UDC 621.923.1

<https://doi.org/10.29202/nvngu/2019-5/14>

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DETERMINATION OF INSTANTANEOUS TEMPERATURE IN THE CUTTING ZONE DURING ABRASIVE PROCESSING

Purpose. Experimental research on the temperature state in the cutting zone for abrasive grinding and mathematical modeling of the stress-strain state of the workpiece surface under the influence of the determined temperature regime.

Methodology. In this work, experimental methods were used to study the values of instantaneous temperature in the cutting zone. Specifically, we used non-contact method for measuring temperature with a thermal imager TI160, which has very high temperature sensitivity, which allows you to find the smallest temperature differences and build precise thermal images. The finite element method was used to study stresses and deformations that arise under the influence of instantaneous temperatures in the processing zone.

Findings. The main factors influencing the instantaneous temperature during abrasive processing were identified. As a result of experiments, the values of instantaneous temperature were determined at different grinding conditions. Based on the experimental values of the temperatures, mathematical simulation was carried out and deformation, strain and displacement dependencies of the workpiece surface on the instantaneous grinding temperature were determined. The recommendations of the optimal grinding modes, at which the instantaneous temperature will be the smallest are given.

Originality. Dependence of deformations, stresses and landslides in the workpiece under the influence of instantaneous temperature in the cutting zone, with different grinding modes is determined.

Practical value. As a result of the research, practical recommendations have been developed regarding the choice of optimal grinding modes, in which the instantaneous temperature has the slightest effect on the occurrence of defects during processing.

Keywords: *instantaneous temperature, mathematical modeling, finite element method, abrasive grinding, abrasives, grinding modes*

Introduction. When grinding, a very large amount of heat is released in the contact area of the grinding wheel and workpiece. The temperature in the processing zone reaches 1000–1600 °C. During the blade processing, a lot of heat is released, but with abrasive treatment the most. This can be explained by the high cutting speeds that are 10–20 times higher than with other types of processing and the large area of contact of the surface of the wheel and the workpiece. The heat which is released in the cutting zone heats the abrasive wheel, the workpiece and the environment. In [1, 2], it was discovered that when cutting a single grain of a grinding wheel in the displacement plane, 94 % of the total heat released during processing, goes away in the shaving and wheel, and only 6 % – in the surface of the workpiece. And according to [3, 4], the air and the wheel have a small thermal conductivity, and therefore most of the heat goes into the detail. In particular, the amount of heat absorbed by the workpiece when removing 1000 mm³ of metal by the abrasive wheel is 10.7–13.5 kcal, only 2–8 % of the shavings, and 70–80 % of the released heat in the workpiece.

There are 3 types of temperatures when grinding [2, 3, 5]:

- instantaneous development in the grinding area with grinding grain;
- the contact, which is located in the contact area of the wheel with the workpiece;
- average temperature in the surface layer of the workpiece.

Thermal phenomena during grinding significantly affect the quality of the treated surfaces, causing phase and structural changes. The instantaneous and contact temperature has the greatest impact on the quality of the treated surface. And they are the most interesting ones for research.

Literature review. Instantaneous temperatures arise due to plastic deformations of cutting chips and friction of abrasive grain in the grinding area. According to [6, 7], the contact temperature is much lower than the instantaneous, due to the intense heat removal from the cutting zone. An increase in the contact temperature results in the growth of residual stresses, changes in the micro-hardness and the appearance of spillages and cracks in the surface layer of the workpiece, which significantly reduces the quality of the detail.

The appearance of continuous burning on the surface of the detail can be caused by the following reasons [7, 8]:

1. Excessive depth of grinding, resulting in an average thickness of the shavings removed by one grain of the grinding wheel, is very large; resulting in a sharp increase in the pressure of abrasive grains on the treated surface; increased friction and increased surface heating.
2. Excessive hardness and inconsistency of working conditions of the selected grinding wheel, which also causes excessive pressure of grinding grains on the surface of the detail; increased friction and increased surface heating.
3. Insufficient cooling intensity and incorrect selection of coolant.

4. Reduced frequency of rotation of the detail. In this case, the heated scratch, made by abrasive grain, does not have time to cool before the next grain is caught in it, causing additional heating of the surface.

That is why the issue of study of deformations caused by the instantaneous and contact temperatures in the cutting zone and giving recommendations on the choice of cutting modes that contribute to the reduction of temperature deformations are topical issues.

Unsolved aspects of the problem. The question of the establishment of experimental dependences of instantaneous temperature values in the grinding zone on the cutting modes is underinvestigated.

Purpose. Determining experimentally instantaneous temperature value of the workpiece in the cutting zone during abrasive processing and giving practical advice on grinding modes that reduce the value of instantaneous temperatures in the processing area.

Results. To choose the main factors that affect the grinding temperature, we use the rank correlation method.

On the basis of the analysis of literary sources [9, 10], the following factors influencing the temperature at grinding were determined:

- 1) cutting speed;
- 2) feed of a workpiece;
- 3) depth of cutting;
- 4) ambient temperature;
- 5) bunch of a grinding wheel;
- 6) diameter of the grinding wheel;
- 7) grain size of the wheel;
- 8) porosity of the wheel;
- 9) hardness of the wheel;
- 10) hardness of the workpiece;
- 11) lubricating and cooling fluid;
- 12) rigidity of the technological complex.

Each factor has its operational definition, designation, dimension, and measurement interval. For each factor experts bring value in the order that is considered correct and appropriate. Then calculations are made and the most important factors are determined.

After analyzing the data of the expert survey, the most significant factors were found:

- 1) cutting speed;
- 3) depth of cutting;
- 2) feed of the workpiece;
- 6) diameter of the grinding wheel;
- 11) lubricating and cooling fluid;
- 10) hardness of the workpiece;
- 7) grain size of the wheel;
- 5) bunch of the grinding wheel;
- 9) hardness of a wheel;
- 8) porosity of the wheel;
- 12) rigidity of the technological complex;
- 4) ambient temperature.

As we can see, the most significant are cutting speed, cutting depth, blade feed, wheel diameter and lubricant-coolant fluid. Given that the diameter of the wheel and the speed of the rotation are constant, and the lubricating coolant cannot be used for the convenience of measurements, therefore, for the alternating factors for our experiment, we accept the depth of grinding and feed of workpiece. The concordance coefficient, which determines the coherence of opinion of the interviewed specialists, was almost 87 %.

The processing of workpieces, in our experiment, was carried out on a double-sided end-grinding machine model 3342 ADO. The machines of this model are intended for grinding of two parallel ends of workpieces of the ring type of a diameter from 10 to 40 mm, with a height from 36.4 to 46.6 mm. On this machine, the feed of workpieces takes place in a drum, which is provided with a circular movement, as shown in Fig. 1.

This machine is designed for processing workpieces such as rings, pins, clips, that is, short cylindrical workpieces. Overall dimensions of the workpieces directly depend on the drum, in which they are fixed.

For the experimental studies, a roller with a diameter of 20.5 mm and a length of 44 mm was selected. The material of the workpiece is steel 45. Steel 45 is structural carbon steel of high quality.

During our experiment, the thermal imager TI160 was used (Fig. 2). The TI160 thermal imager has a very high temperature sensitivity of 65 mK, which allows you to find the slightest temperature differences and build extreme temperature images. The temperature measurement error is $\pm 2^\circ\text{C}$.

The main cutting modes include: cutting speed, depth of cut and feed. The correct choice of grinding modes determines the quality and accuracy of the treated surface. During the experiment, one of the main tasks was the practical detection of the effect of cutting modes on the temperature in the cutting zone.

The grinding speed is directly proportional to the diameter of the wheel and the speed of rotation. When conducting an experiment on a double-sided end-grinding machine model 3342 ADO, the speed was constant. The diameter of the wheel did not change and was equal to $D_w = 450$ mm. The speed of its rotation was also unchanged (for this machine, the spindle rotation frequency is a non-variable value) and was equal to $n_w = 1500$ rpm.

The depth of grinding during the experiment was in the range of 0.002 mm to 0.18 mm (Table 1).

The speed of the drum feed, taking into account the number of experiments, is listed in Table 2.

At a speed of 1.13 rpm, 20 basic experiments were carried out, and at other speeds auxiliary experiments were conducted to refine the data and obtain the graphs of the dependence of the grinding temperature on the feed workpiece.

Fig. 1 Feed of workpieces on a double-sided end-grinding machine model 3342 ADO

Fig. 2. The thermal imager TI160

Table 1

Depth of grinding during the experiment

No. exp.	Depth of grinding, mm	No. exp.	Depth of grinding, mm	Auxiliary points 15 verification experiment on different circular feed	Depth of grinding, mm
1	0.002	11	0.034		
2	0.004	12	0.04		
3	0.006	13	0.05		
4	0.008	14	0.06		
5	0.01	15	0.07		
6	0.014	16	0.08		
7	0.018	17	0.08		
8	0.022	18	0.1		
9	0.026	19	0.16		
10	0.03	20	0.18		

Table 2

Drum feed rate during the experiment

Number of experiments	Feed rate, r/min
23	1.13
3	1.33
3	1.64
3	1.85
3	2

After the output of the workpiece from the processing area, it is necessary to send the ray of the thermal imager to the detail and in a few seconds we obtain a color image of the device on the screen, which shows the temperature distribution on the end of the detail and the temperature as precisely as possible from the cutting zone. All obtained results are entered in the table for further analysis.

After each experiment, the detail was left outdoors and further cooled with water. Cooling occurred until the detail had an internal temperature close to the initial temperature. At an initial temperature of the workpiece it was taken 28 °C.

As a result of each research, color images were obtained with the temperature values in the zone closest to the cutting zone (Fig. 3).

As we see from the images taken with the help of a thermal imager, the instantaneous grinding temperature is quite large and increases with increasing depth of cutting. Also, from these images, we can conclude that the thermal flow in different ways extends to the workpiece, but with a greater inclination to the edge, which first came out of the cutting area. This fact can be explained by the fact that it is on this edge that cutting the grinding wheel into the workpiece occurs, and therefore the cutting and friction forces there will be the highest, which causes a rise in the temperature in this zone.

Another task of our study was to determine the dependence of temperature on the feed of workpiece.

We perform the first test without changing the feed (1.13 rpm). We install a depth of 0.02 mm on a limb and conduct an experiment. The experiment is carried out three times for each filing. Picture of the thermal imager is shown in Fig. 4.

The latest experiment we conducted was an experiment with a feed at 2 rpm, Fig. 5.

Based on recent experiments, it can be said that the temperature, depending on the feeding of the workpiece to a certain point, increases, but reaching a certain value of the feed begins to decrease. This can be explained by the fact that with increasing feed time, the workpiece in the contact area with the grinding wheel decreases.

There were 35 experiments for each, following which we got a graphic representation of the distribution of heat on the front surface of the workpiece, which stands out in the cutting zone and immediate value of the highest temperature at the exit of the workpiece.

The next stage is the justification and processing of the actual data obtained during the experimental work.

For each value of the depth of cutting, we got their temperature. It is quite easy to see the growing dependence of the grinding temperature on the depth of cutting, but some points are repeated, some are smaller than the previous ones, this is the measurement error.

We obtained the same data for other experiments in which the feed was changed. For each submission, three experiments were conducted.

Having convenient data for operation, we can build graphs of the temperature of grinding from the depth of cutting and feed. Since we received a large number of experimental values,

Fig. 3. The results of experiments at a depth of 0.02 mm (a) and 0.18 mm (b)

Fig. 4. Data from the thermal imager, feed 1.13 rpm

Fig. 5. Data from the thermal imager, feed 2 rpm

as well as taking into account the measurement error, an approximation of data was performed.

Since the dependence has a growing character, one of the main laws that can be used for approximation is either the linear dependence $f(x) = kx$ or the exponential – $f(x) = e^x$. Since the graph on the linear is not similar, then as an approximation we choose the exponential law and get the graph depicted in Fig. 6. With this approximation, we obtained a smooth graph of the instantaneous temperature dependence from the depth of cutting at a constant cutting speed and feed rate.

We will construct a graph of the dependence of the instantaneous grinding temperature on the feed of workpieces. For each feed value, three experiments were performed.

The graph shows four types of data: blue – data obtained during the first experiment, red – the second experiment, green – the third one. Black points show the average value for all experiments (Fig. 7).

After obtaining an approximated graph, it can be argued that with an increase in the feed of workpiece, the instantaneous temperature decreases.

The temperature, depending on the feeding of the workpiece to a certain point, increases, but reaching a certain value of the feed begins to decrease. This can be explained by the

fact that with increasing feed time, the workpiece in the contact area with the grinding wheel decreases.

So, for the determination of plastic deformations in the workpiece from the action of instantaneous temperature, we carried out thirty-five experiments, each of which received the corresponding instantaneous temperature values using a thermal imager.

Determination of the magnitudes of plastic deformations and residual stresses in the workpieces under the influence of instantaneous temperature in the cutting zone was carried out by the SolidWorks licensed software complex.

The result of the calculation in the program is the stress and deformation maps obtained at different temperature values (Fig. 8).

Fig. 6 Approximate graph of the dependence of instantaneous temperature on the depth of cutting

Fig. 7 Approximate graph of the dependence of instantaneous temperature on the circular feed

Fig. 8. Map stresses:
 $t = 0.18 \text{ mm}$, $T = 350 \text{ }^{\circ}\text{C}$

Fig. 9. Approximate graph of dependence of maximum stresses on instantaneous temperature

Fig. 10. Approximate graph of dependence of maximum deformations on instantaneous temperature

The data obtained will be used in the further analysis for plotting stress and strain dependency graphs from the instantaneous grinding temperature for the 3342DAO double-sided grinding machine.

The experimental curves were approximated by exponential dependence $f(x) = e^x$ (Figs. 9 and 10).

Comparing the graph of the dependence of instantaneous temperature on the depth of cutting (Fig. 7) and the dependence we obtained, it can be argued that increasing the depth of cutting also increases the maximum residual stresses in the workpiece.

Conclusions. Thus, using SolidWorks, there were determined residual stresses and maximum deformations in the workpieces due to the instantaneous temperature effect when grinding at constant cutting speed and variable feedings and cutting depths.

It was found out that with increasing depth of cutting, the maximum stresses and deformations of the workpiece are increased, which is easily explained by an increase in the instantaneous grinding temperature; with increasing feed of workpieces, the maximum stresses and deformations are reduced, which is caused by a decrease in the instantaneous grinding temperature.

If the minimum residual stresses and deformation are chosen as an optimality criterion, at constant cutting speed it can be recommended to set a minimum depth of cut, and the maximum feed of workpieces.

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Визначення миттєвої температури в зоні різання під час абразивної обробки

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Мета. Експериментальне дослідження температурного стану в зоні різання при абразивному шліфуванні та математичне моделювання напружено-деформованого стану поверхні заготовки під впливом визначеного температурного режиму.

Методика. У цій роботі для дослідження значень миттєвої температури в зоні різання були використані експериментальні методи. Зокрема, ми використовували безконтактний метод вимірювання температури з тепловізором TI160, що має дуже високу роздільну здатність, яка дозволяє виявляти найменші температурні відмінності та створювати точні теплові зображення. Метод кінцевих елементів був використаний для визначення напружень і деформацій, що виникають під впливом миттєвих температур у зоні обробки.

Результати. Виявлені основні чинники, що впливають на миттєву температуру при абразивній обробці. У результаті дослідів були визначені значення миттєвої температури за різних умов шліфування. Виходячи з експериментальних значень температур, було проведено математичне моделювання та визначена залежність деформації та залишкових напружень поверхні заготовки від миттєвої температури шліфування. Наведені рекоменда-

ції оптимальних режимів шліфування, за яких миттєва температура буде найменшою.

Наукова новизна. Визначена залежність деформацій, напружень і зміщень у заготовці під впливом миттєвої температури в зоні різання за різних режимів шліфування.

Практична значимість. У результаті досліджень були розроблені практичні рекомендації щодо вибору оптимальних режимів шліфування, в яких миттєва температура найменше впливає на виникнення дефектів під час обробки.

Ключові слова: миттєва температура, математичне моделювання, метод скінчених елементів, абразивне шліфування, абразивні матеріали, режими шліфування

Определение мгновенной температуры в зоне резания во время абразивной обработки

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Цель. Экспериментальное исследование температурного состояния в зоне резания при абразивной шлифовке и математическое моделирование напряженно-деформированного состояния поверхности заготовки под воздействием определенного температурного режима.

Методика. В этой работе для исследования значений мгновенной температуры в зоне резания были использо-

ваны экспериментальные методы. В частности, мы использовали бесконтактный метод измерения температуры с тепловизором ТП160, который имеет очень высокое разрешение, что позволяет выявлять малейшие температурные различия и создавать точные тепловые изображения. Метод конечных элементов был использован для определения напряжений и деформаций, возникающих под влиянием мгновенных температур в зоне обработки.

Результаты. Выявлены основные факторы, влияющие на мгновенную температуру при абразивной обработке. В результате опытов были определены значения мгновенной температуры при различных условиях шлифования. Исходя из экспериментальных значений температур, было проведено математическое моделирование и определена зависимость деформации и остаточных напряжений поверхности заготовок от мгновенной температуры шлифования. Приведены рекомендации оптимальных режимов шлифования, при которых мгновенная температура будет наименьшей.

Научная новизна. Определена зависимость деформаций, напряжений и смещений в заготовке под влиянием мгновенной температуры в зоне резания при различных режимах шлифования.

Практическая значимость. В результате исследований были разработаны практические рекомендации по выбору оптимальных режимов шлифования, в которых мгновенная температура меньше влияет на возникновение дефектов во время обработки.

Ключевые слова: мгновенная температура, математическое моделирование, метод конечных элементов, абразивное шлифование, абразивные материалы, режимы шлифования

*Рекомендовано до публікації докт. техн. наук
Г. П. Болотовим. Дата надходження рукопису 17.07.18.*