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THERMODYNAMIC PATTERN OF THE WORKPIECE MACHINING BY THE RHEOLOGICAL IMITATION MODELLING IN DEFORM-3D SYSTEM

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Аналіз теплофізичної реологічної картини різання, реалізованої в системі DEFORM 2D (3D), дає змогу зробити висновок про те, як динамічні показники температурних деформацій впливають на якість оброблюваної поверхні та дослідити вплив термодинамічних показників на напружено-деформований стан заготовки та інструмента. Доведено, що найбільша кількість теплоти, що утворюється внаслідок деформації, залишається у стружці (60–80 % усієї теплоти різання, а за швидкісних режимів різання понад 90 %) і частково поглинається оброблюваною деталлю (до 20-40 % усієї теплоти). І лише 3–5 % теплоти спрямовується в інструмент/

Analysis of thermal physical rheological model of cutting system implemented in software DEFORM 2D (3D), makes it possible to investigate the effect of dynamic parameters on the stress-strain state of the workpiece and tool. It is shown that most quantity of the heat cutting, which formed as a result of chip deformation (60-80 % of the heat cutting and for the ultra-speed cutting conditions for more than 90 %) remains in the chips and partly absorbed machined workpiece (up to 20-40 % of the heat).

Problem statement recent research and analysis. Thermal effects, arising as a result of cutting process, are one of the most important factors determining the stress-strain state in the zone of the chip formation and part surface forming. Heat laws explain phenomena associated with support of the cutting process parameters, tool life and surface finish quality. Thermal rheological cutting process pattern is necessary to build an effective structure and parameters of technological process model. Then we can analyze how dynamic performance thermal deformation affects to the workpiece quality and to investigate the influence of thermodynamic parameters on the stress-strain state of the workpiece and the tool.

The cutting process heat Q_Σ is formed by the [7]:

1) internal friction between particles of treated metal during deformation process - Q_1;

2) external friction at the chip to the face of tool - Q_2;

3) external friction of the cutting surface and machining surface to the back of tool - Q_3;

4) separation, chip deformation and chip dispersion Q_4.

$$Q_\Sigma = Q_1 + Q_2 + Q_3 + Q_4 .$$

(1)

Description of main idsas. The most intense heat is in chip forming zone adjacent to the cleavage plane (Fig. 1). In this zone, the heat released as a result of two synchronous processes: first, as a result of plastic deformation displacement elements newly chips on the cleavage plane, and secondly, as a result of plastic deformation and partly shear deformation adjacent to the plane of the allowance slice.
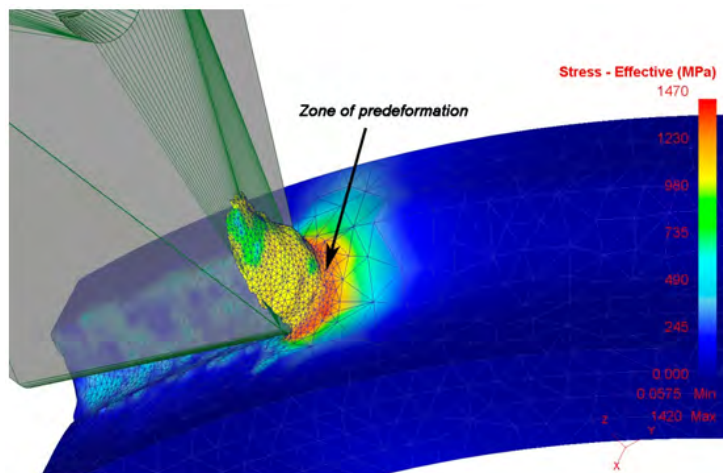

Fig. 1. Elastic-plastic deformation area ahead chip
forming zone, formed before the cleavage plane

Elastic deformation is always preceded by plastic deformation during cutting metals [7,11] (Fig. 1). The quantity of heat released as a result of elastic deformation is relatively small, but neglect the influence of this process on the thermal characteristics of the cutting process is impossible. The influence of this parameter on the temperature field's formation for different materials will be explained later.

On the other hand, the heat generated during the cutting process, does not accumulate in areas of it generation, and gradient extends from areas of higher temperature to areas of lower temperature. Moreover, according to the laws of thermodynamics, the intensity of the flow ($\frac{\partial T}{\partial x}$) the higher, the greater for the temperature difference or a smaller distance between the heat-affected zones. Cutting heat is removed from the chip (q_1), transferred to the workpiece (q_2) and to the tool (q_3) and distributed in environment (q_4) (Fig. 2). Heat balance of the cutting process can be described by the equation:
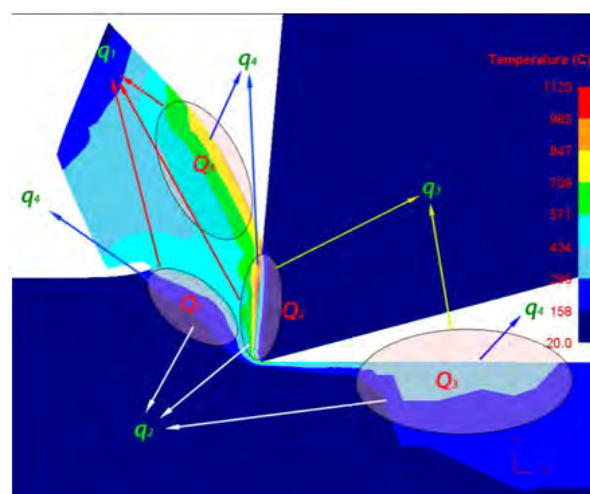
$$Q_\Sigma = q_1 + q_2 + q_3 + q_4 . \tag{2}$$

Fig. 2. Location of heat sources in the cutting zone

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The greatest quantity of heat Q_1 remains in chips (q_1) and partly absorbed by machined workpiece q_2. The heat, created by friction Q_2 chip to the tool, remains mostly also in chips (q_1) and partially (3-5 %) is sent to the tool (q_3). The heat Q_3, created by tool back friction, directed in workpiece (q_2) and to the cutter (q_3). 20-40 % of the heat is given to the tool during cutting of metals with low thermal conductivity, such as high-temperature alloys and titanium alloys [5]. Heat of chip's dispersion Q_4 almost completely absorbed by chips (q_1) or excreted into the technological environment (q_4) (to the coolant or air). Chips quickly formed in the cutting zone and as quickly pass zone of contact with the tool. The losses of heat by convection and radiation in the cutting process are very small. Therefore, only a small quantity of heat goes into the workpiece q_2. However, the heat absorbed by the high-temperature steels and alloys workpiece increases sharply at low speeds and can reach 35-45 % of the cutting heat [5]. We can neglect the work of friction on the tool back, which occurs at a sharp cutting edge and a large relief angle. First of all, the quantity of heat depends from the cutting speed, feed and depth of cut when cutting structural steels. Over 90 % of heat is absorbed by chips for high-speed cutting conditions (more than 20000 rpm).

As we know from scientific sources [5, 7, 11], which is confirmed by the analysis of rheological models, implemented by the author in the system Deform 2D (3D) [8], the highest temperature observed in the cutting chips in the contact with the face of tool because there is concentrated the greatest quantity of heat generated by chips friction and deformation on this surface (Fig. 3)
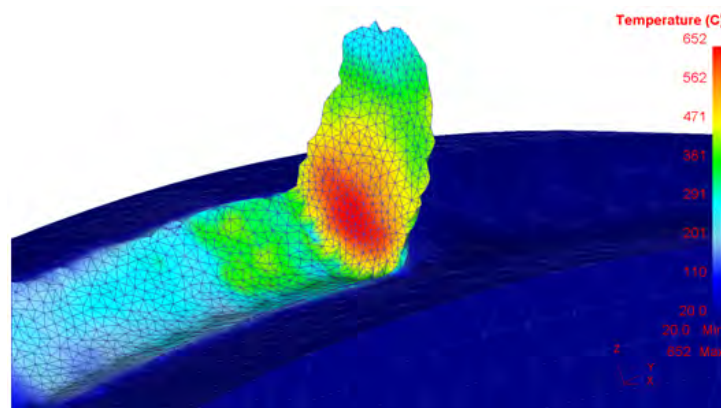

Fig. 3. Zone of thermal field concentration (tool demo not shown)

Whereas that the mechanical work of cutting completely converted into heat, we obtain:

$$Q = R = P_X \cdot V ,$$

(3)

Q – quantity of heat in joules; R - cutting work in Nm/min.

However, not all the work of cutting converted into heat in the real-life environment. A small portion of the heat goes into the potential energy of the crystal lattice distortion. Therefore, the formula written in full as follows:

$$Q = P_X \cdot V \cdot \alpha_0$$

(4)

α_0 – coefficient taking into account the losses associated with the deformation of the crystal structure of the material.

It is important to know not only the quantity of heat, but also its distribution, ie, as the concentration of heat in different parts of the workpiece, chip and tool for efficient and adequate analysis of the impact of the temperature fields in the cutting process. On the other hand, if all the heat quickly and evenly distributed to workpiece and tool, this would lead to the equilibrium in the cutting process, to support thermodynamic stability and uniform wear of the tool. In fact, the process proceeds differently: a large quantity of heat is concentrated in certain zones, significantly increasing their temperature. So loss of tool life is inevitable. The nonuniformity of heat distribution leads to the tool dulling. Metallographic structural change in the surface layer of the machined surface is even possible. Determination of the gradient distribution of temperature is very important. Controlling the flow of heat can positively influence to the cutting process [4].

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Laws of cutting temperature changes (on the contact of the chip with face of tool) can be found from rheological simulation process heat. We can also determine the effect of temperature cutting tool and workpiece depending from various engineering factors and to compare the findings with the results of theoretical and experimental studies [3].

We can define work of chip's deformation, taking into account the above statement that most heat is generated as a result of chips friction with the face of tool:

$$R_D = P_{Xf} V - P_T V \frac{1}{\xi}, \qquad (5)$$

V – cutting speed; ξ – shrinkage of the cutting chip.

Because $P_T = P_X \sin\gamma + P_Y \cos\gamma$ (neglect the force of friction on the clearance face), work of chip's deformation:

$$R_D = P_X V \left[1 - (\sin\gamma + \mu_0 \cos\gamma) \frac{1}{\xi} \right], \qquad (6)$$

where $\mu_0 = \dfrac{P_f}{P_T}$.

Temperature rise as a result of chips deformation:

$$(T_D - T_0) = \frac{\alpha_0 P_X V \left[(1-\beta_0) - (\sin\gamma + \mu_0 \cos\gamma) \frac{1}{\xi} \right]}{c\rho baV} \qquad (7)$$

T_D - average temperature of the chip, when it comes out from the deformation zone, in Celsius degree; T_0 — initial temperature, in Celsius degree; α_0 —coefficient taking into account the loss of heat to the latent energy of deformation (take $\alpha_0 = 0.95$); β_0 — coefficient taking into account the transition of heat in the workpiece (by Weiner - $\beta_0 = 0,1$ for V=100 m/min, $\beta_0 = 0,05$ for V = 300 m/min [7]); c - heat capacity of chip in kcal/H deg; ρ — chips density ($7,8 \times 10^{-6}$ kg/mm^3); b — cut width in mm; a — slice thickness in mm.

Taking the specific cutting force, neglecting $p = \dfrac{P_X}{ba}$, MP and T_0, we get:

$$T_D = \frac{\alpha_0 p \left[(1-\beta_0) - (\sin\gamma + \mu_0 \cos\gamma) \frac{1}{\xi} \right]}{c\rho} \qquad (8)$$

Chip, which heated to the temperature T_D, contacts with the face of tool with the speed V at the contact area width b and length l.

The heat of friction on the front edge per unit time is:

$$Q_2 = \frac{P_T V}{\xi}. \qquad (9)$$

Tool seems as a solid bar with a cross section - bl in order to determine the temperature on the front surface, obtained as a result of friction chips. Constant temperature T_P is maintained on one side of the bar [2]. The heat equation is used to solve the problem [9, 10]:

$$\frac{\partial T_P}{\partial \tau} = \omega \frac{\partial^2 T_P}{\partial x^2}, \qquad (10)$$

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where $\omega = \dfrac{\lambda}{c\rho}$ — thermal conductivity; λ — heat conductivity of the tool; c — heat capacity of the cutter; ρ — density; τ — time during which the chip is in the contact area length l:

$$\tau = \frac{1}{V_{CTP}} = \frac{l\xi}{V}.$$ (11)

Under the initial and boundary conditions $T_X = T_P$ at x = 0 and $T_P = 0$ when $\tau = 0$, we get the equation:

$$T_{\tau,X} = T_P\left(\frac{x}{\Delta} - \frac{2}{\pi}e^{\frac{\pi^2\sigma^2}{\Delta^2}}\sin\frac{\pi x}{\Delta}\right),$$ (12)

де $T_{\tau.x}$ —temperature that occurs at the point with the coordinate x at the time τ; Δ — the depth to which the heat penetrates during time τ.

Neglecting the temperature of the environment, we receive:

$$T_T = \frac{P_T\sqrt{V\dfrac{1}{\xi}\pi}}{2b\sqrt{\lambda c\rho l}}.$$ (13)

Summing temperature deformation chips and friction with the tool face, we get cutting temperature, i.e., the average temperature at the contact area of the chip and tool:

$$T_\Sigma = T_D + T_T = \frac{\alpha_0 p\left[(1-\beta_0) - (\sin\gamma + \mu_0\cos\gamma)\dfrac{1}{\xi}\right]}{c\rho} + \frac{P_T\sqrt{\dfrac{V}{\xi}}\dfrac{\sqrt{\pi}}{2}}{b\sqrt{\lambda c\rho l}}.$$ (14)

This formula describes the pattern of cutting temperature changes depending on various factors. And, as a rule, with an increasing of the cutting speed deformation temperature is decreases, but friction temperature increases – and vice versa.

It should be noted that the temperature of cutting really should be higher than the temperature calculated by theoretical formulas, because the heat of friction on the clearance face is not included in the formulas. This component will be more important with increasing cutting speed and during tool dulling. Workpiece is heated mainly by heat deformation. It is obvious that the temperature of the workpiece should decrease with increasing cutting speed, because T_D decreases. However, the situation changes as far as tool become blunted and a significant reduction of the tool clearance α and the cutting edge angle φ. In this case the temperature of workpiece increases when cutting speed V increase. At the same time, the temperature of the workpiece decreases with increasing feed S. This is quite natural, since the frictional force on the clearance face of the tool remains almost unchanged with increasing of feed, but at a certain length of parts is reduced relative path of the tool (processing time) and, therefore, reduces the work of the cutting force.

Theoretical calculation of cutting temperature is not always adequate, because the calculation formulas independent variables are interdependent parameters. For example, thermal capacity c increases and thermal conductivity λ decreases with increasing temperature. Length of chip and tool contact decreases with increasing cutting speed, but significantly increases during tool wear. In addition, the temperature in the cutting zone depends from the use of lubricating fluids. Therefore, the empirical formula commonly used for calculation of cutting temperature change depending from the various factors. These formulas are adequate only for the specific conditions of machining [5].

Therefore, the use of rheological models simulation can most realistically predict the thermodynamic state of the workpiece and the tool especially for cut-in conditions, change of tool direction and so on.

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Rheological simulation for turning process cutting speed V = 100 m/min in the system Deform 2D is according to the theoretical calculations. Material of the workpiece is a steel AISI 45. Material tool is tungsten-cobalt alloy BK6.

As a result modeling confirmed that most of the heat released in the chips (Fig. 4).
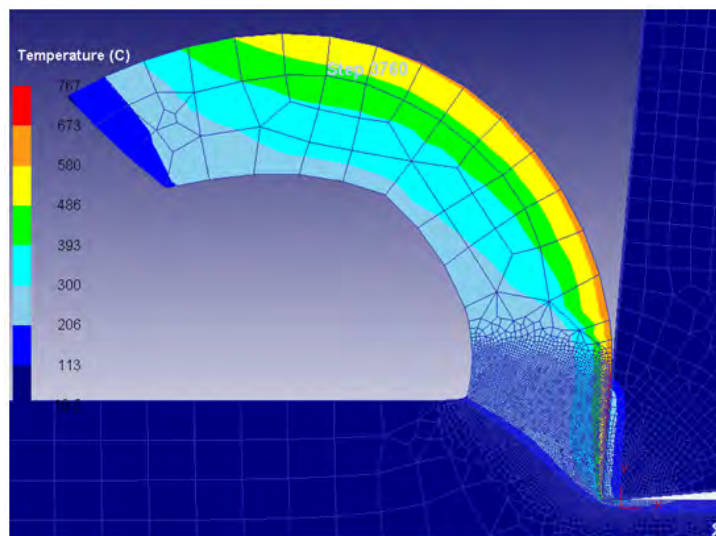

Fig. 4. Distribution of heat between the chip, tool
and workpiece for the cutting speed V=100 m/min

Percentage distribution of temperature in the cutting zone is shown in Fig. 5. Found that the maximum temperature in the cutting zone at cutting speeds 100 m/min is 767° C, and the mean value of – 231° C. The experiment showed that the maximum quantity of heat released in the contact zone between the face of tool and workpiece (Fig. 6).
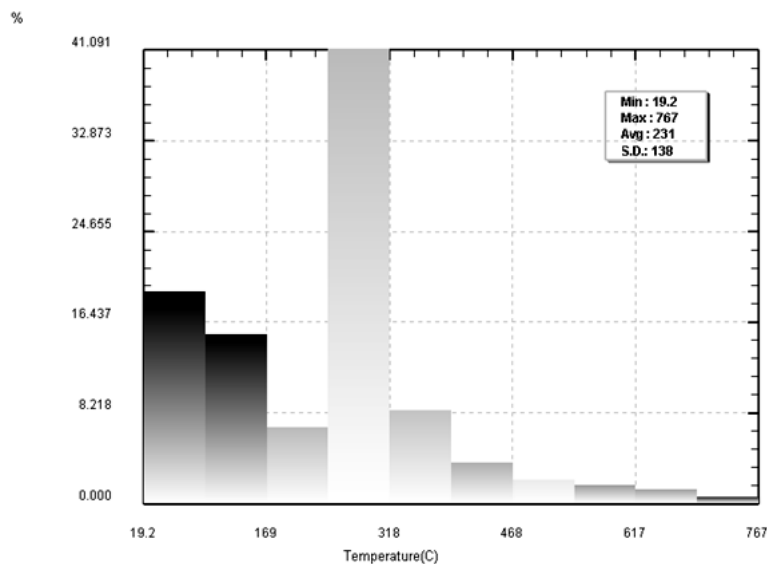

Fig. 5. Percentage distribution of temperature in the cutting zone

A similar pattern of temperature fields distribution occurs when milling steel AISI 45 (Fig. 6).

The highest tool temperature that is centered near the front surface of the cutting edge due by the interference of the major source of heat – Q_1, Q_2, Q_3. The Fig. 7 shows the temperature field and cutter

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that obtained as a result of the rheological modeling of the steel AISI 45 machining (feed S = 0,25 mm; cutting depth t = 1 mm, cutting speed V = 120 mm/min). Isotherms in the chip forming zone are parallel to the surface displacement and for tool - almost concentrically around the front cutting blade. In this case, the heat flow must be directed normal to the isotherms. In the diagram (Fig. 7) heat flows are shown as vectors: D - in workpiece; S - in chip; I - in tool. It should be noted that these data correlate well with the theoretical data [3, 5, 7].
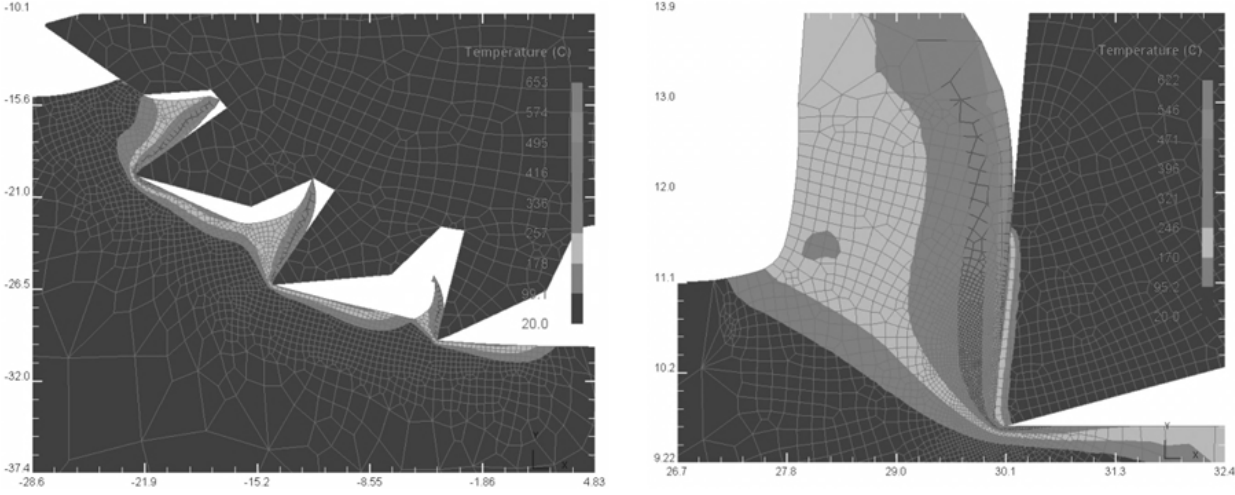

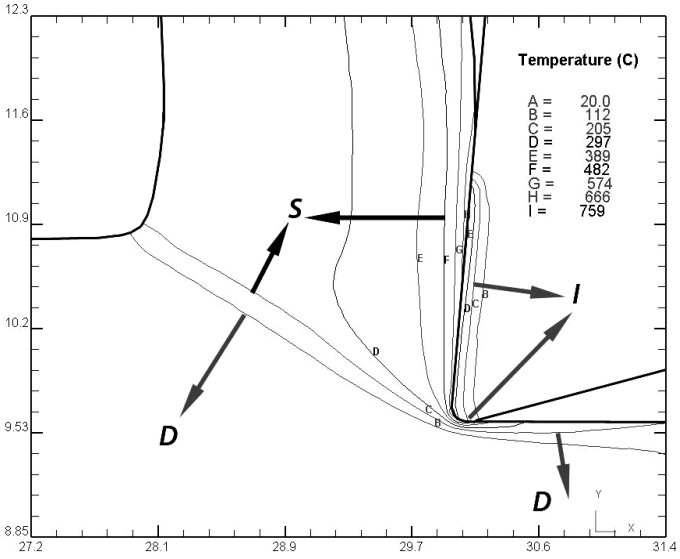Fig. 6. The temperature field in the contact tool and workpiece during milling

Fig. 7. Temperature fields of the chip and tool (feed S = 0,25 mm,
cutting depth t = 1 mm, cutting speed V = 120 mm/min)

In the zone of chip formation temperature is highest near the cutting edge and in the chip buildup. The real temperature field is more complicated, since cutting temperature also depends on the length of the contact cutting surface and chip on the back and front surfaces of the tool [6]. The smaller the length of the contact on the back surface, the lower the average temperature of the cutting and the closer to the cutting edge positioned its maximum. When cutting structural steel with speed $V > 100$ m/min temperature reaches 800°C, and the friction surface on the front face temperature reaches 1200°C.

Obviously, the temperature is more concentrated and the position of maximum temperature moves away from the cutting blade when shaving decreases the length of contact with the front surface of the tool (Fig. 8). It is essential to ensure the tool life and parts precision.
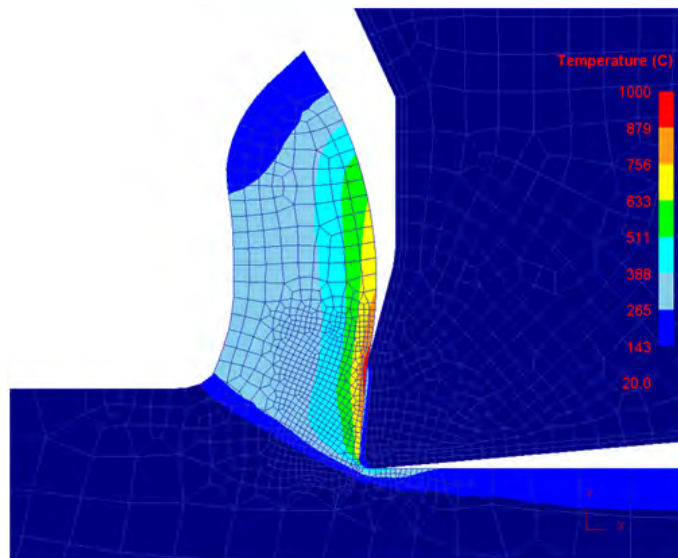
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Fig 8. Picture influence shorter contact with the front surface
of the chip on the distribution of temperature fields in the tool and workpiece

In order to analyze the influence of cutting speed on the temperature in the chip forming zone, modeled the process of turning steel AISI 45 workpiece (cutting speeds 100 m/min; 150 m/min; 200 m/min; 250 m/min; 300 m/min) by the tungsten-cobalt alloy tool.
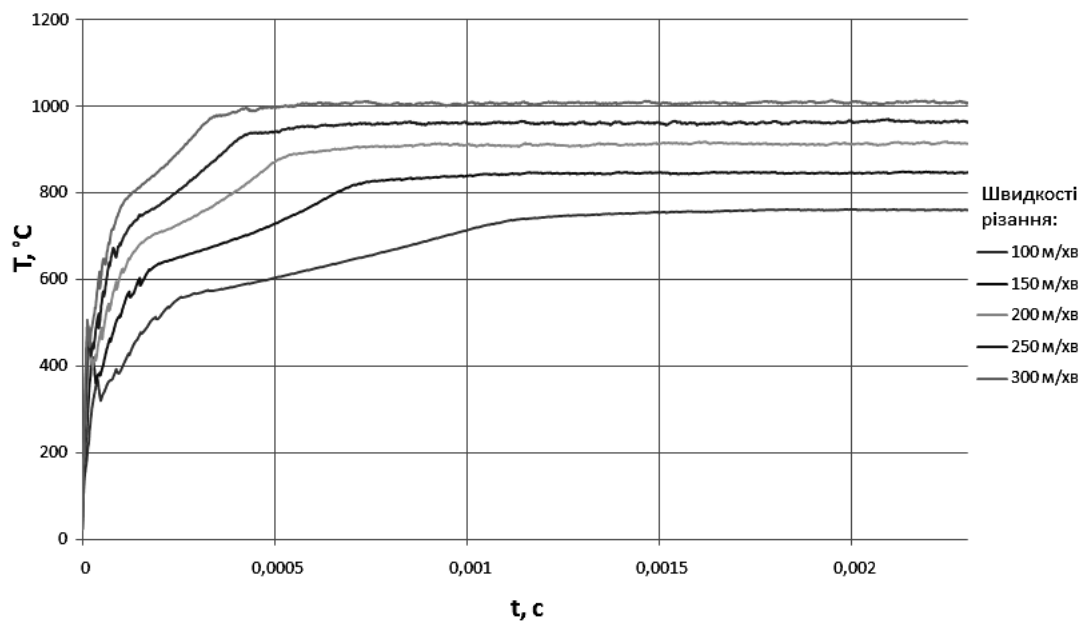

Fig. 9. Graphs of temperature dependence from the cutting speed

Obviously, the cutting temperature increases less rapidly than the cutting speed. During the heating tool temperature difference between the chip and the tool is reduced, and therefore decreases the intensity of the heat from the chip to the tool. Thus, with increasing cutting speed V, tool temperature rises significantly, but slower than the speed. Modern experimental research of cutting high-strength steel with ultra speeds (up to 72,000 m/min) argue that cutting process occurred almost adiabatically (without heat exchange) [1]. This phenomenon is accompanied by a sharp reduction of cutting forces and a significant increase of the brittleness of the metal in zone of chip forming. This process facilitates the rapid separation of the chip from the workpiece in the absence of plastic deformation (shrinkage) chips. Moreover, the negative contraction (lengthening chips) is a result of centrifugal forces at ultra-high cutting speeds.

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We can easily predict the relationship between the depth of cut t, feed S and temperature in cutting zone. Thus, the chip pressure on the cutter grows, and job strain grows too. But while chip shrinkage decreases and thus the work of deformation is also reduced. Friction on the back of the tool with increasing supply varies little. Therefore, the amount of heat generated in the chips will increase less compared to the feed increasing. The extraction of heat is improved when increasing the thickness of the chip, as the contact area of the chip cutter expands. As a result, the cutting temperature increases with increasing feed, but to a lesser extent than at higher cutting speed.

Cutting depth influences to the temperature less, than the load per unit length of the cutting edge does not change. Length of cutting blade at a constant angle in terms of proportion increases when increasing the depth of cut. But the heat sink equivalent increases. Thus, per unit length of the cutting edges increase the heat to very low. As a result of temperature changes little with increasing depth of cut. A simulation model was developed in the system DEFORM 2D to confirm these theoretical considerations. Simulation results allow analyzing the influence of cutting depth on temperature in the chip forming zone. The process of turning for cutting depth: 0.1 mm, 0.4 mm, 0.7 mm, 1.0 mm, 1.3 mm was investigated. It is confirmed that the temperature grows when depth of cut increases, but only in the range $S = 0,1 ... 0,4$ mm (20 %). The temperature difference varies between 50... 70 % with a large feed increasing. This difference is 5-7 % of the nominal value of the temperature (Fig. 10). Thus, the cutting depth significantly changes the temperature of the cutting tool by changing the power of heat flow. Feed changing bring to the changes in temperature cutting, cutting forces, wear intensity and path length cutting tool. In the short-term machining temperature change is a consequence of sharp changes in temperature and heat flow values designed into the tool. During prolonged treatment effects tool wear will greatly affect to the value of the temperature in the cutting zone as well.
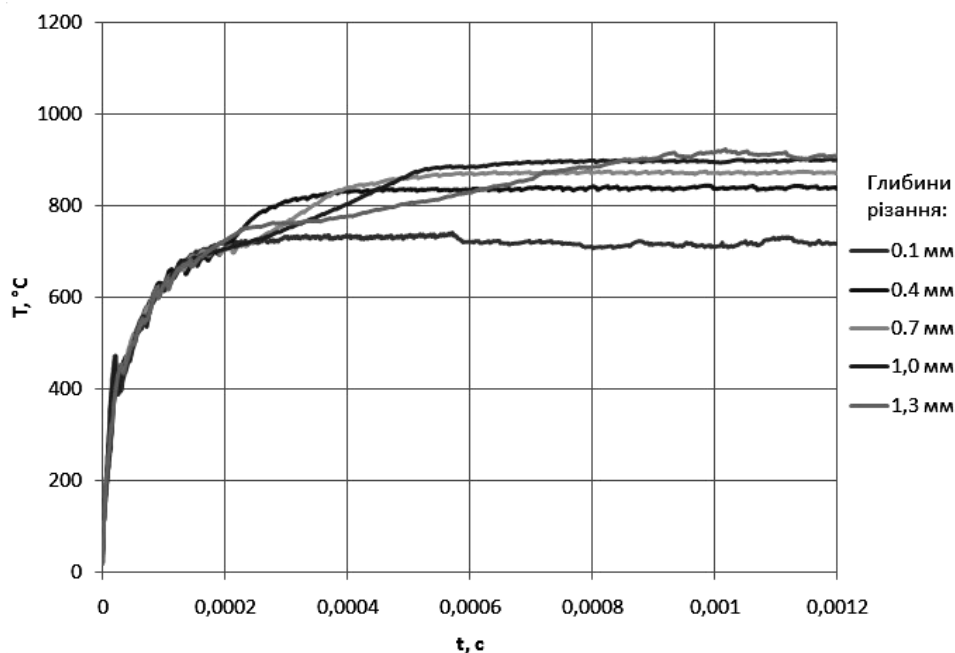

Fig. 10. The dependence of the thermal measure from the cutting depth

Coefficient of friction chips and tool is an important factor to the temperature measure in the technological environment. Moreover, this factor is determined not only physical quantity pairs: tool material - the material of the workpiece, but also the influence of lubricoolant. The process of turning for the coefficients of friction: 0.2, 0.3, 0.4, 0.5, 0.6, 0.7 is modeled. Workpiece material is a steel AISI 45. Material tool is a tungsten carbide. It is confirmed that the temperature in the contact zone increases proportionally when coefficient of friction increases (Fig. 11).
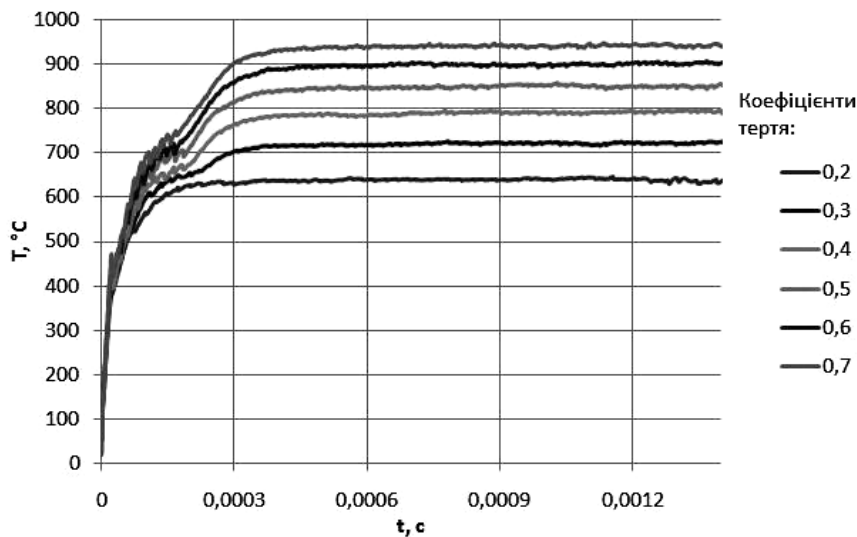
Fig. 11. The dependence of the thermal measure from the friction ratio

As shown in Fig. 12, the temperature in the contact zone increases to a certain value (section AB), and then goes into default mode and remains constant (beyond point B).
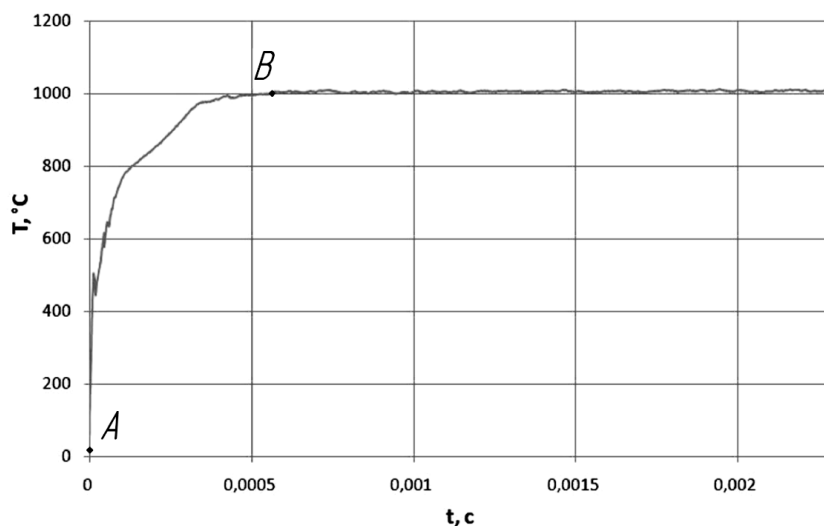

Fig. 12. The variation of temperature in the cutting time

Obviously, the physical, chemical and mechanical characteristics of the workpiece material (heat capacity, thermal conductivity, density, coefficient of friction, etc.) significantly affect to the temperature field in the cutting zone. Simulation rheological studies for various structural steels and alloys carried out to analyze the impact of these factors on the thermodynamic parameters of the cutting process (Fig. 13). Thus, the temperature of cutting brittle metals such as steel AISI 45 is significantly lower (20 %) than when cutting steel AISI 20. Low-temperature conductivity of heat-resistant chromium-nickel alloy XH60 cause concentration temperature (up to 1000°C) at the front cutting edge and creates significant thermal deformation of the chip and the cutting tool. We can draw similar conclusions for the temperature fields during machining of titanium alloy BT6. In this case significant temperature difference (10... 12 %) due to adiabatic chip forming process. This heat generated as a result of plastic deformation is localized in a narrow zone. Shear deformation becomes more concentrated, and chip is cyclical cell. Cutting temperature is low during the processing of aluminum alloy AD33 (about 360°C). This can be explaining not only by small load, but as a result of high aluminum thermal conductivity.
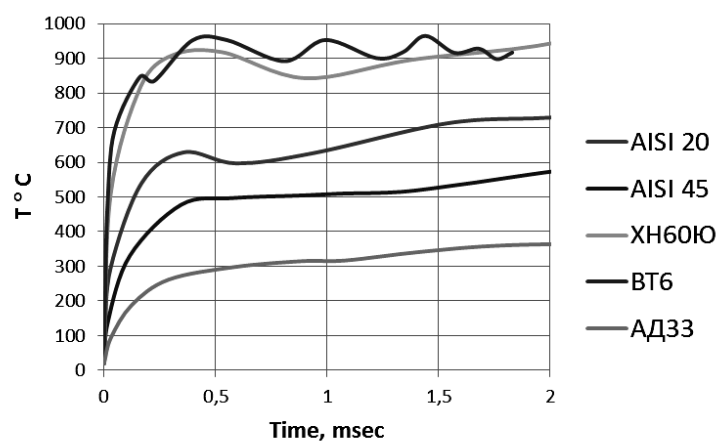
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Fig. 13. The dependence of the thermal measure from the physical,
chemical and mechanical characteristics of the workpiece material
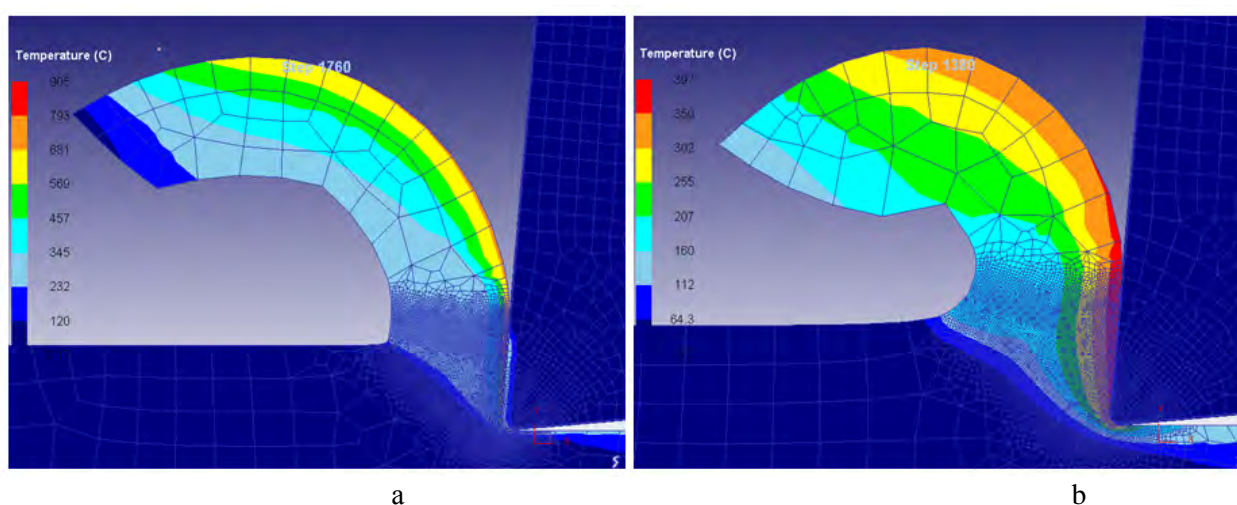

| a | b |

Fig. 14. Thermal fields in the chip forming zone for: а) steel AISI 45; б) aluminum alloy AL 6061

The geometry of the cutting tool makes a significant impact to the cutting temperature. Experimental studies [5,7] show that the cutting force increases when the front corner γ reduced. This causes an increase in the quantity of heat which generated in the chip forming zone and, as a result, cutting temperature increases as well. These results support the findings of rheological cutting model in software DEFORM 2D (Figure 15). The extraction of heat will intensify when the tool edge angle β will increase. In terms of the angle φ also affects to the cutting temperature. The load on the cutter increases when approach angle φ decreases and, seemed like, that temperature in the cutting zone must to grow. However, it is the opposite: cutting edge extended when the angle φ decreases, and as a result, heat transfer significantly improves.

Conclusions. 1. Analysis of thermal physical rheological model of cutting system implemented in software DEFORM 2D (3D), makes it possible to investigate the effect of dynamic parameters on the stress-strain state of the workpiece and tool.

2. It is shown that most quantity of the heat cutting, which formed as a result of chip deformation (60-80 % of the heat cutting and for the ultra-speed cutting conditions for more than 90 %) remains in the chips and partly absorbed machined workpiece (up to 20-40 % of the heat). Only 3-5 % of the heat goes into the tool. The loss of heat by convection and radiation during the cutting process and the quantity of heat that goes into workpiece, are very small. This is because the chips rapidly formed in the cutting zone and just as quickly leaves the zone of contact with the tool.
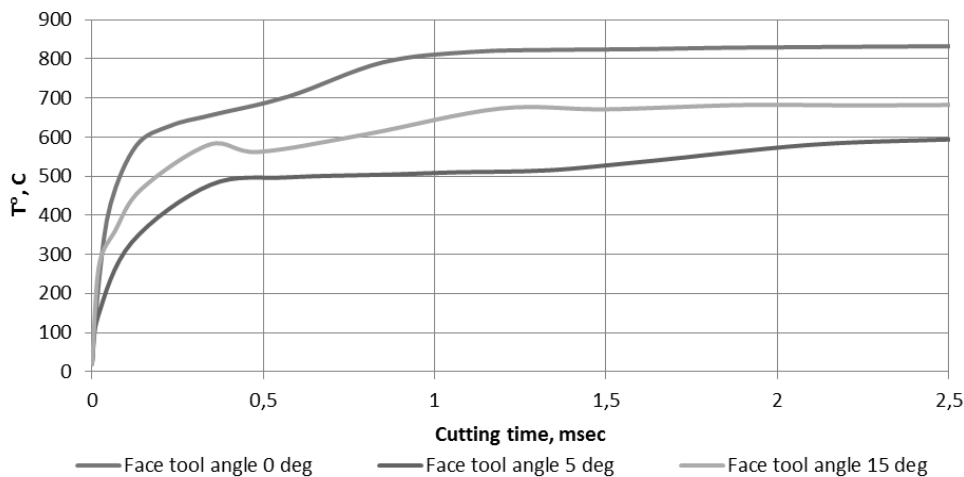
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Fig. 15. The dependence of the thermal measure from the cutting tool geometry

3. Zone of maximum cutting temperature almost coincides with the area where the chip element is subject to elastic deformation. This is proved by the analysis of rheological experiment. We can conclude that the zone of plastic deformation is heated much less (for the above article in the experiment - about 100°C).

4. It is shown that the cutting temperature increases less intensive than cutting speed. The difference between the temperature of the chip and the temperature of the tool is reduced during heating tool. Therefore, the intensity of the heat from the chip to the tool decreases. Investigation of ultra-speed (up to 72000 m/min) cutting of high-strength steels suggests that the process of heat production occurred almost adiabatically. This phenomenon is accompanied by a useful reduction of the cutting forces and a significant increase of the metal brittleness in the cutting zone. This process facilitates the rapid separation of the chip from workpiece with the absence of the chip plastic deformation.

5. The geometry of the cutting tool makes a significant impact to the cutting temperature. Experimental studies show that the cutting force increases when the front corner γ reduced. This causes an increase in the quantity of heat which generated in the chip forming zone and, as a result, cutting temperature increases as well. The extraction of heat will intensify when the tool edge angle β will increase. In terms of the angle φ also affects to the cutting temperature. The load on the cutter increases when approach angle φ decreases and, seemed like, that temperature in the cutting zone must to grow. However, it is the opposite: cutting edge extended when the angle φ decreases, and as a result, heat transfer significantly improves.

6. Using a simulation by the rheological models can most realistically predicts the thermodynamic state of the workpiece and the tool in rapidly cutting conditions, especially when cutting tool change direction quickly, in condition of tool build-up, fast changes of feed and so on.

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АНАЛІЗ СПОТВОРЕННЯ ПРОФІЛЮ ЗУБЦЯ ЦИЛІНДРИЧНОГО ЗУБЧАСТОГО КОЛЕСА ГІПЕРБОЛОЇДНИМ ШЛІФУВАЛЬНИМ КРУГОМ ЗАСОБАМИ КОМП'ЮТЕРНОГО МОДЕЛЮВАННЯ

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На основі математичної моделі, яка описує процес зачеплення циліндричного зубчастого колеса і гіперболоїдного шліфувального круга, отримано комп'ютерну модель для моделювання цього процесу. Модель дала змогу дослідити спотворення профілю зубця циліндричного зубчастого колеса під час застосування гіперболоїдного і циліндричного шліфувальних кругів. Наочно показані місця, схильні до найбільших спотворень і відхилення форми профілю зубця циліндричного зубчатого колеса за зміни окремих параметрів інструмента.

On the basis of a mathematical model which is describe the process of engaging the spur gear and the wheel hyperboloid a computer model to simulate the process obtained. The model allowed investigate the profile distortion of the tooth spur gear in the application of hyperboloid and cylindrical grinding wheels. It has been amply demonstrated the places most affected by distortions and the change of tool with changing some of its parameters.

Постановка проблеми. Високий рівень науково-технічного розвитку збільшує темпи освоєння на практиці нових машин і механізмів. В основу більшості частин машин, що рухаються, покладено принцип зубчастого зачеплення. Причому зубчасте зачеплення проявляється не тільки у час використання готових деталей, але й у процесі їх виготовлення чи виправлення. Так, під час вивчення принципів формоутворення циліндричних зубчастих коліс, особливо можна виділити інструменти, що мають гвинтові поверхні, які уможливлюють прискорити процес одержання деталі й підвищити його точність. Питання точності виготовлення особливо актуальне на етапах фінішної обробки виробу. Зміна форми інструмента здатна підвищити точність або швидкість оброблення зі збереженням прийнятої точності. Так, розглядаючи процес шліфування циліндричних зубчастих коліс, застосування гіперболоїдних поверхонь [1] дає змогу підвищити продуктивність порівняно із циліндричними черв'ячними шліфувальними кругами [2]. Аналіз зміни точності доцільно проводити, застосовуючи сучасні інструменти. Сьогодні рівень розвитку комп'ютерної техніки та програмних пакетів оброблення інформації уможливлює прискорити процес аналізу та скоротити об'єм матеріалу й необхідного часу на виготовлення дослідних зразків та оснащення. Оскільки кожне завдання свого роду унікальне і моделювання гіперболоїдних

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