Наведено теоретичний підхід до розрахунку та управління параметрами силової й теплової напруженостей процесів лезової та абразивної обробки з урахуванням забезпечення мінімаль-но можливої енергоємності процесу різання. Теоретично визначено умови зменшення сили й температури різання й підвищення якості та продуктивності при шліфуванні й лезовій оброб-ці. Вони полягають головним чином в зменшенні умовного кута зсуву оброблюваного матеріалу й, відповідно, енергоємності шляхом підвищен-ня ріжучої здатності інструменту. Аналітично встановлено, що при шліфуванні сила й темпе-ратура різання більше, ніж при лезовій оброб-ці, в зв'язку з інтенсивним тертям зв'язки шлі-фувального круга з оброблюваним матеріалом та наявністю негативних кутів на передніх поверхнях ріжучих зерен. Показано, що зменши-ти температуру різання при шліфуванні можна застосуванням схеми багатопрохідного шліфу-вання, а також схем високопродуктивного гли-бинного шліфування торцем круга та кругом з двостороннім конічним профілем. На цій осно-ві розроблено підхід до створення ефективних високопродуктивних бездефектних технологій лезової та абразивної обробки деталей машин і твердосплавних ріжучих інструментів.

Отримала практичне застосування розроб-лена технологія зубошліфування за методом про-фільного копіювання на сучасному зубошліфу-вальному верстаті моделі HOFLER RAPID 1250 із застосуванням спеціального високопористо-го профільного абразивного круга з двосторон-нім конічним профілем. Цей круг характери-зується високою ріжучою здатністю в умовах високопродуктивного глибинного шліфування. Порівняно з традиційною схемою зубошліфу-вання за методом обкату, здійснюваною в умо-вах багатопрохідного шліфування, це дозволило до 5 разів збільшити продуктивність обробки. Розроблено технологію високопродуктивного глибинного круглого зовнішнього шліфування ріжучих багатолезових твердосплавних інстру-ментів (фрез, розверток) алмазними кругами на високоміцних металевих зв'язках із застосуван-ням методу електроерозійної правки. Це дало змогу в 2–3 рази підвищити продуктивність та забезпечити високоякісну бездефектну обробку твердосплавних інструментів

Ключові слова: управління якістю і продук-тивністю обробки, механічна обробка, сила і температура різання

DETERMINING THE CONDITIONS FOR DECREASING CUTTING FORCE AND TEMPERATURE DURING MACHINING

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1. Introduction

Machining processes with edge and abrasive cutting tools are widely used in the manufacture of machine parts due to low power consumption. At the same time, with increasing requirements for the quality and accuracy of machined surfaces and the emergence of new materials with improved physical and mechanical properties, there are constant prob-lems of expanding the technological capabilities of machining in terms of improving technical and economic indicators.

This especially applies to finishing technologies, where indicators of quality and accuracy of machined surfaces are finally formed. However, practice shows that grinding operations do not always ensure technical requirements for machining, mainly due to the formation of temperature defects on machined surfaces (burns, microcracks, etc.). For example, operations of gear grinding and carbide tool grinding. In these cases, the problem of improving the quality and rate of machining is still acute due to the high cutting temperature and formation of temperature defects on machined surfaces. Therefore, edge cutting finishing methods, characterized by lower power consumption, force and temperature of cutting are more often used instead of grinding. However, it is not possible to use them in the indicated grinding operations. In this regard, there is a need to improve the quality and rate of grinding and edge cutting and abrasive machining as a whole, based on the search for effective methods to reduce the force and temperature of the cutting process. An important factor in this direction is the scientifically substantiated choice of optimum machining conditions. It becomes very urgent to determine the effect of power consumption of the cutting process on the conditions of reducing the cutting force and temperature and, accordingly, improving the quality and rate of machining. This is because a decrease in power consumption fundamentally changes the laws of the cutting process and opens up new opportunities for controlling the quality and rate of machining. However, this requires new generalized theoretical solutions based on the analytical representation of cutting force and temperature in relation to the power consumption of machining. This needs the development of a new theoretical approach to the calculation of force and temperature parameters of machining, allowing a scientifically sound approach to managing the quality and rate of machining.

2. Literature review and problem statement

In [1], it is proposed to calculate cutting force using empirical relationships determined on the basis of experimental data. However, empirical relationships are only valid for very specific particular machining conditions. Therefore, they are difficult to apply to a generalized comparative analysis of various edge cutting and abrasive machining processes. In addition, there are no relationships linking the cutting force with the power consumption of the cutting process, which would allow determining the conditions for reducing the force of the cutting process.

In [2], the quantitative assessment of grinding temperature is based on the calculation of the temperature field in the cutting zone. However, the calculations do not take into account friction between the grinding wheel bond and the machined material, which is known to have a significant effect on grinding temperature.

In [3], the calculation of cutting temperature is based on solving the differential heat equation of the material. However, in order to simplify the calculations, this solution is based on the existence of an infinite depth of heat penetration into the surface layer of the workpiece. In real machining conditions, the depth of heat penetration into the surface layer of the workpiece takes a final value. Therefore, the exclusion of this condition from the calculation limits the possibility of theoretical analysis of thermal processes during machining, taking into account the distribution of heat going to the surface layer of the workpiece and chips.

In [4], the temperature of grinding of the tooth profile of the spur gear made of 20CrMnTi mild steel is theoretically determined. However, the calculations do not take into account the distribution of heat going to the workpiece and chips, although it has been found that the calculated temperature distribution along the tooth profile is fairly well consistent with the experimental result.

In [5], mathematical modeling of the temperature field of grinding of the involute gear in a three-dimensional coordinate system is carried out by the finite element method. However, numerical methods of grinding temperature calculation are useful for analyzing specific machining conditions. Unlike analytical calculation methods, their application limits the possibilities of a generalized comparative analysis of grinding temperature of various machining processes.

In [6], the cutting force arising under the conditions of impact interaction of the cutting tool with the machined material is experimentally determined. However, using the research results obtained in this way, it is difficult to predict the direction of reducing the force of the cutting process and optimal machining conditions.

In [7], a simplified calculation of the grinding temperature is made taking into account the established finite value of the depth of heat penetration into the surface layer of the workpiece. However, it is assumed in the calculations that all the heat generated during cutting goes into the surface layer of the workpiece, and the heat that goes into the chips is not taken into account. This does not allow the calculation results to be reasonably applied to determine the optimal conditions of the form grinding process considered in the work.

In [8], the results of calculating the parameters of only machining force are given. No cutting temperature calculations are available. This does not allow a reasonable approach to the selection of optimal machining conditions.

The work [9] shows the possibility of using milling for finish machining of gear teeth. However, the advantage of this method in terms of reducing the force and temperature of the cutting process compared to gear grinding, which is the main finishing method of gear tooth machining, is not substantiated.

In [10], the advantages of using high-velocity single-pass gear grinding are shown. However, the conditions for reducing the cutting force and temperature are not justified theoretically.

The literature review showed the absence of generalized analytical relationships linking the cutting force and temperature with the power consumption of the cutting process, which should determine the conditions for reducing the force and temperature of the cutting process. The conditions for reducing the power consumption of the cutting process during edge cutting and abrasive machining are also not theoretically defined in a generalized form.

When solving the heat equation, the infinite depth of heat penetration into the surface layer of the workpiece is assumed, whereas in real conditions it takes a finite value. This does not allow one to theoretically determine the true thickness of the heat-affected surface layer of the workpiece, i. e., the thickness of the affected layer of the machined material – the main parameter of the thermal process during cutting.

There is no analytically established and sufficiently justified the distribution of the heat generated by grinding between the resulting chips and the surface layer of the workpiece. This limits the possibility of theoretical determination of true cutting temperatures and conditions for reducing

the temperature of the cutting process and, accordingly, improving the quality and rate of machining. Therefore, the lack of generalized analytical relationships for determining the cutting force and temperature, related to the power consumption of the cutting process, does not allow a scientifically sound approach to managing the quality and rate of edge cutting and abrasive machining.

Therefore, the task is posed from the new theoretical positions to calculate cutting force and temperature, taking into account the power consumption of the cutting process during edge cutting and abrasive machining. To do this, it is necessary to separately analytically take into account the amount of heat going into the surface layer of the workpiece and the chips. It is also necessary to analytically establish the finite value of the depth of heat penetration into the surface layer of the workpiece and obtain analytical relationships linking cutting forces and temperatures with the power consumption of the cutting process. This will make it possible to more deeply justify the conditions for reducing the force and temperature of machining and on this basis determine conditions for improving the quality and rate of machining. The task is to develop an approach to creating technologies of effective high-velocity defect-free edge cutting and abrasive machining. This applies especially to the development of effective technologies of gear grinding and carbide tool grinding, where the acute problem of improving the quality and rate of machining due to the formation of temperature defects on machined surfaces is acute.

3. The aim and objectives of the study

The aim of the study is to identify conditions for reducing the power consumption of machining, cutting force and temperature in machining technology. This will provide an opportunity to improve the quality and rate of machining.

To achieve the aim, the following objectives were set:

– to develop a theoretical approach to calculating force and temperature parameters of edge cutting and abrasive machining processes, taking into account the provision of the minimum possible energy consumption of the cutting process;

– to theoretically determine conditions for reducing the cutting force and temperature and improving the quality and rate during grinding and edge cutting machining;

– to develop an approach to managing the quality and rate of edge cutting and abrasive machining to create technologies of effective high-velocity defect-free edge cutting and abrasive machining of machine parts and carbide cutting tools.

4. Calculation of force and temperature parameters of edge cutting and abrasive machining processes

It is shown in [11] that during turning under the condition of equal cutting work $A = P_z \cdot V \cdot \tau$ and amount of heat $Q = c \cdot m \cdot \theta$ released during the cutting process and completely passing into chips, cutting temperature θ is determined by the analytical relationship:

$$\theta = \frac{\sigma}{c \cdot \rho},\qquad(1)$$

where $P_z = \sigma \cdot S$ is the tangential component of the cutting force, N; σ is relative cutting stress, N/m²; S is the cross-sec-

tional area of the cut, m²; V is cutting speed, m/s; τ is machining time, s; c is the specific heat of the machined material, J/(kg·K); $m = \rho \cdot \upsilon$ is the weight of the removed material, kg; ρ is the density of the machined material, kg/m³; $\upsilon = S \cdot l$ is the volume of the removed material, m³; $l = V \cdot \tau$ is the length of the layer of the removed material, m.

It follows from (1) that cutting temperature θ is uniquely determined by the relative cutting stress σ. The smaller σ, the lower the cutting temperature θ. The relative cutting stress σ can be reduced by increasing the sharpness of the cutting tool edge and reducing the friction intensity in the cutting area.

It is experimentally found [12] that the relative cutting stress σ during machining always exceeds the compressive strength of the machined material σ_{cp}. This is because the relative cutting stress σ is determined by the relationship $\sigma = P_z / S$. In real conditions, instead of the cross-sectional area of the cut S, it is necessary to consider the actual area of contact between the resulting chips and the cutter face, which is larger than the cross-sectional area of the cut S. In this case, $\sigma \to \sigma_{cp}$.

It should be noted that the specific cutting work A_0 (corresponding to the power consumption of machining) is $A_0 = A/\upsilon = \sigma$. This shows that when cutting materials, the specific cutting work A_0 (power consumption of machining) is equal to the relative cutting stress σ. Therefore, the value of the specific cutting work A_0 (power consumption of machining) taking into account J=N·m takes the form of J/m³=N/m², which corresponds to the value of relative cutting stress σ. For physical-chemical methods of machining, power consumption should be considered in a general way, determined by the ratio of the work spent on removing a certain amount of material to the volume of this material, in J/m³.

In [12], the analytical relationship for determining the relative cutting stress is given:

$$\sigma = \frac{\sigma_{cp}}{K_{cut}} \cdot \left(1 + \sqrt{1 + K_{cut}^2}\right),\qquad(2)$$

where $K_{cut} = P_z / P_y$ is cutting factor; P_z, P_y are tangential and radial components of cutting force, N.

The nature of changes in the relationship σ/σ_{cp} described by (2) is shown in Table 1 and Fig. 1.

Table 1

Calculated values of the relationship σ/σ_{cp}

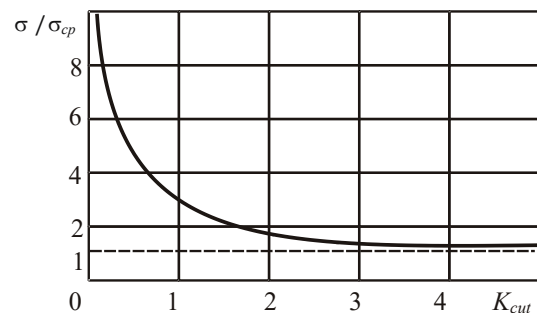| K_{cut}	0.1	0.5	1	2	3	4	8
σ/σ_{cp}	20	4.24	2.41	1.62	1.39	1.28	1.13

Fig. 1. Dependence of the relationship σ/σ_{cp} on the cutting factor K_{cut}

As can be seen, the greater the cutting factor K_{cut}, the smaller the relationship σ/σ_{cp} and, accordingly, the relative cutting stress σ. Under $K_{cut}\rightarrow\infty$, the relative cutting stress σ asymptotically approaches the ultimate compressive strength σ_{cp} of the machined material. Therefore, the main condition for reducing σ is an increase in the cutting factor K_{cut}, which is determined by the analytical relationship $K_{cut}=\mathrm{tg}2\beta$ [12], where β is the relative shear angle of the machined material.

With an increase in the angle β within 0...45°, the cutting factor $K_{cut}=\mathrm{tg}2\beta$ increases from zero to an infinite value, and the relationship σ/σ_{cp} – according to (2) – from infinity to unity.

If we substitute the expression for determining the cutting factor $K_{cut}=\mathrm{tg}2\beta$ into (2), then we have $\sigma/\sigma_{cp}=\mathrm{ctg}\beta$. Therefore, by increasing the relative shear angle β of the machined material, it is possible to reduce the relative cutting stress σ.

According to the known formula [12]:

$$\beta = 45° + \frac{\gamma - \psi}{2}, \qquad (3)$$

the angle β can be increased by increasing the positive rake angle γ of the tool and decreasing the relative angle of friction of the cutting tool with the machined material ψ (or the friction coefficient $f=\mathrm{tg}\psi$).

Edge tools are made with both positive and negative rake angles, while grinding wheel cutting grains always have a relative negative rake angle. Therefore, the relative shear angle of the machined material β during grinding is smaller than during turning, and the cutting factor $K_{cut}=\mathrm{tg}2\beta$, on the contrary, is larger during turning. So, based on the relationship (3), it is possible to achieve a reduction in the relative cutting stress σ during edge cutting machining. This is confirmed by the experimental data given in [12], according to which, the relative cutting stress σ during grinding is greater than during turning. An additional condition for increasing the relative cutting stress σ during grinding is also the presence of intense wheel bond friction with the machined material. Proceeding from this, the calculated cutting temperature θ, according to (1), during turning will take smaller values than during grinding. These cutting temperatures θ may be lower or higher than the melting point of the machined material.

It should be noted that, as determined by calculations [12], the chip thickness compression ratio $K_L=\sigma/\sigma_{cp}=\mathrm{ctg}\beta$ is directly proportional to the relative cutting stress σ and is determined by the angle β. Therefore, it is possible to reduce the chip thickness compression ratio K_L and, accordingly, the force of the cutting process by increasing the relative shear angle β of the machined material.

In [13], it is experimentally found that the contact temperature t_c (cutting temperature θ) during single grain micro-cutting with SHKH15 steel with an increase in cut thickness h_m increases to the value of 1500 °C (Fig. 2), i. e., to the temperature close to the melting point of SHKH15 steel.

The values of the cutting temperature θ calculated from (1) exceed this temperature. Thus, it is experimentally found that, with a cut thickness $h_m=10$ µm, the relative cutting stress is $\sigma=16\cdot10^3\,\mathrm{N/mm^2}$. Accordingly, the cutting temperature θ calculated according to (1) is 3200 °C. This discrepancy between the calculated and experimental values of cutting temperature is due to the fact that part of the heat released during micro-cutting is spent on heating both the chips (39 %) and the surface layer of the machined material (61 %). In this case, at a cutting temperature of $\theta=1500$ °C (approximately equal to the melting point of SHKH15 steel),

the relative cutting stress is $\sigma=6.25\cdot10^3\,\mathrm{N/mm^2}$. The rest of the relative cutting stress $\sigma=9.75\cdot10^3\,\mathrm{N/mm^2}$ determines the intensity of force impact on the surface layer of the machined material. As can be seen, less heat is consumed in the resulting chips than in the surface layer of the machined material [14–16].
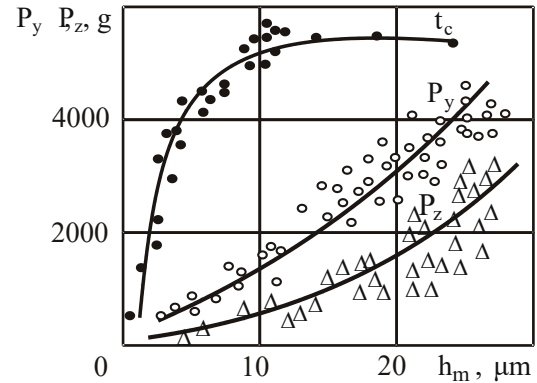

Fig. 2. Dependence of contact temperature t_c and cutting force components P_y, P_z (in grams) on cutting depth h_m during taper micro-cutting of SHKH15 crude steel at a speed of 27.5 m/s

During grinding, the fraction of heat going into the surface layer of the machined material is even greater (up to 80–90 %) than into the chips. This is due to the presence of an additional process of friction between the grinding wheel bond and the machined material. Therefore, it is necessary to reduce the intensity of the friction process during grinding by increasing the cutting capacity of the grinding wheel using effective wheel dressing methods, highly porous, impregnated and intermittent wheels [17–21]. A particularly significant positive grinding effect is achieved by using grinding wheels with intermittent working area. In this case, on the one hand, at the moment of interruption of the grinding process, partial cooling of the machined surface occurs and heating temperature decreases. On the other hand, as a result of the impact-cyclic interaction of the intermittent wheel with the workpiece and the occurrence of increased loads, intensive destruction of the working surface of the intermittent wheel occurs. Therefore, continuous dressing during grinding is performed, which increases the cutting capacity and reduces the cutting force and temperature. As a result, a decrease in cutting temperature during intermittent grinding occurs by two channels: due to periodic interruption of the grinding process and partial cooling of the machined surface and due to continuous restoration of the intermittent wheel cutting capacity during grinding.

In [18, 19], on the basis of experimental studies, it is found that during intermittent grinding, cutting force and temperature decrease, the life of the intermittent wheel increases and wear of the intermittent wheel increases. As a result, this creates favorable conditions for defect-free machining, especially when grinding products made of materials with enhanced physical and mechanical properties. Moreover, as it is found, in conditions of intermittent grinding, abrasive wheels of increased hardness are quite functional, which under normal grinding conditions quickly get blunt, greasy and lose cutting capacity.

The calculations revealed that up to 90 % of the heat generated during grinding goes into the workpiece, and the rest

actually goes into the chips. During turning, on the contrary, up to 90 % of the heat generated during cutting goes into the chips. On this basis, fundamentally different analytical relationships are obtained for determining the cutting temperature: during peripheral surface grinding:

$$\theta = \sigma \cdot \sqrt{\frac{t \cdot V_w}{c \cdot \rho \cdot \lambda} \cdot \sqrt{\frac{2 \cdot t}{R_{wh}}}}, \qquad (4)$$

where λ is the heat conductivity of the machined material, W/(m·K); t is grinding depth, m; V_w is workpiece speed, m/s; R_{wh} is wheel radius, m.

In the edge cutting machining, cutting temperature is determined by (1).

The calculations revealed that the second factor (square root) in (4) is always less than unity and takes values of 0.05...0.2. Therefore, the temperature of edge cutting should be about an order of magnitude higher than the grinding temperature because during grinding virtually all the heat generated due to the heat conductivity of the material goes into the workpiece. However, this does not actually happen. As practice shows, grinding temperature is always higher than edge cutting temperature. This regularity can be explained on the basis of the obtained relationship for determining the relative cutting stress:

$$\sigma = 2 \cdot \sigma_{cp} \cdot tg(\psi - \gamma). \qquad (5)$$

With respect to the edge cutting process, this relationship (5) contains the trigonometric function tg($\psi-\gamma$), and as applied to the grinding process – the trigonometric function tg($\psi+\gamma$). As shown above, this is because the grinding wheel cutting grains always have a relative negative rake angle. Therefore, during edge cutting, the relative cutting stress σ takes very small values, since $\gamma \to \psi$ and ($\psi-\gamma$)$\to$0, and during grinding, on the contrary, very large values, because ($\psi+\gamma$)$\to$90° and tg90°$\to\infty$. It follows that the grinding temperature calculated according to (4) will always be higher than the edge cutting temperature calculated according to (1). This is also facilitated by the intense friction of the wheel bond with the machined material. Therefore, the share of friction in the total power consumption of the grinding process can be many times greater than the share of the edge cutting process. As a result, significant grinding temperatures are formed that exceed the limit values and cause burns, microcracks and other temperature defects on machined surfaces. The main way to reduce temperature in this case is to ensure a high cutting capacity of the grinding wheel, which significantly reduces the friction intensity of the wheel bond with the machined material and, accordingly, the relative cutting stress σ.

Similar results are obtained on the basis of the design diagram proposed in [22] for determining thermal process parameters during grinding (Fig. 3).

Based on the above design diagram, the equation for determining the cutting temperature θ is determined:

$$\left(1 - \frac{\theta}{\theta_{max}}\right) \cdot e^{\frac{\theta}{\theta_{max}}} = e^{-\frac{c \cdot \rho \cdot V_{cut}^2}{\lambda} \tau}, \qquad (6)$$

taking into account the time $\tau = t/V_{cut}$ of contact of the grinding wheel with a fixed cross-section of the workpiece surface

(or with adiabatic rods, which conventionally present stock removal in the design diagram of the grinding process):

$$\left(1 - \frac{\theta}{\theta_{max}}\right) \cdot e^{\frac{\theta}{\theta_{max}}} = e^{-\frac{c \rho}{\lambda} Q_0 \cdot \sqrt{\frac{t}{2 \cdot R_{wh}}}}, \qquad (7)$$

where $V_{cut} = V_w \cdot (t/2 \cdot R_{wh})^{0.5}$ is the speed of heat source movement deep into the surface layer of the machined material at the moment of contact of the wheel with radius R_{wh} with the workpiece during surface grinding, m/s; $\theta_{max} = \sigma/(c \cdot \rho)$ is the maximum cutting temperature, degrees; $Q_0 = V_w \cdot t$ is specific machining rate, m²/s.
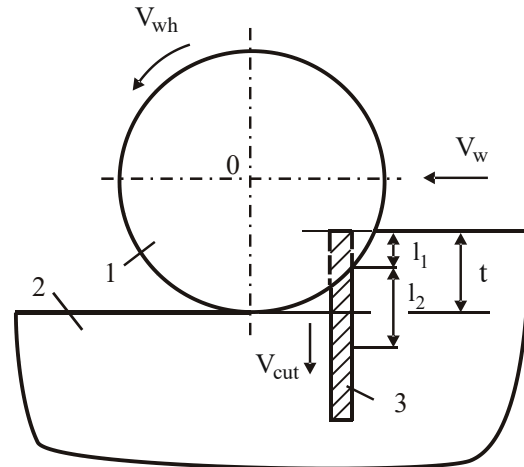

Fig. 3. Design diagram of cutting temperature during surface grinding, taking into account the wheel cutting of adiabatic rods, a set of which represents stock removal: 1 — grinding wheel; 2 — machined material; 3 — adiabatic rod (l_1 — length of the cut part of the adiabatic rod; l_2 — depth of heat penetration into the surface layer of the workpiece; V_{wh} — wheel speed)

5. Determination of conditions for cutting temperature reduction during grinding and edge cutting machining

Table 2 and Fig. 4 show the values of time τ calculated from (6) for the given values of the relationship θ/θ_{max} and initial data (when grinding SHKH15 steel): $V_{cut} = 3.33 \cdot 10^{-3}$ m/s; heat conductivity of SHKH15 steel – $\lambda/(c \cdot \rho) = 8.4 \cdot 10^{-6}$ m²/s.

From Fig. 4 it follows that over time τ, the relationship θ/θ_{max} continuously increases, asymptotically approaching unity. Table 2 and Fig. 5 show the values of t calculated from (7) for the given values of θ/θ_{max}, $Q_0 = V_w \cdot t$ and $R_{wh} = 0.2$ m when grinding SHKH15 steel – $\lambda/(c \cdot \rho) = 8.4 \cdot 10^{-6}$ m²/s.

According to Fig. 5, with an increase in grinding depth t, the relationship θ/θ_{max}, as in Fig. 4, increases, asymptotically approaching unity.

Moreover, the grinding depth t varies over quite wide limits, covering the ranges of both grinding processes (including high-velocity creep-feed grinding) and abrasive cutting of material with very large cutting depths.

It follows from (7) that with an increase in specific machining rate $Q_0 = V_w \cdot t$, the relationship θ/θ_{max} increases with greater intensity, covering a smaller range of possible changes in grinding depth t.

Table 2

Calculated values of thermal process parameters during grinding

| θ/θ_{max}	0	0.2	0.4	0.6	0.8	0.9	1
$e^{\theta/\theta_{max}}$	1	1.2214	1.4918	1.8221	2.2255	2.4596	2.7183
$\left(1-\dfrac{\theta}{\theta_{max}}\right)\cdot e^{\frac{\theta}{\theta_{max}}}$	1	0.9771	0.8951	0.7288	0.4451	0.24596	0
$\dfrac{c\cdot\rho\cdot V_{cut}^2}{\lambda}\cdot\tau$	0	0.02	0.11	0.32	0.81	1.4	∞
τ, s	0	0.0264	0.1452	0.4224	1.0692	1.848	∞
$Q_0=1{,}000$ mm²/min							
t, mm	0	0.0696	2.11	17.84	114.0	341.5	∞
V_w, m/min	∞	14.37	0.47	0.056	0.09	0.03	0
$Q_0=2{,}000$ mm²/min							
t, mm	0	0.0174	0.5275	4.46	28.5	85.375	∞
V_w, m/min	∞	115.0	3.8	0.45	0.07	0.023	0
$Q_0=4{,}000$ mm²/min							
t, mm	0	0.00435	0.1318	1.115	7.125	21.343	∞
V_w, m/min	∞	919.5	30.35	3.6	0.56	0.19	0
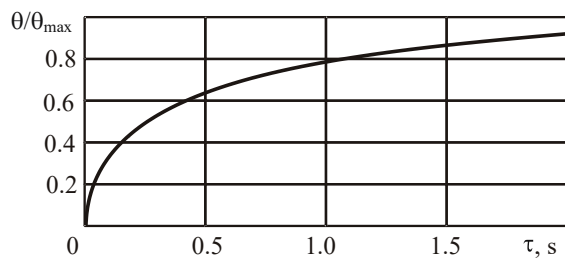
Fig. 4. Dependence of the relationship θ/θ_{max} on time τ
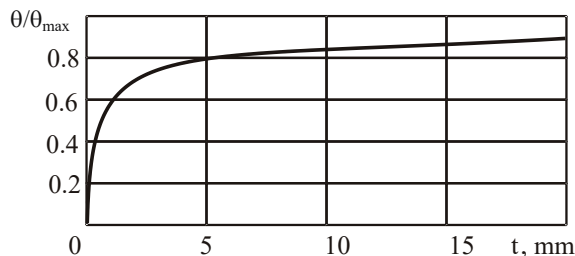

Fig. 5. Dependence of the relationship θ/θ_{max} on grinding depth t at $Q_0=4{,}000$ mm²/min

The workpiece speed V_w decreases significantly with increasing grinding depth t, which involves the use of the creep-feed grinding pattern. The multipass grinding pattern (with increased workpiece speed V_w) is feasible mainly with relatively small values of the relationship $\theta/\theta_{max}<(0.2...0.4)$ with a specific machining rate $Q_0=1{,}000$ mm²/min (Table 2). This actually explains the effectiveness of practical application of the multipass grinding pattern and limited application of the creep-feed grinding pattern (with low workpiece speed) due to an increase in grinding temperature θ. However, when grinding with $Q_0=2{,}000–4{,}000$ mm²/min, it is advisable to use creep-feed grinding, since the multipass grinding pattern is practically impossible because of the need to significantly increase the workpiece speed. As a result, machining rate can be increased up to 5 times compared to multipass grinding.

Thus, it is shown that over time τ of contact of the grinding wheel with the fixed cross-section of the workpiece surface (or with the adiabatic rod), the cutting temperature θ continuously increases, asymptotically approaching the maximum value $\theta_{max}=$ $=\sigma/(c\cdot\rho)$. From a physical point of view, this means that over time τ, the amount of heat generated during grinding and going into the workpiece decreases. Accordingly, the amount of heat going in the resulting chips increases, approaching the total amount of heat generated during grinding.

From (1) it follows that when the cutting temperature is close to the maximum value $\theta_{max}=\sigma/(c\cdot\rho)$, grinding parameters and machining rate can be increased infinitely. This opens up new technological possibilities for improving the efficiency of the grinding process. However, it is extremely difficult to put them into practice, since when grinding (as shown above), the calculated maximum cutting temperature $\theta_{max}=\sigma/(c\cdot\rho)$ takes values that exceed the melting point of the machined material.

Thus, using equation (1), it is possible to separately analytically determine the amount of heat going into the workpiece and the resulting chips. This is of great practical importance, since when calculating the cutting temperature, as a rule, the character of heat distribution is generally assumed on the basis of experimental data that are valid for specific machining conditions [11]. As a result, it is not possible to generally quantify the cutting temperature over a wide range of changes in cutting parameters, including edge cutting machining and grinding. For example, it is believed that in grinding virtually all the heat released goes into the workpiece, so the calculations do not take into account the heat going in the chips, and this reduces the reliability of the results.

During edge cutting, the equation (6) for determining the cutting temperature θ taking into account the relations $\tau=a/V_{cut}$ and $V_{cut}=V\cdot tg\beta$ takes the following form (Fig. 6) [22]:

$$\left(1-\frac{\theta}{\theta_{max}}\right)\cdot e^{\frac{\theta}{\theta_{max}}}=e^{-\frac{c\rho}{\lambda}a\cdot V\cdot tg\beta},\qquad(8)$$

where a is the thickness of cut, m; V is cutting speed, m/s; β is the conventional shear angle of the machined material.
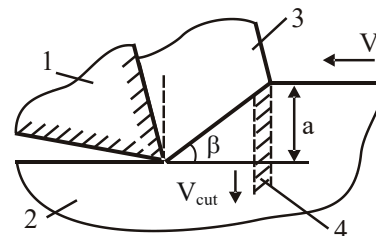

Fig. 6. Design diagram of the thermal process parameters during turning: 1 — cutter; 2 — machined material; 3 — forming chips; 4 — adiabatic rod

In this case, the nature of changes in cutting temperature θ is the same as in grinding. However, the maximum

value of the cutting temperature $\theta_{max}=\sigma/(c\cdot\rho)$ is lower than during grinding, owing to the lower value of the relative cutting stress σ.

The established laws governing changes in cutting temperature during edge cutting machining and grinding are confirmed by experimental data [22], especially during turning where the calculated values of the maximum cutting temperature $\theta_{max}=\sigma/(c\cdot\rho)$ can be lower than the melting point of the machined material (steel).

As noted above, the calculated values of the maximum cutting temperature $\theta_{max}=\sigma/(c\cdot\rho)$ during grinding, as a rule, are higher than the melting point of the machined material. Therefore, the experimentally established values of cutting temperature θ approach the melting point of the machined material (steel), Fig. 2.

The theoretical solution obtained makes it possible, unlike the known analytical solutions, to determine the finite (rather than infinite) value of the depth of heat penetration into the surface layer of the workpiece l_2. It can be used to determine the thickness of the defective layer after machining:

$$l_2 = \sqrt{\frac{2\cdot\lambda\cdot\tau}{c\cdot\rho}}. \tag{9}$$

As follows from (9), the value l_2 is determined solely by the time of heat exposure τ on the fixed cross-section of the workpiece surface (or on the adiabatic rod, Fig. 6). The greater τ, the greater l_2. For the established thermal process (Fig. 4), i. e., when the condition $\theta_{max}=\sigma/(c\cdot\rho)$ holds, the value l_2 is described by the relationship:

$$l_2 = \frac{\lambda}{c\cdot\rho}\cdot\frac{1}{V_{cut}}. \tag{10}$$

In this case, the depth of heat penetration into the surface layer of the workpiece l_2 is determined by the speed V_{cut} of heat source movement deep into the surface layer of the machined material at the moment of wheel-workpiece contact. As can be seen, the higher this speed, the lower l_2. This can explain the efficiency of high-speed cutting, since the speed $V_{cut}=V\cdot tg\beta$ depends on the cutting speed V. The higher the cutting speed V, the higher the speed V_{cut}, the lower the depth of heat penetration into the surface layer of the workpiece l_2 and the higher the machining quality. In this case, virtually all the heat generated during cutting goes into the chips, and a small part of the heat goes into the workpiece. This creates favorable conditions for high-quality machining, eliminates the formation of burns, microcracks and other temperature defects on the machined surface, and also allows an actually unlimited increase in machining rate without increasing the cutting temperature.

6. Development of technologies of effective high-velocity defect-free grinding of machine parts and tools

The contact time τ of the grinding wheel with the workpiece and the corresponding value l_2 can be reduced by multipass grinding with an increased workpiece speed V_w (similar to high-speed edge cutting). This also allows reducing the relative cutting stress σ and cutting temperature θ, based on the equation (1).

Reducing the contact time τ of the intermittent grinding wheel face with the workpiece is an important condition for reducing the depth of heat penetration into the surface layer of the workpiece l_2 and improving the quality of machining, which is confirmed by experimental data [18, 19].

Taking $V_{cut}=t/\tau$ and $\tau=l/V_w$, the equation (6) is described:

$$\left(1-\frac{\theta}{\theta_{max}}\right)\cdot e^{\frac{\theta}{\theta_{max}}} = e^{-\frac{c\cdot\rho}{\lambda}\frac{t\cdot Q_0}{l}}, \tag{11}$$

where l is the wheel-workpiece contact length, m.

With an increase in cutting temperature θ, the calculated values:

$$\left(1-\frac{\theta}{\theta_{max}}\right)\cdot e^{\frac{\theta}{\theta_{max}}}$$

decrease (Table 2). Therefore, the cutting temperature θ can be reduced by increasing the right-hand side of the equation (11), i. e., by increasing the function $e^{-\frac{c\cdot\rho}{\lambda}\frac{t\cdot Q_0}{l}}$. This is achieved by reducing the grinding depth t, specific machining rate $Q_0=V_w\cdot t$ and increasing the wheel-workpiece contact length l. In this regard, it is advisable to use the wheel-face grinding pattern, in which the parameter l is greater than during peripheral grinding, and the cutting temperature θ, conversely, is lower.

In order to achieve the predetermined cutting temperature and ensure the maximum possible machining rate, based on the equation (11), it is necessary to reduce the grinding depth t and increase the workpiece speed V_w, i. e., use the multipass grinding pattern.

This, for example, can explain the effectiveness of gear grinding by the generating process, carried out with the wheel tapered on both sides and with the apex angle α (Fig. 7). In this case, the contact length of the grinding wheel with the workpiece l is increased and, accordingly, the cutting temperature θ is decreased. The relative radius of the taper part of the wheel R_{rel} is [23]:

$$R_{rel} = \frac{R_{wh}}{\sin\frac{\alpha}{2}}. \tag{12}$$

Since the angle $\alpha<90°$, the relative radius of the taper part of the wheel R_{rel} is greater than the wheel radius R_{wh}. This means that in double-disc grinding (compared to peripheral grinding), the length l and the number of cutting grains are greater. The cutting temperature θ in this case is determined by the relationship (7), considering the relative radius R_{rel} instead of the wheel radius R_{wh}. As can be seen, the larger R_{rel}, the lower the cutting temperature θ.

Based on the relationship (11), this means that with an increase in the wheel-workpiece contact length l, it is possible to simultaneously increase the grinding depth t and the specific machining rate $Q_0=V_w\cdot t$. Accordingly, it is possible to make the transition to the creep-feed grinding area and fast stock removal for one pass of the wheel. As a result, the time taken to reverse the grinding table is reduced, and machining rate is increased without compromising the quality of machined surfaces. And the use of highly porous abrasive wheels, which can significantly reduce the friction intensity in the grinding zone and the relative cutting stress σ, opens up wide prospects for reducing the cutting temperature θ and improving the quality and rate of machining.
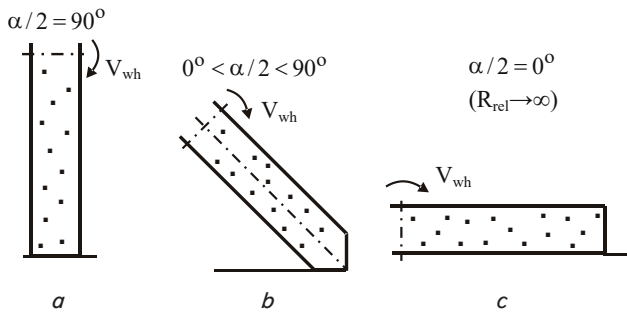
Fig. 7. Grinding patterns:
a — peripheral; *b* — double-disc; *c* — wheel-face

Based on the theoretical solutions obtained, an effective defect-free form grinding technology is developed. For its implementation, a modern HOFLER RAPID 1250 (Germany) gear grinding machine and a special highly porous form abrasive wheel (tapered on both sides and with the apex angle α) are used. Such a wheel has a high cutting capacity in conditions of high-velocity creep-feed grinding (Fig. 8) [22].
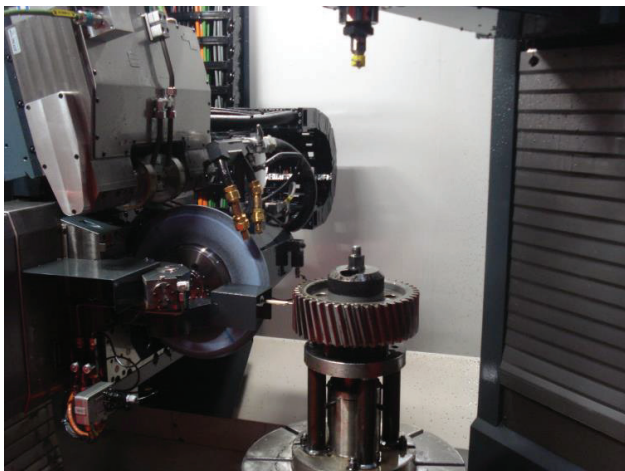

Fig. 8. Gear machining on the HOFLER RAPID 1250 gear grinding machine

Stock removal of 0.4 mm per side is performed in 4 passes of the grinding wheel with a relatively low speed of movement along the machined tooth, equal to 3 m/min and wheel speed of 40 m/s. Compared with traditional gear grinding by the generating process, carried out under conditions of multipass grinding and applied at the enterprise, this allowed increasing machining rate up to 5 times. As a result, the annual gear machining program is carried out on a single HOFLER RAPID 1250 gear grinding machine, which made it possible to free 4 gear grinding machines operating by the generating process. Moreover, the machined surfaces have no burns, microcracks and other temperature defects, which indicates a relatively low grinding temperature and high cutting capacity of the wheel in creep-feed grinding conditions. The increase in machining rate is also facilitated by a significant reduction in the auxiliary machining time due to a decrease in the number of wheel passes, which is extremely important for the gear grinding operation, characterized by high labor intensity [24–26].

The obtained theoretical solutions are used for high-velocity creep-feed external grinding of multipoint carbide cutting tools (milling cutters, reamers) with high-strength

metal-bonded diamond wheels. It is proposed to carry out grinding with a cutting depth $t=0.1...6$ mm, workpiece speed $V_w=0.5...3$ m/min and a longitudinal feed close to the wheel height. In order to ensure the high cutting capacity of the metal-bonded diamond wheel, electrical discharge dressing was periodically performed. As a result, it was possible to increase the machining rate to 20 thousand mm^3/min and higher and reduce the temperature of the grinding process – to prevent the formation of temperature defects on machined surfaces. At the same time, preliminary and final grinding was carried out in virtually one operation, ensuring high quality requirements of machined surfaces (Fig. 9).
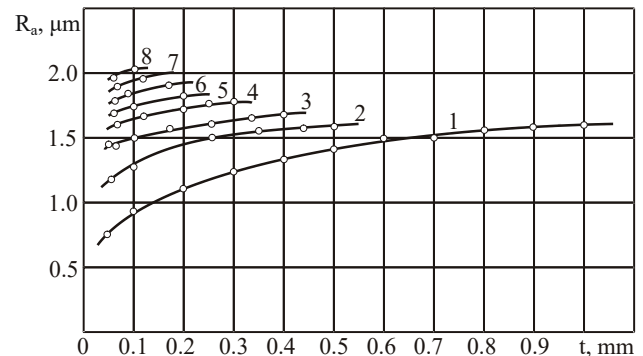

Fig. 9. Dependences of changes in the roughness parameter of the machined surface R_a during external grinding: 1A1 300×25 AS6 200/160 A1 4 M1-01 diamond wheel ($V_{wh}=35$ m/s; machined material — VK8 carbide): workpiece speed V_w: 1—6 respectively 1...6 m/min, 7 — 8 m/min, 8 — 10 m/min

As follows from Fig. 9, the use of high-velocity diamond creep-feed grinding of carbide tools ($V_w=1$ m/min) allows reducing the roughness parameter of the machined surface R_a compared to multipass grinding carried out with an increased workpiece speed ($V_w=10$ m/min).

Table 3 shows the results of experimental studies of the parameters of the crystalline substructure and stress state of the VK8 carbide surface layer after high-velocity diamond creep-feed grinding. The 1A1 300×25 AS6 200/160 A1 4 M1-01 diamond wheel was used. Wheel speed $V_{wh}=$ $=35$ m/s; longitudinal feed $S_0=22.5$ mm/rev. 3 % soda solution in water with 0.5 % NaNO$_3$ solution was used as a cutting fluid. Grinding was carried out with the specific machining rate $Q_0=500$ mm^2/min. This corresponded to the machining rate of $Q=11,250$ mm^3/min.

Table 3

Parameters of the crystalline substructure and stress state of the VK8 carbide surface layer after high-velocity diamond creep-feed grinding

V_w, m/min	t, mm	$\varepsilon=(\Delta d/\Delta x)\cdot10^4$	L_E, µm	$-(\sigma_1+\sigma_2)$, MPa
1.0	0.5	4	17.7	2.6
2.0	0.25	3	16.8	3.0
3.0	0.17	3	16.5	3.0
4.0	0.125	2	14.9	3.4
5.0	0.1	2	15.2	3.2
6.0	0.08	2	15.6	3.2
8.0	0.06	3	16.2	3.0
10.0	0.06	4	16.9	2.8

The main quality criteria of machining are the following parameters: $(\sigma_1+\sigma_2)$ – the sum of principal macrostresses, MPa; L_E – the size of coherent scattering regions, nm. Measurement of the quality parameters was carried out according to the known methods.

As follows from Table 3, regardless of the combination of grinding parameters V_w and t, the sum of principal macrostresses $(\sigma_1+\sigma_2)$ is always negative. This indicates that during high-velocity diamond creep-feed grinding of VK8 carbide, the influence of the thermal factor is insignificant, i. e., the force factor prevails, which does not cause defects in the VK8 carbide surface layer. Therefore, the use of diamond creep-feed grinding of carbide tools allows, along with the rate increase, achieving high-quality defect-free machining.

7. Discussion of the results of studying conditions for improving the quality and rate of machining

The analytical relationships obtained as a result of the studies for determining the force and temperature parameters of edge cutting and abrasive machining processes made it possible to justify the conditions for reducing the cutting force and temperature. They consist mainly in reducing the power consumption of machining by increasing the relative shear angle of the machined material by reducing the friction intensity in the cutting zone. It is found that cutting temperature with increasing machining rate continuously increases in accordance with the relationship (7), asymptotically approaching the maximum value determined by the relationship (1). Consequently, it becomes possible to increase machining rate virtually without increasing the cutting temperature, i. e., without compromising the quality of the machined surface. This opens up new opportunities for the intensification of machining processes. It is found that in this case, the heat generated during cutting goes mainly into the resulting chips. A small part of the heat goes into the surface layer of the workpiece, which ensures an increase in machining quality. This condition can be realized with edge cutting machining, characterized by relatively small values of power consumption and maximum cutting temperature, determined by the relationship (1).

During grinding, the power consumption of machining takes sufficiently large values due to intense friction of the grinding wheel bond with the machined material. As a result, the maximum cutting temperature exceeds the melting point of the machined material. Most of the heat goes into the surface layer of the workpiece, which can lead to temperature defects on the machined surface. According to the relationship (11), to reduce cutting temperature in this case, it is necessary to use the patterns of multipass wheel-face and double-disc grinding.

It is found that in creep-feed grinding, cutting temperature is higher than in multipass grinding. However, in high-velocity grinding, for example, with a specific machining rate of 2,000–4,000 mm^2/min, based on Table 2, the multipass grinding pattern is virtually impracticable due to the need to significantly increase the workpiece speed. Therefore, it is advisable to use high-velocity creep-feed grinding with a relatively low speed of the workpiece. The increase in cutting temperature in this case should be compensated by a decrease in the power consumption of machining due to the use of highly porous wheels having high cutting capacity. In addition, an increase in machining rate during creep-feed grinding is also achieved by reducing the time taken to reverse the grinding table. As a result, the rate of creep-feed grinding can be increased up to 5 times in comparison with multipass grinding (Table 2).

On this basis, a highly efficient technology of form grinding using a special highly porous form abrasive wheel is developed. The technology of high-velocity creep-feed external grinding of multipoint carbide tools with high-strength metal-bonded diamond wheels using the electrical discharge dressing method is also developed.

It should be noted that the theoretical solutions obtained are valid for a wide range of grinding depth changes. Having the set value θ/θ_{max} (Table 2), by calculation it is possible to determine the optimal values of grinding depth and workpiece speed for various machining conditions, which are very difficult to find experimentally. This is especially true for significant stock removal (more than 1 mm) during grinding, when it is necessary to combine preliminary and finishing machining in one grinding operation and to ensure high quality and rate. The solution to this problem is of great scientific and practical importance, for example, in the machining of complex parts, carried out solely by grinding methods. However, based on Table 2, the specific machining rate cannot exceed 4,000 mm^2/min, since it is difficult to realize the required workpiece speed on a grinding machine under conditions of both multipass and creep-feed grinding. This is the main limitation of the practical application of the proposed solutions.

The development of this study may consist in further improvement of various technologies of finishing edge cutting and abrasive machining of machine parts and tools in order to improve the quality and rate of machining.

8. Conclusions

1. The theoretical approach to calculating the force and temperature parameters of machining, which allows a scientifically sound approach to managing the quality and rate of machining is developed. Its peculiarity is the ability to determine the conditions for reducing the cutting force and temperature during edge cutting and abrasive machining by the criterion of minimum power consumption. It is shown that by reducing the maximum cutting temperature below the melting point of the machined material, it is possible to increase machining rate virtually without increasing the cutting temperature. This is quite feasible in edge cutting machining, characterized by relatively low power consumption. During grinding, it is almost impossible to realize this condition due to increased power consumption of machining. Therefore, it is advisable to use creep-feed grinding with a relatively low speed of the workpiece, which provides a predetermined cutting temperature and up to 5 times higher rate compared with multipass grinding. At the same time, wheel-face and double-disc machining is effective.

2. The theoretical solutions obtained made it possible to determine the optimal values of grinding depth and workpiece speed during form grinding using a special highly porous form abrasive wheel tapered on both sides. This made it possible to reliably prevent burns on machined surfaces and increase the rate up to 5 times compared to gear grinding by the generating process.

3. The technology of high-velocity creep-feed external grinding of multipoint carbide cutting tools with high-strength metal-bonded diamond wheels using the electrical discharge dressing method is developed. This made it possible to increase the rate by 2–3 times and ensure high-quality,

defect-free machining, and replace the inefficient multipass grinding technology with conventional abrasive wheels. In this case, the surface roughness parameter R_a assumes values of 1.0–1.5 mm, which are smaller than in multipass grinding, and compressive stresses are formed in the surface layer, which increase the quality of machining.

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