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The study of end milling temperature of low-alloy steel in coarse-grained and ultrafine-grained states

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Abstract: The paper presents the results of the study of the end milling temperature of low-alloy steel depending on the cutting modes and the type of crystalline structure. The experiment was carried out on a PROMA FHV-50PD universal milling machine. The blanks were processed using a 12-12D-30C-75L-4F HRC55 carbide milling cutter. No cooling was used during processing. The obtained data were statistically analyzed to identify the dependence of the end milling temperature of low-alloy steel on the processing modes and the steel crystalline structure. When creating a mathematical model of cutting temperature, the authors carried out a bootstrap analysis to identify the significance of the parameters of the processing modes. The mathematical model was chosen using the Akaike informative criterion. It was found that mathematical models of the temperature dependence on processing modes for both types of crystalline structure include the cutting depth in the second power. At the same time, for steel in an ultrafine-grained state, both the cutting depth and the feed are statistically significant. It was not possible to detect the influence of cutting speed on temperature in the studied range of processing modes. Thus, when milling this group of materials, the force component primarily determined by the cutting depth exerts the predominant influence on the temperature regime. The level of cutting temperature when processing steel in an ultrafine-grained state is generally higher than when processing steel in a coarse-grained state, which should be associated with the increased physical and mechanical properties of steel with an ultrafine-grained crystalline structure.

Keywords: material cutting; coarse-grained (CG) and ultrafine-grained (UFG) structure; low-alloy steel; cutting temperature; end milling.

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INTRODUCTION

The study of the properties of bulk nanostructured metal materials with an ultrafine-grained (UFG) structure is one of the most promising areas of modern materials science [1; 2]. However, despite the growing interest in such materials on the part of researchers and engineers, there is insufficient data on the cutting machinability of materials with a UFG structure. There is data on the surface roughness dependence on the type of crystalline structure of the material being processed when milling B95 aluminum alloy [3]. It follows from the results of the study [3] that when processing an alloy with a UFG structure, the surface quality is higher as compared to an alloy with a coarse-grained (CG) structure. Similar studies were carried out for turning 12H18N10T stainless steel [4]. The paper also notes a significant decrease in roughness parameters when processing materials with a UFG structure. It follows from work [5], that the microhardness and microstructure of the near-surface layer of the blank, after milling, differ for steel with coarse and fine grains. In work [6] dealing with the study of end milling of microchannels in a UFG low-carbon steel blank, a decrease in surface roughness parameters when processing UFG material is also observed.

The work [7] proposes a convenient and effective method to determine the constants of the Johnson – Cook model for UFG titanium. The authors subsequently, used the obtained values of the constants, to calculate the cutting forces when processing UFG titanium [8]. The work [9] describes a fast and accurate algorithm for calculating the temperature when cutting UFG titanium, and notes that the cutting temperature of the VT6 titanium alloy, with an UFG structure, is significantly lower than the cutting temperature of an alloy with a CG structure. The authors of [10] note an increase in cutting force when processing UFG VT6 titanium alloy, as well as a decrease in the size of burrs compared to CG titanium. In [11], based on a study of the chip parameters, and thermal conductivity of CG and UFG titanium, the authors concluded on a potential increase in cutting machinability, and reduction in cutting tool wear when changing to a structure with fine grains.

At the same time, there is no data on the influence of steel structure, and processing modes, on cutting temperature. Cutting temperature is an important factor that must be taken into account by a technologist, when designing operations for mechanical machining of materials [12]. Cutting temperature affects the cutting tool durability, the machined surface roughness, the dimensional accuracy of processing, and many other parameters of the cutting process [13; 14]. Moreover, cutting temperature can be used as one of the main diagnostic signals along with cutting force [15; 16]. The use of cutting temperature, as a feedback signal when developing automatic control systems for the treatment process, is worth noting individually [17; 18].

The purpose of this work is to study the influence of the coarse-grained, and ultrafine-grained crystalline structure of 09G2S steel, and its processing modes on the cutting temperature during end milling.

METHODS

09G2S low-carbon low-alloy steel, GOST 19281-2014 (Table 1) was chosen as the material for the study.

Two samples with dimensions of 40×15×10 mm each in one of two states were studied: as-delivered state with a CG structure, and after equal channel angular pressing (ECAP) according to the Conform scheme (ECAP-C) with a UFG structure. The ECAP-C technology included: homogenizing annealing of steel at 820 °C followed by quenching in water + tempering at 350 °C + cold ECAP-C, 4 passes along the Vs (*Bc*) route + additional annealing at 350 °C, with a holding time of 10 min. The production technology and properties of the UFG steel are given in more detail in [19; 20]. Table 2 gives the mechanical properties of 09G2S steel before and after ECAP-C.

The experiment was carried out on a PROMA FHV-50PD universal milling machine. The blanks were processed using a 12-12D-30C-75L-4F HRC55 carbide milling cutter. No cooling was used during processing. The cutting temperature was recorded using a Seek Thermal Compact XR thermal imager. Thermal imager characteristics: temperature range is from −40 °C to +330 °C, viewing angle is 20°, resolution is 412×312 pixels, and frame refresh rate is 9 Hz.

When creating a model using a limited amount of data, bootstrap analysis was used. By creating multiple random samples with replacement from the original sample, a test statistic is created to find confidence intervals. Bootstrap analysis was carried out for a confidence interval of 0.95, with a number of samples of 999, the type of confidence intervals is BCa (corrected percentile), and the sampling method is sample of objects. All calculations were carried out in the R programming environment.

To search for the best structure of the mathematical model of cutting temperature, the method of automatic processing of models and discarding insignificant parameters, was used. The selection of the regression model was carried out, using the technique of stepwise forward/backward search, assessing the effectiveness of the model, according to the AIC criterion, and discarding insignificant parameters. The Akaike Informative Criterion (commonly called AIC), is a criterion for choosing between statistical models. The informative criterion considers the fit of the model to the data, taking into account the number of model parameters. When evaluating, preference is given to the model with the minimum criterion value.

Table 1. *Chemical composition of the 09G2S steel (wt. %)*
Таблица 1. *Химический состав стали 09Г2С (мас. %)*

Steel	C	Si	Mn	P	S	Ni	Cr	Al	Cu	Fe
09G2S	0.09	0.64	1.26	0.007	<0.003	0.1	0.08	0.02	0.14	the rest

Table 2. *Average grain size (d_{av}) and mechanical properties of the 09G2S steel in different states*
Таблица 2. *Средний размер зерна (d_{av}) и механические свойства стали 09Г2С в различных состояниях*

Steel state	d_{av}, µm	HB	$\sigma_в$, MPa	$\sigma_{0.2}$, MPa	δ, %
Initial (CG state)	20.00	143	485±3	354±11	25±1.8
After ECAP-C (UFG state)	0.45	331	838±12	655±44	10±1.5

RESULTS

The results of measuring the cutting temperature for the 09G2S steel with CG and UFG structure, are given in Tables 3, 4. It can be observed, that the cutting temperature depends on both the modes and the type of crystalline structure, of the alloy.

Fig. 1 shows distribution graphs (box plot) of cutting temperature for the 09G2S steel in CG and UFG states. In the graphs, one can see the extreme values (range), outliers, quartile boundaries, and a median. The graph for steel in the CG state shows the cutting temperature distribution, with possible outliers for experiments No. 3 and 5 (Fig. 1 a). For steel in the UFG state, no outliers were detected (Fig. 1 b). Fig. 1 shows that the interquartile range (rectangle height) for UFG steel is 2 times larger, and the median is significantly higher. Thus, the temperatures when processing 09G2S steel in the UFG state, are generally higher, than when processing 09G2S steel in the CG state.

Fig. 2, 3 show bootstrap analysis graphs. Bootstrap analysis displays an assessment of the significance of processing parameters when calculating cutting temperature. Thus, for steel in the CG state, the cutter rotation speed n and the feed s are insignificant, as can be observed from Fig. 2 b, 2 c (the abscissa of the peak value of the graph is near zero for n and s). Therefore, for steel in the coarse-grained state, the only significant parameter of the model is the cutting depth t. For the model of the cutting temperature of steel in the UFG state, the feed s (Fig. 3 c), as well as the depth of cut in the first and second degrees (Fig. 3 b, 3 d) are significant.

The model of the cutting temperature dependence, on processing modes, for 09G2S steel in the CG state is expressed by the formula

$$T = k + c \cdot t + d \cdot t^2,$$

where T is temperature, °C;
t is cutting depth, mm;
k, c, d are adjustable model parameters.

Fig. 4 shows a diagram of the model parameters with residuals for CG steel. The graphs represent the convergence of the model for all parameters. This is evident from the closeness of the values with residuals (solid line) and the model values (dashed line).

The model of the cutting temperature dependence on processing modes for 09G2S steel in the UFG state is expressed by the formula

$$T = t + s + I \cdot t^2,$$

where I is the model parameter.

Fig. 5 shows a diagram of model parameters with residuals for UFG steel. High model convergence is observed.

While studying the influence of processing modes on the temperature during end milling of blanks made of 09G2S steel in the CG and UFG states, the authors obtained the following results: for steel in the CG state, the cutting depth t has the greatest influence on the cutting temperature; for steel in the UFG state – the cutting depth t and feed s. In both cases, the dependence of temperature on cutting depth is described by a second-degree polynomial.

DISCUSSION

The experimental data analysis showed a different nature of the cutting temperature dependence on processing modes for steel in CG and UFG states. Probably, the higher temperature when processing steel in the UFG state can be explained by the increased level of physical and mechanical properties of this steel. This result is opposite to that obtained in [7] for the cutting temperature of titanium.

Apparently, to answer fully the question about the influence of the type of alloy crystalline structure on the cutting temperature, it is necessary to take into account the complex of physical and mechanical properties of the material. Thus, the 09G2S steel studied in this work is characterized by a significant increase in mechanical properties with grain refinement. This is most evident from the increase in the strength of the 09G2S steel, which increases by 1.7 times (from 485 to 838 MPa) during ECAP, as well as from the increase in the yield strength of steel by 1.85 times (from 354 to 655 MPa). At the same time, the thermal conductivity of steel is higher than that of titanium. Therefore, one can expect different patterns of temperature distribution, when cutting steel and titanium. The process of end milling of 09G2S steel, in the CG and UFG states is characterized by the absence of influence of the cutting speed on the temperature, in the studied range of processing modes. Thus, when milling this group of materials, the force component primarily determined by the cutting depth, exerts the predominant influence on the temperature regime. Further research could be aimed at investigating the milling temperature of steel, with different types of crystalline structure, within a wider range of cutting speeds. In this case, to carry out experiments, one may need both higher-speed machining equipment, and a thermal imager with a wider temperature measurement range, since the cutting temperature increases with increasing cutting speed.

The research is also complicated by the fact that at present, blanks from alloys with a UFG structure for cutting experiments, are produced in single-piece quantities. The shortage of processed material greatly limits the range of research carried out. Therefore, one can expect that in the near future, a lack of experimental data on the cutting processing of alloys with a UFG structure will continue to be. Partially, mathematical modeling of experimental results, with a small number of experiments, helps to find a way out of the situation. Statistical methods similar to the bootstrap analysis, used in this work, allow identifying the significance of factors, and formulating analytical dependencies for processing parameters, based on a relatively small sample of experimental data. Thus, the approach proposed in this study will help, in the future, to continue research into the cutting of alloys with different types of a crystalline structure. These studies will be necessary to design technological processes, for the production of parts from alloys, with an ultrafine-grained crystalline structure.

Table 3. *Milling temperature of the 09G2S steel in the initial state*
Таблица 3. *Температура фрезерования стали 09Г2С в исходном состоянии*

No. of experiment	**Spindle speed *n*, rpm**	**Feed *s*, mm/min**	**Cutting depth *t*, mm**	**Cutting temperature, *T*, °C**
1	720	65	0.6	91.3
2	875	65	0.8	84.5
3	720	65	1.0	198.0
4	720	100	0.6	94.0
5	875	100	1.0	259.0*
6	720	470	0.6	90.0
7	720	470	1.0	130.3
8	875	470	0.8	126.3
9	875	185	0.6	115.5
10	720	65	0.8	110.3

*Note. *A higher temperature value is possible, since the obtained value is close to the upper limit of the instrument measurement range (300 °C).*
*Примечание. *Возможно большее значение температуры, поскольку полученное значение близко к верхней границе диапазона измерения прибора (300 °C).*

Table 4. *Milling temperature of the 09G2S steel after ECAP-C*
Таблица 4. *Температура фрезерования стали 09Г2С после РКУП-К*

No. of experiment	**Spindle speed *n*, rpm**	**Feed *s*, mm/min**	**Cutting depth *t*, mm**	**Cutting temperature, *T*, °C**
1	720	65	0.6	95.5
2	875	65	0.8	97.3
3	720	65	1.0	163.0
4	720	100	0.6	94.3
5	875	100	0.8	109.5
6	875	100	1.0	195.3
7	720	185	0.6	168.8
8	875	185	0.8	170.3
9	875	185	1.0	258.3*

*Note. *A higher temperature value is possible, since the obtained value is close to the upper limit of the instrument measurement range (300 °C).*
*Примечание. *Возможно большее значение температуры, поскольку полученное значение близко к верхней границе диапазона измерения прибора (300 °C).*

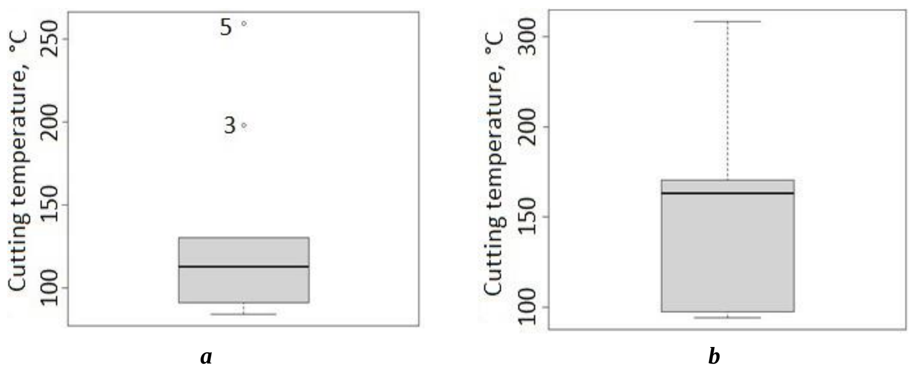

Fig. 1. *Box plots for cutting temperature of the 09G2S steel in CG and UFG states.*
The rectangle shows the boundaries of the lower and upper quartiles, the median is indicated by a dash:
a *– for CG state;* ***b*** *– for UFG state*
Рис. 1. *Графики распределения температуры резания для стали 09Г2С в КЗ и УМЗ состояниях.*
Прямоугольник отображает границы нижнего и верхнего квартилей, чертой обозначена медиана:
a *– для КЗ состояния;* ***b*** *– для УМЗ состояния*

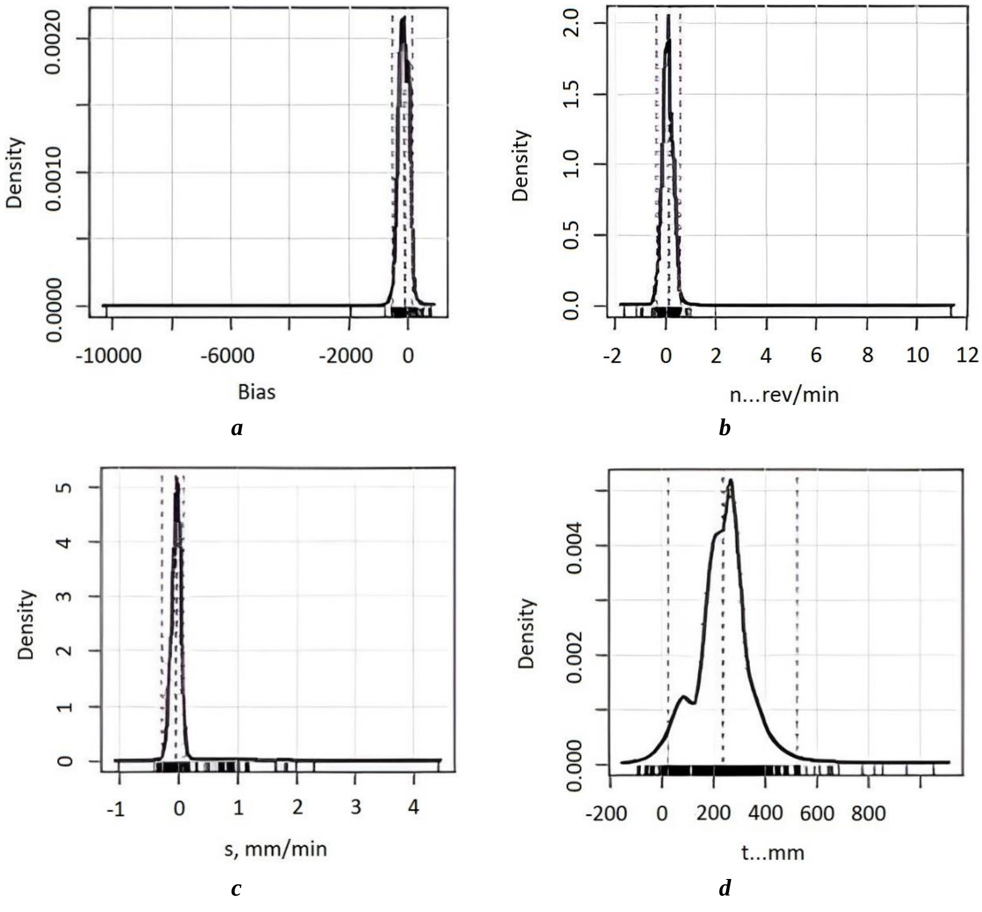

Fig. 2. *Bootstrap-analysis graphs for CG steel:*
a *– bias;* ***b*** *– n, rev/min;* ***c*** *– s, mm/min;* ***d*** *– t, mm*
Рис. 2. *Графики бутстреп-анализа для КЗ стали:*
a *– смещение;* ***b*** *– n, об/мин;* ***c*** *– s, мм/мин;* ***d*** *– t, мм*

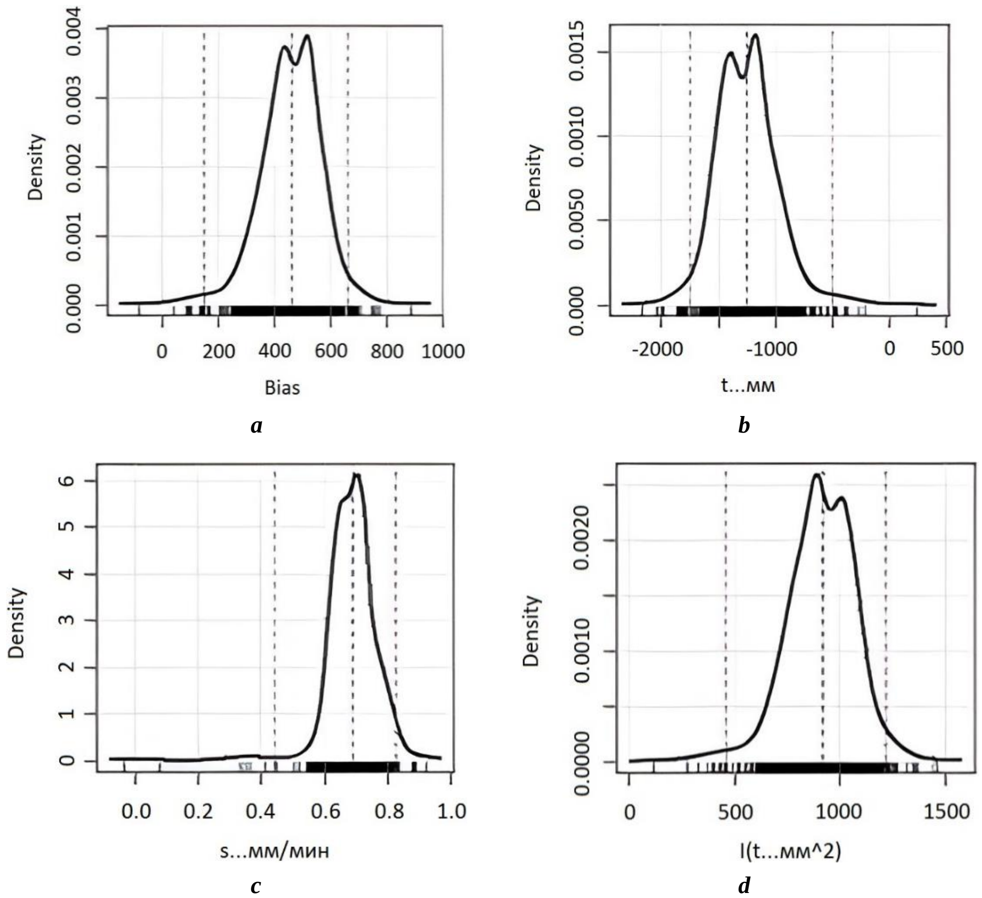

Fig. 3. *Bootstrap-analysis graphs for UFG steel:*
a *– bias;* ***b*** *– t, mm;* ***c*** *– s, mm/min;* ***d*** *– I(t, mm^2)*
Рис. 3. *Графики бутстреп-анализа для УМЗ стали:*
a *– смещение;* ***b*** *– t, мм;* ***c*** *– s, мм/мин;* ***d*** *– I(t, мм^2)*

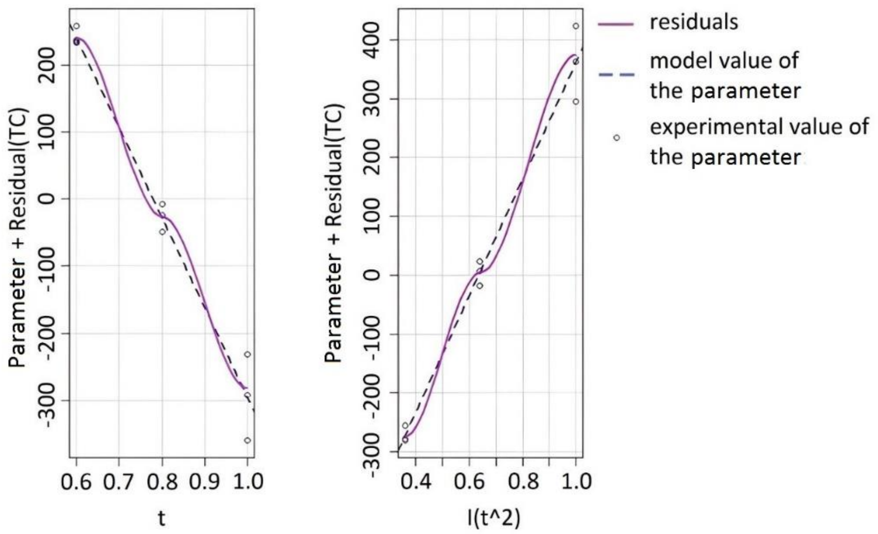

Fig. 4. *Diagram of the model parameters with residuals for CG steel*
Рис. 4. *Диаграмма параметров модели с остатками для КЗ стали*

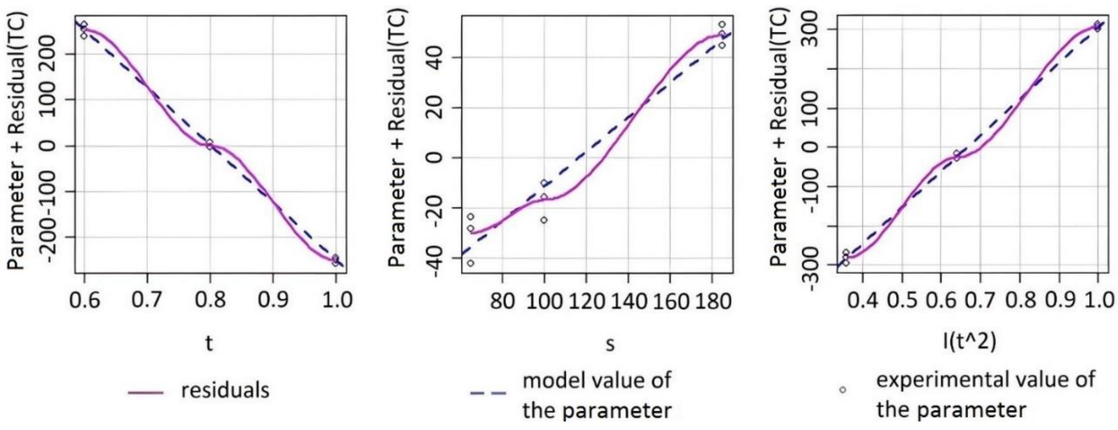

Fig. 5. *Diagram of the model parameters with residuals for UFG steel*
Рис. 5. *Диаграмма параметров модели с остатками для УМЗ стали*

CONCLUSIONS

The main factor influencing the end milling temperature of 09G2S steel in coarse-grained and ultrafine-grained states, is the cutting depth. For steel in the ultrafine-grained state, a significant factor in calculating the cutting temperature, aside from the cutting depth, is the feed, and its cutting temperature level is generally higher than that of steel in the coarse-grained state.

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Исследование температуры концевого фрезерования низколегированной стали в крупнозернистом и ультрамелкозернистом состояниях

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Аннотация: Представлены результаты исследования температуры концевого фрезерования низколегированной стали в зависимости от режимов резания и типа кристаллической структуры. Эксперимент проводился на универсальном фрезерном станке PROMA FHV-50PD. Обработку заготовок осуществляли твердосплавной фрезой 12-12D-30C-75L-4F HRC55. В ходе обработки охлаждение не использовалось. Полученные данные подвергались статистическому анализу с целью выявления зависимости температуры концевого фрезерования низколегированной стали от режимов обработки и кристаллической структуры стали. При создании математической модели температуры резания проводился бутстреп-анализ для определения значимости параметров режимов обработки. Выбор математической модели производился с использованием информационного критерия Акаике. Обнаружено, что математические модели зависимости температуры от режимов обработки для обоих типов кристаллической структуры включают глубину резания во второй степени. При этом для стали в ультрамелкозернистом состоянии статистически значима не только глубина резания, но и подача. Влияния скорости резания на температуру в исследуемом диапазоне режимов обработки обнаружить не удалось. Таким образом, при обработке фрезерованием данной группы материалов преобладающее влияние на температурный режим оказывает силовая составляющая, в первую очередь определяемая глубиной резания. Уровень температуры резания при обработке стали в ультрамелкозернистом состоянии в целом выше, чем при обработке стали в крупнозернистом состоянии, что должно быть связано с повышенными физико-механическими свойствами стали с ультрамелкозернистой кристаллической структурой.

Ключевые слова: резание материалов; крупнозернистая (КЗ) и ультрамелкозернистая (УМЗ) структура; низколегированная сталь; температура резания; концевое фрезерование.

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