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# Tribological Aspects of the Dynamic and Thermal Phenomena Modelling in the Cutting Process

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*Abstract:* - The complex of specific physical phenomena that characterize the cutting process and that influence its development, were not studied as a process as a whole, the processing was done as separate influences for certain specific cases and can be generalized only for small areas. The interpretation of the cutting process as a system in which dynamic and thermal phenomena occur leads to the conclusion that the relationships established until now between the elements that contribute to the cutting process and the effects produced by them give only a global and more qualitative imaging of the process and their use for concrete practical cases can be accepted only by admitting a large margin of error in evaluating the values that characterize the real effects (efforts, wear, temperatures). It was necessary to develop a physical model of the phenomenon in order to perform the researches; in fact, the phenomenon is a conventional image of the real status, representing the basics of mathematical modelling. The model has mathematical equations, functionally describing the physical model, and through it, the real phenomenon. For mathematical model solving, difficult to be analytically solved, there have been used numerical methods to obtain solutions for the differential equations. In essence, the central objective of the this paper is to unify in a single model the multiple phenomena of a dynamic, thermal and tribological nature, in order to assess in advance the intensity with which wear will occur and determine how it can be influenced.

*Key-Words:* - cutting process, tribosystem, intensity wear, heat, comprehensive model

## 1 Introduction

Metal cutting, due to the action of tool blade pushed on the processed material, leads to a complex status of forces and deformations in the cutting area. A simplified diagram of cutting process is shown in figure 1, where the machine tool, by means of the cutting tool, exerts force *P* able to overcome the resistance forces in the processed material. This simple diagram is the base for any detailed study on cutting process. It is a basic physical model, completing other specific models of elasticity and plasticity, thermodynamics, tribology, thus forming a complex model, more or less detailed according to requirements or claims. For almost 100 years of researching on cutting process, many theoretical and experimental data have been gathered, but they are far beyond from being a unitary whole [1-3].

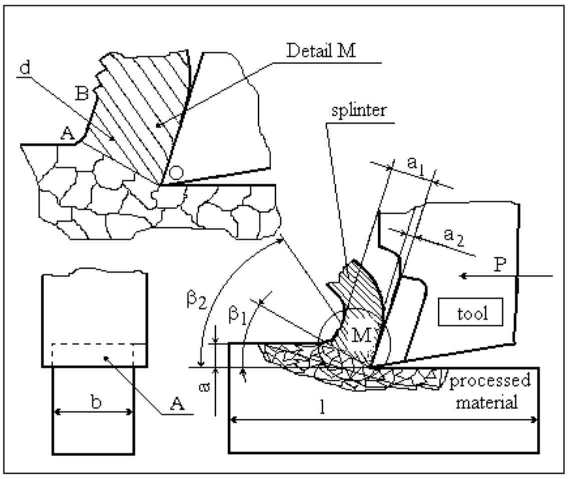


Fig. 1 Plastic deformation of the processed material in front of the tool blade

The present paper develops on this quite applicable, enough explored, but still insufficiently understood field of application.

Based on the knowledge, the definition of the splinter appearance process has been stated, containing also the essence of interdisciplinary aspects.

The essence of these aspects is already shown in the specialty literature, in detail (figure 1), and this paper deals only on those aspects considered able to be improved [1-3].

The analysis of some definite aspects solving manner presented in the specialty literature led to the conclusion that errors have been done, errors able to stray from the real status. The main phenomena and processes accompanying the cutting process are friction, tribosystem heating and tool wear. The tribosystem, consisting of tool, workpiece and splinter, can be considered as a system with direct contact, where no lubricating film is present. Based on his own researches and taking into account some results of his predecessors, Coulomb stated the three dry friction rules, which are often partially confirmed. It can be reminded that friction depends on the relative speed, this fact being experimentally ascertained at the beginning of the XIX century, as shown in figure 2 [4-6].

The experimental researches drawn up so far led to the conclusion that dry friction force depends on many factors such as: the normal pressure force, the relative sliding speed, the type of the contact and the value of the contact area, the quality and the roughness of the surface, the nature of materials in contact, the character of the friction areas: rigid or elastic, tenacious or fragile. Even human and materials resources were highly implied in research, the complex friction phenomenon did not allow a universal valid theory elaboration, for at least from the quality point of view.

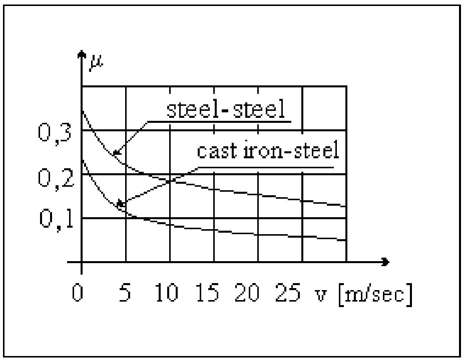


Fig. 2. The variation of friction coefficient on speed, according to Galton

Friction having a preponderant role in heating the elements of tribological system: the workpiece - cutting tool, with influence on the wear of the cutting tool, we considered it necessary to undertake a research regarding the coefficient of friction for a specific case of cutting and thus to highlight the fact that in this case the coefficient of friction is non-coulombian type. As for the dry or lubricated cutting friction, its framing in the dry friction category is based on the finding that the cooling fluids do not enter into the friction area. The researches shown that the mechanical work necessary for volume plastic deformation in the cut metal layer is partially transformed into caloric energy that heats the cutting area; this process depends on the thermal conductivity of the cut metal and on the working conditions of cutting process.

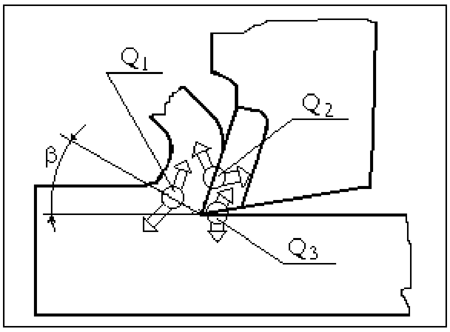


Fig. 3. Mechanical work dissipative in heat

The mechanical work consumed in the cutting process, entirely transformed in heat, $L_1$, $L_2$ and $L_3$ components, generates the heating sources $Q_1$, $Q_2$ and $Q_3$, figure 3, ordered by their intensity, as follows: $Q_1>Q_2>Q_3$ [6].

In reality, depending on the actual cutting process, different heat exchanges may occur between the workpiece, the splinter, the tool, depending on the nature of the cutting process, making the temperatures in the splinter, tool and workpiece not respect the distribution of sources intensities. The factors that influence the amount of heat generated by cutting are: the physical-mechanical characteristics of the cuted material; the cutting tool material; the geometrical parameters of the tool cutting; the parameters of the cutting conditions.

Since the blade of cutting tool temperature is the main wear-influencing factor, the actual researches went towards finding the empiric relations between blade temperature and the main cutting tool elements, less interest being paid to the aspect of heat quantities evaluation.

The paper shows the influences of different cutting parameters on tool blade temperatures. The blade tool wear behaviour depends in a large measure on its temperature. The experimental researches performed so far show that there is some proportionality between wear intensity and blade tool temperature, the variation rules demonstrating obvious parallelisms. That is why, in order to accurately evaluate wear intensity (and wear evolution) depending on cutting parameters, it is necessary to know the cutting temperature, including the tool blade temperature, depending on the cutting parameters.

Based on the researches performed [5], a series of dependence relations between the tribosystem elements temperatures have been defined. The mathematic model shown by the specialty literature [6] suits to an uniform stationary thermal status, respective to the same temperature in the entire splinter and tool blade and time constant, quite far from reality even for a qualitative and phenomenological analysis.

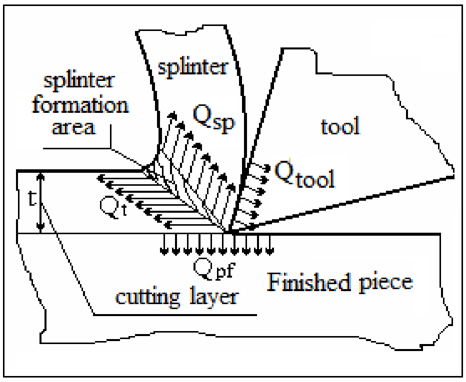


Fig. 4. Distribution of the amount of heat developed in cutting process

The hypothesis taken into consideration, figure 4 according to which heating in the cutting area is uniform and stationary can be appreciated as a particular case that cannot be real. That is why a specific model is required for the heating sources, able to lead to a correct determination of real thermal status, non-stationary and non-uniformly distributed, that, in time, leads to a stationary and non-uniformly distributed thermal status, depending on the influencing factors, the most important of them being as follows: the cutting process parameters; the physical and mechanical properties of the tool blade and splinter; the environmental heat exchange; the feed-back interdependence between different influencing factors; the cutting process dynamic phenomena. Cutting wear comes up because of interfering factors effects and it is important to be known, especially regarding the cutting tool. Tool wear is progressive and it manifests under many aspects (temperature increasing, processed area deterioration, cutting forces increasing), finally leading to their stop functioning.

The researches highlighted more blade wear types, as shown in figure 5 that represents these wear influences and makes possible an appreciation of their weight as part of total wear. The diagram shows that the abrasive wear has the highest influence; it is determined by the friction conditions of areas in contact: tool - workpiece-splinter. The splinter temperature increases due to the energy exclusively obtained from friction: the friction between the splinter and the tool cutting and the friction between inter- and intracrystals that comes up during splinter formation and separation. The higher the temperature the more plastic is the splinter, some of its areas pass to the liquid phase, the intensity of the above mentioned frictions decreases, smaller amounts of energy are freed, splinter temperature decreases, the splinter is more solid, more intense frictions develop tending to increase the temperature, and so on. Therefore, a combination of effects with opposite tendencies takes place leading to a splinter temperature, which is not equal to the melting temperature of the processed part, but an equilibrium temperature beyond the melting one.

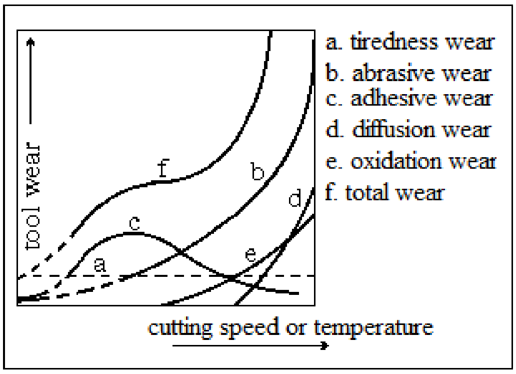


Fig. 5. The influences of partial wear on total wear

Speed increasing, especially for high cutting speed, leads to a feedback chain, according to figure 6.

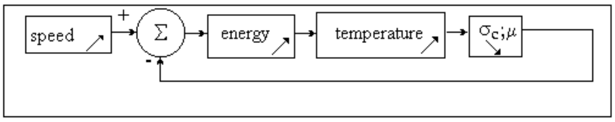


Fig. 6. The feedback influence of the temperature increase on the mechanical characteristics of the processed material

According to this chain, cutting speed increasing leads to cutting area temperatures increasing, the effect is a deformation resistance and mechanical work decreasing, thus implying wear reducing and a higher tool durability.

The analysis of cutting conditions influences on the tool temperature and tool wear leads to the conclusion that the variation of wear medium intensity is very similar to the variation of the temperature on the tool blade.

Knowing the current level of studies on the behaviour of the splinter-tool blade tribosystem allowed the formulation of some conclusions, presented at the end of this chapter, based on were nominated some researches to lead to elucidation of problems reported as unsatisfactory.

In essence, the central objective of the this paper is to unify in a single model the multiple phenomena of a dynamic, thermal and tribological nature, in order to assess in advance the intensity with which wear will occur and determine how it can be influenced.

## 2 Research Methodology and Means Used

Among the considered objectives, there can be mentioned: the research of dynamic phenomena; the research of thermal and wear phenomena.

It was necessary to develop a physical model of the phenomenon in order to perform the researches; in fact, the phenomenon is a conventional image of the real status, representing the basics of mathematical modeling. The model has mathematical equations, functionally describing the physical model, and through it, the real phenomenon. For mathematical model solving, difficult to be analytically solved, there have been used numerical methods to obtain solutions for the differential equations.

The stages covered for phenomenon modeling are, as follows:

- cutting area forces modeling, based on Merchant model for free orthogonal cutting, figure 7, where is taken into consideration the fact that the splinter is balanced by two categories of external and internal forces;
- heating sources modeling, figure 3;

It is thought that the heating source consists both by the non-conservative mechanical work wasted by plastic deformation in the cutting plane area and by the non-conservative mechanical work from the friction on the escaping and on the laying tool area.

- heat dispersing modeling.

The heat disperses into a non-homogeneous environment consisting of splinter, blade and tool body, each having different caloric coefficients, both as value and temperature dependence.

Solving the problem of heat dispersing under transitory conditions and in a heterogeneous environment leads to temperature knowing for every moment and in each point of the considered environment.

The theoretical study program, including the above-mentioned models, materialized in a very complex physical and mathematical computer model, enables the researching of the influence of different factors, such as: the parameters of the cutting conditions (speed, advance, depth); tool blade material; the cutting mode (continuous or interrupted). So already shown, the friction in the cutting area unfolds in very particular conditions, high pressures, relatively high speeds and the absence of any lubrication. Bibliographic research has shown that Coulombian-type friction is an exaggerated approximation of dry friction.

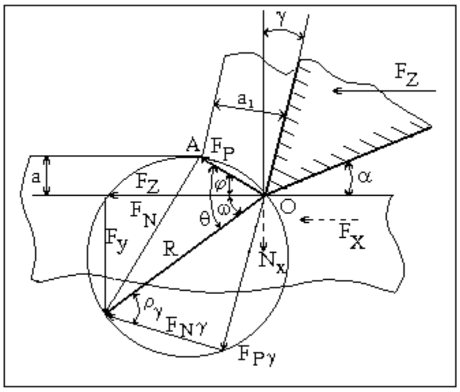


Fig. 7. Cutting area forces based on Merchant model for free orthogonal cutting

As long as a realistic mathematical model is desired, the friction model for the cutting area should have a friction coefficient depending on speed for the couple splinter- tool blade.

By mathematical modeling, the differential equation for heat conducting is:

$$\rho \cdot c \cdot \frac{\partial \theta}{\partial t} = \lambda \cdot \left( \frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} + \frac{\partial^2 \theta}{\partial z^2} \right) \quad (2)$$

that for an anisotropic and non-homogeneous material generally turns to:

$$\frac{\partial}{\partial t}(\rho \cdot c \cdot \theta) = \frac{\partial}{\partial x}\left(\lambda_x \cdot \frac{\partial \theta}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \cdot \frac{\partial \theta}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_z \cdot \frac{\partial \theta}{\partial z}\right)$$

(3)

where: $\rho$ - material density (kg/m$^3$); $c$ - material specific heating (J/kgK); $\lambda_x$, $\lambda_y$, $\lambda_z$ - material thermal conductivity (W/mK).

The integration of the differential equation (3) is analytically difficult to solve, and the specialty literature does not offer exact solutions for each practical case. To obtain an analytical result, the following solution is used:

$$\theta(t, x, y, z) = T(t) \cdot F(x, y, z)$$

(4)

Heat exchanges inside and on the areas of the tribosystem the mathematic model, knowing the border conditions, extremely difficult to be analytically described, materializes elements and that is why numerical integration is preferred, the most suited being the finite differences method.

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## 3 Presentation of the Modeling Program of Dynamic and Thermal Phenomena in the Cutting Process

The heat which appears during the cutting process is distributed between the elements of the tribosystem through conduction, convection and radiation.

Figure 8 shows schematically, in plan, the elements of the tribological system, tool-splinter-workpiece and their limits, the marking being in fact the researched area. The figure shows, in addition to the boundaries of the researched area, the ways of heat transfer between this area and the neighboring areas, respectively by conduction, convection and radiation.

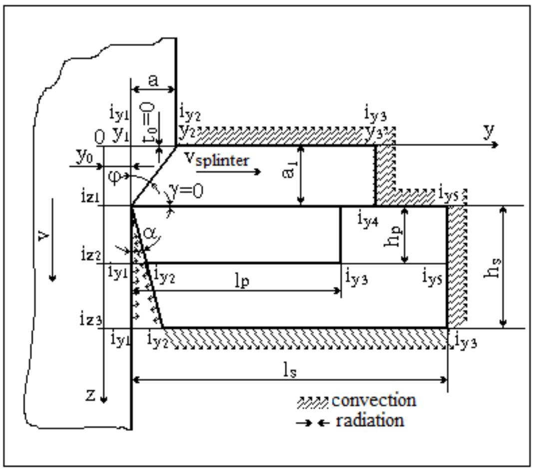



Fig. 8. Heat transfer between the researched area and the neighboring areas

The heat equation, which is actually a conduction equation, is applicable in volumes bounded by the free surfaces of the cutting edge and the splinter. Apart from these volumes there is radiation, convection, conduction in another environment (air). Convection is a process of heat transfer between a solid surface and a fluid, between which there is direct contact and relative motion. Convection heat exchange, in the cutting case, eliminates in the environment, environment composed of air or coolants, part of the heat resulting from the development of the cutting process, having a beneficial role on the elements of the tribosystem. The effect of convection is dependent on the relative speed of movement and the physical-thermal characteristics of the environment. For certain convection surfaces, the solution is as follows. Through the convection surface, for example a surface normal to the x-axis, is valid the heat exchange :

$$\lambda_x \cdot \frac{\partial \theta}{\partial x} = \alpha_x \cdot (\theta_s - \theta_f)$$

(6)

Solving the equation 6 on the desired surfaces ($x = 0$, $x = x_{max}$, $y = 0$, $y = y_{max}$) is determinated the temperature on the surfaces, $\theta_{(0,y,t)}$, $\theta_{(xmax,y,t)}$, $\theta_{(x,0,t)}$, $\theta_{(x,ymax,t)}$, etc. The calculation formula becomes, replacing in (6) $\theta_S$ with its expression, as a function of spatial and temporal coordinates, $\theta(x,y,t)$:

$$\theta_{(0,y,t)} = \frac{\lambda_x \cdot \theta_{(0+\delta_x,y,t)} - \delta_x \cdot \alpha_x \cdot \theta_f}{\lambda_x + \delta_x \cdot \alpha_x} \quad (7)$$

Radiation is a process of heat exchange between a body with a high temperature and a body with a lower temperature, the bodies being separated in space. In the cutting case, it can be considered that there would be such a heat exchange between the elements of the tribosystem, splinter-cutting tool or cutting tool- cutting material. Of these, the radiation in the cutting tool-material area is considered to influence the thermal state of the system. The following clarifications can be made about this heat exchange by radiation:

The power exchanged by radiation (appears as a negative source in the warmer body and as a positive source in the colder body) is:

$$Q = A \cdot C_{1,2} \cdot \left[ \left( \frac{\Theta_1}{100} \right)^4 - \left( \frac{\Theta_2}{100} \right)^4 \right] [W] \quad (8)$$

Radiation, whose effect is dependent on the 4th power of temperature, has an insignificant weight on free surfaces with low temperatures and more distant between them, as the convection does not have too high an effect in narrow interstices where not exists the relative movement of the fluid.

Therefore, the border conditions will be described by the radiation only in the space between the back edge of the cutting edge and the part, the other free surfaces being considered to be subject to convection in the air. The heat exchanges in volume and on the surfaces of the tribosystem elements are materialized in the mathematical model by knowing some border conditions, extremely difficult to describe analytically and therefore numerical integration is preferred, the most suitable being the method with finite differences. By this method, the differential equation is transformed into an algebraic equation by approximating derivatives with finite differences; time is divided into equal time increments $\tau$ and the space into equal space increments $\delta_x$, $\delta_y$, $\delta_z$, resulting in a network of nodes in a 4-dimensional space, in which is defined the temperature. By discretizing the 4-dimensional space in a network of discrete nodes (grid), the continuous coordinates *t*, *x*, *y*, *z* are transformed into discrete coordinates *j*, $i_x$, $i_y$, $i_z$. As a result, the continuous function $\theta(t,x,y,z)$ becomes a discrete function $\theta_{j,i_x,i_y,i_z}$. Derivatives and differentials become finite differences. For the numerical solution of the system of heat transfer equations, the considered area $l_S \times h_S$ is discredited in surface elements of the size $\delta_y \times \delta_z = 0{,}01 \times 0{,}01 [mm^2]$ thus resulting, on this surface, a number of nodes. At this level of discretization the calculation errors are less than 5%.

Considering for the researched area the following dimensions:

$l_S = 19mm; h_S = 15mm; y_0 = 1mm; a = 0{,}2mm$ results that in the formed network will be included a number of nodes determined with the relation: $\frac{h_s + a_1}{\delta_y} \cdot \frac{l_s}{\delta_z} = \frac{15 + 0{,}27}{0{,}01} \cdot \frac{19}{0{,}01} = 2901300$ nodes.

The network of nodes with the corresponding thermal values will be stored on the HDD in user-named files and will be exploited in this way.

## 4 Simulation of the Cutting Process on the Specialized Program Previously Developed

The friction coefficient used by the computing program was experimentally determined by using energetic methods. The results obtained for the coefficient of friction clearly lead to the conclusion that in this case the friction is non-Colombian. Its dependence on speed is as shown in figure 9. The coefficient of friction used in the calculation program was determined using a stand made physically.

The present paper also uses the results obtained by a classical research regarding tool wear, results taken out from a research project performed for manufacturing assimilation of metallic carbide cutting plates. These results were synthesized in wearing diagrams, VB = f(T), as shown in figure 10, for some specific processing cases. These wear curves, continuous in time, enabled the study of wear evolution correlated to the suggested mathematical modeling.

Taking into account the fact that the speed mostly determines process thermal status, with implications on cutting tool wear, it was considered necessary to be analyzed for the heating process, especially on the laying area, in order to diminish the implications and wear reducing. By solving the mathematical model using the specialized developed program, thermal areas are obtained, which analyzing for different cutting processes, with the required parameters *v*, *s* and *t*, appreciations on wear and durability of cutting tools can be stated. With the obtained data a temperature dependence curve can be drawn depending on the speed cutting, as shown in figure 11.

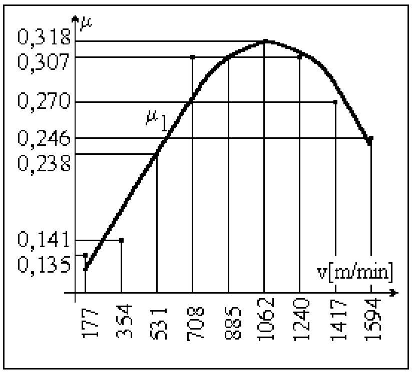
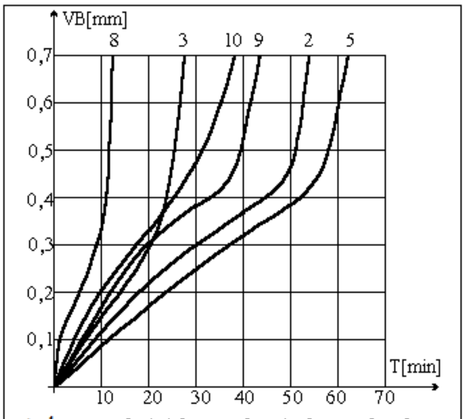



Fig. 9. The variation of friction coefficient with relative speed




| task | v[m/min] | s[mm/rot] | t[mm] |
|---|---|---|---|
| 2 | 350 | 0,16 | 0,5 |
| 3 | 275 | 0,315 | 0,5 |
| 5 | 275 | 0,16 | 1 |
| 8 | 350 | 0,315 | 1 |
| 9,10 | 310 | 0,224 | 0,7 |

Fig. 10. VB wear of TNGG 22.04.12/P10 plates for steel lathing 8550/97HB

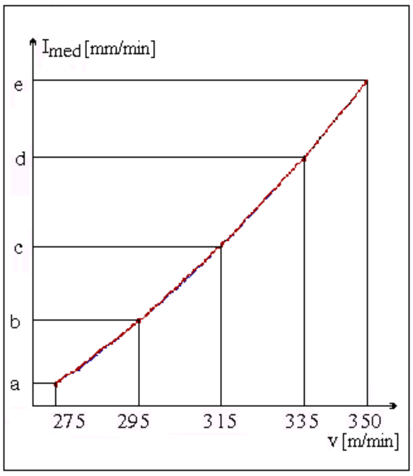



Fig. 11. The variation of medium intensity with cutting speed

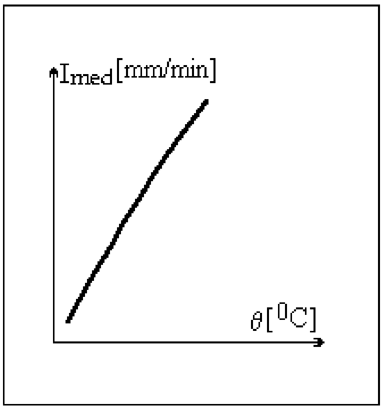



Fig. 12. The variation of wear medium intensity with maximum temperature

Notice the similitude between θ°[C] = f(v) curve and $I_{med}$=f(v) curve, figure 11; a direct relation $I_{med}$=f(θ°C) for case (P10) can be stated, as shown in figure 12. Diagram analysis concludes that there is a good proportionality of wear medium intensity with the maximum temperature of cutting process, an experimentally stated fact, also presented by the specialty literature.

Experimental and theoretical researches regarding tool blade temperature and wear medium intensity settled up similitude between the evolutions of the two phenomena, leading to the conclusion that thermal phenomena evolution modeling enables the evolution of wear medium intensity, by applying a constant of proportionality, experimentally known, which remains the same for a couple splinter- tool blade.

## 5 Conclusion

Based on the performed studies, a series of conclusions have been stated, among which are, as follows:

- the friction between splinter and tool blade is, for certain, a dry friction;
- stand measurements have shown the dependence of the friction coefficient on the relative speed between the tribosystem elements, the dependence way being influenced by the nature of materials of the friction couple; it has been noticed a continuous decreasing dependence of friction coefficient on speed for steel-steel couples and a dependence with a maximum point for steel-metallic carbide couples;
- the complete and correct research of the thermal phenomena from the cutting area is possible only with the consideration of the feedback type relationship between the elements that physically and phenomenologically compose the studied tribosystem and with consideration movement in time of the splinter, having as effect on the one hand a continuous supply with cold layers of material of the splinter formation area, on the other hand a heat dissipation by physical transport of heated splinter;
- the most important thermal sources, such as the source created by plastic deformations in the cutting plane and the source created by the friction between the splinter and the tool blade escaping area, have intensities and distributions depending on the values of the cutting conditions parameters and on the splinter-blade tool couple. They heat the cutting area to temperatures non-homogeneous distributed, and the temperatures influences those materials constants related to heating sources intensity;
- thermal status in the cutting area is characterized by a maximum in the splinter pressure center on the escaping area, as long as, in the wear area (the laying area) the temperature is much lower;
- it has been stated a dependence relation between a parameter characteristic tool blade wear, such as wear medium intensity, and cutting area temperature; the relation is, with pretty small deviations, a directly proportional dependence one; thus, by measuring the tribosystem temperature, the wear medium intensity can be evaluated, at least for the cutting process.

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