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Vadym Stupnytskyy
Lviv Polytechnic National University, Lviv, Ukraine

INVESTIGATION OF THE INFLUENCE OF MACHINING FACTORS ON THE WORKPIECE DEFORMATION MODE IN THE CHIP-FORMING ZONE BY THE FINITE ELEMENT METHOD

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Abstract. The results of studies of the impact strength, temperature factors and parameters of cutting tool geometry on the formation of the stress-strain and thermodynamic state of surfaces with different types of engineering materials in the cutting process are described in the article. Analysis of simulation modeling of power, temperature and deformation parameters is the basis for making of forecasting models of influence of the structure and process parameters on the formation of complex operational properties of the product.

Keywords: machining factors, strength, cutting tool, thermodynamic state, deformation.

Introduction

The magnitude and distribution of dynamic cutting forces are required for analysis of plastic and elastic deformations and residual stresses of machined workpiece layer and the intensity of tool parts vibration. These indicators form the parameters of accuracy and quality of processed surfaces. The studies conducted in the dynamics of cutting can be done by 2 methods: 1) analytical solution of the equation system for calculating of cutting forces by analyzing the process as a particular case of the process of plastic deformation (shear); 2) determination of the cutting forces on the basis of simulation modeling rheological system based on the finite element method (FEM). Last type of research is not only to determine the adequacy of the theoretical bases of forming machined surfaces, but mostly for the efficient analysis of dynamic stress-strain state of the workpiece and the tool in different areas of the chip-forming zone at various boundary conditions modeling (geometry tools, materials, cutting conditions, etc.) for use in optimization models in order to implement functionally-oriented process [1].

Problem statement and calculation model

Let us consider a system of forces acting in the orthogonal cutting diagram (Fig. 1) [2]. The total power is based on the vector sum of the forces of internal friction F_1, which is directed along the front surface of the wedge tool and cutting force R, acting in the feed direction. Since the resultant force can change the direction of action, it is better to describe it as the vector sum of tangential force P_z and perpendicular to the radial force R_y.

These forces are determined by formulas [3]

$$P_Z = \frac{a \cdot a_c \cdot \tau \cdot \cos\omega}{\sin\phi \cos(\phi + \omega)}, \tag{1}$$

$$P_Y = \frac{a \cdot a_c \cdot \tau \cdot \sin\omega}{\sin\phi \cos(\phi + \omega)}, \tag{2}$$

where τ is shear stress in the plane shift (Fig. 1); ϕ is shear angle ; a , a_c is slice thickness and chips, respectively; ω is the angle between the action and the resulting force feed direction.

Cutting forces in shear plane are described by formulas:

$$\begin{aligned} R_\tau &= P_z \cdot \cos\phi - P_y \cdot \sin\phi, \\ N_1 &= P_y \cdot \cos\phi + P_z \cdot \sin\phi. \end{aligned} \tag{3}$$

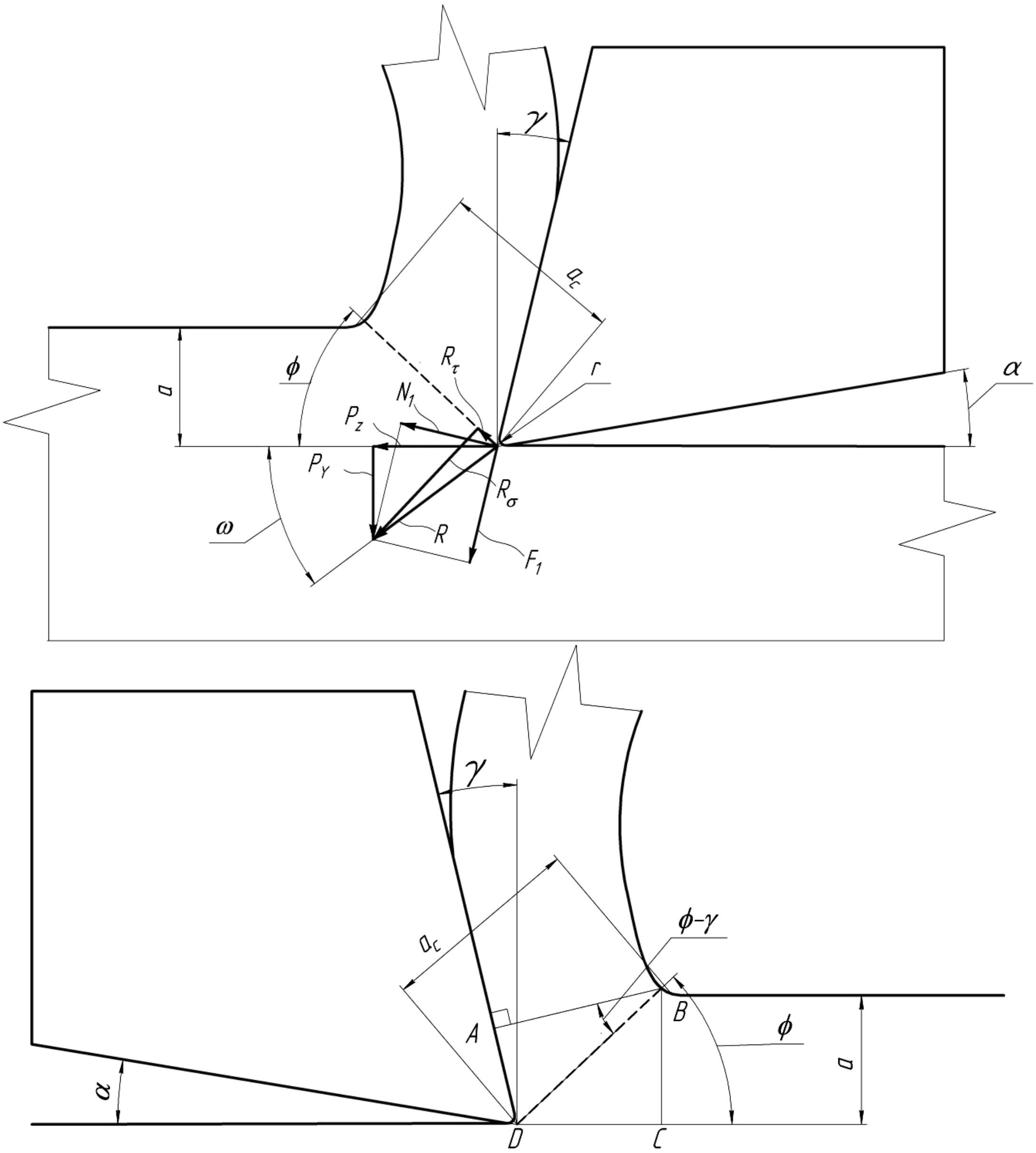


Fig. 1. *Scheme of force interaction between workpiece and tool in the chip-forming zone*

Friction forces on the front surface of the cutting edge:
Friction forces on the front surface of the cutting edge:

$$F_1 = P_z \cdot \sin\gamma + P_y \cdot \cos\gamma,$$
$$N_1 = P_z \cdot \cos\gamma - P_y \cdot \sin\gamma. \qquad (4)$$

Synthesis friction:

$$\mu = \frac{F_1}{N_1} = \frac{P_z \cdot \sin\gamma + P_y \cdot \cos\gamma}{P_z \cdot \cos\gamma - P_y \cdot \sin\gamma} = \frac{P_z + P_y \cdot \mathrm{tg}\gamma}{P_z - P_y \cdot \mathrm{tg}\gamma}. \qquad (5)$$

Shrinkage chips:

$$\xi = \mathrm{ctg}\phi \cdot \cos\gamma + \sin\gamma. \qquad (6)$$

Then shift angle may be defined as follows:

$$\phi = \mathrm{arcctg}\left(\frac{\cos\gamma}{\xi - \sin\gamma}\right). \qquad (7)$$

Then tangential and normal stress may be defined as:

$$\begin{cases} \tau = \dfrac{(P_z \cos\phi - P_Y \sin\phi)\sin\phi}{a \cdot a_c}; \\ \sigma = \dfrac{(P_z \sin\phi - P_Y \cos\phi)\sin\phi}{a \cdot a_c}. \end{cases} \tag{8}$$

The velocity of the chips on the front surface of the cutting wedge is given as [3]:

$$V_C = \frac{\sin\phi}{\cos(\phi-\gamma)} V_w = \frac{V_w}{\xi}. \tag{9}$$

The value of shear deformation zone (Fig. 2):

$$\varepsilon = \frac{AD}{CD} + \frac{DB}{CD} = \mathrm{tg}(\phi\text{-}\gamma) + \mathrm{ctg}(\phi). \tag{10}$$

The intensity of deformation changes (strain rate), which has a dominant influence on the formation fracture criterion when cutting:

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt} = \frac{\cos\phi}{\cos(\phi-\gamma)} \cdot \frac{V_w}{\Delta y}. \tag{11}$$

where Δy is cross shear size of the plastic deformation zone.

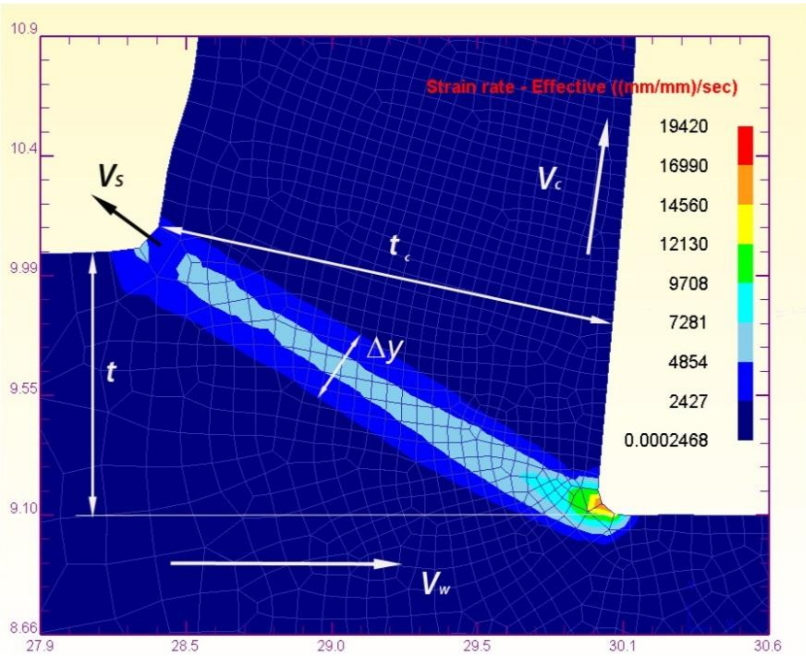


***Fig. 2.** Scheme for the determination of strain shear zone*

Model of the adequacy

Let's make the study simulation model of parts cutting made of AISI45 steel for the analysis of the adequacy of theoretical calculations and data rheological model (feed S = 0.4 mm; cutting depth t = 0.5 mm; cutting speed V = 120 m/min) [2]. Let us choose any point in the shear plane – R_1 (Fig. 3). Front cutting angle γ=5°. Analysis of plane geometry gives a possibility to determine the displacement angle $\varphi \approx 35°$. Then the strain in the point P1 may be determined by formula (6):

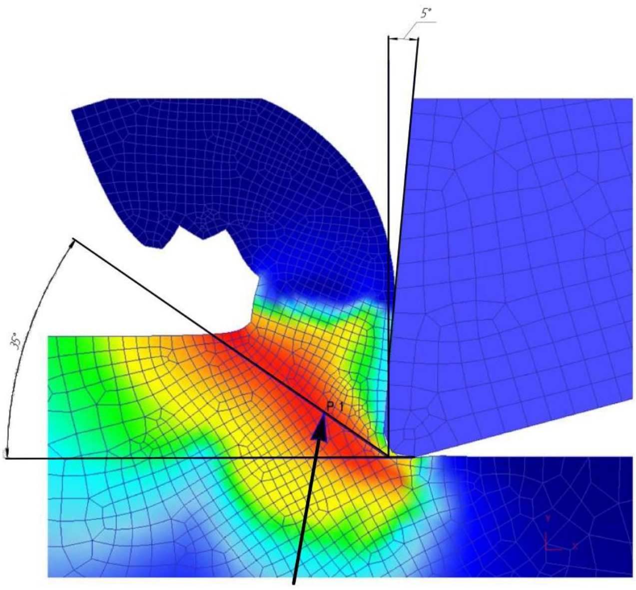
$$\varepsilon = \mathrm{tg}(35\text{-}5) + \mathrm{ctg}(35) = 1.97 \;\; mm/mm.$$

Deformation at the point P1 is $\varepsilon = 2{,}03\ mm/mm$, according to the simulation rheological model shown in Fig.3. It means, the error of theoretical and experimental data is 2.9 % only.

Similar calculations are made for determination of the intensity of deformation. Rheological shift pattern for determination of the intensity of deformation is shown in Fig. 3. The size of plastic zone displacement is within Δy = 0.07–0.14 mm. The value of the intensity of deformation in point P1 equals 10400 (mm/mm)/s).

The chip's speed in point R1 according rheological model is $V_w = 1240$ mm/s. Then the intensity of deformation of the workpiece material in point P1 will be determined by formula (11):

$$\dot{\varepsilon} = \frac{\cos 5}{\cos(35-5)} \cdot \frac{1240}{0.13} = 10670 \text{ (mm/mm)/s).}$$



$\varepsilon(P1)=2{,}03$ mm/mm

Fig. 3. *Scheme for the determination of strain in the point P1*

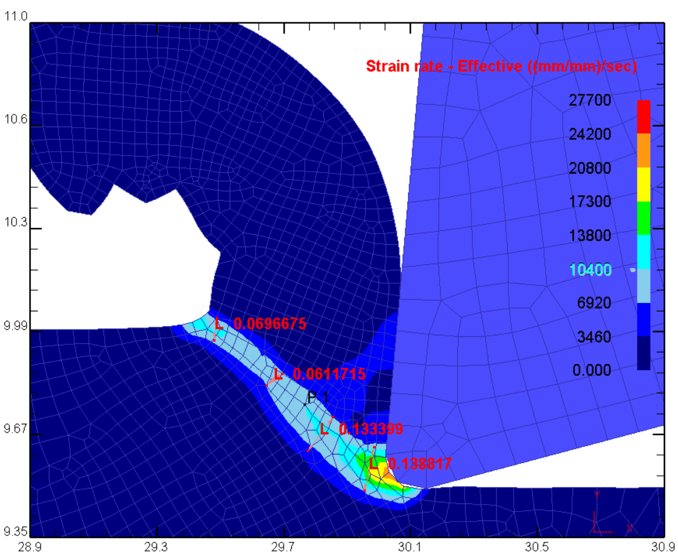
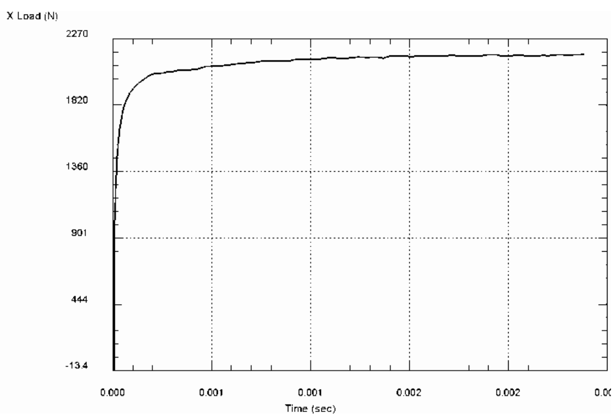


Fig. 4. *Scheme for the determination of the intensity of deformation in the point P1*

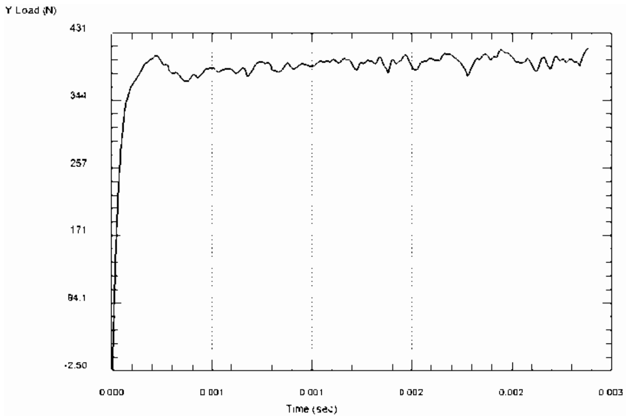
The study of the cutting forces when machining of the carbon steels by FEM method

Simulation studies with the different materials, machining modes and geometrical parameters of cutting tools are made to analyze the impact of various factors on the rheological pattern of cutting. The chemical composition, mechanical properties, microstructure essentially (intensively) influence the machinability of steel and the temperature in the cutting zone.

Graphs of cutting forces for the carbon steels AISI1020 (a) and AISI1045 (b) (feed - S = 0,25 mm; cutting depth - t = 1 mm; cutting speed V = 120 m/min) are shown in Fig. 5, *a–d*.



a



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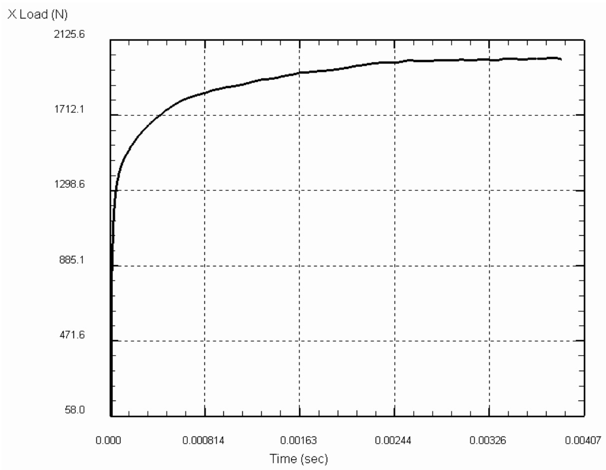

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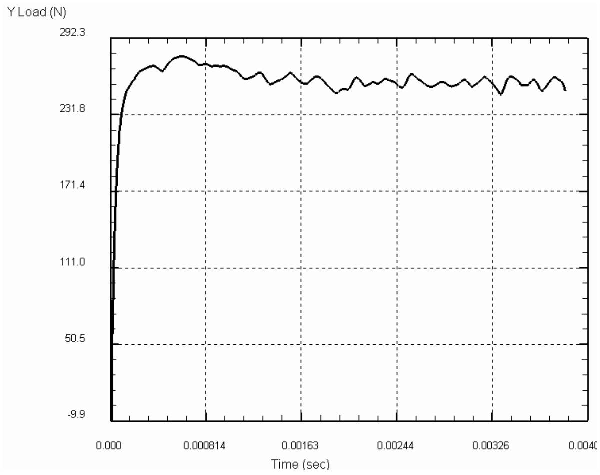


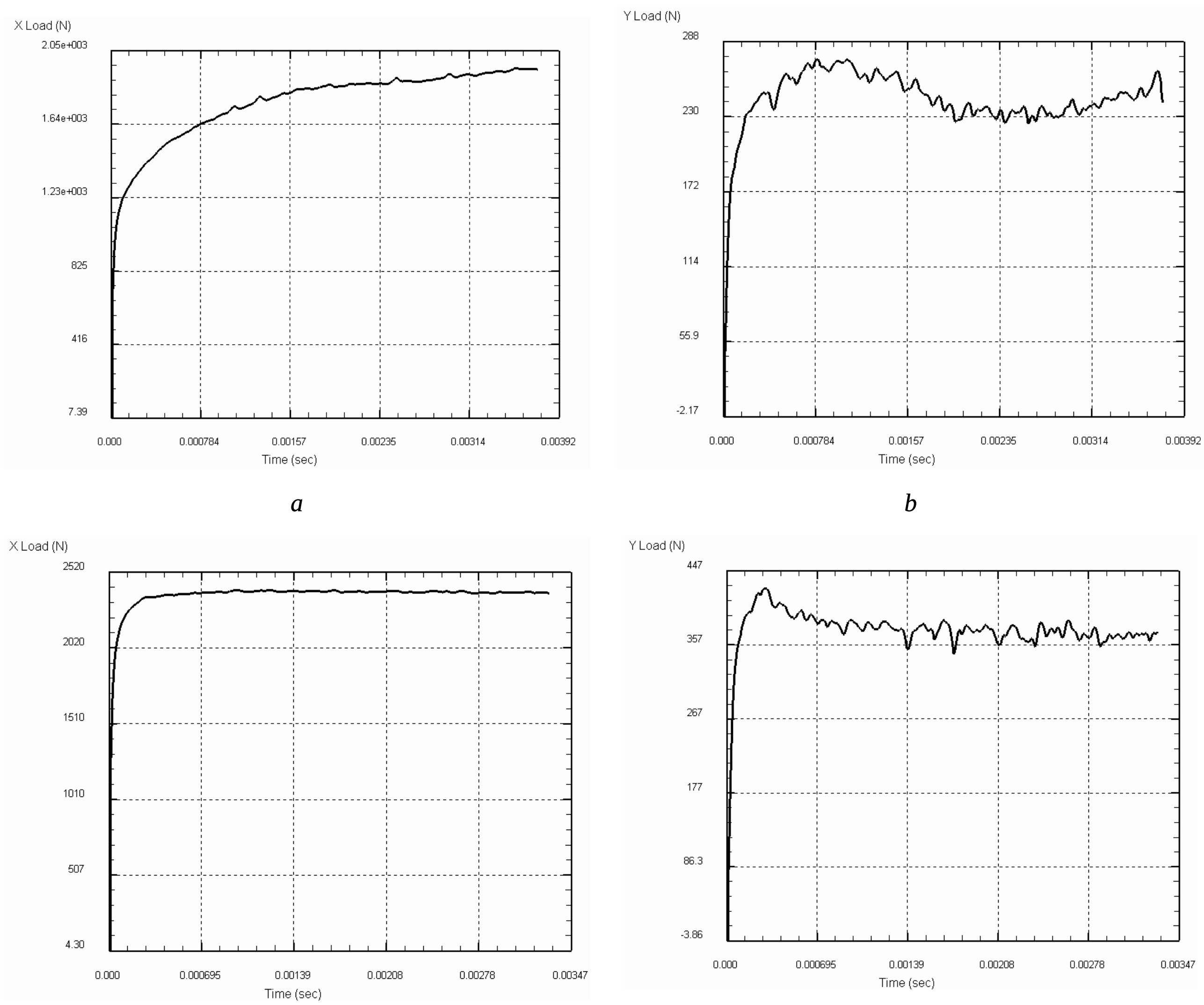
d

Fig. 5. *Components of cutting forces when machining of parts made of carbon AISI1020 and AISI1045 steels, determined by analyzing the rheological simulation models in the Deform 2D software*

The study of the cutting forces when machining of the alloy steels by FEM method

For low-alloyed steels the influence of carbon is more complex as it is related with the formation of carbides of different composition, their size, hardness, etc. The presence of manganese in steel strengthens ferrite, lowers the ductility of steel and this causes the increasing of cutting forces. This is confirmed by rheological analysis modeling of machining of alloyed steels (Fig. 6). The process of cutting is significantly improved for the following combinations C < 0.20 % and Mn < 1.5 %. At a high manganese content (over 10 %), the steel has a tendency to hardening under the influence of cutting forces, as a result of which the strength sharply increases, the flexibility of the part's surface layer reduces, the ferrimanganese carbides are being formed along the grain boundaries and the austenite partially is being transformed to martensite [4]. The machinability in this case is very low. The improvement workability may be improved by preheating of workpieces to a temperature of 400...600 °C and harmful effects of hardening ma br annihilated. In the case of presence of a certain amount of sulfur in steel the manganese sulfides are formed, which act as lubrication on friction surfaces. Phosphorus, sulfur, lead are used as additives that improve the workability of steels. In turn, the increased silicon content significantly affects the machinability of steel due to the formation of silicate abrasive substances. The presence of molybdenum, vanadium, chromium, tungsten increases the strength and toughness of steel and deteriorate the workability. These elements form solid solutions with iron and carbides of different composition and hardness. As a result, the material ability of quick worning of blade cutting tool increases. Chromium promotes coagulation of carbide particles at delivery and significantly reduces the thermal conductivity of the material. Cobalt, on the contrary, slows the coagulation of carbides, increasing the thermal conductivity. It has little effect on reducing of viscosity and strength of alloyed steels, because it creates a chemically stable compound of iron. The presence of nickel in solid solution promotes the strength of the part's material, but lowers machinability of steels.

Graphs of cutting forces when cutting of corrosion-resistant alloyed steel – steel 316h and 43401 (feed S = 0.25 mm; cutting depth t = 1 mm; cutting speed V = 120 m/min) are shown in Fig. 6 [5, 6, 7].



a *b* *c* *d*

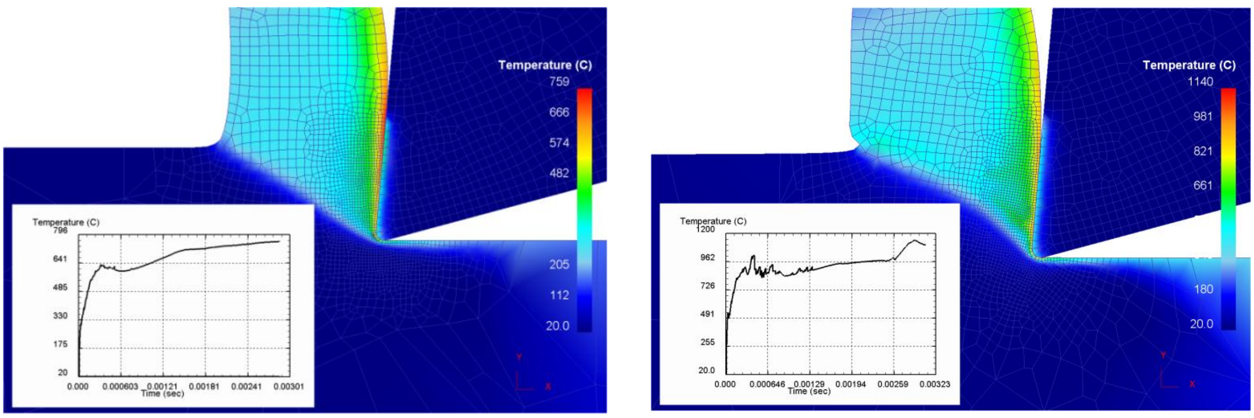
Fig. 6. *The components of cutting forces for 316h (a, b) and 43401 (c, d) alloyed steel, determined by analyzing of the rheological simulation models in the Deform 2D software*

On the basis of analysis of rheological models, we may conclude that the increase in carbon content by 3.5 times (for the above example – machining of 316h and 43401 steels) improves the cutting power by 20 % (from 2.05 kN to 2.5 kN). In addition, for the steel 316h the great time for stabilization of the cutting forces (3.5 ms) and significant macrooscillations of the Py component of cutting force ($\Delta P_y \approx 80$ H, approximately 25–27 % of the radial component of cutting force (Fig. 6)) are typical. Terms of quality surface treatment are much worse, because of increasing of tool self-oscillations. The main reason of this growth is the presence in the steel structure of 17 % of chromium carbide which causes the coagulation of impurities during dispensing, which significantly reduces the thermal conductivity of the material, and thus creates problems of effectively heat emmision in the cutting zone. However, for stainless steel 43401 the cutting forces stabilization occurs in a short time (about 0.4 ms) and the fluctuations of radial component of the cutting force do not exceed 8–10 % [5, 6, 7].

The study of the cutting forces when machining of the high-temperature alloys and stainless steels by FEM method

More coplicated workability of the high-temperature alloys and stainless steels in comparison with structural steels is determined by their physical and mechanical properties, chemical properties, structure, thermal performance. Analyzing the overall impact of chemical elements on the machinability of cutting parts [8, 9, 10], we may note the high strengthen of the material of heat resistant steels and alloys during the process of its cutting destruction. Heat-resistant stainless steels are often applyed to the austenitic steels class containing crystallites with face-centered crystal lattice. In this regard, the alloys of austenitic class have low yield point and constant tensile strength. For high-temperature steels the ratio of proof strength corresponding to 0.2 % of permanent deformation to the tensile strength is only 40–45 %, while for structural steels this value is 60–65 % or more [11].

Heat-resistant stainless steel and alloys have low thermal conductivity in comparison with traditional engineering carbon steels. During their cutting a significant amount of heat allocates and the temperature in the cutting zone sharply increases. When comparing temperatures during machining of steel AISI1020 and superalloys IN718, we can conclude that the temperature in the cutting zone of heat-resistant alloy is 50 % higher than the temperature during machining of steel AISI1020 (Fig. 7). This helps to enhance the adhesion and diffusion processes and intensifies the deterioration of working surfaces of tools.



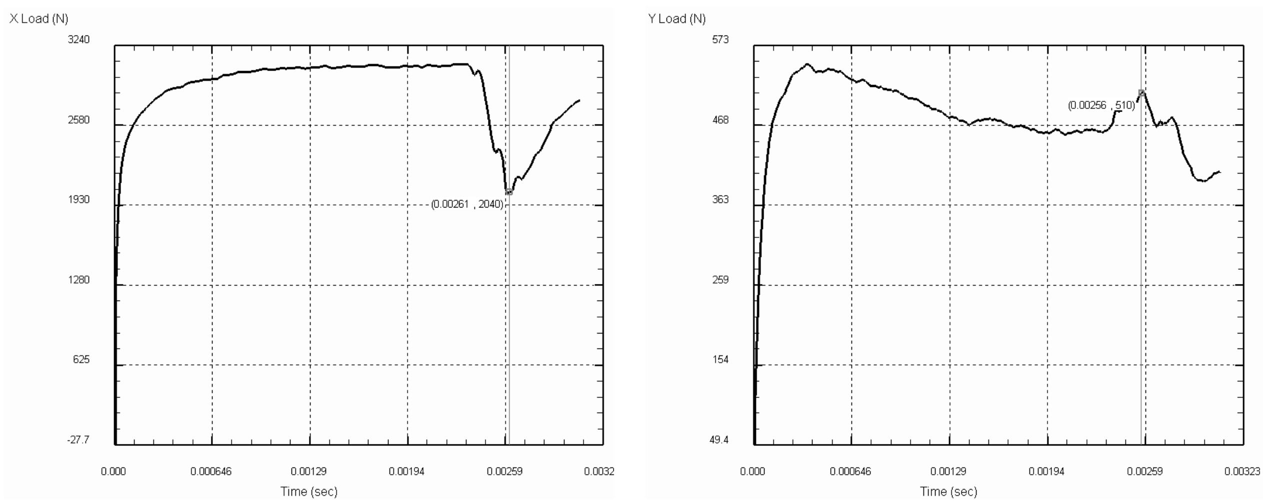
a *b*

Fig. 7. *Comparison of temperature fields during the machining of steel AISI1020 (a) and superalloys IN 718 (b) (feed S = 0.25 mm; cutting depth t = 1 mm; cutting speed V = 120 m/min)*

The ability of these materials to keep the original strength and stiffness at large temperatures affect the fact that in the process of cutting the tool is influenced by high specific loads. Thus, when the alloy is heated to a temperature 700 °C its temporary resistance is σ_B = 900–1000 MPa, and at 800 °C – σ_B = 800–900 MPa. In turn, when heating of steel AISI45 to this temperatures the value σ_B decreases by 3–5 times [9]. Very weak softening of heat-resistant stainless material during the heating to high temperatures leads to the fact that the front surface of the cutting tools are influenced by high specific loads (up to 7000...11000 MPa) corresponding to the load that occur when cutting of hardened steels with 60...64 HRC. High chemical similarity of processed material and tool material causes their seizing and even destruction of the contact areas. The largest capacity for adhesion is typical for metals that have high ductility, with atomic diameters differing by no more than 15–18 % (eg, iron – chromium, iron – copper) [10].

Great erasing ability of the heat-resistant and stainless steels is caused by the presence of phase states when intermetallic or carbide inclusions are being formed. This contributes to enhanced wear of the tool. During the plastic deformation of heat-resistant and stainless materials the allocation of carbides, the hardness of which is close to the hardness of tungsten carbide-cobalt and titanium-cobalt groups, is carried out. As a result, the ability of abrasive ability of high-temperature alloys, especially those with nickel basis, sharply increases. For these materials the essential variation of grain sizes and uneven allocation of carbides and intermetallic phases after forging, stamping and casting is typical. The presence of such zones leads to a sharp increase of cutting forces and temperature, which largely determines the tool dulling and the destruction of the tools cutting edge.

Taking into account the considered features, the physical nature of cutting stainless and heat resistant materials can be summarized as follows. First, the tool cuts into the unstable metal, and under its influence the plastic deformation of the metal layer is conducted, which is accompanied by the absorption of energy that is applied from the outside; cutting layer of metal is being hardened and becomes brittle. Then the shear starts and the formation of chips begins. Due to low thermal conductivity of the processed material the cutting heat is concentrated in the chip-forming zone and promotes adhesion and activation of diffusion, causing destruction of the cutting edges of the tool. These effects together with the increasing of abrasive and mechanical properties of stainless and heat-resistant materials at high temperature and variable effect of these factors, caused by vibrations, intensify the process of cutting tool wear. These features of heat-resistant and stainless steels and alloys degrade a workability of machining in comparison with the conventional steels and irons. Cutting speed decreases by 10–20 times in comparison with treating of carbon steel AISI1045 with increasing of heat resistance of hard steels and alloys. The cutting forces increase by 1.5 times (2120 H – AISI1045 (Fig. 5, *c*) and 3240 H – alloy IN718 (Fig. 8, *a*)), which causes higher temperatures in the cutting zone, and the short periods of stability of the cutting tool.



a *b*

Fig. 8. *The components of cutting forces in superalloys IN718 identified by analyzing of the rheological simulation model in the Deform 2D software*

Conclusions

At the beginning of the cutting process in the chip forming zone the intense processes occur, accompanied by rapid changes of force and stress-strain state of a product. They are a source of tool oscillations, the loss of stability of the workpiece, termodeformations phenomena that affect the formation of precise and other performance properties of the product. During the materials cutting with low carbon content the stabilization of cutting force occurs quickly – in about 1.0 ms. Herewith, the oscillation of radial component P_x is small – about 5–7 % of the total cutting force, so the ensuring of high quality of the worked surface is quite acceptable due to sharp handling modes. The carbon content in steel within 0.10–0.20 % is considered as the best content in terms of tool life period insuring. The presence in low-carbon steels ($C < 0,3\%$) lamellar pearlite and small ferrite includes significantly increases their machinability. With an increase in steels of carbon content within 0.30–0.50 % (as it is illustrated by the AISI 1045 machining) causes an increase of stabilization time of cutting forces by 2.5 times (to 2.5 ms) and a noticeable increase of vibrations of radial component P_x, which is about 15–17 % of the total cutting force. This significantly complicates the process of control while ensuring high precision of processing.

As a result of low thermal conductivity of the heat-resistant and stainless steels and alloys, the cutting heat is concentrated in the chip-forming zone and promotes adhesion and activation of diffusion, causing destruction of the cutting edges of the tool. These phenomena intensify the process of cutting tool wear. These features of heat-resistant stainless steels and alloys degrade a workability of their machining in comparison with conventional steels and irons. With increasing of heat resistance of hard steels and alloys the cutting speed decreases by 10–20 times in comparison with the treatment of carbon steel AISI1045 (for example). The cutting force increases by 1.5 times.

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