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Improving the efficiency of the milling tool by reducing the temperature in the milling zone depending on the main mode parameters

Poprawa wydajności narzędzia frezującego poprzez zmniejszenie temperatury w strefie frezowania w zależności od parametrów trybu głównego

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ABSTRACT: Maintenance of equipment and tools used in the overhaul of oil and gas wells depends on the reliability and durability of the tool. The recovery process of damaged wells can be accelerated by choosing the right repair equipment and following the rules and regulations in force. Cutting equipment and tools operating under high pressure and load are deformed, in the cutting zone – dispersion, i.e., a tense situation is created, and as a result of corrosion in the tribonodes, high temperatures, such as 1000–1200°C, are observed. The stress-strain state created in the shear-disintegration zone causes the formation of microcracks in the working zone of the tool, which will grow over a certain period of time. Thus, the cutting elements wear out quickly, in some cases break and quickly fail. In this case, the structural composition of the cutting elements changes, and the structural lattice in metals is destroyed, resulting in riveting. To maintain the equipment and tools used in repairs in working order, one of the important conditions is their special care and adjustment of the mode parameters. This article discusses the increase in the efficiency of the milling tool with the use of cooling agents in the process of milling various metal objects left during accidents in the wellbore. To do this, experimental data were processed, based on regression analysis, mathematical formulas were obtained that describe the temperature process depending on various regime parameters of the grinding process, and their graphical dependences were plotted. A transition from linear regression to non-linear regression has been made. The results obtained make it possible to predict the classification and design schemes of borehole cutters and the choice of composite materials for reinforcing the cutting part.

Key words: thermal regime, milling process, milling tool, experimental data processing in MS Excel, non-linear regression equations.

STRESZCZENIE: Konserwacja sprzętu i narzędzi stosowanych w naprawach odwiertów ropnych i gazowych zależy od niezawodności i trwałości narzędzia. Proces odzyskiwania uszkodzonych odwiertów może być przyspieszony poprzez wybór właściwego sprzętu naprawczego oraz przestrzeganie obowiązujących zasad i przepisów. Sprzęt tnący i narzędzia pracujące pod wysokim ciśnieniem i obciążeniem ulegają odkształceniu, w strefie cięcia powstaje dyspersja, tj. warunki naprężenia, a w efekcie korozji w węzłach tribologicznych pojawiają się wysokie temperatury rzędu 1000–1200°C. Stan naprężeń-odkształceń wytworzony w strefie ścinania-dezintegracji powoduje powstawanie w strefie pracy narzędzia mikrospękań, które w pewnym okresie czasu będą się rozwijać. Co za tym idzie, elementy tnące zużywają się szybko, a w niektórych przypadkach łamią się i szybko ulegają uszkodzeniu. W tym przypadku skład strukturalny elementów tnących zmienia się, a sieć strukturalna w metalach ulega zniszczeniu, co jest przyczyną nitowania. Aby utrzymać sprzęt i narzędzia stosowane w naprawach w stanie gotowości do pracy, jednym z istotnych warunków jest szczególne dbanie o nie i dostosowywanie parametrów trybu. Niniejszy artykuł omawia zwiększanie wydajności narzędzia frezującego przy zastosowaniu czynników chłodzących w procesie frezowania różnych obiektów metalowych pozostawionych podczas awarii w otworze wiertniczym. Aby to osiągnąć, przetworzono dane doświadczalne, a w oparciu o analizę regresji uzyskano wzory matematyczne, które opisują proces temperaturowy zależny od różnych parametrów reżimu procesu ścierania, zależności te przedstawione zostały również w formie graficznej. Wykonano przekształcenie z regresji liniowej na regresję nieliniową. Uzyskane wyniki umożliwiają przewidzenie klasyfikacji i schematów konstrukcji otworowych narzędzi tnących oraz wybór materiałów kompozytowych dla wzmocnienia części tnącej.

Słowa kluczowe: reżim termiczny, proces frezowania, narzędzie frezujące, przetwarzanie danych doświadczalnych w MS Excel, równania regresji nieliniowej.

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Introduction

In the development of the oil and gas industry, the main directions for increasing oil and gas production are the introduction of new equipment, as well as the commissioning of idle wells, associated with the need to speed up restoration work. Constructive measures are needed to improve and further develop drilling and restoration work to preserve the well stock, increase the efficiency of their operation and reduce the number of idle wells (Pustovoytenko, 1987; Mukhametshin, 2017). There are various ways to carry out restoration work in the well. One of them is the milling of an emergency item in the well. It is known that the indicators of drilling and milling processes depend, first of all, on the durability and efficiency of the downhole tool (Aramcharoen et al., 2008; Aurich et al., 2022). In turn, the durability of the tool, along with its design and material, is related to the conditions of its operation at the bottom of the well.

Relevance of the work

One of the main factors determining the performance of drilling and milling tools is the thermal regime in its zone of operation, which depends primarily on the physical and mechanical properties of the object being destroyed, and the mode of drilling and milling (Mustafayev and Pashayeva, 2017; Mustafayev et al., 2021a, 2021b). The tool is subjected to temperature effects from interaction with destructible objects, and, at the same time, a large amount of heat is released on its working surface (Mustafayev, 2017; Mustafayev and Nasirov, 2021, 2022). As a result, the tool heats and this leads to a decrease in destructive ability, accelerated wear of the cutting elements and premature failure.

Aim of the work

Reduce the temperature in the milling zone using various coolants, find the dependence of the heating temperature of the milling tool on the main operating parameters (angular velocity of the milling tool, axial load on the tool, tensile strength of the milled object, coolant and air supply) and make the transition from a linear to non-linear regression equation for milling.

Experimental data processing technique

The experiments and their results were described in sufficient detail in the work of Mustafayev et al. (1997).

In the article, the experimental data, given below in Table 1 have been processed. The analysis package of the MS EXCEL 2016 program was used for processing the experimental data.

Table 1. The results of the experiments [1]
Tabela 1. Wyniki doświadczeń [1]

No.	T	ω	P	σ	Q_l	Q_a
	[°C]	[s^{-1}]	[N]	[MPa]	[ml/s]	[m^3/s]
1.	573	104.6	1700	380	50	0.20
2.	463	104.6	1700	500	80	1.60
3.	482	104.6	1700	650	40	1.20
4.	644	104.6	1700	750	65	0.64
5.	470	104.6	1700	950	100	1.30
6.	502	104.6	2800	380	100	1.60
7.	653	104.6	2800	500	50	1.20
8.	737	104.6	2800	650	80	0.64
9.	696	104.6	2800	750	40	1.30
10.	759	104.6	2800	950	65	0.72
11.	669	104.6	3700	380	65	1.20
12.	671	104.6	3700	500	100	0.64
13.	741	104.6	3700	650	50	1.30
14.	742	104.6	3700	750	80	0.72
15.	796	104.6	3700	950	40	1.60
16.	942	104.6	4900	380	40	0.64
17.	706	104.6	4900	500	65	1.30
18.	668	104.6	4900	650	100	0.72
19.	821	104.6	4900	750	50	1.60
20.	699	104.6	4900	950	80	1.20
21.	553	104.6	6400	380	80	1.30
22.	1170	104.6	6400	500	40	0.72
23.	716	104.6	6400	650	65	1.60
24.	551	104.6	6400	750	100	1.20
25.	408	74.3	1700	380	100	1.60
26.	428	74.3	1700	500	50	1.20
27.	579	74.3	1700	650	80	0.64
28.	440	74.3	1700	750	40	1.30
29.	526	74.3	1700	950	65	0.72
30.	535	74.3	2800	380	65	1.20
31.	597	74.3	2800	500	60	0.64
32.	577	74.3	2800	650	50	1.30
33.	615	74.3	2800	750	80	0.72
34.	584	74.3	2800	950	40	1.60
35.	634	74.3	3700	380	40	0.64
36.	578	74.3	3700	500	65	1.30
37.	615	74.3	3700	650	100	0.72
38.	602	74.3	3700	750	50	1.60
39.	650	74.3	3700	950	65	1.20
40.	505	74.3	4900	380	80	1.30
41.	802	74.3	4900	500	40	0.72

cont. Table 1/cd. Tabela 1

No.	*T* [°C]	*ω* [s⁻¹]	*P* [N]	*σ* [MPa]	Q_l [ml/s]	Q_a [m³/s]
42.	578	74.3	4900	650	65	1.60
43.	509	74.3	4900	750	100	1.20
44.	913	74.3	4900	950	50	0.64
45.	696	74.3	6400	380	50	0.72
46.	473	74.3	6400	500	80	1.60
47.	996	74.3	6400	650	40	1.20
48.	815	74.3	6400	750	65	0.64
49.	468	74.3	6400	950	100	1.30
50.	372	52.3	1700	380	65	1.20
51.	463	52.3	1700	500	100	0.64
52.	346	52.3	1700	650	50	1.30
53.	464	52.3	1700	750	80	0.72
54.	232	52.3	1700	950	40	1.60
55.	424	52.3	2800	380	40	0.64
56.	456	52.3	2800	500	65	1.30
57.	520	52.3	2800	650	100	0.72
58.	429	52.3	2800	750	50	1.60
59.	446	52.3	2800	950	60	1.20
60.	444	52.3	3700	380	80	1.30
61.	557	52.3	3700	500	40	0.72
62.	466	52.3	3700	650	65	1.60
63.	438	52.3	3700	750	100	1.20
64.	695	52.3	3700	950	50	0.64
65.	558	52.3	4900	380	50	0.72
66.	395	52.3	4900	500	80	1.60
67.	526	52.3	4900	650	40	1.20
68.	609	52.3	4900	750	65	0.64
69.	388	52.3	4900	950	100	1.30
70.	247	52.3	6400	380	100	1.60
71.	583	52.3	6400	500	50	1.20
72.	547	52.3	6400	650	80	0.64
73.	765	52.3	6400	750	40	1.30
74.	706	52.3	6400	950	65	0.72
75.	178	37.0	1700	380	40	0.64
76.	267	37.0	1700	500	65	1.30
77.	358	37.0	1700	650	100	0.72
78.	189	37.0	1700	750	50	1.60
79.	265	37.0	1700	950	80	1.20
80.	330	37.0	2800	380	80	1.30
81.	354	37.0	2800	500	40	0.72
82.	323	37.0	2800	650	65	1.60
83.	316	37.0	2800	750	100	1.20
84.	483	37.0	2800	950	50	0.64
85.	393	37.0	3700	380	50	0.72
86.	311	37.0	3700	500	80	1.60
87.	377	37.0	3700	650	40	1.20

cont. Table 1/cd. Tabela 1

No.	*T* [°C]	*ω* [s⁻¹]	*P* [N]	*σ* [MPa]	Q_l [ml/s]	Q_a [m³/s]
88.	479	37.0	3700	750	65	1.60
89.	300	37.0	3700	950	100	1.30
90.	216	37.0	4900	380	100	1.60
91.	412	37.0	4900	500	50	1.20
92.	441	37.0	4900	650	80	0.64
93.	496	37.0	4900	750	40	1.30
94.	534	37.0	4900	950	65	0.72
95.	302	37.0	6400	380	65	1.20
96.	314	37.0	6400	500	100	0.64
97.	440	37.0	6400	650	50	1.30
98.	403	37.0	6400	750	80	0.72
99.	677	37.0	6400	950	40	1.60
100.	191	26.0	1700	380	80	1.30
101.	106	26.0	1700	500	40	0.72
102.	154	26.0	1700	650	65	1.60
103.	179	26.0	1700	750	100	1.20
104.	221	26.0	1700	950	50	0.64
105.	284	26.0	2800	380	50	0.72
106.	221	26.0	2800	500	80	1.60
107.	179	26.0	2800	650	40	1.20
108.	353	26.0	2800	750	65	0.64
109.	195	26.0	2800	950	100	1.30
110.	165	26.0	3700	380	100	1.60
111.	269	26.0	3700	500	50	1.20
112.	355	26.0	3700	650	80	0.64
113.	287	26.0	3700	750	40	1.30
114.	398	26.0	3700	950	65	0.72
115.	221	26.0	4900	380	65	1.20
116.	260	26.0	4900	500	100	0.64
117.	298	26.0	4900	650	50	1.30
118.	317	26.0	4900	750	80	0.72
119.	430	26.0	4900	950	40	1.60
120.	388	26.0	6400	380	40	0.64
121.	240	26.0	6400	500	65	1.30
122.	213	26.0	6400	650	100	0.72
123.	328	26.0	6400	750	50	1.60
124.	257	26.0	6400	950	80	1.20

T – the temperature of the milling tool; P – axial load on the milling tool; ω – the angular velocity of the milling tool; σ – the yield strength of the milled material; Q_l – supply of cooling liquid to the milling tool; Q_a – supply of cooling air to the milling tool

Using the analysis package of the MS EXCEL 2016 program, a regression analysis of Table 1 was carried out, and a linear regression equation $T(\omega, P, \sigma, Q_l, Q_a)$ was obtained with the highest approximation reliability (1). For this, the built-in statistical formulas CORREL and LINEST were used. The tech-

Table 2. Correlation coefficients between the values given in Table 1.

Tabela 2. Współczynniki korelacji między wartościami podanymi w Tabeli 1.

	T	ω	P	Σ	Q_l	Q_a
T	1	0.75122728	0.28818395	0.12400406	–0.24671205	–0.21788307
ω	0.751227281	1	–0.0205584	–0.0206618	0.000507316	0.000190684
P	0.288183947	–0.0205584	1	–0.0193524	0.025923651	0.013264277
σ	0.124004059	–0.0206618	–0.0193524	1	0.000438513	0.027304593
Q_l	–0.24671205	0.00050732	0.02592365	0.00043851	1	0.005651792
Q_a	–0.21788307	0.00019068	0.01326428	0.02730459	0.005651792	1

Table 3. The result of the LINEST values for Table 1

Tabela 3. Wynik wartości LINEST dla Tabeli 1

–82.253262	–1.6439	0.2388	0.046099331	5.825665226	0
21.6171857	0.36459	0.03834	0.005021855	0.295940398	#N/A
0.96572912	97.8211	#N/A	#N/A	#N/A	#N/A
670,66708	119	#N/A	#N/A	#N/A	#N/A
32087956,9	1138707	#N/A	#N/A	#N/A	#N/A

nique of using these functions for the analysis of experimental data is described in detail in (Agapova and Bitekhtina, 2012).

CORREL function (array1, array2) – returns the correlation coefficient between two data sets. In parentheses, instead of array1 and array2, the intervals of values of the table columns are indicated, between which it is required to find the correlation coefficient. Table 2 was obtained using the CORREL function.

LINEST (Known_y_values, Known_x_values, Const, Statistics) – returns linear approximation parameters on the least squares method. In other words, it calculates the coefficients of linear regression, the coefficient of determination R^2, F-statistics. In the field "Known_y_values" the range of values of the dependent quantity is entered; "Known_x_values" are the range of values of all arguments; "Const" takes logical values, it is set on 0 if it is known in advance that the free member is 0, and on 1 otherwise; "Statistics" also takes logical values and is set on 0 if no additional regression analysis information is needed, and on 1 otherwise (Agapova and Bitekhtina, 2012). In our case, using the LINEST function (Interval of all T values from Table 1, Interval of all argument values from Table 1, 0, 1), Table 3 was obtained.

Linear regression equation

To obtain a linear equation, Table 3 is considered. The 1st row of values in Table 3 corresponds to the coefficients in front of the values ω, P, σ, Q_l, Q_a, in reverse order (the order is indicated in Table 1), for the linear equation $T(\omega, P, \sigma, Q_l, Q_a)$. The 1st column of the 3rd row shows the value of the approximation reliability R^2 (Jacyna et.al., 2022). The foregoing, the following linear regression equation, which describes the dependence of temperature on the operating parameters of milling is obtained:

$$T = 5.825665 \cdot \omega + 0.046099 \cdot P + 0.2388 \cdot \sigma - 1.6439 \cdot Q_l - 82.253262 \cdot Q_a \quad (1)$$

$$R^2 = 0.965729117 \quad (2)$$

Non-linear regression equation. To calculate the non-linear regression equation, the transformations specified in Table 4 (Agapova and Bitekhtina, 2012) are used. Thus, the solution of non-linear regression is reduced to the solution of linear regression (Archontoulis and Miguez, 2015; Geistanger et al., 2022).

To find the regression equation of the dependencies specified in Table 1, the following calculations were performed in the MS EXCEL 2016 program:

1. For the arguments listed in Table 1, the following transformations were performed:
   a) $\omega' = 1/\omega$; $\omega'' = \ln(\omega)$
   b) $P' = 1/P$; $P'' = \ln(P)$
   c) $\sigma' = 1/\sigma$; $\sigma'' = \ln(\sigma)$
   d) $Q_l' = 1/Q_l$; $Q_l'' = \ln(Q_l)$
   e) $Q_a' = 1/Q_a$; $Q_a'' = \ln(Q_a)$
2. Dependency graphs are built:
   a) T–ω dependencies (at average values of P, σ, Q_l, Q_a):
      i $T = A + B\omega$
      ii $T = A + B\omega + C\omega^2$
      iii $T = A + B\ln\omega = A + B\omega'$
      iv $T = A + B\ln\omega + C\ln\omega^2 = A + B\omega'' + C(\omega'')^2$
      v $T = A + B(1/\omega) = A + B\omega'$
      vi $T = A + B(1/\omega) + C(1/\omega)^2 = A + B\omega' + C(\omega')^2$

b) T–P dependencies (at average values of ω, σ, Q_l, Q_a):
   i $T = A + BP$
   ii $T = A + BP + CP^2$
   iii $T = A + B\ln P = A + BP''$
   iv $T = A + B\ln P + C\ln P^2 = A + BP'' + C(P'')^2$
   v $T = A + B(1/P) = A + BP'$
   vi $T = A + B(1/P) + C(1/P)^2 = A + BP' + C(P')^2$
c) T–σ dependencies (at average values of ω, P, Q_l, Q_a):
   i $T = A + B\sigma$
   ii $T = A + B\sigma + C\sigma^2$
   iii $T = A + B\ln\sigma = A + B\sigma''$
   iv $T = A + B\ln\sigma + C\ln\sigma^2 = A + B\sigma'' + C(\sigma'')^2$
   v $T = A + B(1/\sigma) = A + B\sigma'$
   vi $T = A + B(1/\sigma) + C(1/\sigma)^2 = A + B\sigma' + C(\sigma')^2$
d) T–Ql dependencies (at average values of ω, P, σ, Q_a):
   i $T = A + BQl$
   ii $T = A + BQl + CQl^2$
   iii $T = A + B\ln Ql = A + BQl''$
   iv $T = A + B\ln Ql + C\ln Ql^2 = A + BQl'' + C(Ql'')^2$
   v $T = A + B(1/Ql) = A + BQl'$
   vi $T = A + B(1/Ql) + C(1/Ql)^2 = A + BQl' + C(Ql')^2$
e) T–Qv dependencies (at average values of ω, P, σ, Ql):
   i $T = A + BQa$
   ii $T = A + BQa + CQa^2$
   iii $T = A + B\ln Qa = A + BQa''$
   iv $T = A + B\ln Qa + C\ln Qa^2 = A + BQa'' + C(Qa'')^2$
   v $T = A + B(1/Qa) = A + BQa'$
   vi $T = A + B(1/Ql) + C(1/Ql)^2 = A + BQl' + C(Ql')^2$

3. All the above graphs in paragraph 2 were approximated, analyzed and the most appropriate equations were chosen to describe the milling process (Figures 1–5):
4. After plotting the functions Figures 1-5 and finding the coefficients (A, B, C) of the equations, the standard deviations for each of the functions (Table 7) were found. and functions were chosen for further construction of the non-linear regression equation, which best describe the temperature dependence on the arguments (ω, P, σ, Q_l, Q_a) with the smallest standard deviations.
5. The non-linear regression equation was converted to linear (3):

$$\mathrm{T} = k_\omega T_\omega + k_P T_P + k_\sigma T_\sigma + k_{Ql} T_{Ql} + k_{Qa} T_{Qa} + k_T T_0 \quad (3)$$

Following from the previous paragraph 4, the values of the temperature components (T_ω, T_P, T_σ, T_{Ql}, T_{Qa}, T_0) will be represented as:

a) For the temperature component of the angular velocity, the equation is selected from Figure 1:

$$T_\omega = C\cdot(1/\omega)^2 - B\cdot 1/\omega = 318995\cdot(1/\omega)^2 - 30097\cdot 1/\omega \quad (4)$$

b) For the temperature component from the axial load, the equation is selected from Figure 2:

$$T_P = B\cdot\ln P = 135.79\cdot\ln P \quad (5)$$

c) For the temperature component of the tensile strength, the equation is selected from Figure 3:

$$T_\sigma = B\cdot\ln\sigma = 81.902\cdot\ln\sigma \quad (6)$$

d) For the temperature component from the liquid supply, the equation is selected from Figure 4:

$$T_{Ql} = B\cdot\ln Ql = -147.92\cdot\ln Ql \quad (7)$$

e) For the temperature component from the air supply, the equation is selected from Figure 5:

$$T_{Qa} = B\cdot\ln Qa = -124.44\cdot\ln Qa \quad (8)$$

f) For constant temperature component T_0 from Figures 1, 2, 3, 4 and 5:

$$T_0 = A_\omega + A_P + A_\sigma + A_{Ql} + A_{Qa} = 1842.338 \quad (9)$$

Since T_0 = const, when finding the regression equation, equation (9) can be neglected.

6. Table 1 was converted to Table 5 in order to apply the LINEST function to Table 5, and find the coefficients (k_ω, k_P, k_σ, k_{Ql}, k_{Qa}, k_T) for the regression equation (3):
   Table 6 was obtained after processing Table 5 using the LINEST function built into Excel:
   The coefficients k_T, k_ω, k_P, k_σ, k_{Ql}, k_{Qa} in equation (3) correspond to the values of the 1st row of Table 6, in reverse order:

$$\begin{cases} k_\omega \approx 1.0111 \\ k_P \approx 0.9927 \\ k_\sigma \approx 0.9695 \\ k_{Ql} \approx 1.0662 \\ k_{Qa} \approx 1.0315 \\ k_T \approx 0 \end{cases} \quad (10)$$

Substituting the values of the coefficients (10) into equation (3) and we obtain the non-linear regression equation in linear form (11):

$$T = 1.0111\cdot T_\omega + 0.9927\cdot T_P + 0.9695\cdot T_\sigma + \\ +1.0662\cdot T_{Ql} + 1.0315\cdot T_{Qa} \quad (11)$$

Substituting all the values of the temperature components (4), (5), (6), (7), (8) into equation (11) and obtain the non-linear regression equation (12):

$$\begin{aligned} T &= 1.0111\cdot[318995\cdot(1/\omega)^2 - 30097\cdot 1/\omega] + \\ &+0.9927\cdot[135.79\cdot\ln P] + \\ &+0.9695\cdot[81.902\cdot\ln\sigma] + \\ &+1.0662\cdot[-147.92\cdot\ln Ql] + \\ &+1.0315\cdot[-124.44\cdot\ln Qa] = \\ &= 322532.5\cdot(1/\omega)^2 - 30430.8\cdot 1/\omega + \\ &+\ln(P^{134.8}\cdot\sigma^{79.4}/Ql^{157.7}\cdot Qa^{128.4}) \end{aligned} \quad (12)$$

For convenience, the coefficients in equation (12) are denoted:

$$\begin{cases} a \approx 322532.5 \\ b \approx 30430.8 \\ c \approx 134.8 \\ d \approx 79.4 \\ e \approx 157.7 \\ f \approx 128.4 \end{cases} \qquad (13)$$

Thus, replacing the coefficients in equation (12) with their letter designations in (13), a non-linear regression equation describing the dependence of the heating temperature of the milling tool on the mode parameters of milling (14) was obtained:

$$T = \frac{a}{\omega^2} - \frac{b}{\omega} + \ln \frac{P^c \cdot \sigma^d}{Ql^e \cdot Qa^f} \qquad (14)$$

In Table 6, the 1st column of the 3rd row corresponds to the R^2 value for (14): $R^2 \approx 0.9757$ is an approximation accuracy for non-linear regression equation (14).

Table 4. Linear transformation of non-linear functions
Tabela 4. Transformacja liniowa funkcji nieliniowych

No.	The equation	Replacement $x \to x^*$	Replacement $y \to y^*$	Calculation a by a^*	Calculation b to b^*
1.	$y = a + b/x + \lambda$	$x^* = 1/x$	$y^* = y$	$a = a^*$	$b = b^*$
2.	$y = 1/(a + bx + \lambda)$	$x^* = x$	$y^* = 1/y$	$a = a^*$	$b = b^*$
3.	$y = x/(a + bx + x\lambda)$	$x^* = 1/x$	$y^* = 1/y$	$a = b^*$	$b = a^*$
4.	$y = ae^{(bx+\lambda)}$	$x^* = x$	$y^* = \ln y$	$a = e^{a^*}$	$b = b^*$
5.	$y = ae^{(b/x+\lambda)}$	$x^* = 1/x$	$y^* = \ln y$	$a = e^{a^*}$	$b = b^*$
6.	$y = 1/(a + be^{-x} + \lambda)$	$x^* = e^{-x}$	$y^* = 1/y$	$a = a^*$	$b = b^*$
7.	$y = ax^b e^{\lambda}$	$x^* = \ln x$	$y^* = \ln y$	$a = e^{a^*}$	$b = b^*$

Table 5. Transformed table for finding the non-linear regression equation
Tabela 5. Tabela przekształceń w celu określenia równania regresji nieliniowej

No.	T [°C]	T_{ω} [°C]	T_P [°C]	T_{σ} [°C]	T_{Ql} [°C]	T_{Qa} [°C]
1.	573	–258.5787247	1010.058100	486.5119059	–578.6664430	40.87904609
2.	463	–258.5787247	1010.058100	508.9888325	–648.1893798	–58.48725162
3.	482	–258.5787247	1010.058100	530.4769905	–545.6590489	–22.68809453
4.	644	–258.5787247	1010.058100	542.1972358	–617.475365	55.53596705
5.	470	–258.5787247	1010.058100	561.5579495	–681.1967739	–32.64860907
6.	502	–258.5787247	1077.816110	486.5119059	–681.1967739	–58.48725162
7.	653	–258.5787247	1077.816110	508.9888325	–578.6664430	–22.68809453
8.	737	–258.5787247	1077.816110	530.4769905	–648.1893798	55.53596705
9.	696	–258.5787247	1077.816110	542.1972358	–545.6590489	–32.64860907
10.	759	–258.5787247	1077.816110	561.5579495	–617.4753650	40.87904609
11.	669	–258.5787247	1115.662603	486.5119059	–617.4753650	–22.68809453
12.	671	–258.5787247	1115.662603	508.9888325	–681.1967739	55.53596705
13.	741	–258.5787247	1115.662603	530.4769905	–578.6664430	–32.64860907
14.	742	–258.5787247	1115.662603	542.1972358	–648.1893798	40.87904609
15.	796	–258.5787247	1115.662603	561.5579495	–545.6590489	–58.48725162
16.	942	–258.5787247	1153.806338	486.5119059	–545.6590489	55.53596705
17.	706	–258.5787247	1153.806338	508.9888325	–617.4753650	–32.64860907
18.	668	–258.5787247	1153.806338	530.4769905	–681.1967739	40.87904609
19.	821	–258.5787247	1153.806338	542.1972358	–578.6664430	–58.48725162
20.	699	–258.5787247	1153.806338	561.5579495	–648.1893798	–22.68809453
21.	553	–258.5787247	1190.070793	486.5119059	–648.1893798	–32.64860907
22.	1170	–258.5787247	1190.070793	508.9888325	–545.6590489	40.87904609
23.	716	–258.5787247	1190.070793	530.4769905	–617.4753650	–58.48725162

cont. Table 5/cd. Tabela 5

No.	T [°C]	T_ω [°C]	T_P [°C]	T_σ [°C]	T_{Ql} [°C]	T_{Qa} [°C]
24.	551	–258.5787247	1190.070793	542.1972358	–681.1967739	–22.68809453
25.	408	–347.2902043	1010.058100	486.5119059	–681.1967739	–58.48725162
26.	428	–347.2902043	1010.058100	508.9888325	–578.6664430	–22.68809453
27.	579	–347.2902043	1010.058100	530.4769905	–648.1893798	55.53596705
28.	440	–347.2902043	1010.058100	542.1972358	–545.6590489	–32.64860907
29.	526	–347.2902043	1010.058100	561.5579495	–617.4753650	40.87904609
30.	535	–347.2902043	1077.816110	486.5119059	–617.4753650	–22.68809453
31.	597	–347.2902043	1077.816110	508.9888325	–605.6354476	55.53596705
32.	577	–347.2902043	1077.816110	530.4769905	–578.6664430	–32.64860907
33.	615	–347.2902043	1077.816110	542.1972358	–648.1893798	40.87904609
34.	584	–347.2902043	1077.816110	561.5579495	–545.6590489	–58.48725162
35.	634	–347.2902043	1115.662603	486.5119059	–545.6590489	55.53596705
36.	578	–347.2902043	1115.662603	508.9888325	–617.4753650	–32.64860907
37.	615	–347.2902043	1115.662603	530.4769905	–681.1967739	40.87904609
38.	602	–347.2902043	1115.662603	542.1972358	–578.6664430	–58.48725162
39.	650	–347.2902043	1115.662603	561.5579495	–617.4753650	–22.68809453
40.	505	–347.2902043	1153.806338	486.5119059	–648.1893798	–32.64860907
41.	802	–347.2902043	1153.806338	508.9888325	–545.6590489	40.87904609
42.	578	–347.2902043	1153.806338	530.4769905	–617.4753650	–58.48725162
43.	509	–347.2902043	1153.806338	542.1972358	–681.1967739	–22.68809453
44.	913	–347.2902043	1153.806338	561.5579495	–578.6664430	55.53596705
45.	696	–347.2902043	1190.070793	486.5119059	–578.6664430	40.87904609
46.	473	–347.2902043	1190.070793	508.9888325	–648.1893798	–58.48725162
47.	996	–347.2902043	1190.070793	530.4769905	–545.6590489	–22.68809453
48.	815	–347.2902043	1190.070793	542.1972358	–617.4753650	55.53596705
49.	468	–347.2902043	1190.070793	561.5579495	–681.1967739	–32.64860907
50.	372	–458.8464477	1010.058100	486.5119059	–617.4753650	–22.68809453
51.	463	–458.8464477	1010.058100	508.9888325	–681.1967739	55.53596705
52.	346	–458.8464477	1010.058100	530.4769905	–578.6664430	–32.64860907
53.	464	–458.8464477	1010.058100	542.1972358	–648.1893798	40.87904609
54.	232	–458.8464477	1010.058100	561.5579495	–545.6590489	–58.48725162
55.	424	–458.8464477	1077.816110	486.5119059	–545.6590489	55.53596705
56.	456	–458.8464477	1077.816110	508.9888325	–617.4753650	–32.64860907
57.	520	–458.8464477	1077.816110	530.4769905	–681.1967739	40.87904609
58.	429	–458.8464477	1077.816110	542.1972358	–578.6664430	–58.48725162
59.	446	–458.8464477	1077.816110	561.5579495	–605.6354476	–22.68809453
60.	444	–458.8464477	1115.662603	486.5119059	–648.1893798	–32.64860907
61.	557	–458.8464477	1115.662603	508.9888325	–545.6590489	40.87904609
62.	466	–458.8464477	1115.662603	530.4769905	–617.4753650	–58.48725162
63.	438	–458.8464477	1115.662603	542.1972358	–681.1967739	–22.68809453
64.	695	–458.8464477	1115.662603	561.5579495	–578.6664430	55.53596705
65.	558	–458.8464477	1153.806338	486.5119059	–578.6664430	40.87904609
66.	395	–458.8464477	1153.806338	508.9888325	–648.1893798	–58.48725162
67.	526	–458.8464477	1153.806338	530.4769905	–545.6590489	–22.68809453
68.	609	–458.8464477	1153.806338	542.1972358	–617.4753650	55.53596705
69.	388	–458.8464477	1153.806338	561.5579495	–681.1967739	–32.64860907

cont. Table 5/cd. Tabela 5

No.	T [°C]	T_{ω} [°C]	T_{P} [°C]	T_{σ} [°C]	T_{Ql} [°C]	T_{Qa} [°C]
70.	247	–458.8464477	1190.070793	486.5119059	–681.1967739	–58.48725162
71.	583	–458.8464477	1190.070793	508.9888325	–578.6664430	–22.68809453
72.	547	–458.8464477	1190.070793	530.4769905	–648.1893798	55.53596705
73.	765	–458.8464477	1190.070793	542.1972358	–545.6590489	–32.64860907
74.	706	–458.8464477	1190.070793	561.5579495	–617.4753650	40.87904609
75.	178	–580.4192841	1010.058100	486.5119059	–545.6590489	55.53596705
76.	267	–580.4192841	1010.058100	508.9888325	–617.4753650	–32.64860907
77.	358	–580.4192841	1010.058100	530.4769905	–681.1967739	40.87904609
78.	189	–580.4192841	1010.058100	542.1972358	–578.6664430	–58.48725162
79.	265	–580.4192841	1010.058100	561.5579495	–648.1893798	–22.68809453
80.	330	–580.4192841	1077.816110	486.5119059	–648.1893798	–32.64860907
81.	354	–580.4192841	1077.816110	508.9888325	–545.6590489	40.87904609
82.	323	–580.4192841	1077.816110	530.4769905	–617.4753650	–58.48725162
83.	316	–580.4192841	1077.816110	542.1972358	–681.1967739	–22.68809453
84.	483	–580.4192841	1077.816110	561.5579495	–578.6664430	55.53596705
85.	393	–580.4192841	1115.662603	486.5119059	–578.6664430	40.87904609
86.	311	–580.4192841	1115.662603	508.9888325	–648.1893798	–58.48725162
87.	377	–580.4192841	1115.662603	530.4769905	–545.6590489	–22.68809453
88.	479	–580.4192841	1115.662603	542.1972358	–617.4753650	–58.48725162
89.	300	–580.4192841	1115.662603	561.5579495	–681.1967739	–32.64860907
90.	216	–580.4192841	1153.806338	486.5119059	–681.1967739	–58.48725162
91.	412	–580.4192841	1153.806338	508.9888325	–578.6664430	–22.68809453
92.	441	–580.4192841	1153.806338	530.4769905	–648.1893798	55.53596705
93.	496	–580.4192841	1153.806338	542.1972358	–545.6590489	–32.64860907
94.	534	–580.4192841	1153.806338	561.5579495	–617.4753650	40.87904609
95.	302	–580.4192841	1190.070793	486.5119059	–617.4753650	–22.68809453
96.	314	–580.4192841	1190.070793	508.9888325	–681.1967739	55.53596705
97.	440	–580.4192841	1190.070793	530.4769905	–578.6664430	–32.64860907
98.	403	–580.4192841	1190.070793	542.1972358	–648.1893798	40.87904609
99.	677	–580.4192841	1190.070793	561.5579495	–545.6590489	–58.48725162
100.	191	–685.6908284	1010.058100	486.5119059	–648.1893798	–32.64860907
101.	106	–685.6908284	1010.058100	508.9888325	–545.6590489	40.87904609
102.	154	–685.6908284	1010.058100	530.4769905	–617.4753650	–58.48725162
103.	179	–685.6908284	1010.058100	542.1972358	–681.1967739	–22.68809453
104.	221	–685.6908284	1010.058100	561.5579495	–578.6664430	55.53596705
105.	284	–685.6908284	1077.816110	486.5119059	–578.6664430	40.87904609
106.	221	–685.6908284	1077.816110	508.9888325	–648.1893798	–58.48725162
107.	179	–685.6908284	1077.816110	530.4769905	–545.6590489	–22.68809453
108.	353	–685.6908284	1077.816110	542.1972358	–617.4753650	55.53596705
109.	195	–685.6908284	1077.816110	561.5579495	–681.1967739	–32.64860907
110.	165	–685.6908284	1115.662603	486.5119059	–681.1967739	–58.48725162
111.	269	–685.6908284	1115.662603	508.9888325	–578.6664430	–22.68809453
112.	355	–685.6908284	1115.662603	530.4769905	–648.1893798	55.53596705
113.	287	–685.6908284	1115.662603	542.1972358	–545.6590489	–32.64860907
114.	398	–685.6908284	1115.662603	561.5579495	–617.4753650	40.87904609
115.	221	–685.6908284	1153.806338	486.5119059	–617.4753650	–22.68809453

cont. Table 5/cd. Tabela 5

No.	T	T_ω	T_P	T_σ	T_{Ql}	T_{Qa}
	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]
116.	260	–685.6908284	1153.806338	508.9888325	–681.1967739	55.53596705
117.	298	–685.6908284	1153.806338	530.4769905	–578.6664430	–32.64860907
118.	317	–685.6908284	1153.806338	542.1972358	–648.1893798	40.87904609
119.	430	–685.6908284	1153.806338	561.5579495	–545.6590489	–58.48725162
120.	388	–685.6908284	1190.070793	486.5119059	–545.6590489	55.53596705
121.	240	–685.6908284	1190.070793	508.9888325	–617.4753650	–32.64860907
122.	213	–685.6908284	1190.070793	530.4769905	–681.1967739	40.87904609
123.	328	–685.6908284	1190.070793	542.1972358	–578.6664430	–58.48725162
124.	257	–685.6908284	1190.070793	561.5579495	–648.1893798	–22.68809453

Table 6. Result of LINEST values for Table 1

Tabela 6. Wynik wartości LINEST dla Tabeli 1

1.031457864	1.066184367	0.969492456	0.992717111	1.011089359	0
0.168818332	0.140929704	0.208721152	0.095766232	0.048071006	#N/A
0.975692951	82.38269679	#N/A	#N/A	#N/A	#N/A
955.3398506	119	#N/A	#N/A	#N/A	#N/A
32419021.86	807642.1389	#N/A	#N/A	#N/A	#N/A

For formulas a–e (i-vi). 30 graphical dependencies were constructed. Among them, five were identified to adequately describe the dependence of these parameters (angular velocity. axial load. tensile strength. liquid coolant. and air supply) on temperature:

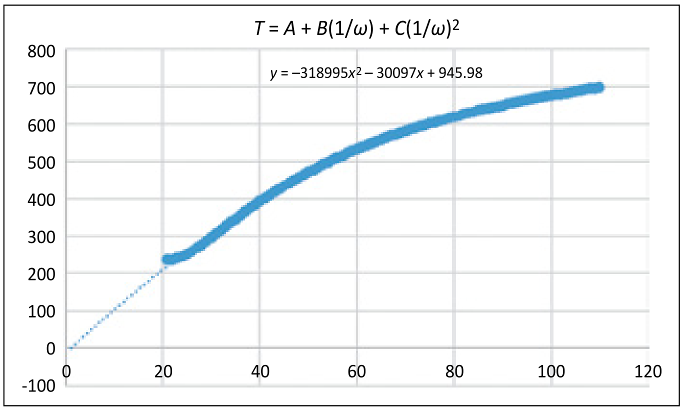

Figure 1. Graph for formula a.vi: $y = T$; $x = 1/\omega$; $A = 945.98$; $B = 30097$; $C = –318995$

Figura 1. Wykres dla wzoru a.vi: $y = T$; $x = 1/\omega$; $A = 945,98$; $B = 30097$; $C = –318995$

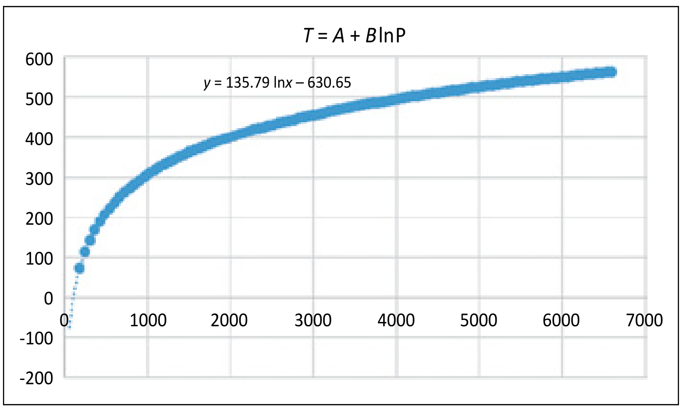

Figure 2. Graph for formula b.iii: $y = T$; $x = P$; $A = –630.65$; $B = 135.79$

Rysunek 2. Wykres dla wzoru b.iii: $y = T$; $x = P$; $A = –630,65$; $B = 135,79$

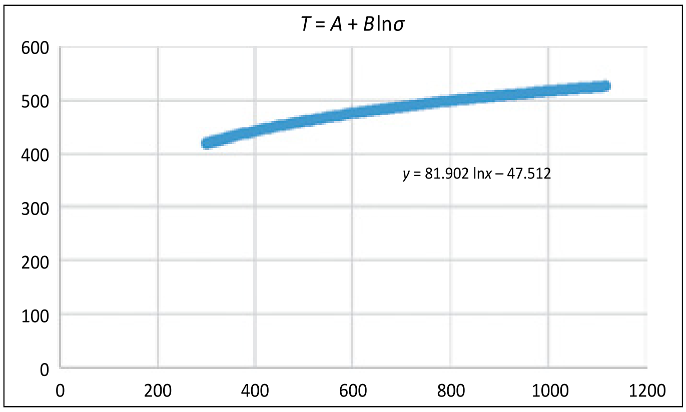

Figure 3. Graph for formula c.iii: $y = T$; $x = \sigma$; $A = -47.512$; $B = 81.902$

Figura 3. Wykres dla wzoru c.iii: $y = T$; $x = \sigma$; $A = -47,512$; $B = 81,902$

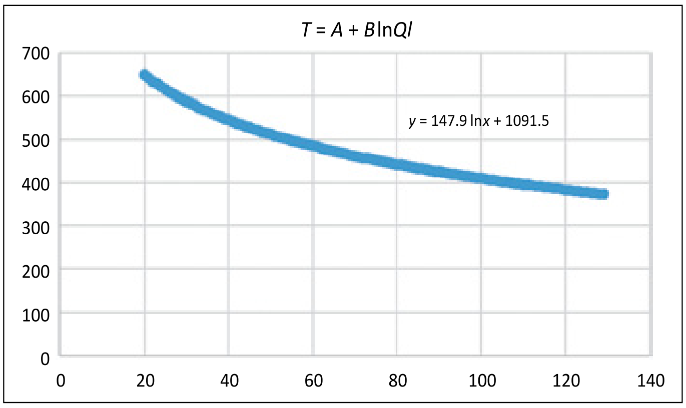

Figure 4. Graph for formula e.iii: $y = T$; $x = Ql$; $A = 1091.5$; $B = -147.9$

Rysunek 4. Wykres dla wzoru e.iii: $y = T$; $x = Ql$; $A = 1091,5$; $B = -147,9$

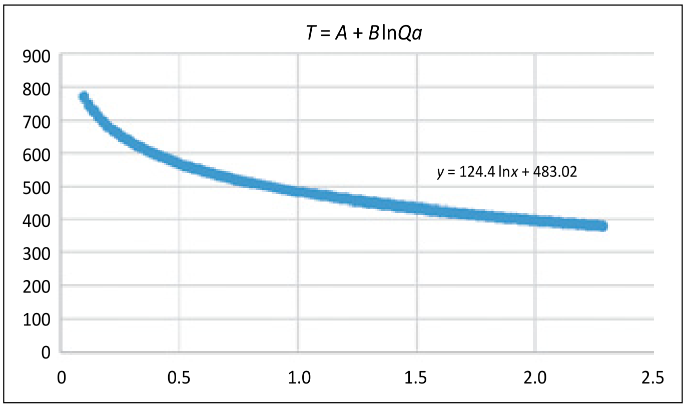

Figure 5. Graph for formula f.iii: $y = T$; $x = Qa$; $A = 483.02$; $B = -124.4$

Figura 5. Wykres dla wzoru f.iii: $y = T$; $x = Qa$; $A = 483,02$; $B = -124,4$

Table7. Table of calculated values of the arguments, with the average values of the rest

Tabels 7. Tabela obliczonych wartości argumentów z wartościami średnimi dla reszty

Angular speed of milling tool [s^{-1}]		26	37	52.3	74.3	104.6	Standard derivation
1.	$T = A + B\omega$	304.4274000	363.2763	445.1298	562.8276	724.9295	167.7177011
2.	$T = A + B\omega + C\omega^2$	261.9060000	364.1620	483.0522	606.4106	684.3967	172.3009023
3.	$T = A + B\ln\omega$	261.5622633	371.8013	479.9335	589.6393	696.5074	173.9870259
4.	$T = A + B\ln\omega + C(\ln\omega)^2$	255.7130273	374.9131	485.8961	592.4835	690.4926	173.0045527
5.	$T = A + B(1/\omega)$	231.1376923	398.8705	514.8520	597.9007	655.0910	173.0307645
6.	$T = A + B(1/\omega) + C(1/\omega)^2$	260.2891716	365.5607	487.1336	598.6898	687.4013	172.1354632
Axial load on the milling tool (N)		**1700**	**2800**	**3700**	**4900**	**6400**	**Standard derivation**
1.	$T = A + BP$	401.4700000	440.1900	471.8700	514.1100	566.9100	64.28217793
2.	$T = A + BP + CP^2$	372.2700000	474.0200	539.2700	601.0700	637.8200	105.64561400

cont. Table 7/cd. Tabela 7

Angular speed of milling tool [s^{-1}]		26	37	52.3	74.3	104.6	Standard derivation
3.	$T = A + B\ln P$	379.4080995	447.1661	485.0126	523.1563	559.4208	69.61544544
4.	$T = A + B\ln P + C(\ln P)^2$	359.0514065	465.2055	503.8139	527.7246	536.4924	72.23515956
5.	$T = A + B(1/P)$	363.2041176	460.9493	497.6938	525.6896	545.9209	72.01011447
6.	$T = A + B(1/P) + C(1/P)^2$	342.4455363	461.5008	497.9694	522.7158	538.9628	78.45784420
Yield strength of milled material [MPa]		380	500	650	750	950	Standard derivation
1.	$T = A + B\sigma$	445.1580000	460.1700	478.9350	491.4450	516.4650	27.64398648
2.	$T = A + B\sigma + C\sigma^2$	434.7140000	468.7700	499.1900	511.9700	519.5300	34.98685518
3.	$T = A + B\ln\sigma$	438.9999059	461.4768	482.9650	494.6852	514.0459	29.13518829
4.	$T = A + B\ln\sigma + C(\ln\sigma)^2$	429.8291035	467.8008	491.3686	498.9773	503.4355	30.37182747
5.	$T = A + B(1/\sigma)$	433.7952632	464.4060	486.7754	496.7173	510.3221	30.04208342
6.	$T = A + B(1/\sigma) + C(1/\sigma)^2$	413.0905817	460.5920	485.2143	493.4224	501.9272	35.78763196
Coolant supply to milling tool [ml/s]		40	50	65	80	100	Standard derivation
1.	$T = A + BQl$	539.5880000	516.4300	481.6930	446.9560	400.6400	55.28896721
2.	$T = A + BQl + CQl^2$	532.0900000	517.3900	488.9650	452.8900	392.8900	55.82357365
3.	$T = A + B\ln Ql$	545.8409511	512.8336	474.0246	443.3106	410.3032	53.88659930
4.	$T = A + BQl + C(\ln Ql)^2$	532.2374138	519.5236	487.6770	449.5267	395.7755	55.51041171
5.	$T = A + B(1/Ql)$	549.9725000	506.9080	467.1562	442.3113	420.7790	51.67102912
6.	$T = A + B(1/Ql) + C(1/Ql)^2$	532.8431250	522.6108	483.4353	444.4570	401.6577	54.71681487
Cooling air supply to the milling tool [m^3/s]		0.64	0.72	1.2	1.3	1.6	Standard derivation
1.	$T = A + BQa$	533.5056000	523.9488	466.6080	454.6620	418.8240	48.36581197
2.	$T = A + BQa + CQa^2$	540.3785952	524.7717	455.6753	446.5763	430.2367	49.58374079
3.	$T = A + B\ln Qa$	538.5559671	523.8990	460.3319	450.3714	424.5327	49.23455520
4.	$T = A + BQa + C(\ln Qa)^2$	541.0925808	522.9992	456.8688	448.3242	428.4543	49.43577445
5.	$T = A + B(1/Qa)$	542.5493750	521.7872	455.3483	447.6823	430.4338	49.41300479
6.	$T = A + BQa + C(1/Qa)^2$	539.0888477	524.5358	458.6290	449.1283	426.3173	49.41024582

Conclusions

1. As a result of the regression analysis of the experimental data (Table 1) in MS EXCEL 2016, linear (1) and non-linear (14) regression equations describing the dependence of the heating temperature of the milling tool were obtained depending on 5 regime parameters: the angular velocity of the milling tool, axial load on the tool, tensile strength of the milled object, liquid coolant, and air supply.
2. The results obtained provide an opportunity for the implementation of the task, i.e. improvement of the work of the milling tool with a decrease in temperature in the milling zone.

Nomenclature

T – temperature,
ω – angular speed of milling tool,
P – axial load on the milling tool,
σ – yield strength of milled material,
Q_l – coolant supply to milling tool,
Q_a – cooling air supply to milling tool,
R – multiple correlation coefficient,
T_ω – temperature component of the angular velocity,
T_P – temperature component from the axial load,
T_σ – temperature component of the tensile strength,
T_{Ql} – temperature component of the liquid supply,
T_{Qa} – temperature component of the air supply,
T_0 – constant temperature component,
A, B, C – constant coefficients,
k_ω, k_P, k_σ, k_{Ql}, k_{Qa}, k_T – regression equation coefficients,
a, b, c, d, e, f – coefficients of indexed parameters.

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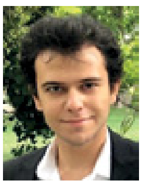

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