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THERMAL STUDY OF THE CREEP-FEED GRINDING – A REVIEW

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Abstract: *Creep-feed grinding is an advanced machining process widely used in the manufacturing industry of complex engineering parts and components. The research and application show that the creep-feed grinding process is an excellent choice for productive material removal with quality surface finish. However, due to a large contact line length and contact time between grinding particles and workpiece material, a large quantity of thermal energy develops in the creep-feed grinding within a relatively narrow cutting zone. The generated thermal energy leads to high cutting temperatures which result in various physical and chemical properties of tool and workpiece. Based on the theoretical investigations, an analytical dependence was established between the parameters of thermal energy and creep-feed grinding performance. In addition, the values of thermal energy and cutting temperatures were experimentally investigated for different machining conditions. The results obtained represent a knowledge base for the selection of optimal parameters in the creep-feed grinding process.*

Key words: *Advanced grinding process, thermal energy, heat flux, cutting temperature, grinding performance.*

Toplotna studija dubokog brušenja - pregled. *Duboko brušenje je napredni proces obrade koji se široko koristi u proizvodnoj industriji složenih inženjerskih delova i komponenti. Istraživanje i primena pokazuju da je postupak dubokog brušenja odličan izbor za produktivno uklanjanje materijala uz kvalitetnu površinsku obradu. Međutim, zbog velike dužine i vremena kontakta između abrazivnih čestica i materijala obratka, kod dubokog brušenja razvija se velika količina toplotne energije unutar relativno uske zone rezanja. Generisana toplotna energija dovodi do visokih temperatura rezanja što dovodi do različitih fizičkih i hemijskih promena na alatu i obratku. Na osnovu teorijskih istraživanja utvrđena je analitička zavisnost između parametara toplotne energije i performansi dubokog brušenja. Pored toga, eksperimentalno su ispitivane vrednosti toplotne energije i temperature rezanja za različite uslove obrade. Dobijeni rezultati predstavljaju bazu znanja za izbor optimalnih parametara procesa dubokog brušenja.*

Ključne reči: *Napredno brušenje, toplotna energija, toplotni fluks, temperatura rezanja, performanse brušenja.*

1. INTRODUCTION

The industrial manufacturing sector is facing a number of global challenges on an everyday basis. Productivity, quality, flexibility, reliability, adaptability, responsiveness and sustainability are the most important market requirements of product oriented manufacturing systems. Due to rapidly growing trends in deploying advanced materials, components and products, only contemporary industrial systems will be able to adjust their manufacturing process to all the complex demands and challenges [1-4].

Because of the above, along with the development of new products and services, manufacturing industrial concept implies improvement of existing production technologies and development of new applications and solutions. In this context, there can be no doubt production technologies, especially material removal processes will remain important in the modern manufacturing industries. The main advantages of material removal processes are high quality and cost effective with the ability to cope with different materials and geometrical configurations of engineering products [5-13].

Grinding process is considered one of the most important machining processes in the manufacturing industry. It is estimated that grinding accounts for about 20% of all the machining processes in general [14]. The grinding process is usually one of the last steps in the machining operations chain. Advantages of grinding as a manufacturing process include good dimensional tolerances and superior surface finish [15]. In this context, grinding application in finishing operations, but as well as for the difficult-to-machine materials, makes it a very important process. Basic operations of grinding are surface grinding, cylindrical grinding and form grinding, Fig. 1.

The grinding processes can be broadly classified into two categories based on machining characteristics, namely, conventional grinding technologies and high-performance grinding technologies, Fig. 2. The emphasis in conventional grinding is the finish, respectively accuracy and surface integrity, while in high-performance grinding the emphasis is on the generation of the required form and material removal rate [16]. The conventional grinding uses high workpiece speeds and very small depth of cut. The concept with high-performance grinding is to accelerate the cutting speed (high-speed grinding) or/and to slow the workpiece speed to allow to increase the depth of cut (creep-feed grinding). These grinding methods are used in order to increase the low productivity which has been considered the main drawback of the conventional grinding operations. However, the high-performance grinding conditions considerably change the kinematics and thermal aspects of the cutting process [17,18].

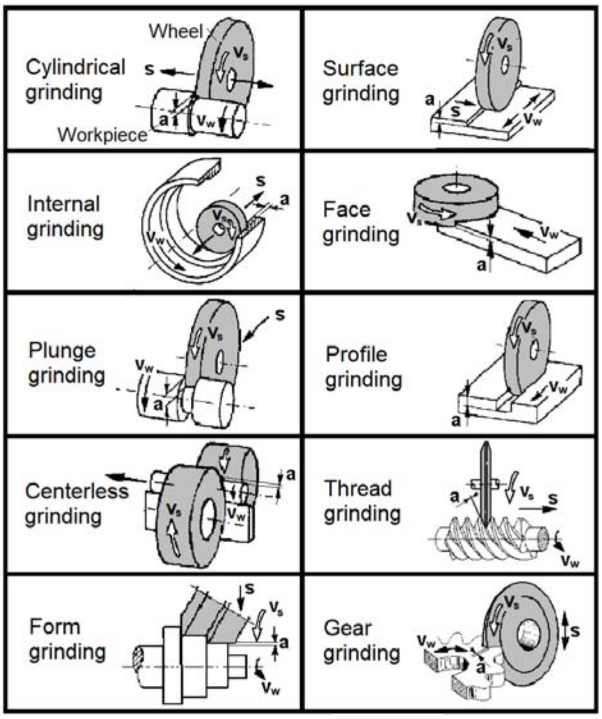

Fig. 1. Basic types of grinding operations

High-speed grinding develops about the same productivity as creep-feed grinding. Thereby, high-speed grinding is characterized by small cross-section of chip and short time of the workpiece and abrasive grains contact, but with a more intense friction in the cutting zone. Unlike high-speed grinding, creep-feed grinding has very long contact between the wheel and workpiece, which leads to especially intense friction. This increased contribution of the friction leads to a more intense development of thermal energy in the grinding zone [19]. The strong thermal effect, primarily in the surface layer of the workpiece material, represents the basic limitation for further development of high-performance grinding. For that reason, in the high-performance grinding the attention is focused on the control of the thermal effects of machining [20].

In the present work, the object of research is thermal aspect of the creep-feed grinding process. Since the main task of the creep-feed grinding is to achieve the required machining quality with high productivity, special attention is directed on the effect of thermal energy produced by cutting. If the cutting conditions are poorly chosen, the thermal and temperature efficiency can substantially diminish exploitation features of the creep-feed grinding process. Therefore, in order to enable highly productive machining of the parts with a good surface quality, it is necessary to investigate the thermal properties of the creep-feed grinding.

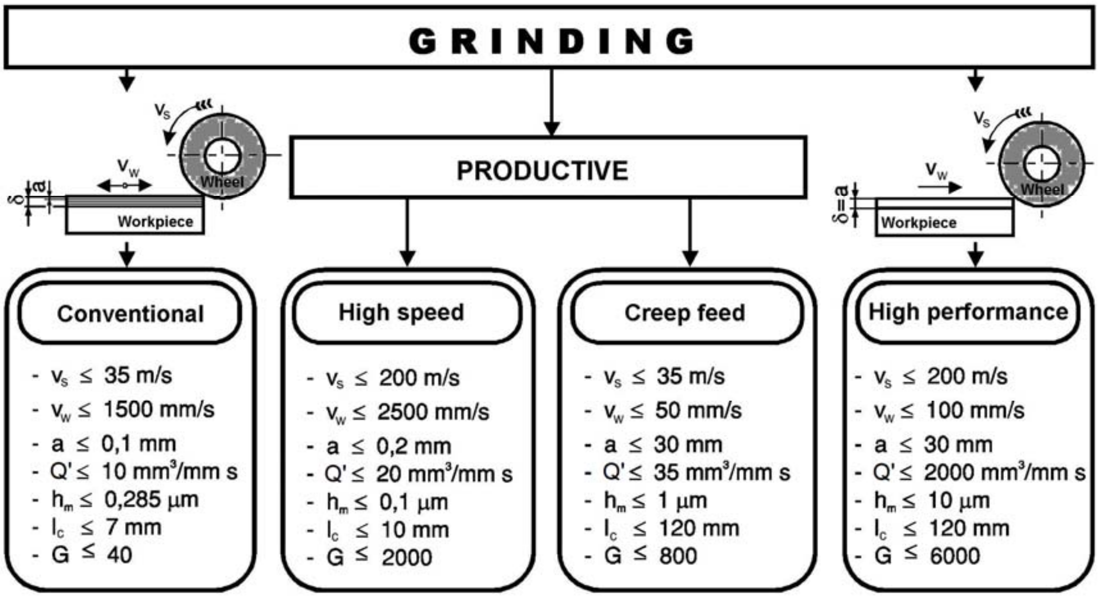

Fig. 2. Classification of grinding processes based on machining characteristics

2. BASICS OF CREEP-FEED GRINDING

The creep-feed grinding is an accurate, highly productive and cost-effective process of the machining complex shapes in a wide variety of challenging materials. Of course, it is primarily final surface grinding operation which is used for over fifty years.

Compared to a conventional process, the creep-feed grinding employs a large depth of cut combined with a slow traverse rate, which allows machining in a single pass for shorter cycle time. In this context, it replaces milling, broaching or other types of cutting, especially when processing hard materials. Besides, the creep-feed grinding is characterized by a reduced machine wear, longer wheel life, fine tolerance and good surface roughness. However, a prolonged contact arc length and time of contact between the wheel and workpiece, result in possible metallurgical alterations of the surface layer of the workpiece material due to high thermal energy in the cutting zone [19].

2.1 Machining mechanism

The creep-feed grinding process, as already stated above, differs from the multi-pass conventional grinding. During the creep-feed grinding, slow (creep) traverse feed rate and very large depth of cut is used. For that matter, the mechanism of cutting process in creep-feed grinding is realized through a large number of abrasive grains that catch a very deep surface layer of the workpiece material that is inserted in the space between the abrasive grains and in the pores of the grinding wheel, Fig.3. When the abrasive grains come out of the workpiece material, grinding chips leave the pores under the influence of centrifugal force and cooling medium [21].

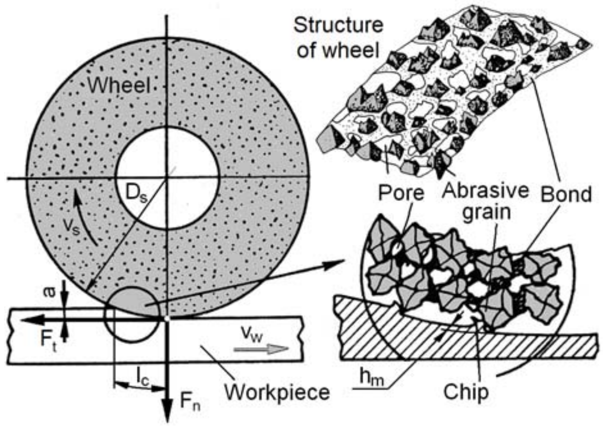

Fig. 3. Mechanism of creep-feed grinding

2.2 Grinding parameters definitions

The creep-feed grinding process itself is defined by the kinematic and geometric parameters [17]. The basic kinematic parameters are: wheel cutting speed v_s and workpiece feed rate v_w, i.e. grinding speed ratio q_s. The geometrical parameters are: wheel diameter D_s, depth of cut a, length of contact l_c and average chip thickness h_m.

The length of contact in surface creep-feed grinding is active distance that abrasive grain exceeds from the moment of contact with the material workpiece until exit from a contact:

$$l_c = \sqrt{a \cdot D_s} \tag{1}$$

The average chip thickness is the approximate thickness cut with abrasive grains, and determined by:

$$h_m = \frac{a \cdot v_w}{v_s} = \frac{a}{q_s} = \frac{Q'_w}{v_s} \tag{2}$$

In the previous equation (2) is observed grinding **s**peed ratio, which shows how often an abrasive grain passes over the same place on the workpiece:

$$q_s = \frac{v_s}{v_w} \tag{3}$$

and specific material removal rate, which defined as the volume of material removed per unit of time in relative to the contact width of the grinding wheel:

$$Q'_w = a \cdot v_w \tag{4}$$

For evaluating tool life of the grinding wheel the G-factor is used. It is relationship volume of workpiece material removed V_w and volume of material removed from the wheel by wear V_s, respectively:

$$G = \frac{V_w}{V_s} \tag{5}$$

2.3 Mechanic of grinding

Mechanic of grinding includes dynamic machining process. Compared to single-point cutting tools, grinding processes have an undefined number of cutting points with an infinite number of orientations, making these operations much more complex.

In the processing by grinding, as a result of plastic deformation in the cutting zone and friction between the abrasive grains and workpiece material, occurs cutting force. The resulting cutting force on the grinding wheel was created at the same time by the number of active abrasive grains that are penetrating into the workpiece material. The size and character of the grinding force depends on the machining conditions, characteristics of the grinding wheel, properties of the workpiece material, stiffness of the machining system, effect of the cooling conditions, the entire process of dressing a wheel etc.

For practical reasons, the resulting grinding force is split into components in several interesting directions [22]. In the case of surface creep-feed grinding, where there is no lateral movement of the machine table, the resulting force has been divided on tangential component F_t and normal component F_n. The tangential grinding force acts in the direction of the tangent to the surface of the grinding wheel and workpiece, i.e. in the direction of the cutting speed. The normal grinding force acts normally to the contact surface of the wheel and workpiece. As the diameter of the grinding wheel is far greater than the depth of cut, it can be assumed that the tangential and normal grinding force supine in a horizontal and vertical plane, Fig. 3.

The relationship of the normal and tangential grinding force is defined as the grinding force ratio:

$$\lambda = \frac{F_n}{F_t} = \frac{F'_n}{F'_t} \tag{6}$$

where the components of the grinding force are reduced per unit width of grinding b, as a matter of the fact specific grinding force (*F'=F/b*).

The tangential grinding force is authoritative for determining the power of machine tool, while the normal grinding force is significant from the point of processing accuracy and surface quality. These components of the grinding forces are determined by measurement and calculation.

One well-known empirical equation for determining tangential grinding force by Kronenberg, reads as follows [1]:

$$F'_t = h_m \cdot k_c \tag{7}$$

where k_c is the specific cutting resistance.

On the basis of the grinding force can be expressed specific grinding energy, which defines how much energy is consumed per unit volume of the material removed:

$$u = \frac{P'}{Q'_w} = \frac{F'_t \cdot v_s}{a \cdot v_w} = \frac{F'_t}{h_m} \quad (8)$$

where is the $P'=F_t'\cdot v_s$ specific grinding power.

3. MATHEMATICAL ANALYSIS OF THERMAL ENERGY IN CREEP-FEED GRINDING

In the creep-feed grinding, due to intensive friction between the abrasive grains and the workpiece material, a substantial quantity of thermal energy is released during machining. Namely, because of large depth of cut and slow workpiece feed rate, there is a longer contact of the grinding wheel with the workpiece and this results in the generation of high heat with a prolonged time of her effect. However, on the other hand, a longer contact contributes to better distribution of the heat from the grinding zone, which results in the decreased thermal energy per unit area [23-26].

Efficient determination of the thermal aspects during the creep-feed grinding largely depends on the knowledge of fundamental principles of the generation and distribution of heat and the character of the temperature field within the grinding zone. The identification of thermal effects in the creep-feed grinding process based on mathematical and experimental methods is gaining popularity in the current research.

3.1 Analytical approach

The amount of thermal energy which is generated in the grinding process is equivalent to mechanical work which is spent on executing the process of cutting. Thereby, almost all of the mechanical work is transformed through deformation, friction and separation into heat, Fig. 4. The heat which is generated this way is evacuated from the grinding zone through the grinding wheel, workpiece material, chip, coolant and environment. Generally, the heat is transferred by conduction, convection and radiation [27,28].

The largest part of the generated heat should be distributed through the grinding chip and coolant. On the other hand, the use of inadequate parameters of the creep-feed grinding can lead to development of large amount of the heat which would be distributed through the workpiece and causes the undesirable effects in the surface layer of the workpiece material.

The thermal energy of the creep-feed grinding zone can be defined by heat sources and heat sinks. The generated thermal energy depends on the intensity and duration of the heat sources, while the distribution of thermal energy depends on the heat sinks performance.

The heat source intensity in the grinding zone is the basic source parameter of thermal energy. The heat source intensity is most often expressed by means of heat flux density q, i.e. relationships the amount of heat transferred across a unit area placed S, in a unit amount of time t, that is:

$$q = \frac{Q}{\int dS \int dt} \cong \frac{Q}{S \cdot t} \quad (9)$$

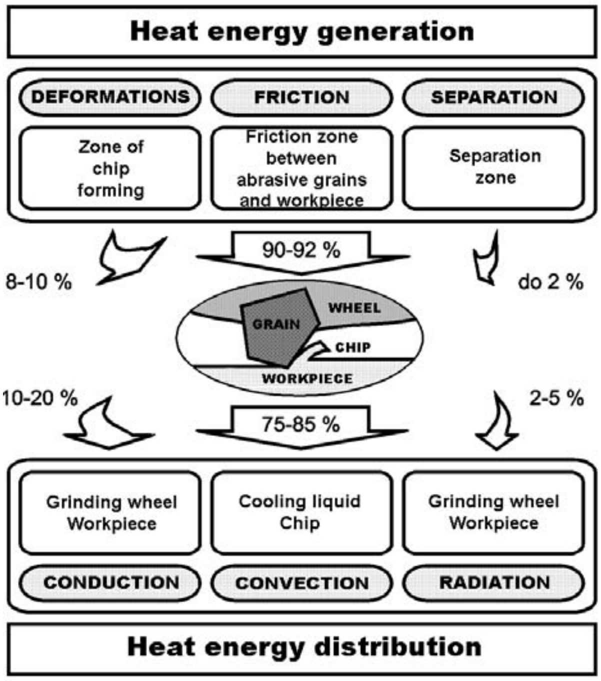

Fig. 4. Balance of heat flows in the grinding

An analytical definition of the heat source intensity considers the fact mentioned that in the grinding, whole mechanical work transforms into heat energy:

$$Q = F_t \cdot v_s \cdot t \quad (10)$$

Substituting Eq. (10) into Eq. (9), an expression for heat flux density is found:

$$q = \frac{F_t \cdot v_s}{S} \quad (11)$$

If, in Eq. (11), the contact between the grinding wheel and workpiece is $S=l_c\cdot b_c=(a\cdot D_s)^{1/2}\cdot b_c$, and the tangential grinding force is reduced per a unit width of grinding ($F_t=F'_t\cdot b_c$), then is:

$$q = \frac{F'_t \cdot v_s}{\sqrt{a \cdot D_s}} \quad (12)$$

By substituting Eqs. (7) and (2) in Eq. (12), the final expression for the heat flux density as a function of the grinding conditions is:

$$q = k_c \cdot v_w \sqrt{\frac{a}{D_s}} \quad (13)$$

On the other hand, duration of heat source has a prominent influence on the thermal energy being evacuated from the grinding zone into the workpiece material. The duration of heat source is expressed as the ratio between the length of contact l_c and workpiece feed rate v_w, that is:

$$t = \frac{\sqrt{a \cdot D_s}}{v_w} \quad (14)$$

Considering the output performance of the creep-feed grinding, the quantity of thermal energy evacuated through workpiece material is of the most importance. The ratio of the heat reaches in workpiece q_w and the amount of the total thermal energy q is determined by energy partition, which is expressed by the following equation:

$$R_q = \frac{q_w}{q} \tag{15}$$

In all past researches, as a foundation for analytical determination of the energy partition, simple heat model of tribological contact according to Jaeger is used [29].

One of the most detailed ways for determining the energy partition has the following form [30,31]:

$$R_q = \frac{1}{1+\sqrt{\frac{(k\rho c)_c \cdot v_c}{(k\rho c)_w \cdot v_w}}} \tag{16}$$

where is the $k\rho c$ thermal and physical material properties of the grinding wheel and workpiece (k is the heat conductivity, ρ is the material density, c is the specific heat capacity).

The generation of a large quantities of thermal energy, located within the general area of the cutting zone, causes extremely high cutting temperature in creep-feed grinding. This high cutting temperature instantly reaches a maximum value, has a short duration of action and a pronounced negative effect on grinding wheel wear, machining accuracy and workpiece surface quality.

As for the analytical approach, the Green's function method for a point heat source is generally accepted as the fundamental for determination of the temperature [29]. If assumed that an ideally isolated heat source is used, in case of maximum cutting temperature there follows the final expression:

$$T_{\max} = \frac{2}{\sqrt{\pi}} q \sqrt{\frac{l_c}{(k\rho c)_w \cdot v_w}} \tag{17}$$

3.2 Numerical analysis

As previous research has shown, complex, non-stationary and non-linear systems that involve highly intensive heat transfer can be reliably solved using an inverse problem of heat source [32-34]. In the case of creep-feed grinding process, the inverse heat transfer problem is practically the only way to reliably determine the heat flux distribution and the cutting temperature. Namely, for the measured temperature within the surface layer of the workpiece material, applying the inverse numerical method is estimated the temperature field as well as the heat flux density in the grinding zone.

The role of numerical methods for solving energy problems in creep-feed grinding process is to adopt the adequate thermal model, Fig. 5. It can be assumed that the elementary heat source of the micro cutting of the grinding grain is a result of deformation and friction at the contact surface. Summarizing the heat sources of all the grinding grains, gives the total heat source in the grinding zone. This heat source acts continuously, and shifting across the workpiece surface with feed rate. Thereby, considering that the depth of cut is many times smaller than the length and width of the grinding contact, and that the heat source is produced within a small volume of material, the heat source can be treated as an isolated, with exponential heat distribution [35-37].

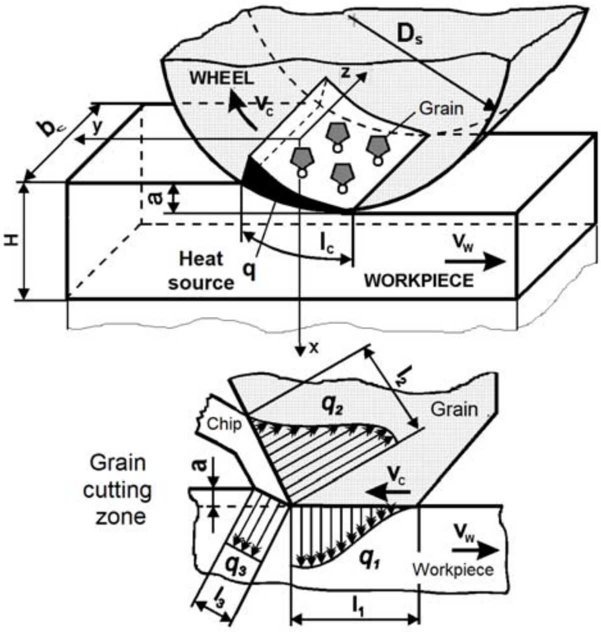

Fig. 5. Thermal model of creep-feed grinding

Using the defined thermal model of creep-feed grinding is following general three-dimensional heat conduction equation:

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+v_w\frac{\partial T}{\partial y} \tag{18}$$

with the initial temperature distribution:

$$T(x,y,z,t)\big|_{t=0} = T_0 \tag{19}$$

under the additional condition, measured temperature:

$$T(x,y,z,t)\big|_{\substack{x=H\\y=0\\z=0}} = T_m \tag{20}$$

and the heat flux boundary conditions:

$$\begin{gathered} -k\frac{\partial T(x,y,z,t)}{\partial x}\bigg|_{\substack{x=0\\y\le l_c/2\\z\le b_c/2}} = q_w(t) \\ -k\frac{\partial T}{\partial x}\bigg|_{x=\infty} = 0;\ -k\frac{\partial T}{\partial y}\bigg|_{y=\infty} = 0;\ -k\frac{\partial T}{\partial z}\bigg|_{z=\infty} = 0 \end{gathered} \tag{21}$$

where T is the temperature, α is the thermal diffusivity and H ($0<H\le\infty$) is the certain point on the workpiece.

By solving Eqs. (18-21) of the inverse heat transfer problem, the unknown heat flux boundary condition on the surface of the workpiece material and the cutting temperature is determined.

The partial differential Eq. (18) is mostly solved using the two numerical methods: finite differences method and finite element method.

The concept of finite differences method resembles the physical basis of the process, where the temperature at a certain point is calculated as the result of heat exchange with the adjacent points. If the explicit finite differences method is selected, based on the three known temperatures at the adjacent points, the close temperature and heat flux condition at the next moment in time is calculated, through the following expression [32]:

$$\{T\}^{t+\Delta t} = [\boldsymbol{\alpha}]\cdot\{T\}^{t} + \{q\} \tag{22}$$

where {T} is the temperature vector, [α] is the thermal diffusivity matrix and {q} is the heat flux vector.

The finite element method is based on variational principles, where is the method of integrating a differential equation to replace by the minimum value of integral [38]. There are more methods that are applied for solving the unknown temperatures and heat flux at the next time. Galerkin's method that is used to solve differential equation of heat conduction can be expressed in matrix form as:

$$[\mathbf{k}]\cdot\{T\}^{t} + [\mathbf{c}]\frac{\partial\{T\}^{t-\Delta t}}{\partial t} = \{q\} \tag{23}$$

where [**k**] is the heat conductivity matrix and [**c**] is the specific heat matrix.

4. EXPERIMENTAL INVESTIGATION OF THERMAL EFFECTS IN CREEP-FEED GRINDING

Based on the mathematical discussion, it is evident that in creep-feed grinding a substantial quantity of thermal energy is generated. Since the main task of the creep-feed grinding is to achieve the good machining quality with as much productivity as possible, special attention is focused on the effect of thermal energy and thus a temperature, on the exploitation characteristics of the products. Thereby, the identification of thermal aspects in the creep-feed grinding is most easily determined by the experimental investigation of the character of the temperature field in the cutting zone.

4.1 Experimental setup

The experimental investigations were conducted on the 3-axis creep-feed grinding machine type CF 412 CNC, manufactured by Majevica from Republic of Serbia. Water-based coolant (emulsion 6 %) was used during the creep-feed grinding test with a flow rate of 175 l/min.

The high porosity grinding wheels were selected: Norton grinding wheel type 32A54 FV BEP, dimensions 400×80×127 mm, respectively Winterthur grinding wheel type 53A80 F15V PMF, dimensions 400×50×127 mm. The wheels are with high quality aluminium oxide abrasive grain, medium grain size, wheel hardness soft, open structure wheel, and made of ceramic binder. All of the experiments were conducted with sharp abrasive grains, and dressing is done with a diamond tool with a depth of dressing cut 0.01 mm and dressing feed rate 0.1 mm/rev.

The workpiece material used in the experiments was the high speed tool steel (HSS). Designation of the selected steel is DIN S 2-10-1-8 (W. Nr. 1.3247). The surface hardness on samples was the range 66±1 HRC. Experimental specimens consisted of tiles whose dimensions were 40×20×16 mm.

The machining conditions were the depth of cut and the workpiece feed rate at a constant specific material removal rate Q_w'=2.5 mm^3/mm s. The range of the depth of cut was a=0.05 to 1 mm, while the workpiece feed rate was chosen from the interval v_w=2.5 to 50 mm/s. The grinding wheel cutting speed was constant at v_c=30 m/s.

The cutting temperature was measured in the surface layer of the workpiece material using a type K thermocouple, ø0.2 mm diameter wire. The thermocouple was built into the workpiece at a variable clearance from the grinding wheel-workpiece interface. Measuring, monitoring and control of the temperature during the process of creep-feed grinding were performed with the help of an information system, Fig. 6.

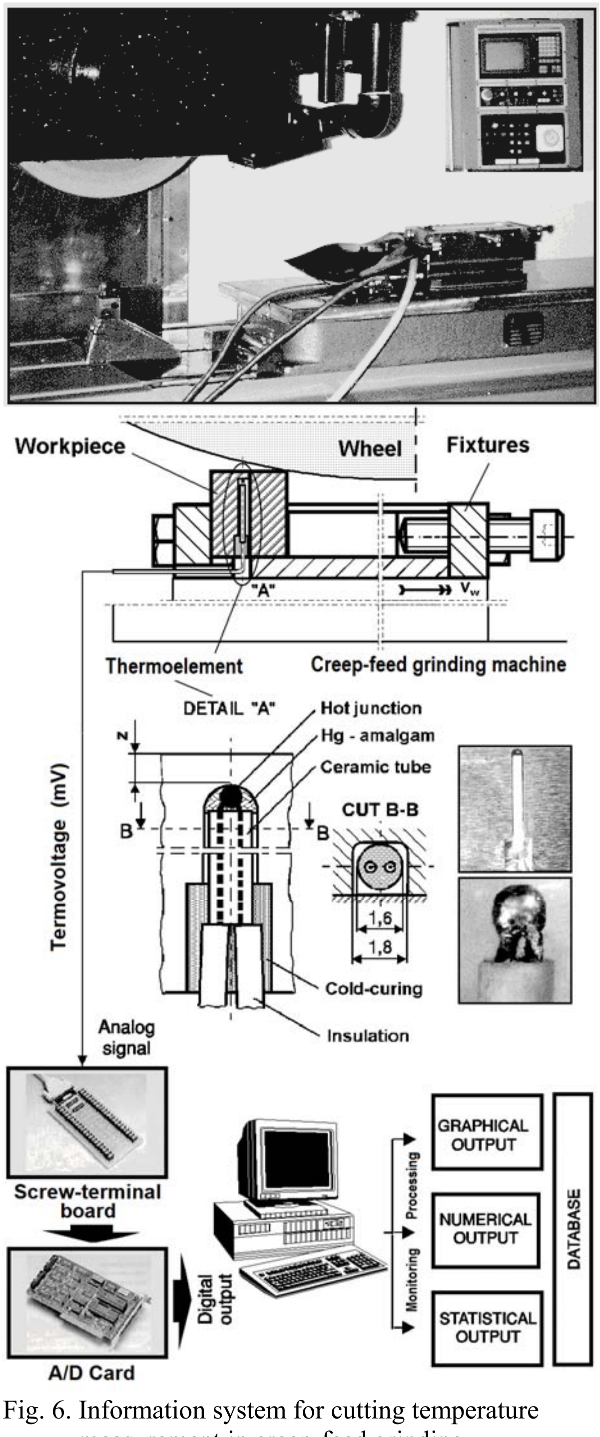

Fig. 6. Information system for cutting temperature measurement in creep-feed grinding

4.2 The results of thermal modeling

Analytical determination of thermal effects in creep-feed grinding is evaluated on the basis of generation and distribution of heat in the cutting zone [39-41]. The identification of thermal aspects in the grinding process is most often expressed by means of parameters of thermal energy, i.e. heat flux density and duration of heat source (Eqs. (13) and (14)). Shown in Fig. 7 is the analytical dependence between the parameters of thermal energy and the creep-feed grinding conditions, for a constant specific material removal rate. The values of the heat flux density and duration of heat source were calculated using experimentally measured values of cutting forces. Fig. 8 shows the relationship between the specific cutting resistance and the average chip thickness, which was experimentally determined by the creep-feed grinding of high speed tool steel.

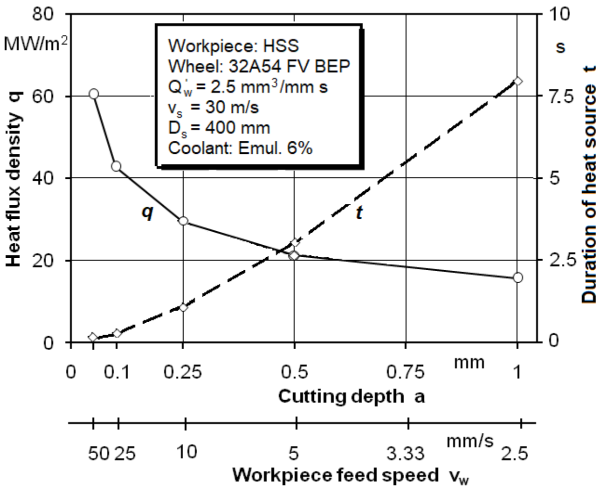

Fig. 7. Dependence of the parameters of thermal energy in creep-feed grinding

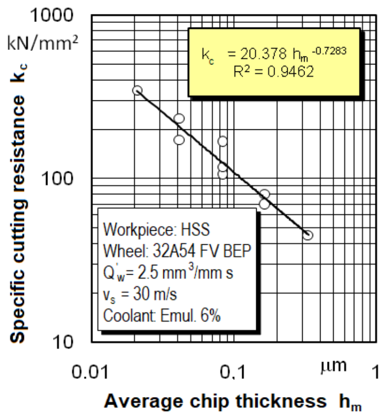

Fig. 8. Dependence of specific cutting resistance on average chip thickness

From the analytical dependence of the parameters of thermal energy during the creep-feed grinding, it can be seen that the duration of heat source increases with machining conditions, however the heat source intensity has a decreasing trend. Consequently, it is clear that basic grinding machining parameters (workpiece feed rate and depth of cut) have an opposite effect on the change of parameters of thermal energy, which largely complicates thermal analysis of the creep-feed grinding process.

To experimentally and numerically investigate the heat source intensity in the creep-feed grinding zone, i.e. the heat flux distribution on the grinding wheel-workpiece interface, an inverse heat transfer problem was used (Eqs. (18) to (21)). In this case, to model the thermal process by the inverse problem, following thermo-physical properties of the workpiece material (high speed tool steel) were taken: heat conductivity k=21.378+0.0275·T W/m°C and thermal diffusivity $\alpha=7.5\cdot10^{-6}$ m^2/s. Also, the contact temperature was not allowed to exceed the tempering temperature, which was experimentally established at 550 °C for the selected high speed tool steel.

The computed heat flux density defines the thermal energy in the surface layer of the workpiece material. The heat flux distribution on the workpiece clearly shows the direct relationship between parameters of thermal energy, i.e. the heat source intensity and the duration of heat source. Evidently, for the greater the heat source intensity the shorter the duration of heat source, and vice versa.

Fig. 9 shows the heat flux distribution on the workpiece by the finite differences method. The heat flux distribution in the surface layer of the workpiece material by the finite element method is shown in Fig. 10.

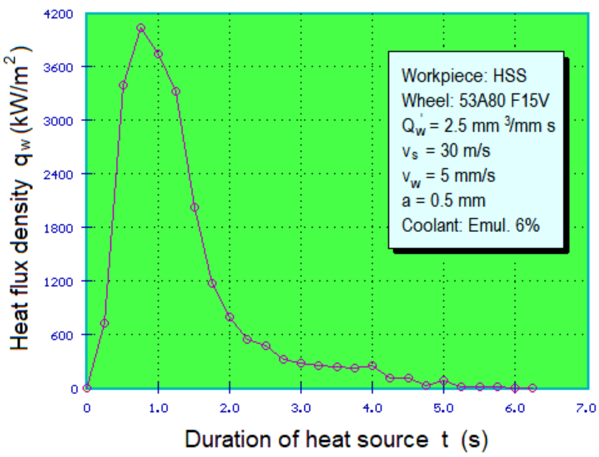

Fig. 9. Heat flux density on workpiece

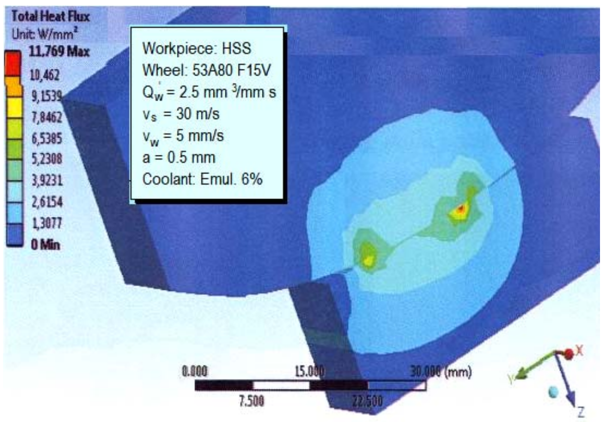

Fig. 10. Heat flux distribution in grinding zone

4.3 The results of temperature distribution

Experimental determination of the temperature during the grinding process is the most accurate procedure possible, especially with the use of various types of thermocouples [42,43]. Application of the thermocouple is best choice, because it is reliable, cost-efficient, and does not interfere with the real machining conditions. The measurement was carried out with the previously defined information system (Fig. 6).

The cutting temperature was measured in the surface layer of the workpiece material using a thermocouple built into the workpiece at a specified distance from the grinding wheel-workpiece interface. On that way, temperature distribution was measured at various locations in the workpiece surface layer. Fig. 11 shows a characteristic graphical representation of how cutting temperature of the creep-feed grinding changes in time, obtained through gradual coming of the grinding wheel to the hot junction of the thermocouple. From the diagram it can be concluded that the maximum cutting temperature was reached just after passing of the grinding wheel above the thermocouple. Beside this, it can be seen that the heat source intensity is increasing, and the duration of heat source is decreasing as it approaches surface contact.

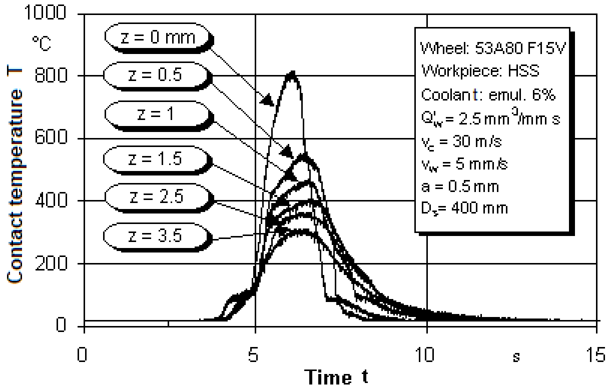

Fig. 11. Grinding temperature distribution in the surface layer of the workpiece material

Shown in Fig. 12 is the experimentally measured temperature distribution in the creep-feed grinding, which illustrates the influence of the workpiece feed rate and the depth of cut at the constant specific material removal rate. It can also be seen the aspects of parameters of thermal energy on the surface layer of the workpiece material.

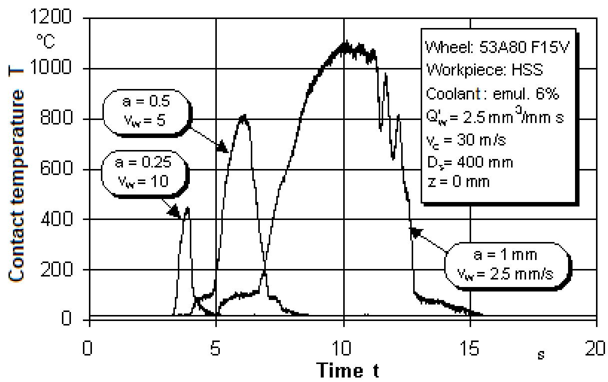

Fig. 12. Temperature distribution in the grinding zone for different machining conditions

On the basis of experimental investigations it can be concluded that in the creep-feed grinding process very high grinding temperature is developed. Fig. 13 shows that, for a constant specific material removal rate, the value of the contact grinding temperature is higher when the depth of cut is bigger, respectively the workpiece feed rate is lower. Accordingly, a smaller degree of temperature increase is a consequence of the good heat conductivity of the cutting zone due to a longer contact of the grinding wheel and workpiece.

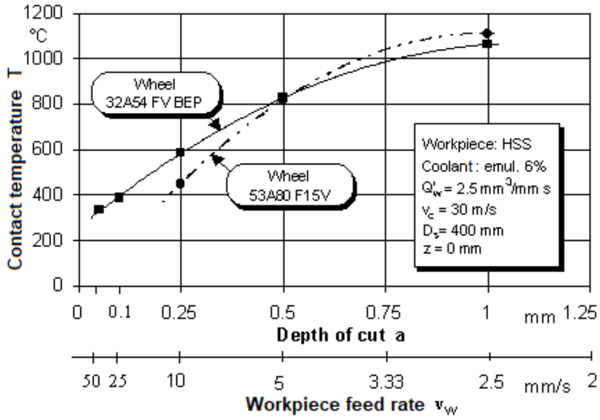

Fig. 13. Change of the grinding temperature depending on machining conditions

Numerical analysis of the temperature distribution of the creep-feed grinding zone in the surface layer of the workpiece material was conducted on the basis of experimental investigation. Fig. 14 shows the temperature distribution in the workpiece by the finite differences method. The temperature distribution in the grinding zone by the finite element method is shown in Fig. 15.

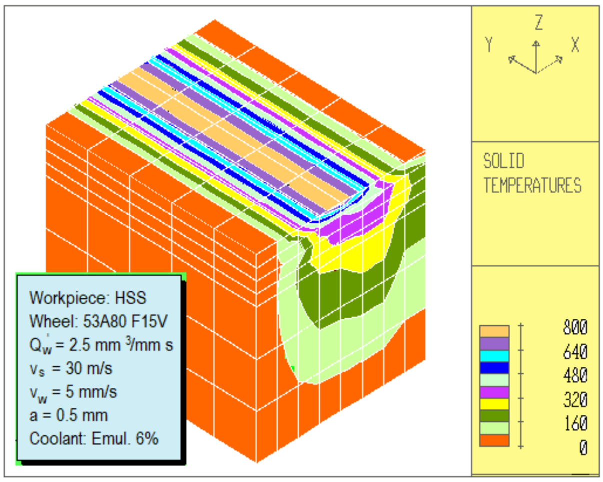

Fig. 14. Temperature distribution in workpiece

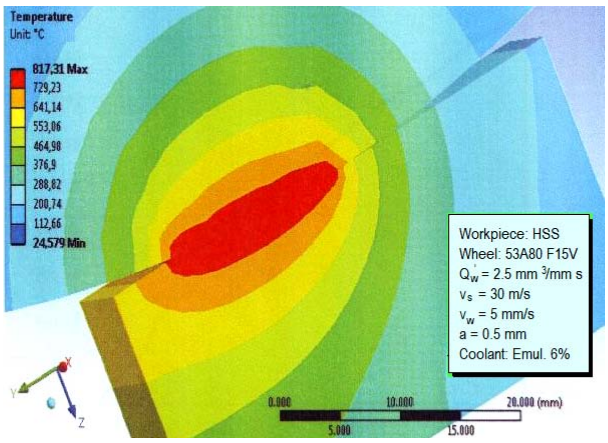

Fig. 15. Temperature distribution in grinding zone

5. CONCLUSIONS

Based on the literature review, it follows that advanced grinding processes are becoming important segment of the manufacturing industry. Creep-feed grinding is an advanced high productivity and machining quality process widely used in machining complex surface parts made from difficult-to-machine materials. Compared to a conventional grinding technique, the creep-feed grinding process uses a large depth of cut with a slow workpiece feed rate, which allows cost-effective machining in a single pass with good accuracy and surface finish. However, the creep-feed grinding leads to intense concentration of heat in the cutting zone, which is why special attention is focused on research of thermal effects.

The thermal aspects in the creep-feed grinding process depend on the knowing of the generation and distribution of heat and the character of the temperature field within the grinding zone. In the first approach, based on the theoretical analysis, mathematical dependencies were obtained between the parameters of thermal energy, i.e. the heat source duration and intensity, and creep-feed grinding conditions. In addition, by the Green's function method analytical expression of the maximum grinding temperature was determined. The proposed analytical models of the thermal energy in the creep-feed grinding pretty well describe the real process.

The identification of thermal effects in the creep-feed grinding process is most easily determined by the experimental investigation of the temperature distribution in the cutting zone. The maximum temperature in the cutting zone is measured by the information system, as well as the temperature distribution was measured at various locations in the workpiece surface layer at different machining conditions. On the ground of measured values it can be concluded that increasing the depth of cut and decreasing the workpiece feed rate, at the constant specific material removal rate, leads to a significant increase of the contact temperature because of the increased heat source intensity and duration.

Based on the experimental and numerical investigation, the heat flux distribution in the creep-feed grinding is determined using the inverse heat transfer problem. The heat flux distribution on the workpiece depends on the relationship of the heat source intensity and the duration of heat source. Optimizing parameters of thermal energy allows the calculation of creep-feed grinding conditions.

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