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THE ANALYSIS REGARDING THE DIFFUSION WEAR OF THE CUTTING TOOL

Carmen TACHE, Dumitru DUMITRU

Abstract: *When the elements of the friction couple (chip and cutting tool) are in contact, at the sliding interface, the materials are dissolved if the free energy of a new formatted material decreases during the solution formation. The dissolution speed increase with the growth of the interface temperature. The dissolved material is transported through diffusion into the chip. Through the remove of the dissolved material, it is formatted the "cone" to the rank face of the cutting tool. The chemical instability is the main reason for dissolution of the materials which are part of the friction couple. The energy generated by friction in the contact area contributes to modify the thermal regime and to amplify the phenomena of the diffusive transportation.*

Key words: *diffusion wear, dissolved material, friction couple.*

1. INTRODUCTION

When the elements of a friction coupling with preponderant gliding are in direct contact, on the gliding interface, the materials melt into one another, if the free energy of the "new" material formed decreases during the formation of the solution [1].

The dissolution speed increases as the interface temperature increases.

The diluted material can be transported by means of different mechanisms:

- in chip diffusion;
- convective transportation by macroscopic flow of the material from the contact interface, perpendicular on the front face;
- deterioration of the material layer found under the diluted layer and the formation of wear particles of the diluted material.

By means of removing the diluted material, the crater appears on the front face of the cutting tool.

The weight of any of the transportation mechanisms is different, depending on the material of the tool, the material of the working piece and the local conditions (contact pressure, relative speed and temperature).

The main cause of the mutual dilution of the two materials that form the friction coupling is chemical instability.

The convective transportation of the diluted material from the contact surface of the tool with the chip can be done by the relative tangent movement of the chip (the component of the speed that is parallel to the interface) and by the normal component of the speed.

On the tangent direction of the chip, the convective transportation is limited as a consequence of rapid saturation during gliding on the tool.

The speed on the normal direction on the front face of the tool (Fig. 1) can be determined from the continuity condition for the plane deformation case:

$$\frac{\partial v_x}{\partial x}+\frac{\partial v_y}{\partial y}=0. \tag{1}$$

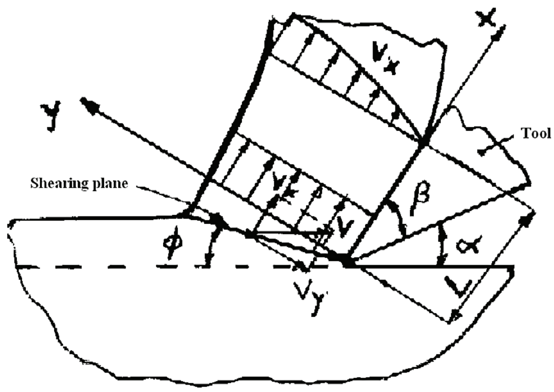

Fig. 1. The speed model of the chip.

For the points of the shear plane, the components of the speed from the directions x (parallel to the front face) and y (normal at the front face) are:

$$\begin{aligned} v_{ox} &= v\cos(\alpha+\beta) \\ v_{oy} &= v\sin(\alpha+\beta). \end{aligned} \tag{2}$$

On the front face and in the main shear plane, the component v_{oy} is null. As a consequence of the friction of the chip on the front face, the speed in x direction decreases, so that at L distance, the speed $v_x = 0$ and the chip separates from the tool.

From the continuity condition (eq. 1) and from the observation of speed reduction in direction x, on the contact surface between a chip and the tool, there can be seen a speed on the normal direction of the tool, from the tool to the exterior (positive speed in direction y).

If the adhesion coefficient (f) of the chip on the tool is considered constant, then the v_x component has a linear variation and out of the limit conditions ($v_x = v_{ox}$ for $x = 0$ and $v_x = 0$ for $x = L$), then it results:

$$\begin{aligned} v_x &= v_{ox}\left(1-\frac{x}{L}\right) \\ v_y &= v_{oy}\left(1+\frac{v_{ox}}{v_{oy}}\cdot\frac{y-b}{L}\right). \end{aligned} \tag{3}$$

2. THE THERMO DIFFUSION IN THE FRICTION PROCESS BETWEEN THE RANK FACE OF THE TOOL AND CHIP DETACHED FROM THE WORKING MATERIAL

As far as the solids are concerned, the diffusion mechanism is a jump mechanism; the transportation is made by successive jumps from an equilibrium position into another. Both forms of diffusion are possible: the self diffusion and inter diffusion.

The temperature gradient can lead to mass transfer from a surface to another, when the energetic conditions of the contact area are insured.

Similar to the concentration gradient (c), by thermal gradient (Dufour effect) mass can be transferred from one surface to another.

Using Fick's second law, $\frac{\partial J}{\partial y}=-\frac{\partial c}{\partial t}$, we can deduce the differential equation of thermo diffusion:

$$\frac{\partial c}{\partial t}=\frac{\partial^2\left[D(y)\cdot c(y,t)\right]}{\partial y^2}, \qquad (4)$$

where: c – molecular concentration, J – concentration flux, D – diffusion coefficient

In the two elements of the friction coupling (cutting tool and chip), there arises a non-steady thermal regimen with gradient on the direction of the common normal of the contact. If the materials of the coupling have different concentrations of some of the components and in the friction area, there are energetic conditions formed, then the thermo diffusion is possible, so the relation 4 can be applied.

We consider a roughness (1) from the material of the cutting tool in contact with the steel surface of the chip (2) with axis Oy oriented towards the steel surface (Fig. 2).

The differential equation of the diffusion process will be [2]:

$$\frac{\partial c}{\partial t}=-\frac{\partial J}{\partial y}=D\frac{\partial^2 c}{\partial y^2}+\frac{\partial c}{\partial y}\left(\frac{\partial D}{\partial y}-D\cdot M\right)-$$
$$-c\left(M\frac{\partial D}{\partial y}+D\frac{\partial M}{\partial y}\right)=D\cdot\frac{\partial^2 c}{\partial y^2}-v\frac{\partial c}{\partial y}-k\cdot c, \qquad (5)$$

where

$$M=\frac{1}{R\theta}\left[\frac{\partial Q}{\partial\theta}-\frac{Q}{\theta}\right]\frac{\partial\theta}{\partial y},\quad v=D\cdot M-\frac{\partial D}{\partial y}=D\cdot M\left(1+\frac{\partial\theta}{\partial y}\right),$$

$$v=D\cdot M-\frac{\partial D}{\partial y}=D\cdot M\left(1+\frac{\partial\theta}{\partial y}\right),\quad k=M\cdot\frac{\partial D}{\partial y}+D\frac{\partial M}{\partial y},$$

R – the universal gases constant, θ – temperature.

The answer of relation 5, for the following conditions (for the limit and initials):

$$c=0,\ t=0,\ y>0,\ c=0,\ t>0,\ y\to\infty$$
$$D\left(\frac{\partial c}{\partial y}\right)_{y=0}=\text{const.}=q_c,\quad t>0,\quad y=0. \qquad (6)$$

It leads to the solution [I1]:

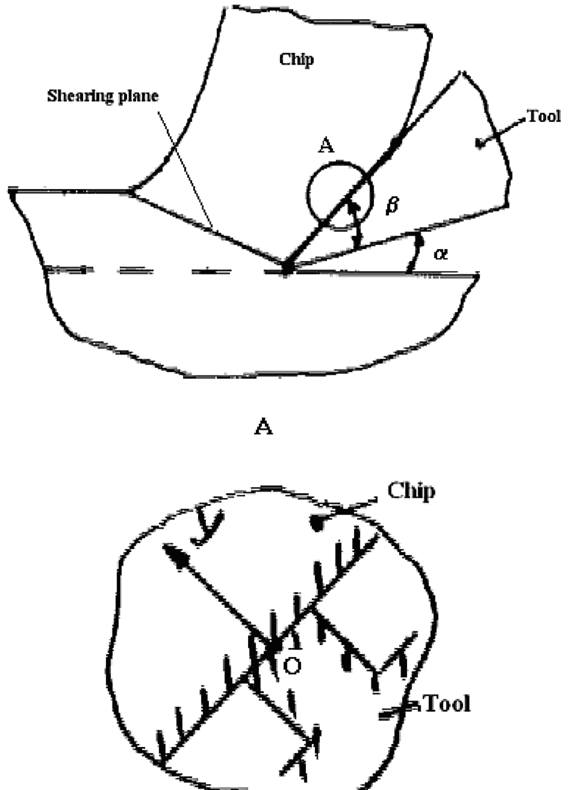

Fig. 2. Model for determination of the differential equation of the diffusion process.

$$c(y,t)=\frac{2q_c\sqrt{D\cdot t}}{D}\,\mathrm{ierfc}\,\frac{y}{2\sqrt{D\cdot t}}=2q\sqrt{\frac{t}{D}}\,\mathrm{ierfc}\,\frac{y}{2\sqrt{D\cdot t}} \qquad (7)$$

where: $\mathrm{ierfc}\,x=\frac{1}{\sqrt{\pi}}\mathrm{e}^{-x^2}-x\left(1-\frac{2}{\sqrt{\pi}}\int_0^x \mathrm{e}^{-y^2}\,\mathrm{d}y\right),$

$q_c=q_0\exp\left(-\frac{E_s}{RT}\right)$, E_s = constant, T – temperature, or:

$$\bar{c}=\frac{c(y,t)}{2q_c\sqrt{\frac{t}{D}}}=\mathrm{ierfc}\,\frac{y}{2\sqrt{D\cdot t}}. \qquad (8)$$

In Fig. 3 tone can see the variation of the concentration of the tool material (c), which diffuses in chip, with depth on chip surface (y) when the time t increases.

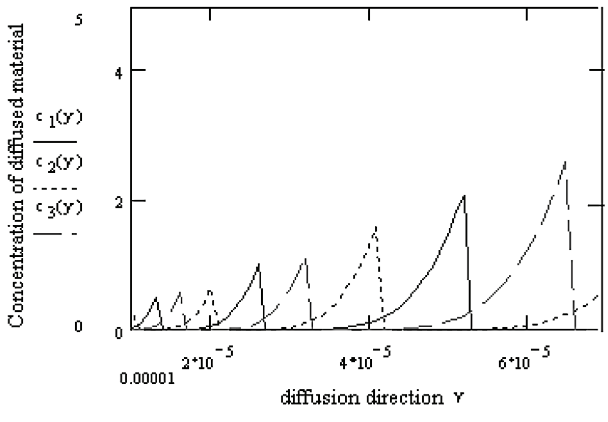

Fig. 3. The variation of the concentration of the tool material diffused in chip (c) with depth on chip surface (y).

3. TRANSFER BY DIFFUSION, WITH DIFFERENT MASS AND ENERGY SOURCE

Two bodies have relative motion and one of them contains a chemical element that can diffuse into the other, when certain thermal conditions are fulfilled.

The energy generated by the friction in the contact area contributes to the modification of the thermal regimen and to the amplification of the diffusive transportation phenomena.

It is considered that the diffusion mass transfer process is similar to the elastic energy and thermal energy transfer processes, because of the fact that the differential equations are identical.

The transfer by concentration gradient diffusion is determined by linear equations, so the superposition principle can be applied and so, for every distribution of the concentration on the friction surface the solution of the "punctual source" can be applied.

It is considered that the semi-space that takes over the substance from the source is uniform and it is characterized by a diffusion coefficient D and constant thermal properties (conductivity λ, density ρ, specific heat c_t and diffusivity a ($a = \lambda / \rho c_t$).

3.1. Mass and energy distributed source

In fact, the mass and thermal energy source is applied on a certain surface. It is considered that this surface is perfectly insulated, so that the temperature and concentration can be obtained by cumulating the effects of the punctual or linear sources.

In Fig. 4 one can notice the mass source M distributed by m_c in the time unit on the surface S. By changing the grid coordinates into polar coordinates (s, ϕ) having the origin in B, in point $E(s, \phi)$, there acts the concentration mass c, $m_c s ds d\phi$ [2].

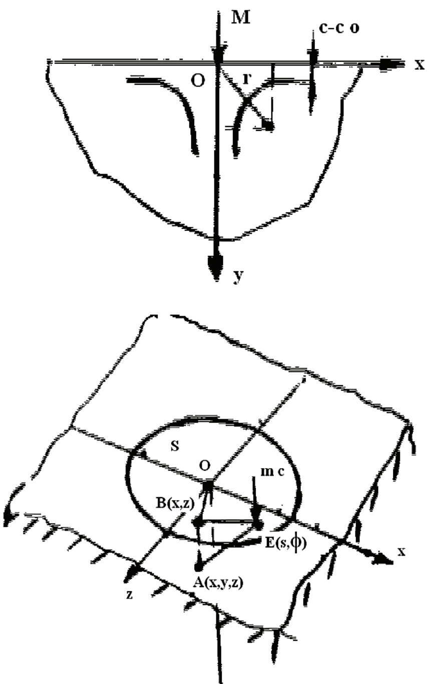

Fig. 4. Model for the analysis of the mass and energy source distributed on a surface S.

The concentration variation $\Delta c = c - c_0$ is:

$$\Delta c = \iint_S \frac{1}{2\pi a} m_c(s, \phi)\, \mathrm{d}s \mathrm{d}\phi \qquad (9)$$

and temperature:

$$\Delta\theta = \iint_S \frac{1}{2\pi a} q(s, \phi)\, \mathrm{d}s \mathrm{d}\phi, \qquad (10)$$

where: a – thermal diffusivity.

For a circular area with the radius R having the source axial distributed symmetrically:

$$m_c = m_{0c}\left(1 - r^2 / R^2\right)^n. \qquad (11)$$

3.2. Mass and energy mobile (circular) source

Mass and energy source is considered to be mobile as compared to the semi-space in which the mass m_c having the concentration c and thermal energy q dissipates itself.

If the source is fixed and the semi-space (the chip) travels with the speed v_x, the concentration and temperature field depend only on the position and not on time.

The surface temperature when the source on the total contact area is circular will be [2]:

$$\Delta\theta(r, \psi) = \frac{1}{2\pi\lambda} \int_0^{2\pi} \left(\int_0^{s'} q(s) \exp\left\{ \frac{v_x s}{2a} \left[1 - \cos(\phi - \psi)\right] \right\} \mathrm{d}s \right) \mathrm{d}\phi, \qquad (12)$$

where s' depends the position of point in which the temperature value (on the circular area with R radius) is determined.

On the analogy of the thermal transmission and the mass transfer determined with concentration gradient, we deduce:

$$\Delta c(r, \psi) = \frac{1}{2\pi D} \int_0^{2\pi} \left(\int_0^{s'} m_c(s) \mathrm{e}^{-\frac{v_x s}{2D}} \left[1 - \cos(\phi - \psi)\right] \mathrm{d}s \right) \mathrm{d}\phi. \qquad (13)$$

where the distributed source (the mass) can be uniform circular $m_c(s) = m_{0c}$ or parabolic $m_c = m_{0c}(1 - r^2/R^2)^{1/2}$, $0 < r < R$ and $m_0 = 3M / 2\pi R^2$.

Based on the detailed analysis of the influence of the invariant $P_e = v_x R/2a$ on the maximum and medium temperature from the contact area established by Tian and Kennedy [3, 4], we can consider by similitude the influence of a diffusion invariant $P_{ed} = v_x R/2D$.

3.3. Maximum and medium temperature and concentration

For the tribological processes, the knowledge of maximum and medium temperature and concentration on the contact surface, according to the operating data (stress, speed, friction coefficient) is important. Based on the relation (12) Tian and Kennedy deduced that the maximum and medium temperatures ($\Delta\theta_{max}$ $\Delta\theta_{med}$) can be approximated efficiently (errors less than 25%) for the circular contact, depending on the thermal invariant P_e.

Similarly we can also deduce that for the mass transfer, the maximum and medium concentrations on the contact surface depend on the diffusion invariant P_{ed}:

- for the uniform distribution of the mass source ($m_c = m_{0c}$ = constant):

$$\Delta\bar{c}_{\max} = \frac{\Delta c_{\max} D}{2Rm_{0c}} = \frac{1}{\sqrt{\pi\left(1.273 + P_{ed}\right)}};$$
$$\Delta\bar{c}_{med} = \frac{\Delta c_{med} D}{2Rm_{0c}} = \frac{0.61}{\sqrt{\pi\left(0.6575 + P_{ed}\right)}}; \quad (14)$$

- for the parabolic distribution of the mass source ($m_c = m_{0c}\left(1 - r^2/R^2\right)^{1/2}$):

$$\Delta\bar{c}_{\max} = \frac{\Delta c_{\max} D}{2Rm_{0c}} = \frac{1.16}{\sqrt{\pi\left(1.273 + P_{ed}\right)}};$$
$$\Delta\bar{c}_{med} = \frac{\Delta c_{med} D}{2Rm_{0c}} = \frac{0.732}{\sqrt{\pi\left(0.874 + P_{ed}\right)}}. \quad (15)$$

In Fig. 5 we can see the variation of the maximum and medium concentration of material on the contact surface, depending on the diffusion invariant P_{ed}, in the case of uniform distribution of the mass source.

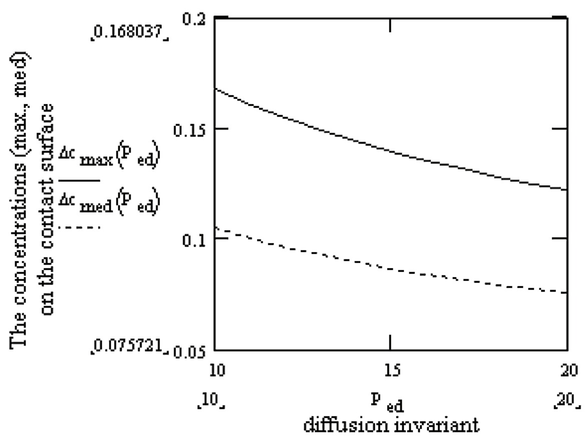

Fig. 5. The variation of concentration $\Delta c_{\max}$ and respectively Δc_{med}, depending on the invariant P_{ed}.

4. CONCLUSIONS

The diffusion of the cutting tool material in the chip during the machining process, determine the apparition of the “crater” on the rank face of the tool. Beginning to the general equations of thermo diffusion [3–6] are determined [2]:

- The variation of concentration of the tool material diffused in chip (c) with depth on chip surface (y); from the figure 1 the concentration of the diffused material increase with the diffusion direction y.
- Analyze of the diffusion process with different source of mass and energy.

Beginning to the relation 12, by analogy of the thermal transmission it is deduced the concentration variation (relation 13).

Based on the detailed analysis of the influence of the invariant P_e, on the maximum and medium temperature from the contact area [3, 4], it is considered by similitude the influence of a diffusion invariant P_{ed}.

Notice that the values of the diffusion invariant P_{ed} (in conditions similar to the thermal ones for friction same speed v_x, radius R) are greater, the diffusion coefficient D being much smaller than the thermal diffusivity (a).

Taking into account all these aspects, we can conclude by saying that the thermal regimen can be found with small Peclet numbers (P_e < 0.1) or in big ones (P_e > 10), but the mass transfer regimen can be found only with big P_{ed} numbers. For the tribological processes there can be conditions for which the diffusion invariant can take values similar to the ones in the Peclet thermal invariant.

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Authors:

Ph. D., Carmen TACHE, associated professor, “Valahia” University of Targoviste, Faculty of Environmental Engineering and Biotechnology, Food Engineering Department,
E-mail: carmen_tache@yahoo.com
Dumitru DUMITRU, lecturer, “Valahia” University of Târgovişte, Faculty of Environmental Engineering and Biotechnology, Food Engineering Department,
E-mail: ddumitru@valahia.ro