS OF COOLING OF A CUTTING ZONE BY AN EMULSION FOG

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The dependence of the average diameter of the drops of an emulsion and their number in a unit volume on the conditions of emulsion-fog generation has been investigated. An individual drop is heated, when it comes into contact with a heated surface, to the boiling and evaporation temperatures. Under certain conditions, the total time of heating and evaporation of all drops making contact with a surface for 1 sec can be smaller than this time. In this case, active substances entering into the composition of the emulsion form a solid lubrication film on the surfaces of a piece, a chip, and a cutting tool. More than 50% of the total heat released can be removed due to the boiling and evaporation of emulsion drops from the cutting zone.

The main requirement imposed on technological lubricating-cooling means (TLCM) is the provision of effective removal of heat from the cutting zone and formation of a lubricating film on the contact surfaces. One of the most important problems arising in the process of using a TLCM is determination of its necessary amount [1]. For example, in the case of boiling of water (representing a main component of an emulsion) there arise bubbles that form, at a fairly large amount of water, a continuous vapor film on a heated surface. This film adjoins to the surface and prevents the surface from being in contact with the aqueous medium. Even though the formation of a vapor film is not a stable process, it eventually deteriorates the heat removal from the cutting zone [2]. A diffused TLCM interacts with a heated surface much better than a liquid jet, which leads to the removal of a large amount of heat [3].

Considerable recent attention has been focused on cooling processes in which a minimum amount of the active component of a TLCM is used. For example, in the case where aerosols are used for cooling, the flow rate of this component is less than 50 ml/h [1, 4]. In this case, of great importance is the fact that the cutting tool, the piece, and the chip formed remain dry. Under these conditions, it is impossible to estimate the consumption of the active component of a TLCM with the naked eye. An increase in this consumption leads, on the one hand, to the formation of a chip that could not be considered as dry, which makes its salvaging much more difficult, and on the other leads to the formation of a film of liquid drops and chip fragments on the surface of a tool [1].

A cutting with the use of a minimum amount of a TLCM can be realized when the active component of aerosols is an emulsion based on water, used for heat removal, or an oil because these substances possess good lubricating properties, decreasing the friction forces in the cutting zone. A compressed air, when used as a transport means for the active component of a TLCM, can serve to remove the chip from the working zone [1].

In the case, where aerosols are used, the output nozzle of an apparatus can be located in the immediate vicinity of the cutting zone [5] or at any distance from it [6]. In this case, of importance are the diameter of the emulsion drops found in an aerosol and the flow rate of the emulsion.

Investigations were carried out with the use of an apparatus having two nozzles, one of which was used for control of the flow rate of a compressed air and the other for control of the active substance (emulsion). In the process of calibration of the apparatus, we measured the diameter of the drops on a plane surface simulating the active surface of a cutting zone with allowance for the fact that the shape of a liquid drop is changed when it comes into contact with a solid surface (it flattens in this case). The diameter of a drop on a surface is related to the diameter of this drop in the air by the following relation [7]:

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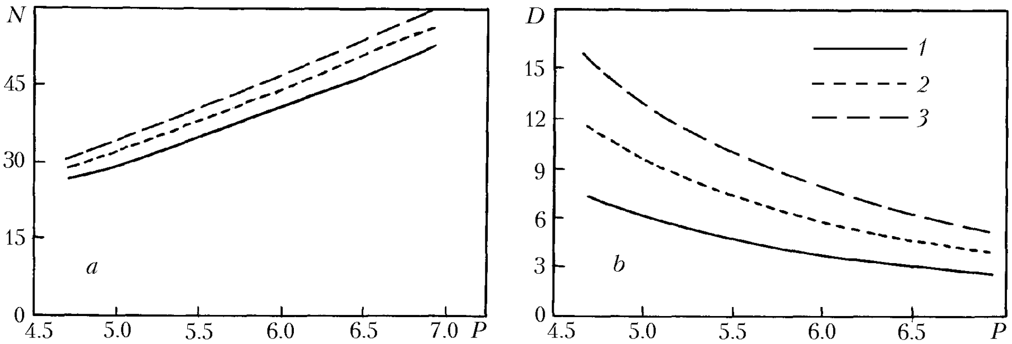

Fig. 1. Dependence of the number of drops (a) and their diameter (b) on the flow rates of a compressed air and an emulsion when the nozzle is located at a distance of 0.4 m from the surface: E = 2 (1), 3 (2), and 4 g/min (3). D, μm.

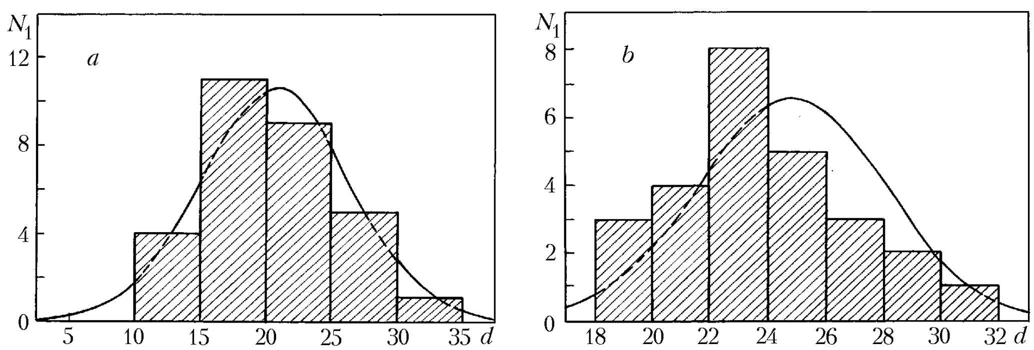

Fig. 2. Histograms of the diameter distribution of emulsion drops in an emulsion fog: a) L = 0.4 m, E = 2.6 g/min, and P = 4.7 m^3/h; (b) 0.3, 3.6, and 4.7.

$$D = md\,. \tag{1}$$

It may be assumed that the coefficient m is equal to 2.5 [8].

As the active component of an emulsion fog, a 4%-concentration OPORTET RG-2 emulsion was used. An emulsion fog was generated under the following conditions: distance between the output nozzle and the surface, 0.3–0.4 m; emulsion flow rate, 1.5–3.5 g/min; compressed-air flow rate, 4.7–6.9 m^3/h. As a result of the calibration of the apparatus, we obtained regression dependences that allowed us to calculate the number of emulsion drops per 1 mm^2 of the contact surface and their average diameter:

$$N = 2.56L^{0.58}E^{0.19}P^{1.772}\,, \tag{2}$$

$$d = 35.9 \cdot 10^{-3} L^{-2.368} E^{1.094} P^{-2.914}\,. \tag{3}$$

The influence of the conditions of emulsion-fog generation on the indicated quantities is demonstrated in Fig. 1. The drop-diameter distribution correlates fairly well with the normal-distribution law (Fig. 2).

The heat supplied to liquid drops initially heats them to the saturation temperature Q_{sat} and then causes them to evaporate. The heat-balance equation for the first stage of the process has the form [7]

$$\frac{\pi D^2}{4}\,\alpha\,(\Theta_{\text{sat}} - \Theta_0)\,\tau_1 = c\,\frac{\pi d^3}{6}\,(\Theta_{\text{sat}} - \Theta_0)\,. \tag{4}$$

The time of heating of a drop to the saturation temperature is equal to

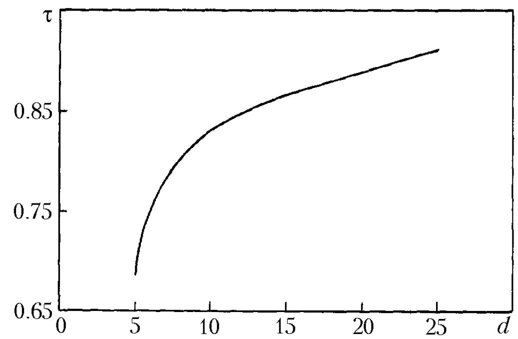

Fig. 3. Influence of the diameter of the emulsion drops on the time of evaporation of all drops falling on the heated surface for 1 sec. d, μm.

$$\tau_1 = \frac{2}{3}\frac{cd}{\alpha m^2} . \tag{5}$$

For the boiling of a drop, we write the following heat-balance equation [7]:

$$\frac{\pi D^2}{4} \alpha (\Theta_s - \Theta_{sat}) \tau_2 = \frac{\pi d^3}{6} \rho r , \tag{6}$$

whence it follows that

$$\tau_2 = \frac{2\rho r d}{3\alpha m^2 (\Theta_s - \Theta_{sat})} . \tag{7}$$

The total time necessary for evaporation of one drop is equal to

$$\tau = \tau_1 + \tau_2 . \tag{8}$$

Knowing the number and diameters of the drops falling on a heated surface in 1 sec, one can determine the time of their evaporation. The calculation data obtained for E = 2.6 g/min, P = 4.7–6.9 m^3/h, and a cooled surface of area 20 mm^2 are presented in Fig. 3. It is clear that there exist conditions under which the whole active component falling on the heated surface evaporates. Under these conditions, a stable lubricating film is formed on a contact surface, which decreases the friction on the contact areas and positively influences the shape of the chip. It may be suggested that, in this case, the emulsion transports the active substances to the cutting zone.

Let us consider the heat transfer under certain tuning conditions. The amount of heat released in a cutting zone in 1 sec is equal to

$$Q = P_z V . \tag{9}$$

The main component of the breaking force can be determined as [6]

$$P_z = tSk_{c0.4} \left[\frac{0.4}{S \sin \varphi}\right]^{0.29} . \tag{10}$$

In the case where the rate of cutting is equal to 200 m/min, the rate of advance of a cutting tool is 0.2 mm/rot, the depth of cutting is 1 mm, the specific breaking force is $k_{c0.4}$ = 2000 MPa [6], and the side rake angle is 70^o, the main component of the breaking force will be equal to 560 N and the amount of heat released in the process of cutting will comprise ≈530 W. The calculations were carried out with allowance for the fact that the actual side rake angle is equal to 48^{o} at the above-indicated values of t, S, and φ when a cutting tool with a nose-radius of 0.8 mm is used.

The amount of heat removed from the cutting zone by one emulsion drop as a result of its heating and subsequent evaporation is equal to

$$Q = Q_1 + Q_2 \,, \tag{11}$$

$$Q_1 = m^2 \left[\frac{\pi d^2}{4} (Q_{\text{sat}} - Q_0) \right] \sqrt[3]{\left(\frac{6K}{\pi d^3} \right)^2} \approx 0.005 \text{ W} \,, \tag{12}$$

$$Q_2 = dr\rho \sqrt[3]{\frac{6K^2}{6}} \approx 0.178 \text{ W} \,. \tag{13}$$

Calculations have shown that the volume concentration of emulsion drops in the emulsion fog is equal to $(2–3)\cdot 10^{-8}$. The net result is that Q = 0.183 W.

It was established that, in the case where the cutting depth t = 1 mm and the velocity of the chip moving along the face surface V_c = 80 m/min, the area of the active chip surface removed from a workpiece in 1 sec is approximately equal to 1300 mm^2. If the heat removed from 1 mm^2 of an emulsion drop in 1 sec measures 0.183 W, 230 W can be removed from the whole surface of the chip. Since the heated surfaces of a cutting tool and a workpiece also participate in the heat transfer, more than 50% of the total amount of heat released can be removed by the emulsion fog.

Thus, depending on the conditions of formation of an emulsion fog, the number and diameters of drops entering the working zone can be different. Under certain cutting conditions, all drops making contact with a heating surface for 1 sec can evaporate from this surface. In this case, all active substances present in the emulsion will be left on the surfaces of the piece, the chip formed, and the cutting blade, and then on their contact surfaces. As a result, on the contact surfaces there arises a lubricating film, decreasing the friction coefficient in the cutting zone and the roughness of the surface worked. The emulsion fog removes a large amount of heat from the cutting zone — more than 50% of the total heat released in certain cases.

NOTATION

c, heat capacity per unit volume of an emulsion, J/(m$^3\cdot$K); D, diameter of the spot of contact of a drop with a surface, m; d, diameter of a drop in the air, m; E, flow rate of the emulsion, g/min; K, volume concentration of emulsion drops in the emulsion fog; $k_{c0.4}$, specific breaking force at a cut diameter of 0.4 mm, MPa; L, distance of a nozzle from the surface, m; m, coefficient accounting for the deformation of a drop on the surface; N, number of emulsion drops per 1 mm^2 of the contact surface, drops/mm^2; N_1, number of definite-diameter emulsion drops falling onto 1 mm^2 of the surface, drops/ mm^2; P, flow rate of a compressed air, m^3/h; P_z, main component of the breaking force, N; Q, amount of heat, J; r, heat of emulsion-vapor formation, J/kg; t, depth of cutting, mm; S, advance, mm/rot; V, rate of chip cutting, m/sec; α, coefficient of convective heat transfer, W/(m$^{2}\cdot{}^{o}$C); φ, side rake angle, deg; Θ, temperature, ^{o}C; ρ, density of an emulsion, kg/m^3; τ, time, sec. Subscripts: sat, saturation; s, surface; c, chip; 0, output of a nozzle; 1, heating; 2, evaporation.

REFERENCES

1. J. Schmidt, H. Lang, and M. Dyck, Trockenbearbeitung ist wirtschaftlich und umweltfreundlich, *Maschinenmarkt*, No. 29, 20–23 (2001).
2. T. Hobler, *Ruch ciepla i wymienniki*, WNT, Warszawa (1986).

3. K. E. Oczoś, Rozwój innowacyjnych technologii ubytkowego kształtowania materiałow, Cz. I. Obróbka skrawaniem, *Mechanik*, No. 8–9, 537–550 (2002).
4. Weniger ist oft mehr, *Maschine + Werkzeug*, No. 9, 81–84 (1996).
5. M. I. Klushin, V. M. Tikhonov, and D. A. Troitskaya, *Cooling and Lubrication of Sprayed Liquids in Cutting of Metals* [in Russian], Volgo-Vyatskoe Knizhnoe Izd., Gor'kii (1966).
6. Catalogue of the Sandvik Coromant Company, C-1102:2-POL/01 (2002).
7. A. N. Reznikov and L. A. Reznikov, *Thermal Processes in Technological Systems* [in Russian], Mashinostroenie, Moscow (1990.
8. Yu. G. Proskuryakov and V. N. Petrov, *Fine-Spray Cooling of Cutting Tools* [in Russian], Mashgiz, Moscow (1962).