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AUTOMATED DUAL-CHANNEL CONTROL OF INTERMITTENT DIAMOND GRINDING BASED ON THERMAL AND VIBRATION STATES

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This paper investigates the thermal behavior of intermittent diamond grinding under conditions of automated control of the tool–workpiece contact structure and energy input intensity. The grinding process is modeled as a closed nonlinear dynamic system with logical switching, in which contact intermittency is formed in real time based on the thermal state of the grinding zone and adaptive correction of the normal grinding force.

Numerical simulations show that in the absence of control the contact-zone temperature increases monotonically and, for the adopted parameters, approaches a steady-state value of approximately 76 °C, exceeding acceptable thermal limits. Implementation of a single-channel temperature-based control results in the formation of a stable thermal limit cycle between 45 °C and 58 °C, with a temperature oscillation amplitude of 12–13 °C and an average cycle period of 4–5 s. In this mode, the mean process temperature is reduced by approximately 10–12% compared to uncontrolled grinding; however, the temperature remains above 90% of the upper admissible limit for 20–25% of the total processing time.

The proposed dual-channel control strategy, combining temperature-based contact intermittency with adaptive adjustment of the grinding force, leads to a pronounced modification of the thermal dynamics. Peak temperatures are reduced by 3–4 °C relative to the single-channel mode, the thermal cycle amplitude decreases to 6–8 °C, and the mean temperature is further reduced by 5–8%. The fraction of time during which the temperature remains close to the upper allowable limit is more than halved and does not exceed 8–10%.

Quantitative analysis of the contact time structure reveals that the contact duty ratio decreases from 0.60–0.65 in the temperature-controlled mode to 0.3–0.4 under dual-channel control, while the switching frequency is reduced from 0.35–0.40 Hz to 0.25–0.30 Hz. This indicates the formation of a less intensive and more uniformly distributed energy input over time. The results demonstrate that adaptive contact intermittency, treated as an active control variable rather than a fixed kinematic feature, provides an effective means of reducing thermal loading and improving thermal stability in intermittent diamond grinding without the use of external cooling.

Keywords: *diamond grinding; intermittent grinding; automated process control; thermal state; contact intermittency; numerical simulation.*

Eq. 6. Fig. 2. Ref. 8.

1. Problem formulation

Diamond grinding is one of the most energy-intensive abrasive processing processes, in which a significant part of the mechanical power is converted into heat in the contact zone "wheel-workpiece". Excess heat generation leads to a deterioration in surface quality, initiates thermal defects in the form of burns and microcracks, accelerates tool wear and reduces process stability. The generalized results of the studies show that it is the thermal state that determines the limiting operating modes of the grinding wheel and the productivity of the process [1, 7].

Classical and modern theoretical concepts of grinding emphasize the crucial role of thermal processes in the formation of cutting forces, energy consumption and conditions of thermal damage to the treated surface. The limitations of permissible modes are determined not only by the geometry of the contact, but also by the

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intensity of heat generation and the ability of the system to remove heat, which is especially critical for hard and brittle materials [2, 5].

A separate practical difficulty is the conditions under which the use of intensive cooling is technologically, environmentally or operationally limited. In such cases, the importance of methods for reducing peak temperatures by structural means increases, in particular by controlling the temporal organization of contact between the tool and the workpiece. Intermittent grinding is considered an effective approach to thermal stabilization of the process due to the alternation of heating and thermal relaxation phases [3, 4].

Thus, the task of automated control of intermittent diamond grinding by temperature and dynamic state is directly related to important practical tasks of improving the quality of processing, tool life, and reliability of abrasive processes in modern mechanical engineering.

2. Analysis of recent research and publications

The fundamentals of the theory of grinding, including the description of heat generation, heat flux distribution and conditions of thermal damage to the surface, are considered in detail in works devoted to the modeling and analysis of abrasive machining processes. These studies show that thermal phenomena are decisive for the formation of surface quality and tool wear [1, 2].

A significant body of work is devoted to intermittent grinding as a method of reducing cutting temperature. In particular, it has been established that optimization of contact discontinuity parameters, such as the number of contacts of working protrusions and the ratio of the lengths of the "protrusion-recess", can lead to a significant decrease in the temperature in the contact zone without reducing productivity [3].

In parallel, a research direction devoted to dry and highly efficient grinding is developing, in which it has been proven that the structural organization of contact and energy input control can partially compensate for the lack of coolant [4, 8].

A separate class of works focuses on the dynamic aspects of grinding, in particular on regenerative oscillations in processes with loss or self-interruption of contact. It has been shown that intermittency significantly changes the conditions for the formation of regeneration and the time parameters of the feedback, which directly affects the dynamic stability of the process [6].

Modern review publications emphasize the need to integrate process models with automated control and monitoring systems, which allows moving from empirical selection of modes to adaptive control of abrasive processing [1].

Despite the existence of thorough studies of thermal processes in grinding and a significant body of work devoted to dynamic stability, these areas are mostly considered separately in the scientific literature. Classical thermal models are based on stationary or quasi-stationary contact modes and do not take into account the variable time structure of the tool-workpiece interaction inherent in intermittent grinding [2, 5].

On the other hand, works on the analysis of regenerative oscillations in processes with self-interruption of contact demonstrate a significant impact of contact loss on the conditions for the formation of oscillations, but are mainly analytical and descriptive in nature and are not focused on the synthesis of control effects that would use discontinuity as an active tool for process stabilization [6].

A separate unresolved issue remains the formalization of the interaction of thermal and dynamic circuits in the tasks of automated control of intermittent diamond grinding. Although modern reviews indicate the prospects of a systemic and multiparametric approach to abrasive machining control, consistent mathematical models of closed control loops that combine temperature and dynamic process states remain underdeveloped [1, 3].

This article is aimed at filling this gap, which determines its scientific novelty and relevance.

3. The purpose of the article

The objective of this study is to develop and validate a mathematical model for automated dual-channel control of intermittent diamond grinding, in which the thermal and vibrational states of the process are used to generate control signals aimed at ensuring thermal stability and limiting the development of regenerative oscillations without the use of intensive external cooling.

4. Results and discussion

The process of intermittent diamond grinding is considered as a non-stationary dynamic system in which the contact between the tool and the workpiece has a controlled temporal character. To formalize this feature, a control contact function is introduced.

$$u(t) \in \{0,1\}, \tag{1}$$

where $u(t)=1$ corresponds to the phase of active grinding, and - $u(t)=0$ the pause phase, during which there is no contact. Thus, the discontinuity of contact is considered as a direct controlling influence on the process.

The study analyzes three operating modes of the system, which are subsequently used to interpret the results of numerical modeling and graphical constructions:

1. mode A (without control) – continuous contact between the wheel and the workpiece, u(t)=1, the pressing force is constant;
2. mode B (temperature control) - controlled contact discontinuity is formed based on temperature thresholds, the pressing force remains constant;
3. mode C (dual-channel control) – controlled contact intermittency is combined with adaptive correction of the pressing force based on vibration.

The thermal state of the grinding zone is described by a generalized heat balance model of the concentrated type:

$$\frac{dT(t)}{dt} = -\frac{T(t) - T_{навк}}{\tau_T} + K_T u(t) F(t), \tag{2}$$

where $T(t)$ – temperature in the contact zone "circle-workpiece"; $T_{навк}$ – ambient temperature; τ_T – constant of thermal inertia of the system, which takes into account the heat capacity of the tool and workpiece; K_T – coefficient of conversion of mechanical energy into heat; $F(t)$ – force of pressing the wheel against the workpiece.

The first component on the right-hand side of the equation describes heat dissipation and temperature relaxation, while the second determines the intensity of heat release, which occurs only in the contact phase. ($u(t)=1$).

The dynamics of regenerative oscillations is described by the equation of motion taking into account the delay characteristic of grinding processes:

$$m\ddot{y}(t) + c\dot{y}(t) + ky(t) = u(t)G\left[y(t) - y(t-\tau)\right], \tag{3}$$

where $y(t)$ – normal deviation of the tool; m –the reduced mass of the machine tool–tool–workpiece system»; c – damping coefficient; k –equivalent stiffness; G – regenerative feedback coefficient; τ – effective delay related to grinding kinematics.

Multiplier $u(t)$ reflects the physical fact that the regenerative mechanism of oscillations is realized only in the presence of direct contact between the tool and the workpiece. In the pause phases, when there is no contact, the regenerative feedback is broken, which leads to a weakening of the conditions for the development of self-excited oscillations and contributes to the dynamic stabilization of the process.

To quantitatively assess the dynamic state of the process, a vibration characteristic is introduced in the form of a moving mean square amplitude:

$$A(t) = \sqrt{\frac{1}{\Delta t}\int_{t-\Delta t}^{t} y^2(\xi)d\xi}, \tag{4}$$

where y(ξ) – normal deviation of the tool relative to the workpiece at a point in time ξ; ξ – time integration variable; Δt – the averaging interval, which determines the time window for evaluating the vibrational state.

The value A(t) is used as an indicator of approaching dynamic instability and is an information variable of the second control channel.

The formation of the temperature control channel is carried out according to the relay law with hysteresis:

$$u(t) = \begin{cases} 0, T(t) \geq T_H, \\ 1, T(t) \geq T_L, \end{cases} \tag{5}$$

where T_H і T_L – upper and lower permissible temperature thresholds. This law ensures the limitation of the maximum temperature and the formation of a stable limiting thermal cycle.

The second control channel implements the correction of the pressing force depending on the vibration state:

$$F(t) = sat\left(F_o - K_A\left[A(t) - A_{доп}\right]_+\right), \tag{6}$$

where F_0 – nominal pressing force; K_A – the sensitivity coefficient of the vibration channel, which sets the intensity of the decrease in the pressing force with increasing vibration activity; $A_{доп}$ – permissible vibration level; $[\cdot]_+$ – negative truncation operator; sat(·) – saturation operator, which takes into account the physical limitations of the actuators.

The saturation operator limits the pressing force within the permissible interval, ensuring, on the one hand, the preservation of contact between the tool and the workpiece, and on the other hand, preventing overloading of the tool and the machine system.

The coordination of the thermal and dynamic subsystems through the control variables u(t) and F(t) forms a closed nonlinear system with logical switching, which creates a formal basis for the analysis of automated control of intermittent diamond grinding. Within the framework of this model, three control modes are considered, which differ in the principle of forming contact discontinuity and the level of energy input into the grinding process, and therefore lead to different thermal modes in the contact zone.

The impact of the selected control modes is assessed using graphical dependencies obtained by numerical integration of the system of differential equations of the thermal and dynamic subsystems. At each time step, the formation of control influences, calculation of the temperature in the contact zone and updating of the system state variables were sequentially carried out, which ensures the correct reproduction of transient and steady-state processes in controlled modes. To ensure comparability of results, numerical modeling in all modes was performed with a single set of parameters and under the same initial conditions: the initial temperature was taken $T(0)=T_{навк}=20$ ⁰C, the nominal pressing force is F0=10 N, and the dynamic subsystem was initiated by a small initial disturbance, which corresponds to the real conditions for starting the grinding process.

The thermal subsystem was described by a first-order model with a constant thermal inertia $\tau_T=8$ s and heat release coefficient $K_T=0{,}70$. Such values correspond to the characteristic time scale of heating and cooling of the contact zone "diamond wheel-workpiece" under dry grinding conditions and ensure the formation of distinct thermal regimes. The temperature control channel is implemented by a relay law with hysteresis, parameterized by thresholds $T_L=45$ ⁰C and $T_H=58$ ⁰C, which allows to limit the maximum temperature and form a stable cyclic mode without excessively frequent switching.

The dynamic subsystem was modeled as a weakly damped oscillatory system with a reduced mass m=1 kg, a natural frequency of about 25 Hz and a relative damping c=0.05. The effective delay of the regenerative feedback $\tau=0.22$ s is consistent with the kinematics of the process and takes into account inertial and delayed effects that affect the formation of the dynamic state when the contact conditions change. The second control channel is parameterized by the permissible level of the dynamic characteristic $A_{доп}=0{,}015$ and the sensitivity coefficient $K_A=180$; the correction of the pressing force was limited to the interval $F_{min}=6$ H…$F_{max}=12$ H, which ensures that contact between the tool and the workpiece is maintained and that both control circuits operate in harmony.

Numerical integration was performed with a step $\Delta t=0.1$ s on the interval $t_{max}=40$ s, which is sufficient for correct reproduction of slow thermal dynamics and controlled contact switching.

The temperature dependences shown in Figure 1 illustrate the fundamentally different thermal behavior of the process in the considered control modes. In the mode without control, the temperature increases monotonically and during the simulation approaches a steady level of about 76 ⁰C, which exceeds the permissible limits by 15–20%. In the temperature control mode (mode B), the average temperature decreases by approximately 10–12%, while a stable limit cycle is formed with an amplitude of temperature fluctuations of about 10–12 ⁰C and an average period of 4–5 s. The maximum temperature values exceed the upper threshold by no more than 1–1.5 ⁰C, which is due to the discrete implementation of relay control and the final integration step.

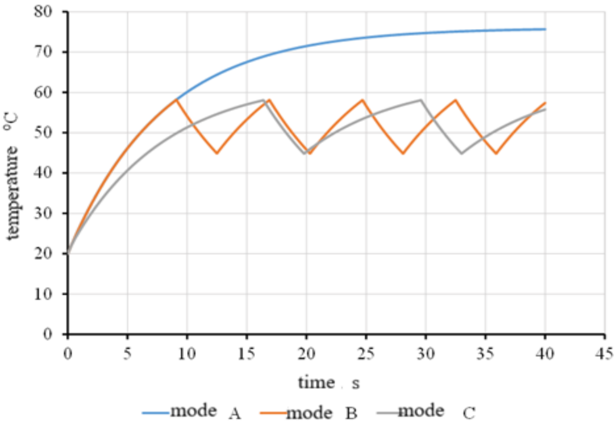

Fig. 1. Temperature dynamics in the contact zone during intermittent diamond grinding for different control modes

In the two-channel control mode (mode C), the cyclical nature of the temperature dynamics is preserved, but the peak temperature values decrease by an average of 3–4 ºC, and the amplitude of the temperature cycle decreases to 6–8 ºC. At the same time, the temperature cycle period increases by approximately 20–30%, which indicates a decrease in the intensity of heat release in the phases of active contact due to adaptive correction of the pressing force by the second control channel. The analysis of the time the temperature stays near the upper permissible threshold is particularly indicative: in the temperature control mode, this time is about 20–25% of the total duration of the simulation, while in the two-channel mode it is reduced by more than half and does not exceed 8–10%, which indicates a significant decrease in the thermal intensity of the process.

The temporal structure of the contact between the diamond wheel and the workpiece, determined by the control function u(t) (Fig. 2), is one of the key characteristics of the automated intermittent grinding process. Its generalized quantitative assessment is expedient to perform using the contact filling factor, which reflects the fraction of the time of the active grinding phase. According to the results of numerical simulation in the temperature control mode (mode B), the contact filling factor is approximately 0.60–0.65, which corresponds to a relatively uniform alternation of contact and pause phases, due exclusively to the thermal inertia of the system and a fixed heat release intensity.

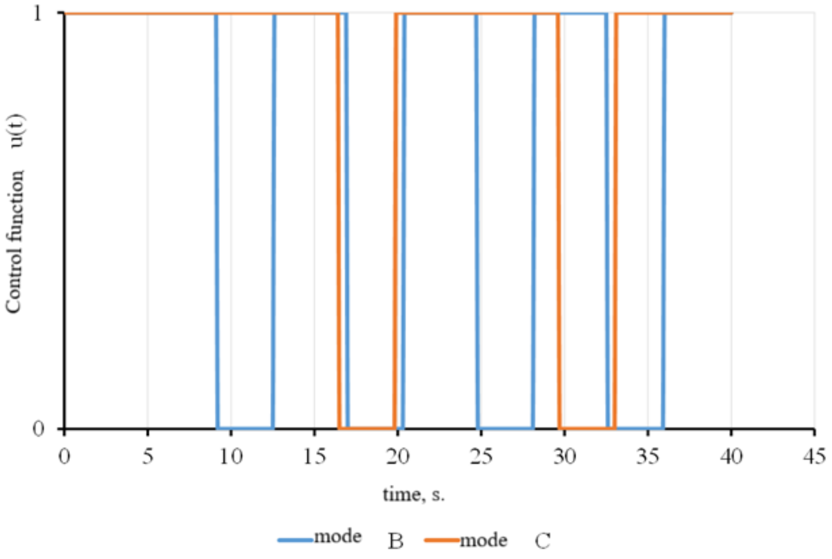

Fig. 2. Controlled discontinuity of contact between the diamond wheel and the workpiece under different control modes

In the two-channel control mode (mode C), the contact filling factor decreases to 0.3–0.4, which is associated with a decrease in the heating rate of the contact zone due to the correction of the pressing force. At the same time, the switching frequency between the contact and pause phases decreases: if in the temperature mode it is about 0.35–0.40 Hz, then in the two-channel mode it decreases to 0.25–0.30 Hz. This means that the contact discontinuity in mode C becomes less frequent, but more energetically “soft”, which reflects the adaptive nature of the control and the coordinated action of the thermal and energy circuits.

The time implementations of the contact control function, shown in Figure 2, clearly confirm these differences: in mode B, the discontinuity has a regular, almost periodic nature, while in mode C, the switching moments are shifted in time and become variable due to changes in the intensity of heat release.

Thus, the quantitative indicators of the temporal structure of the contact and the integral thermal characteristics are consistent with the temperature dependences shown in Figure 1 and confirm that the dual-channel control provides not only a limitation of the maximum temperature, but also a reduction in the average thermal load and the time the process spends in critical temperature zones. This justifies the feasibility of using adaptive formation of contact discontinuity as an effective tool for thermal stabilization of the diamond grinding process.

5. Conclusion

As a result of the conducted research, the possibility of effective thermal stabilization of the process of intermittent diamond grinding was substantiated by automated control of the time structure of the tool contact with the workpiece and the intensity of energy input. It was shown that considering the process as a closed nonlinear dynamic system with logical switching allows us to adequately describe the characteristic modes of heating and thermal relaxation in the grinding zone and to study the influence of control influences on the integral thermal characteristics.

Numerical modeling confirmed that single-channel temperature control ensures the formation of a stable limiting thermal cycle and limiting the maximum temperature, but is accompanied by a relatively high contact filling factor and a significant time of the process near the upper permissible temperature level. The introduction of two-channel control, in which the correction of the pressing force is consistent with the temperature state of the process, leads to a noticeable change in the structure of the thermal cycle: a decrease in peak temperatures, a decrease in the average thermal load and a reduction in the time of residence in critical temperature zones by more than two times. This creates favorable conditions for reducing the thermal stress of the tool and increasing the stability of the machining process.

Quantitative analysis of the time structure of the contact showed that two-channel control leads to a decrease in the contact filling factor and a decrease in the frequency of switching between the contact and pause phases. At the same time, the contact discontinuity becomes adaptive and ceases to be only a consequence of the thermal inertia of the system, turning into an active control mechanism for redistributing energy input in time. The results obtained confirm that it is the coordinated action of the temperature and energy control loops that provides a more “soft” thermal regime compared to the single-channel approach.

The scientific novelty of the study lies in the development and computational substantiation of a two-channel mathematical model of automated control of intermittent diamond grinding, in which the contact discontinuity is considered not as a fixed kinematic feature, but as an adaptive control variable, consistent with the thermal state of the process and the intensity of energy input. Unlike traditional approaches, the proposed model allows quantitatively linking the temporal structure of contact with integral thermal parameters and assessing the effectiveness of control over the parameters of the thermal cycle. Prospects for further research in this direction are associated with the experimental identification of model parameters for specific types of diamond wheels and workpiece materials, as well as with the expansion of the model taking into account the spatial heterogeneity of the temperature field in the grinding zone. It is also advisable to study the influence of controlled contact discontinuity on tool wear and the quality of the machined surface, as well as the integration of the proposed approach with multi-sensor monitoring systems to build more universal algorithms for adaptive control of abrasive processing.

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АВТОМАТИЗОВАНЕ ДВОКАНАЛЬНЕ КЕРУВАННЯ ПЕРЕРИВЧАСТИМ АЛМАЗНИМ ШЛІФУВАННЯМ ЗА ТЕМПЕРАТУРНИМ І ВІБРАЦІЙНИМ СТАНОМ

У цій статті досліджено теплову поведінку переривчастого алмазного шліфування в умовах автоматизованого керування структурою контакту інструмента із заготовкою та інтенсивністю підведення енергії. Процес шліфування змодельовано як замкнену нелінійну динамічну систему з логічним перемиканням, у якій переривчастість контакту формується в реальному часі на основі теплового стану зони шліфування та адаптивної корекції нормальної сили шліфування.

Чисельне моделювання показало, що за відсутності керування температура в зоні контакту монотонно зростає і для прийнятих параметрів наближається до усталеного значення близько 76 °С, перевищуючи допустимі теплові межі. Реалізація одноканального керування за температурою приводить до формування стійкого теплового граничного циклу в межах 45–58 °С, з амплітудою температурних коливань 12–13 °С та середнім періодом циклу 4–5 с. У цьому режимі середня температура процесу знижується приблизно на 10–12 % порівняно з некерованим шліфуванням; однак температура залишається вище 90 % від верхньої допустимої межі протягом 20–25 % загального часу обробки.

Запропонована двоканальна стратегія керування, яка поєднує температурне регулювання переривчастості контакту з адаптивним регулюванням сили шліфування, приводить до суттєвої зміни теплової динаміки. Пікові температури зменшуються на 3–4 °С порівняно з одноканальним режимом, амплітуда теплового циклу знижується до 6–8 °С, а середня температура додатково зменшується ще на 5–8 %. Частка часу, протягом якого температура залишається близькою до верхньої допустимої межі, скорочується більш ніж удвічі і не перевищує 8–10 %.

Кількісний аналіз структури часу контакту показує, що коефіцієнт заповнення контакту зменшується з 0,60–0,65 у режимі температурного керування до 0,3–0,4 за двоканального керування, тоді як частота перемикань знижується з 0,35–0,40 Гц до 0,25–0,30 Гц. Це свідчить про формування менш інтенсивного й більш рівномірно розподіленого в часі енергетичного впливу. Отримані результати демонструють, що адаптивна переривчастість контакту, розглянута як активна керована змінна, а не як фіксована кінематична особливість, є ефективним засобом зниження теплового навантаження та підвищення теплової стабільності при переривчастому алмазному шліфуванні без використання зовнішнього охолодження.

Ключові слова *алмазне шліфування; переривчасте шліфування; автоматизоване керування процесом; тепловий стан; переривчастість контакту; чисельне моделювання.*

Ф. 6. Рис. 2. Літ. 8

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