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SHORT COMMUNICATION

OPTIMIZATION OF THE THERMAL PROCESS OF ABRASIVE METAL WORKING

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ABSTRACT

The main problem that arises from grinding metal is the generation of a large amount of heat. Exceeding a critical temperature will damage the part. However, determining the heat of the metal being processed is a difficult task both practically and theoretically. The correct choice of parameters for the abrasive processing is essential to obtain the required quality. This article describes a mathematical model that simulates the determination of the maximum heat on the surface of a metal part during grinding. This model features the ability to change the initial parameters so that the resulting temperature does not exceed the critical one. The model has been tested by a specially developed web application written in JavaScript. It not only calculates the highest temperature in the machining zone of the workpiece, but also optimizes the thermal grinding process to give appropriate recommendations. The features of such a program are disclosed, including its practical use in production.

Keywords: thermal process; metal; optimization; abrasive processing; model; computer program

INTRODUCTION

The key task in production is to create quality products. In industry, the quality of a product depends on the quality of its parts, which in turn depends on the machining of materials. Abrasive processing is widely used in factories to obtain increased accuracy and surface quality. For this purpose, special circles are used, the cutting elements of which are grains. Continuous improvement of machine tools and abrasive wheels has made this process a highly productive one. The workpieces can be processed with micron precision and excellent roughness, which can be achieved, for example, by grinding or polishing.
A common problem in abrasive metal working is an increase in temperature. Heat is generated when the abrasive grain is loaded. Thermal phenomena arise and are concentrated in rather small areas. The generated heat energy provides intensive heating of the part, which can lead to a decrease in quality or damage. Temperatures can rise so high that changes in the structural composition of the surface layer, local melting, deformation, and the formation of microcracks are possible. As a result, the quality of the workpiece decreases or it becomes unsuitable for further use. This is a significant problem for industry, especially in those industries that require a lot of cutting and grinding. Enterprises thus suffer substantial losses. There are known cases of manufacturer's recalls occurring for batches of already sold product due to the fact that the defect was detected during operation. The fact is that the human eye may not notice thermal damage to the metal. A defected part which becomes part of the final product may make it unusable before the end of the warranty period.
In [1-3] the features of the thermal process in the processing of materials are discussed. This has also been further investigated by many scientists in various aspects [4-7].
Knowing the temperature of not only the part but also the contact surfaces of the cutting grain is important, since thermal conductivity to the grains is possible. Moreover, the temperature of these surfaces determines the diffusion breakdown and wear of the grinding wheels themselves. Therefore, the temperature factor becomes the main limitation in this process.
In [2, 3], contact and non-contact methods of measuring the temperature of the workpiece are studied. The disadvantages and problems of such operations are described. It is even more difficult to measure the temperature inside a metal part.
Temperature can be found from the well-known differential heat equation. However, as a partial differential equation, it has an infinite number of solutions. To select the solution that describes the grinding process from this set, additional conditions must be imposed on the sought temperature function. These are called initial or boundary conditions. Due to the stochasticity of abrasive machining, this is a very difficult task. At the moment, the variety of mathematical descriptions available does not reflect all the nuances of the grinding process. However, this is not necessary if only the basic patterns are being studied. Therefore, scientists followed the path of rational systematization and used simplified models.
The creation of a model that is as close as possible to the real grinding process and the development on its basis of a computer program that calculates the temperature, speed, force, and other parameters of grinding and which gives appropriate practical recommendations will change the production of products around the world. In view of the importance of this model and without exaggeration, I note that the demand for

such a program would be greater than that for the vaccine against COVID-19.

The results of the analysis of publications indicate the great interest of researchers in the problem of thermal modeling in the processing of materials. In the 20th century, many scientists made a significant contribution toward a solution, including Jaeger (1942), Rikalin (1959), Hahn (1962), Rediko (1962), Makino (1966), Malkin (1971), Maslov (1974), Snoeys (1978), Lavine (1989), Morgan (1991), Qi (1993), Rowe (1994), and Tonshoff (1995).

In [8] formulas are obtained that allow calculating temperatures during friction at a constant speed. This studies considers two cases, and it assumes that the friction surface has the shape of a strip or the shape of a square bar. This study makes a significant contribution to the thermal physics of grinding. Thus far, scientists have used these results to study the moving belt heat source [4, 9]. Without diminishing the importance of these studies, I note that in belt grinding, the problem of temperature is not so acute, and it has narrow application in practice.

Another important approach is to consider a single abrasive grain as a source of heat. In this case, the average contact temperatures developing at the grinding site are determined. In [10], a method is proposed for determining the grinding temperature, taking into account the multiple superposition of heat pulses from the grains. Equations are obtained for the temperature not only at the contact surface of the abrasive grain, but also for the part depth. The sought equations are obtained from the differential heat equation. A criticism of this method can be found in [2, p. 124].

A general analysis of the literature of the 20th century makes it possible to conclude that initially the temperature of the part was judged by the nature and intensity of phase transformations in the surface layer during grinding. The dependence of the contact temperature on the grinding conditions was mainly determined experimentally. The theoretical calculation of grinding temperatures was carried out in accordance with the basic laws of heat transfer. Scientists, under certain conditions, determined the amount of heat in the grinding zone, established its distribution between the part and the wheel, or took into account coolants, etc. As a result, formulas and basic laws of thermal phenomena of the process under study were obtained from the differential heat equation, empirical results, the Fourier problem.

The modern metallurgical industry is constantly producing new types of alloys, which have their own coefficients of thermal conductivity, hardness, and other characteristics. Thermal phenomena occur differently for each material. Therefore, abrasive processing should take into account the latest scientific advances in this area such as:

- hard alloys [11],
- ceramics [12],
- polymorphic metals [13],
- aluminum alloys [14-16],
- composite materials [17],
- steels [18-21].

In the new millennium, the number of publications on the problem of thermal modeling has increased. In [9, 21, 22], the modeling of the temperature field of the workpiece, which is formed during the grinding process, is discussed.

Analysis of the literature of the 21st century with a focus on the problem posed makes it possible to conclude that scientists continue to solve the problem for a specific narrow case. The results are interesting, but not all are suitable for computer forecasting or use in factories. For example, the unsuitability for computer processing of the behavior of steel studied in [21] is explained by the use of volumetric heating. In practice, when grinding, this is surface heating.

The purpose of the article is to reveal the features of the thermal model during grinding and, on its basis, to develop a computer program for the approximate calculation of the maximum temperature on the surface of the workpiece and optimization of the grinding process in the thermal aspect.

MATERIAL AND METHODS

Particularly noteworthy is the Reznikov method, which calculates the temperature both on the cutting grain of an abrasive and grinding wheel, and on the material being processed. In [1, p. 126] the temperature on the surface of the part by the calculation method is determined. The method is shown using the example of flat grinding with an abrasive wheel. The law of temperature distribution on the surface of the part in the moving coordinate system associated with the circle is established, which is expressed by the formula:

$$Q_{max} = 52(1 - b^*)\frac{\sqrt{\omega}}{\lambda}\frac{m^{0.05}P_z v}{b\sqrt{v_1}B^{0.4}}, \qquad (1.)$$

where b^*– coefficient characterizing the relative distribution of grinding heat between the wheel and the part,
λ – coefficient of thermal conductivity of the processed material,
ω – coefficient of thermal diffusivity,
P_z – tangential force during grinding,
v – circle speed,
m – the rate of decrease in the intensity of heat generation. Depending on the properties of the circle and the material of the workpiece, m = 0.01-0.03,
B, b – dimensions of the contact area of the circle with the part,
v_1 – speed of the part.

In [4] the theorem for finding maximal temperature in wet grinding is considered. It has been proven that such a temperature always occurs on the workpiece surface in the contact zone. The limitations concerned the constant heat transfer coefficient for the coolant acting on the workpiece surface and a constant or linear heat flux profiles entering into the workpiece.

RESULTS AND DISCUSSION

Mathematical model

To achieve the goal of the article, the following tasks are set:

- to create a mathematical model that allows for the determination of the maximum temperature in the contact zone of a metal part with an abrasive grain;
- to develop a program for calculating such a temperature;
- to create a program that provides pre-calculated values to ensure an optimal temperature for the grinding process.

The subject of research is the thermal process during metal grinding. The objective of the study is to determine the maximum temperature on the surface of the part and to optimize the thermal grinding process.

I will solve the assigned tasks on the assumption that the main results of [1, 4] are correct. Firstly, I will prove the theorem.

Theorem. The maximum temperature occurs on the surface of the grinded material with or without coolants.

Proof. Only two cases are possible when grinding:

(I) using coolants,
(II) not using coolants.

Consider case (I). In [4] it is found that the maximum temperature is reached at the surface of a part during wet grinding. Thus, in this case the theorem is proved.
Consider case (II). The proof is realizable by contradiction.
Suppose that the maximum temperature is not reached at the surface, but inside the material to be processed. I denote this with Q_1. Let Q_1 be at a distance $\Delta r > 0$ from the surface. Let Q_2 be the highest temperature on the surface of the processed material. Then

$$Q_1 > Q_2. \quad (2.)$$

Let me apply coolants at this moment. They come to the surface of the processed material. Therefore, cooling starts from the surface and Q_2 does not increase but can only decrease. According to the proved (I), the temperature Q_2 is the maximum in the entire material:

$$Q_2 > Q_1. \quad (3.)$$

The cooling action will reach the distance Δr in some time $\Delta\tau$. During this time inequality (3) will be fulfilled. But this contradicts inequality (2). The resulting contradiction proves the theorem, and thus the theorem is proved.
According to this theorem, the maximum grinding temperature is reached on the surface of the part, not inside. This means that defects caused by thermal phenomena can be detected from the outside. Moreover, if they are not on the surface, then there is no thermal damage inside the part. Consequently, finding the maximum temperature is reduced to calculating it only in the grinding zone on the surface of the part.
Therefore, I will consider a one-dimensional thermal model, where the maximum temperature is reached at the surface of the processed material. This greatly simplifies the solution to the problem. The purpose of the model is to find the maximum temperature on the surface of the part during grinding. It is important to be able to adjust the grinding parameters (time, depth, speed, thermal diffusivity of the cutting grain, etc.) and to carry out abrasive processing so as not to reach the temperature at which thermal defects of the part occur.
I then get the inequality:

$$Q_{cr} > Q_{max}, \quad (4.)$$

where Q_{max} is the maximum temperature on the surface of the part in the grinding zone, and Q_{cr} is the temperature at which thermal defects of the part begin (burns, microcracks, deformation, etc.). This temperature is referred to as the critical temperature.
Let me consider the operator

$$T: X_0 \rightarrow Q_{max}, \quad (5.)$$

where X_0 is a set of initial conditions or output data.
The model is studied under the assumption that the cutting grain has a cylindrical shape. Ellipses are obtained in their section when grinding. In unimportant cases, ellipses were replaced by circles to simplify calculations. After refining (1), the following equality was obtained:

$$Q_{max} = T(X_0) = 52.19(1 - b^*)\frac{\sqrt{\omega}}{\lambda}\frac{m^{0.05}P_z v}{\sqrt{v_1}bB^{0.4}}. \quad (6.)$$

The operator (5) allows the setting of the maximum temperature on the surface of the part in the grinding zone according to the values of the wheel and part speeds, the thermal diffusivity and thermal conductivity coefficients, the coefficient that characterizes the relative distribution of the grinding heat between the wheel and the part, and the force and dimensions of the contact area of the wheel with the part.
Such a mathematical model provides the possibility for the given initial data to calculate the missing data and find Q_{max}. Moreover, it allows one to analyze the effect on Q_{max} of changes in the initial conditions. The use of coolants can also be attributed to the initial conditions. They have a smell and therefore affect the purity of the air. Their disposal pollutes soil and groundwater. In addition to environmental problems, there are other problems associated with their use. Therefore, in my research I have tried to solve the problem without using coolants.
To meet the set research tasks, it became necessary to automate the implementation of the created mathematical model for determining the temperature on the surface of the part during grinding. To achieve this, I have developed a computer program that, after entering the initial conditions X_0 of the process of abrasive processing of the material, gives the result of the calculations. According to the analysed information needs in production, first of all the computerized algorithm should determine the highest temperature at the contact surface of the wheel with the part.

Model check

Consider task 1. Create a program for calculating the values (6) of operator (5).
First of all, I emphasize that my program allows for the user to enter the parameters of the grinding process. These include data on the material to be processed, the grinding tool, the type and mode of grinding, as well as the dimensions of the contact area of the wheel with the part. In this case, it is taken into account that the circle goes beyond the length of the workpiece being processed.
At the first stage, the program calculates the dimensionless Fourier complex using the formula:

$$F_0 = \frac{\omega_1 \cdot b}{10 \cdot v \cdot x_n^2},$$

where ω_1 is the coefficient of thermal diffusivity of grain, and x_n is found by the formula:

$$x_n = 0.875\bar{x}\sqrt[3]{0.6},$$

where $\bar{x}$ is the most probable grain size.
At the second stage, the algorithm determines the proportion of heat in the part $1 - b^*$, where b^* is found by the formula:

$$b^* = \frac{1}{1+2.25\frac{\lambda}{\lambda_1}A^*\sqrt{F_0}},$$

where λ is the thermal conductivity coefficient of the material being processed, and λ_1 is the thermal conductivity coefficient of the cutting grain, A^* is a function that depends on the time of contact of the grain with the part in one cut and the ratio of the thermal conductivity coefficients of the grain and the circle.
At the third stage, the program calculates the tangential force during grinding P_z, which is a function of the depth of grinding, the speeds of the part and the grinding disk, and the contact area of the wheel with the part. The formulas depend on how the part is machined.
Based on the data obtained, my program has all the necessary values to determine the highest temperature on the contact surface of the wheel with the part according to formula (6). Task 1 has been solved.

After obtaining the maximum temperature at the contact area between the grinding tool and the workpiece, it is necessary to compare it with the critical temperature according to formula (4). If it turns out that the maximum temperature of the part is higher than the critical one, then the grinding process cannot be carried out. To avoid negative consequences, the process must be optimized by changing the grinding parameters, such as speed. This will reduce the heat load and reduce the maximum temperature. The search for the optimal speed is implemented in the second part of the software product.

Consider task 2. Create a program to optimize the temperature process of grinding with a change in speed.

The program provides a critical temperature analysis based on user-defined input values. The algorithm calculates the maximum temperature at the contact surface and compares it with the critical temperature. When inequality (4) is satisfied, the program displays a message that the processing under the given conditions will be of high quality and will not bring any losses. Otherwise, the grinding parameters must be changed to avoid thermal damage to the part. This function is also implemented in my program by changing the speed of the part. The program calculates the speed at which the heating of the part will be decreased. As a result, the workpiece will not suffer thermal damage.

The solution to task 2 depends on the type of grinding, the material being processed, and the characteristics of the grinding wheel. For example, in the case of flat grinding of hard alloys with a cup diamond wheel, the program algorithm is based on formula (7):

$$v_1 = \left(\frac{\lambda Q_{max}}{31.31(1-b^*)\sqrt{\omega}\, m^{0.05} t^{0.69} v^{0.41} b^{0.18} B^{0.78} \prod_i K_i}\right)^{9,09}, \quad (7.)$$

where $\prod_i K_i$ is the product of correction coefficients that take into account the bond of the wheel, the concentration of grains and the processed material. The corresponding coefficient is also taken into account in the case of liquid grinding. Task 2 has been solved.

Similarly, the problem of optimizing the temperature process of grinding is solved depending on the change in depth, grinding force, or characteristics of the wheel. If optimization is not possible under the given initial conditions, or the maximum temperature remains above the critical one, the program issues appropriate recommendations and suggests entering other initial parameters. One of the recommendations is the use of coolants.

Consider an example. **Fig. 1** shows the calculation by the program of the maximum temperature of a workpiece made of hard alloy BK8 during flat grinding with the butt face of a cup diamond wheel, a grain size 80/63, and an organic bakelite bond B1. The obtained temperature turned out to be lower than the critical one (614 < 690), which ensures high-quality processing of the part without thermal defects. Note that 614°C is predicted without the use of coolants. It should be emphasized that an experimental temperature value of 600°C was obtained with the same initial grinding parameters.

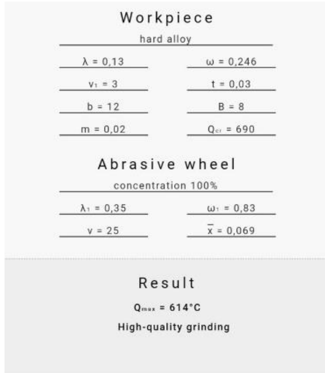

Fig. 1 Calculation of the maximum temperature

Technical features of the program

I have analysed the conditions for further use of the program. For maximum convenience and efficiency of work, I decided to organize the process of interaction with the program continuously. In other words, all input fields are always active, and the result is recalculated whenever the input data changes. This approach is most convenient in various situations in production using different types of devices. From the foregoing, it follows the need to support the software product on a large number of devices running different operating systems. To achieve this goal, the algorithm is implemented as a website, which makes it possible to work from any device with a web browser. Also, the user can enter data using the mouse and keyboard and using touch input. The result is displayed graphically equally well on colour monitors, laptop screens, tablets, and even monochrome displays. An integral advantage is the ability to modernize and expand the program without interfering with client devices on factories, limited only to changes on the server with the site.

Following the current trends in the development of sites using mathematical logic, JavaScript was chosen as the main programming language. It is a flexible tool with dynamic data typing and relatively high performance. It is currently supported by all known browsers and is a generally accepted standard in the field of creating web applications. JavaScript is an object-oriented language. This feature allows you to organize a program as a collection of objects, each of which is an instance of a certain class with support for an inheritance hierarchy.

An equally important part of the application is its appearance and the quality of the interface. I have paid enough attention to this aspect, which will allow even inexperienced users to intuitively interact with the program, as well as spend a minimum of time getting acquainted with the basic functions. At the same time, the speed of work increases, which is an important factor in mass production. The above was achieved using the modern standard of the hypertext markup language – HTML 5. This is the standard for web pages all over the world. The code is interpreted by browsers, and the resulting page is displayed on any display. Styling is applied to the created html document, implemented using a formal language for describing the appearance of web pages – CSS. The latest css3 standard provides the ability to use smooth animations and transitions, which improves the responsiveness of the interface.

The development of my software product was carried out using the editor Sublime Text 3. At the stage of creation, the project was thoroughly checked and tested in the Google Chrome web

browser. Moreover, the use of multi-browser solutions guarantees correct operation in any modern browser.
According to the implementation, there are two ways to run my program. The first one is to copy the project files to the client device and then open the html file in any browser. The described method does not require an Internet connection and does not depend on the performance of a third-party server. However, to update the algorithms of the program, it will be necessary to replace the project files on the device, which will require intervention in each computer or tablet. The second method involves the location of the project on the server. In this case, access to the program is carried out by going to the web address issued by the host provider. To do this, the client devices must have an Internet connection. If the server fails, the program will stop working. The advantage of this method is the convenience of upgrading and expanding the program. It is enough to update the files on the server, and all clients will have access to the new functions. In both cases, the same files are used. Thus, my development can be used in both ways, the choice of which depends on the status of the Internet connection.

CONCLUSION

It has been proven by contradiction that the maximum temperature is reached on the surface of the part during its grinding. The significance of this theorem also lies in the fact that if thermal damage is absent from the outside, then there is none inside the part. If the maximum temperature was reached inside, then the resulting damage might not be visible on the surface. Thus the problem of how to detect this maximum temperature would arise, along with many other problems. However, because the theorem states this is not possible, these problems do not arise by virtue of the theorem.
The considered model makes it possible to determine the maximum temperature of the part during grinding. Based on the model and analysis of parameters that affect the temperature rise of a metal part during grinding, a program has been created. It not only calculates the temperature, but also allows the user to ensure the optimal temperature process by varying the basic parameters of metal processing. If there is a possibility of negative consequences, the algorithm will determine that the maximum temperature on the surface of the part during grinding is higher than the critical one. Comparison of the values obtained experimentally and calculated by the program shows an adequate reflection of real temperatures in the process of grinding. Thus, the mathematical model simulates the process under study reasonably.

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