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Mathematical temperature simulation in tool-to-work contact zone during metal turning[*]

E. V. Bordatchev[1], V. P. Lapshin[2]**
[1] Don State Technical University, Rostov-on-Don, Russian Federation
[2] National Research Council Canada, Ottawa, Canada

Математическое моделирование температуры в зоне контакта инструмента и изделия при токарной обработке металлов[***]

Е. В. Бордачев[1], В. П. Лапшин[2]**
[1] Национальный научно-исследовательский совет Канады, Оттава, Канада
[2] Донской государственный технический университет, Ростов-на-Дону, Российская Федерация

Introduction. Two factors of metal turning are compared: the dissipated temperature and the power of irreversible transformations in the material of the product and the tool. The paper is devoted to the issues of mathematical modeling of their link.
Materials and Methods. The mathematical apparatus is based on the modification of the Volterra equation which involves the use of double integral. It shows how the thermal energy released earlier during cutting affects the current state of temperature in the tool-to-work contact zone. In addition to the proposed new basic mathematical model, the processing effect of the observed data on the power of irreversible transformations and the measured temperature in the tool-to-work contact zone under metal turning are used. The experiments were carried out on 1K625 machine and STD.201-1 stand. A specialized software tool for processing information arrays describing the processes occurring during cutting (reaction forces, tool vibrations and power of irreversible transformations) was created in the Matlab package. The same tool has performed the temperature calculation in the tool-to-work contact zone.
Research Results. The procedure of parametric identification of the proposed basic mathematical model is carried out. The resulting model showed a high degree of proximity of the experimental data on the temperature in the cutting zone and the simulated level of thermal energy; but in the initial section of the measurable temperature dependence, the results of these two approaches are in rather poor agreement. This can be explained by an error of the experimental temperature measurement based on the estimate of the thermoelectromotive force (thermal EMF) output which is generated as a result of the dynamic thermocouple formation in the tool-to-work contact zone.

Введение. Сопоставлены два фактора токарной обработки металлов резанием: рассеиваемая температура и мощность необратимых преобразований в материале изделия и инструмента. Статья посвящена вопросам математического моделирования их связи.
Материалы и методы. Математический аппарат основан на модификации уравнения Вольтерры, которая предполагает использование двукратного интеграла. Он показывает, как выделенная ранее при резании тепловая энергия влияет на текущее состояние температуры в зоне контакта инструмента с обрабатываемой деталью. В работе помимо предложенной новой базовой математической модели использованы результаты обработки экспериментальных данных о мощности необратимых преобразований и об измеряемой температуре в зоне контакта инструмента с деталью при токарной обработке металла. Эксперименты проводились на станке 1К625 и стенде STD.201-1. В пакете Matlab была создана специализированная программа для обработки массивов информации, описывающих процессы, протекающие при резании (силы реакции, вибрации инструмента и мощность необратимых преобразований). В этой же программе выполнен расчет температуры в зоне контакта инструмента и детали.
Результаты исследования. Проведена процедура параметрической идентификации предлагаемой базовой математической модели. Полученная модель показала высокую степень близости экспериментальных данных о состоянии температуры в зоне резания и моделируемого уровня тепловой энергии, однако на начальном участке измеряемой температурной зависимости результаты двух этих подходов не вполне согласуются. Это можно объяснить погрешностью экспериментального измерения температуры на основе оценки вырабатываемой термоэлектродвижущей силы (термоЭДС), которая формируется в результате образования естественной термопары в зоне контакта инструмента и детали.

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[**] E-mail: Lapshin1917@yandex.ru, Evgueni.Bordatchev@nrc-cnrc.gc.ca
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Discussion and Conclusions. The proposed mathematical model enables to adequately describe the conversion of the mechanical component of the cutting energy into the thermal component through the indicator of the total output power of the mechanical interaction in the cutting zone for all the processing time.

Обсуждение и заключения. Предлагаемая математическая модель позволяет адекватно описывать процесс преобразования механической составляющей энергии резания в тепловую составляющую через показатель суммарной выделяемой мощности механического взаимодействия в зоне резания за все время обработки.

Keywords: turning, cutting, power of irreversible transformations, metal working, thermal conductivity of metals, Volterra integral equation, thermoelectromotive force (thermal EMF).

Ключевые слова: точение, резание, мощность необратимых преобразований, обработка металлов, теплопроводность металлов, уравнение Вольтерры, термоэлектродвижущая сила (термоЭДС).

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Introduction. Thermal processes occurring under metal processing on the machine tools (both in metals and in other environments) are hard to describe. Their analysis is based on the Fourier heat condition equation [1]. In cases related to metal cutting, you need to have an idea about the temperature in the tool-to-work contact zone [2–5]. At that, there is no need to control the heat propagation beyond this zone since it does not affect the processing conditions. Similar reasoning can be applied to another widely used method for describing thermal processes, which considers the formation of heat source-drains in a workpiece [6]. Such approaches do not allow using the cutting process dynamics in the description of emerging thermal phenomena in the contact zones and developing a system of equations to represent the conversion of mechanical energy into thermal energy.

During operations with metals on the machine tools, irreversible transformations in workpieces and tools cause the heat generation, which, according to the second law of thermodynamics, is dissipated in space. Thermal processes in metals are more inertial than the treatment process dynamics, therefore dissipation lasts long enough. In the case in hand, the heat generation itself is associated with the power of irreversible transformations [11], which depends on the magnitude of the reaction forces to the tool forming movements [2–5] in the tool-to-work contact zone. At the same time, heat generation is the primary mechanism of dissipation of the released energy of material conversion [12].

The cutting process dynamics and the issues of its simulation are directly related to the representation of forces and reactions in the coordinates of the process state. In this case, as a rule, only the mechanical component is considered, as can be seen from foreign [13–18] and national [19–21] papers. Thus, it is advisable to introduce coordinates describing the temperature variation in the tool-to-work contact zone into the simulation of dynamics of the metal processing processes through consideration of the irreversible transformations. This approach will increase adequacy of the used mathematical apparatus.

Materials and Methods

Mathematical Model Validation. The forces preventing the tool from penetrating into the workpiece material have a complex spatial arrangement in the coordinate system associated with the tool strain axes. In the papers on the analysis of the reaction forces occurring in the cutting zone, it is mostly common to resolve such a reaction into components [4–6, 10, 19–21]. In the case under consideration, the following relations between the components of the reaction forces will be valid [5]:

$$R = \sqrt{P_x^{\ 2} + P_\mathrm{y}^{\ 2} + P_\mathrm{z}^{\ 2}}, \qquad (1)$$

where R is general force response from the cutting process to the forming movements of the tool; P_x is projection of the force response on the axis of the main rotational cutting movement in the feed direction; P_y is projection of force reaction directed along the radius of the main rotational cutting movement of at the cutting top; P_z is projection of the force reaction on the axis coinciding with the main movement speed at the tool tip.

The relationship between $P_x, P_\mathrm{y}, P_\mathrm{z}$ forces introduced depends on many factors: the tool geometry, the tool wear factor, etc. [4]. Thus, in [5], when machining with a sharp cutter with the parameters of $\gamma = 15^0$, $\varphi = 45^0$ and $\lambda = 0^0$, the ratio is on average equal to

$$P_x, P_y, P_z = (0{,}3 - 0{,}4), (0{,}4 - 0{,}5). \quad (2)$$

Similar reasoning can be provided on analyzing the speeds of the relative tool movement along the workpiece, and we obtain the total speed of such movement:

$$V = \sqrt{V_x^{\ 2} + V_{\mathrm{y}}^{\ 2} + V_{\mathrm{z}}^{\ 2}}. \quad (3)$$

With these arguments in view, we define the power of irreversible transformations:

$$N = \sqrt{P_x^{\ 2} + P_{\mathrm{y}}^{\ 2} + P_{\mathrm{z}}^{2}}\sqrt{V_x^{\ 2} + V_{\mathrm{y}}^{\ 2} + V_{\mathrm{z}}^{\ 2}}. \quad (4)$$

Suppose that heat generation during cutting in the metal-cutting machines linearly depends on the power of irreversible transformations:

$$T_p = k_T N\,. \quad (5)$$

Here, T_p is the value describing the temperature increments in the cutting zone (^{0}C); k_T is the coupling coefficient between the power of irreversible transformations in the cutting zone and the magnitude of the increment of thermal energy in the tool-to-work contact zone with c^{0}C/Nm dimension. However, the total temperature value at a specific instant in time and in a given tool-to-work contact zone will be determined not only by the current value of heat gain. Due to the heat dissipation of in the material of the workpiece and tool, the impact of the following should be considered:
- power of irreversible transformations throughout the previous path,
- product processing time.

Imagine processing in the form of a discrete process graph where $N(n)$ is current value of the power of irreversible transformations; $L(n)$ is current value of the tool path during machining; $t(n)$ is current value of the processing time. According to (5), at each point of the discrete graph of the treatment process, heat increment proportionate to the power of non-reversible transformations at this point in space and time will be generated. The current temperature value at n point will be determined by both the heat gain at that point and the effect of temperature increments that previously occurred on the tool path (L) during processing (t). With the increase in time and distance passed, the impact of these factors on the process of heat generation in the contact zone under study weakens; therefore, an approach based on the use of the Volterra operator of the second kind is convenient for the mathematical description [10]. It cannot be applied directly because of the complexity of describing the heat propagation in metals; therefore, we will take the multiplicative criterion for assessing the effect of the previous heat gain on the current value in the form of a double integral as a basic model:

$$T_z = \Theta_s + k_T \iint\limits_D w_L(\gamma - L) w_t(\eta - t) N(\gamma, \eta) d\gamma d\eta\,. \quad (6)$$

Here, T_z is heat value in the tool-to-work contact zone; Θ_s is ambient temperature; $w_L(\gamma - L)$ is the kernel which characterizes the effect of the previously generated power of irreversible transformations along the processing path on the current temperature value; $w_t(\eta - t)$ is the kernel which characterizes the impact of the previously generated power of irreversible transformations in terms of processing time on the current temperature value; D is the domain of integration characterizing the space-time heat dissipation; γ has the distance dimension, m; η has the processing time dimension, s. The kernels of the integral operator themselves are dimensionless gain constants.

The integral operator represented as a double integral (6), can be reduced to a multiple integral of the following form:

$$T_z = \Theta_s + k_T \int\limits_0^{L(t)} w_L(\gamma - L)\, d\gamma \int\limits_0^t w_t(\eta - t) N(\eta) d\eta\,. \quad (7)$$

The tool path is a function of time because each time value can be assigned the value of the distance passed. Therefore, the approach (7) is valid.

It is convenient to use exponential functions of the following form [10] as kernels of the integral operator proposed in (7):

$$\begin{cases} w_L(\gamma - L) = e^{\alpha_1(\gamma - L)} \\ w_t(\eta - t) = e^{\alpha_2(\eta - t)} \end{cases}, \quad (8)$$

where α_1, α_2 are scaling parameters of the integral operator to be identified.

Thus, the integral operator proposed in (7) takes the following form:

$$T_z = \Theta_s + k_T \int\limits_0^{L(\mathrm{t})} e^{\alpha_1(\gamma - L)} d\gamma \int\limits_0^t e^{\alpha_2(\eta - t)} N(\eta) d\eta\,. \quad (9)$$

This operator has the solution for the stationary case when the power of irreversible transformations is constant: $N_0 = N(t)$.

$$T_z = \Theta_S + \frac{k_T N_0}{\alpha_1 \alpha_2}(1 - e^{-\alpha_1 L})(1 - e^{-\alpha_2 t}) . \quad (10)$$

As can be seen from (10), under a stationary machining process, temperature in the

$$T_z = \Theta_S + \frac{k_T N_0}{\alpha_1 \alpha_2} . \quad (11)$$

We illustrate these arguments by setting $\Theta_S = 25$ ^{0}C; k_T = 0.0026 s^{0}C / Nm; $\alpha_1 = 0.03$; $\alpha_2 = 0.01$; $N_0 = 20$ Nm/s (Fig. 1).

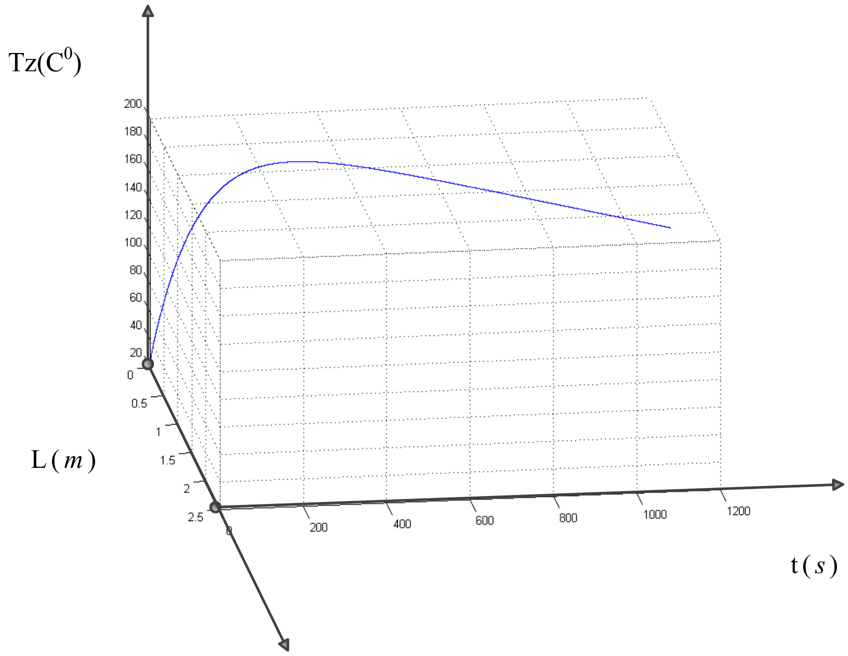

Fig. 1. Implementation of stationary temperature increase in the cutting zone

Fig. 1shows that the stationary heat process in the cutting zone increases exponentially and – having reached some equilibrium state – does not change anymore. Real processes occurring in machine tools are not stationary [11–12]. Based on these considerations, the process shown in Fig. 1 can be regarded as a movement towards which the temperature of the tool-to-work contact zone tends in a steady case. At that, the equation (10) is a generator equation for the integral operator (9).

Research Results

Parametric identification of the model from experimental data and simulation results. For the parametric identification of the model, a full-scale experiment was conducted on 1K625 lathe with the installed STD.201-1 stand. The stand is designed to study dynamic and thermal processes occurring during metal cutting on lathes in various modes.

The basic objective of the experiment was to study the impact of cutting dynamics on thermal processes in the tool-to-work contact zone. The change in cutting dynamics is understood as the cross effect of tool wear and cutting process associated with the force reaction occurring in the cutting zone. Measurement of this reaction and temperature through thermoelectromotive force (thermal EMF) generated in the tool-to-work contact zone allows evaluating the impact of the cutting dynamics on the thermal processes in the specified zone.

During the experiment, continuous turning of a shaft-type part was performed. At this, all processing parameters were preserved and the change in the force response from the cutting process was monitored. The conditions and the basic results of the experiment are described in detail in [22].

The data obtained as a result of a full-scale experiment are of discrete nature; therefore, it is impossible to directly apply the model represented by the integral operator (9) to them. For this reason, it is required to modify the basic mathematical model that describes the thermal process dynamics in the tool-part contact. To begin with, we leave in reasoning only a member of the integral operator depending on the power of irreversible transformations:

$$T_z^{\,N} = k_T \int\limits_0^{L(t)} e^{\alpha_1(\gamma - L)} d\gamma \int\limits_0^{t} e^{\alpha_2(\eta - t)} N(\eta) d\eta . \qquad (12)$$

Since the experiment is already carried out, its completion time (t_k) and $L(t_k)$ path value corresponding to it are constants. Therefore, it will be valid to factor the exponents with these values outside the integrals:

$$T_z^{\,N} = k_T e^{-\alpha_1 L(t_k)} e^{-\alpha_1 t_k} \int\limits_0^{L(t_k)} e^{\alpha_1 \gamma} d\gamma \int\limits_0^{t_k} e^{\alpha_2 \eta} N(\eta) d\eta . \qquad (13)$$

Assume that there is a certain discrete set of the calculated power values of irreversible transformations obtained as a result of analyzing discrete experimental information on the cutting process dynamics, that is $N(t) = N_1, N_2, N_3, N_4$......... On this basis, the integral operator (13) takes the form of the following sum:

$$\begin{aligned} T_z^{\,N} = k_T e^{-\alpha_1 L(t_k)} e^{-\alpha_1 t_k} [N_1 \int\limits_0^{L_1} e^{\alpha_1 \gamma} d\gamma \int\limits_0^{t_1} e^{\alpha_2 \eta} d\eta + N_2 \int\limits_{L_1}^{L_2} e^{\alpha_1 \gamma} d\gamma \int\limits_{t_1}^{t_2} e^{\alpha_2 \eta} d\eta + \Leftrightarrow \\ \Leftrightarrow + N_3 \int\limits_{L_2}^{L_3} e^{\alpha_1 \gamma} d\gamma \int\limits_{t_2}^{t_3} e^{\alpha_2 \eta} d\eta + N_4 \int\limits_{L_3}^{L_4} e^{\alpha_1 \gamma} d\gamma \int\limits_{t_3}^{t_4} e^{\alpha_2 \eta} d\eta + ...] \end{aligned} . \qquad (14)$$

Assuming that $N_1 = 0$, we get the final solution for the case described by the expression (14):

$$\begin{aligned} T_z^{\,N} = \frac{k_T e^{-\alpha_1 L(t_k)} e^{-\alpha_1 t_k}}{\alpha_1 \alpha_2} [N_2 (e^{\alpha_1 L(t_2)} - e^{\alpha_1 L(t_1)})(e^{\alpha_2 t_2} - e^{\alpha_2 t_1}) + \Leftrightarrow \\ \Leftrightarrow + N_3 (e^{\alpha_1 L(t_3)} - e^{\alpha_1 L(t_2)})(e^{\alpha_2 t_3} - e^{\alpha_2 t_2}) + ...] \end{aligned} . \qquad (15)$$

The expression (15) is very convenient for processing large arrays of discrete information on the cutting process. In fact, this is a sum of powers of irreversible transformations weighted relative to the final value.

Consider only one experiment from the series in which there was no wear on the back surface of the tool. In the following cases, the tool wear changed, and hence, the process dynamics (from both a mechanical and a thermodynamic point of view). Note that the results obtained in this experiment are generalized for all other cases, but the length of the paper does not allow them to be considered.

Fig. 2 shows the process response to the forming movements of the tool along *x* axis.

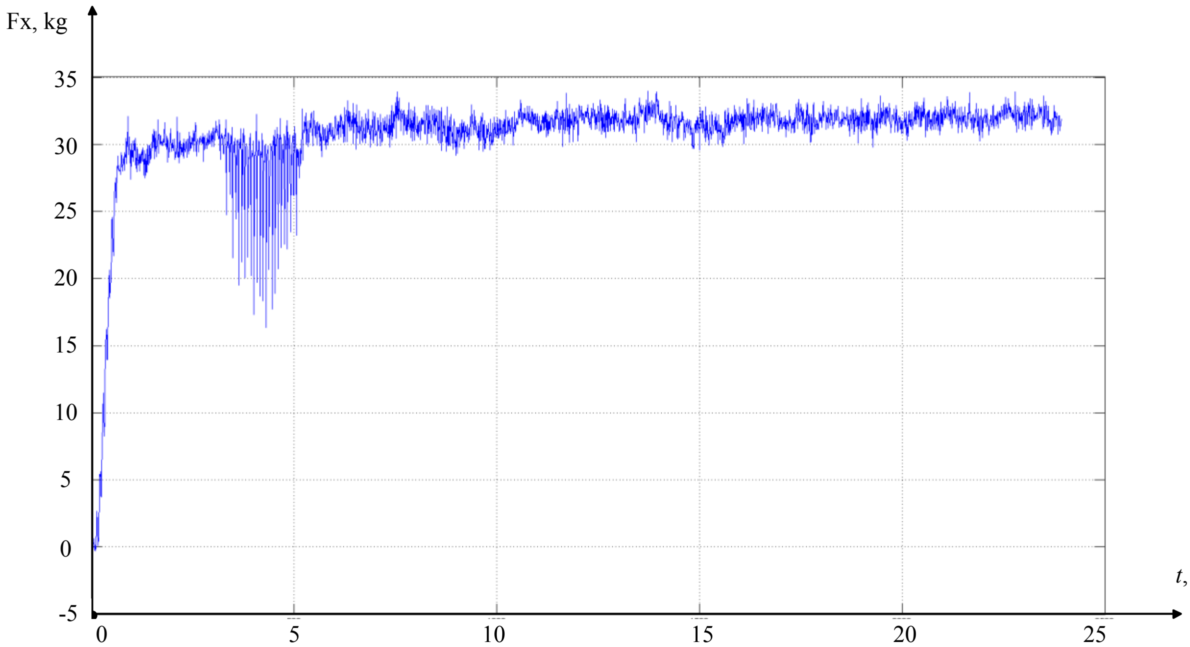

Fig. 2. Process response to forming movements of the tool along *x* axis in the first experiment step

As can be seen from Fig. 2, the reaction to the forming tool movements during turning is essentially nonstationary, but there is a certain attracting variety around which a perturbed toolpath is generated. Similar to that shown in Fig. 2, reactions to the shape-forming tool movements along the remaining axes were obtained in the experiment. In addition, information is available on tool accelerations relative to the workpiece. Integration of these data with consideration of the known cutting elements allowed us to obtain the values of the machining speeds and the toolpath along the workpiece.

A specialized software tool for processing information arrays to describe the processes occurring during cutting (reaction forces, tool vibrations and power of irreversible transformations) was created in the Matlab package. The same tool has performed the temperature calculation in the tool-to-work contact zone according to (15). The model parameters are presented in Table 1.

Table 1

Parameters of the identified model

α_1	α_2	k_T c^{0}C/Нм	Θ_s ^{0}C
0.00099	0.00078	0.000159	24.8

Fig. 3 shows the simulation results of the expression (15) considering the parameters of Table 1, as well as the experimentally measured characteristic.

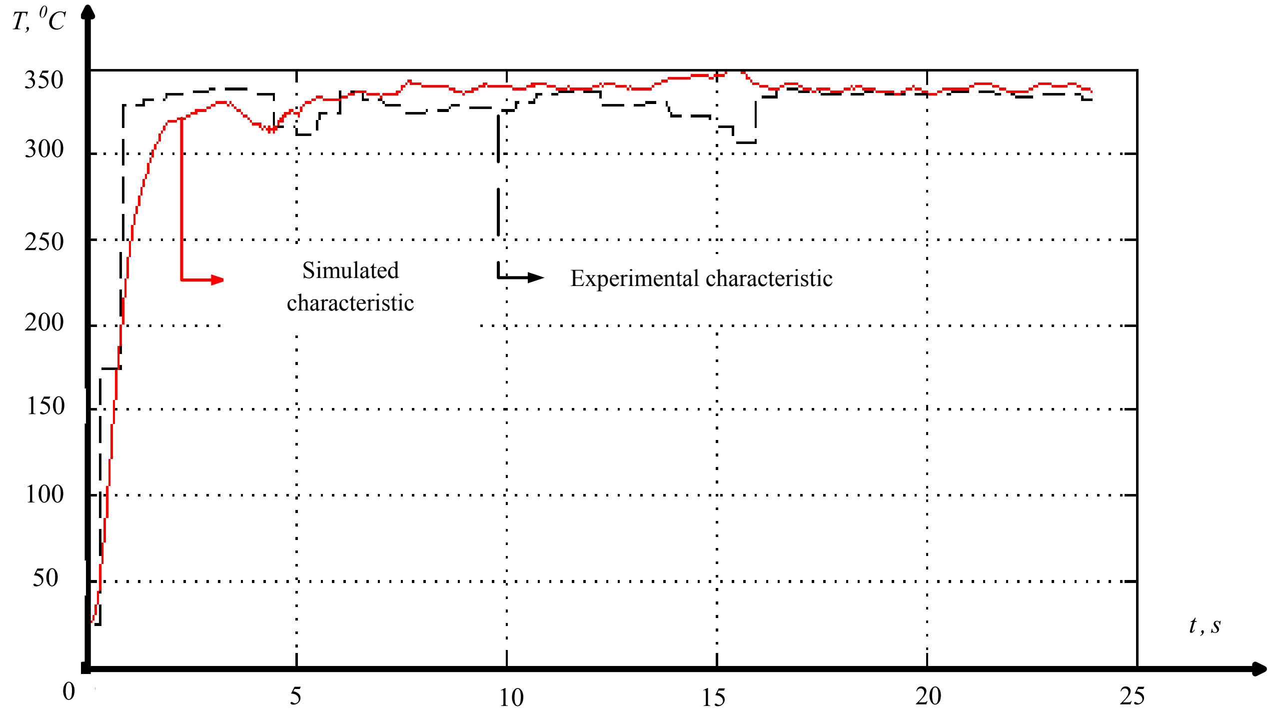

Fig. 3. Comparison of the results obtained in the experiment and calculated from the model

Comparison of Fig. 3 and Fig. 2 shows that the measured temperature value, when the tool enters the workpiece, increases from 25° C (ambient temperature) to 330–340 ° C. According to Fig. 3, first, a faster growth of the measured thermal EMF value is observed, and at the end of the process, the thermal EMF is stabilized.

This is explained by the fact that at STD.201-1 stand, it is not the temperature as such is measured in the contact zone, but the thermal EMF of the natural thermocouple formed at the tool-workpiece contact. At the beginning of the experiment, due to an overshot of the temperature gradients, the thermal EMF shows too large and fast temperature rise, and then, as the temperature gradients diverge, it is stabilized. This effect is widely known. For example, in [5], it is said: “The method of a natural thermocouple is unreliable since the cutting temperature is stabilized within 2–3 s”.

In view of dynamics, the temperature variation (see Fig. 3) obtained as a result of simulating the expression (15) is close to the processes occurring during cutting (see Fig. 2). The graph shows the continuing growth of temperature due to the continuing increase in reaction forces (see Fig. 2). The graph also reflects all the dynamic features of the process including low-amplitude power jumps.

From this we can deduce the following: the proposed model describes the cutting temperature variation more accurately than the data of a dynamic thermocouple. Fig. 3 also shows that the simulated characteristic describing the change in the cutting zone temperature, in general, coincides qualitatively with the experimental dependence. The experimental and simulated characteristics coincide most fully after stabilization of the cutting process, within 15-24 seconds.

Discussion and Conclusions. The study results provide an answer to the following question: how to make the description of the hereditary nature of the heat transfer and accumulation during metal turning be adequate to the experimental data. For this purpose, it is required to simulate the temperature in the tool-to-work contact zone on the basis of the proposed modified Volterra operator.

In science terms, the proposed basic mathematical model and the results of its identification on the basis of the experiment on real metal processing are of the main interest. Here, there is a high degree of coincidence of the simulated values of thermal energy in the tool-to-work contact zone in the period of steady-state processing.

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Authors:

Lapshin, Victor P.,
associate professor of the Production Automation Department, Don State Technical University (1, Gagarin sq., Rostov-on-Don, 344000, RF), Cand.Sci. (Eng.), associate professor,
ORCID: https://orcid.org/0000-0002-5114-0316
lapshin1917@yandex.ru

Bordatchev, Evgueni V.,
professor of the National Research Council Canada (1200 Montreal Road, Ottawa ON, Canada), Ph.D.,Dr.Eng.Sc., professor,
ORCID: https://orcid.org/0000-0003-2347-6338
Evgueni.Bordatchev@nrc-cnrc.gc.ca