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Temperature Measuring Method Accuracy Evaluation in the Microarc Heating Process Based on Reproducibility and Uncertainty Indicators

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Abstract

It is necessary to control temperature using thermoelectric sensors for steel products surface alloying in conditions of microarc heating. The using *S*-type thermocouples possibility has been substantiated, main factors affecting the measurement results have been established, and the the reproducibility index functional dependence on the measured temperature has been determined, as a result of previous studies. However, additional influencing factors that may affect to the heating process kinetics and the temperature measurements results were not taken into account. The purpose of the work was a steel temperature measurement results uncertainty generalized assessment during microarc heating, taking into account most complete influencing factors set. Influencing factors comprise: average coal powder particle size ($X1$), sample diameter ($X2$); chromium content in steel ($X3$). The measurement error was denoted Y. The dependence is obtained: $Y = -4.032X1 - 0.095X2 + 0.0058X3 + 3.414$. Thus, in the studied range of values, an increase in the powder particle and the samples diameter size leads to a decrease in the measurement error, and the chromium content increase leads to its increase. Therefore, the temperature measurement error during microarc heating can be reduced with decrease the sample heating rate, as well as with increase the heat transfer intensity from its surface to the material depth due to an increase the size, and, accordingly, the processed products mass. Next, the studied factors values distribution laws were evaluated. For $X1$ and $X2$, the normal distribution law is adopted, for $X3$ – uniform. Taking into account each factor's influence coefficients, and the total uncertainty estimate introduced assessment by them, a generalized uncertainty estimate was found: $U = 1.1$ °C. The microarc heating temperature measurement method quantitative assessment detailed of the accuracy makes it possible to take into account all significant influencing factors and their total measurement uncertainty contribution. The obtained temperature measurement's total uncertainty value from the three studied factors can be used as a priori information as a type *B* uncertainty during the microarc saturation process.

Keywords: temperature measurement, measurement results uncertainty estimation. microarc heating, steel surface hardening

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Оценка точности метода измерения температуры в процессе микродугового нагрева на основе показателей воспроизводимости и неопределённости

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Для поверхностного легирования стальных изделий в условиях микродугового нагрева необходим контроль их температуры с помощью термоэлектрических датчиков. В ранее проведённых исследованиях обоснована возможность применения термопар типа *S*, установлены основные факторы, влияющие на результаты измерений, определена функциональная зависимость показателя воспроизводимости от измеряемой температуры. Однако при этом не учитывались дополнительные факторы, которые могут оказывать влияние на кинетику процесса нагрева и результаты измерений температуры. Цель работы – обобщённая оценка неопределённости результатов измерений температуры стали при микродуговом нагреве с учётом наиболее полного комплекса влияющих факторов. Определяли влияние факторов: средний размер частиц угольного порошка ($X1$), диаметр образцов ($X2$); содержание в стали хрома ($X3$) на погрешность Y измерения температуры. Получена зависимость: $Y = –4{,}032X1 – 0{,}095X2 + 0{,}0058X3 + 3{,}414$. Таким образом, в изученном диапазоне значений увеличение размеров частиц порошка и диаметра образцов приводит к снижению погрешности измерений, а повышение содержания хрома – к её возрастанию. Поэтому погрешность измерений температуры при микродуговом нагреве может уменьшаться при снижении скорости нагрева образцов, а также повышении интенсивности теплопередачи от их поверхности вглубь материала за счет увеличения размеров, и, соответственно, массы обрабатываемых изделий. Выполнена оценка законов распределения значений исследованных факторов. Для $X1$ и $X2$ принят нормальный закон распределения, для $X3$ – равномерный. С учётом коэффициентов влияния каждого фактора выполнена оценка вносимой ими суммарной неопределённости и найдена общая оценка неопределённости: $U = 1{,}1$ °С. Детализированная количественная оценка точности метода измерения температуры при микродуговом нагреве позволяет учесть все значимые влияющие факторы и учесть их вклад в суммарную неопределённость измерений. При проведении процесса микродугового легирования полученное значение суммарной неопределённости измерений температуры от трёх исследованных факторов можно использовать в качестве априорной информации как неопредёленность типа *B*.

Ключевые слова: измерение температуры, оценка неопределённости результатов измерений, микродуговой нагрев, поверхностное упрочнение стали

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Introduction

The electrophysical action methods are proposed for the to intensify steel products surface hardening traditional processes [1–14].

One of them is microarc alloying. With this method product is immersed in a metal container filled with coal powder, followed by passing an electric current in the circuit: power source – container – coal powder – steel product. As a result, multiple microarc discharges occur at the metal–powder medium boundary, which effect leads to product heating, during which its surface is diffusively saturated with alloying elements to form a hardened coating [15–17].

Process temperature is the main technological parameter during thermally exposed to a material, so, the measuring task of it in accelerated microarc heating conditions is relevant.

It was found in previous studies that the steel microarc heating process and the temperature measurement results using thermocouples are influenced by two factors groups: technological factors, which include electric current in the circuit strength, coal powder burnout degree and size of its particles, which determine the heating intensity, as well as the product size and the chemical composition of its material, which affect the heat removal intensity from the surface deep into the metal, and metrological factors, including the multiple measurements number , thermocouple calibration, thermocouple sample [15–18]. In particular, in [18], the measuring temperature possibility using type S thermocouples in steel microarc heating process was substantiated. Instance of some factors, such as thermocouple calibration, coal powder burnout degree, current in the circuit, multiple measurements number, and the thermocouple influence to the measurement results was established. The other factors' exploration, which influence was required separate confirmation, had been considered inappropriate due to the experiment complexity.

A multifactorial stepwise nested experiment was conducted with the results analysis using the ANOVA method for each temperature level separately in accordance with GOST R ISO 5725-3-2002, the indicators of repeatability and reproducibility, as well as the reproducibility index functional dependence the measured temperature [18].

The aim of this work was to take into account other factors that may also affect the temperature measurements accuracy during microarc heating: the coal powder particle size, the samples diameter, the chemical composition of samples material, in form of their uncertainty comprehensive assessment, considering repeatability and reproducibility indicators which was established previously (based on the recommendations of ISO 21748:2017).

Therefore, it is advisable to comprehensively assess temperature measurement results uncertainty to determine their accuracy, taking into account repeatability and reproducibility indicators which were previously established, as well as the above-mentioned influencing factors effects.

The objective of the work was the accuracy generalized assessment, considered steel temperature measurements results uncertainty in microarc heating process using repeatability and reproducibility estimates with the most complete influencing factors set.

Research methodology

The experimental setup presented in [18] was used for research. Two *S*-type thermocouples were used – working thermocouple (tolerance class 2 with permissible deviations limits ±1.5 °C in the range of 0–600 °C and 0.0025 *T*, where *T* is the measured temperature, in the range from 600 to 1600 °C according to GOST R 8.585-2001), and reference thermocouple (the 2nd category model with an error not exceeding ±0.9 °C, with an operating range of 300–1200 °C following GOST R 52314-2005), which were hammered into the side cylindrical steel samples surface with a length of 35 mm at the same level for fully registration researched factors influence.

An alternating current with a frequency of 50 Hz was used to power the installation, the current in the circuit was 3.0 A, and the current density on the surface of the samples was 0.53 A/cm^2.

Influencing factors had been chosen: coal powder particle size (anthracite grade A according to GOST 25543-2013), samples diameter; steel chromium content as the most common alloying element.

Coal powder particle size is the factor $X1$, which determines the particles number in contact with the sample surface, and, accordingly, the microarc discharges number due to which it is heats and determines the heating kinetics. During the experiments, carbon powders with nominal particle sizes of 0.4, 0.6, 0.8 mm were used.

The samples diameter is the factor $X2$, of which their mass depends on, and, accordingly, the heat in-

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tensity removal from the surface deep into the metal [19]. To assess this factor influence, samples with a diameter of 12, 18, and 24 mm were used.

The steel chromium content is the factor *X*3 that affects the thermal material conductivity, which also determines the heat removal intensity from the surface deep into metal. To assess this factor influence, the values of 0.13 and 28 wt.% Cr were selected. Steels samples were used: grade 20 according to GOST 1050-2013, containing up to 0.25 wt.% chromium, grade 20Cr13 with a chromium content in the range of 12.0–14.0 wt.%, and grades 15Cr28 with a chromium content in the range of 27.0–30.0 wt.% following GOST 5632-2014.

The experiments were carried out at each *X*4 temperature level in the range from 400 to 1200 °C in increments of 200 °C. 27 different experiments were conducted, which results allowed us to obtain 135 conditional equations for determining the regression model.

A 3-level fractional factor plan was adopted for conducting experimental studies. The influencing factors values following the experimental plan are presented in Table 1.

Table 1

Experiment planning matrix in absolute values of factors

Experience number	Factors		
	*X*1, mm	*X*2, mm	*X*3, weight %
1	0.4	12	0
2	0.6	12	0
3	0.4	24	0
4	0.6	24	0
5	0.4	12	13
6	0.6	12	13
7	0.4	24	13
8	0.6	24	13
9	0.8	12	0
10	0.4	18	0
11	0.6	18	0
12	0.8	18	0
13	0.8	24	0
14	0.8	12	13
15	0.4	18	13
16	0.6	18	13
17	0.8	18	13
18	0.8	24	13
19	0.4	12	28
20	0.6	12	28
21	0.8	12	28
22	0.4	18	28
23	0.6	18	28
24	0.8	18	28
25	0.4	24	28
26	0.6	24	28
27	0.8	24	28

The working thermocouple (WT) reading deviation from the actual current temperature value determined by the standard thermocouple (ST) in the microarc heating process was taken as the output value Y.

Thus, the measuring task was to determine coal powder particle size, sample diameter, and the sample material chromium content as input values in each experiment, obtaining the temperature measurement results using the working thermocouple, and determining the measurement result error by comparing it with the measurement result, which was received with standard thermocouple.

The LS-200 sieve analyzer manufactured by HT Machinery (Japan-Taiwan) was used for sieving coal powder, the coal particles sizes were determined using a BT-2900 laser analyzer from Bettersize Instruments Ltd (China) with measurement limits from 0.1 to 1000 μm and accuracy up to 0.01 μm.

The samples diameter measuring following GOST 2590-2006 on the requirements for the steel grade, considered the tolerance of 0.4 mm, was performed with an accuracy significant margin using a micrometer MK-25 with an absolute measurement error value limit of ±5 μm.

The chromium content in the samples was determined using a ZEISS CrossBeam 340 auto-emission scanning electron microscope with an Oxford instruments *x*-max 80 X-ray microanalyzer with a measurement accuracy of up to 0.01 wt.%.

In each experiment, the specified diameter sample made of steel with the specified chromium content was used following the experimental plan. Thermocouples were hammered into the sample surface side, after which it was immersed in a metal container and filled with coal powder with required size particles (Table 1).

After the measurements were performed in each experiment, the sample was replaced with a new one, the thermocouples were capped and a new coal backfill was used.

The experiment was carried out in the temperature range from 400 to 1200 °C in increments of 200 °C, in each experiment the specified range was passed 2 times.

The STATISTICA software package was used for the obtained data statistical processing.

Research results and their discussion

The temperature measurements results following the planning matrix are presented in Table 2.

During obtained results analysis, it was considered that the experiment temperature is a not-controlled factor, and the thermocouple calibration characteristic may be different at the different temperature values ranges. Therefore, temperature can be considered as an additional factor $X4$.

In addition, it has been suggested that changes in the physical properties of $X1$–$X3$ at different temperature levels may affect the measurement error. To verify this assumption, the correlation coefficients following values were obtained: $r(X1, X2) \approx 0$; $r(X2, X4) = 0.00009$; $r(X3, X4) = 0.002$. Thus, it was found that presumably correlated values cannot have a significant joint effect on the output value, and therefore it was decided to reject the model taking into account the researched factors and temperature mutual influence.

It should be considered that the change in the measurement method accuracy at measured temperature different levels was taken into account in the mathematical model for the reproducibility indicator [18]. If the previously studied factors generalized contribution [18] is conditionally represented as a free term d, then the desired dependence can be represented as:

$$Y = aX1 + bX2 + cX3 + d.$$

The found equations system solution has the form:

$$a = -4.03229;\ b = -0.09521;\ c = 0.005765;\ d = 3.414382.$$

Therefore:

$$Y = -4.03229X1 - 0.09521X2 + 0.005765X3 + 3.414382.$$

From the expression obtained, it can be seen that in the studied values range, an increase in the coal powder particles size and the samples diameter shifts the measurement error to a values negative range, and an increase in the chromium content in the heated steel leads to an increase in the positive error component.

The constant term included in the regression equation takes into account the output indicator trend, which is not considered in this regression equation.

Thus, to reduce the temperature measurement error during microarc heating, it is necessary to reduce the sample heating rate and increase the heat transfer intensity from its surface deep into the material.

The sample heating rate is reduced by reducing the carbon particles adjacent number to the sample and, accordingly, the microarc discharges number heating it.

Table 2

Results of experiments

№	Factors			Values of temperature levels, °C																			
	$X1$,	$X2$,	$X3$,	400				600				800				1000				1200			
	mm	mm	w.%	WT	ST	WT	ST	WT	ST	WT	ST	WT	ST	WT	ST	WT	ST	WT	ST	WT	ST	WT	ST
1	0.4	12	0	402.4	401.2	401.4	400.0	598.0	600.4	600.8	602.0	800.1	798.8	801.7	800.2	1004.2	1002.2	1003.0	1001.4	1203.0	1200.6	1203.3	1201.3
2	0.6	12	0	402.9	402.0	403.6	402.1	601.0	602.2	598.9	600.5	803.5	802.1	803.0	802.2	1000.0	1001.3	999.3	1002.0	1200.0	1202.2	1200.1	1202.1
3	0.4	24	0	401.0	399.4	402.6	401.6	600.0	601.5	601.2	602.1	801.0	801.4	800.4	801.4	999.7	1002.1	999.7	1001.7	1198.0	1200.4	1199.2	1201.6
4	0.6	24	0	399.0	398.2	400.2	399.2	601.0	601.7	598.3	598.6	799.8	800.0	800.8	801.2	998.2	999.4	996.2	998.6	1198.4	1200.2	1200.0	1202.2
5	0.4	12	13	399.9	399.5	399.8	397.8	600.8	600.4	600.2	599.2	801.0	800.2	799.6	798.6	1000.1	997.9	1003.4	1001.8	1200.1	1197.9	1202.8	1201.4
6	0.6	12	13	400.4	401.4	401.1	401.7	600.0	599.7	598.9	598.4	798.9	798.4	801.6	800.9	999.6	1000.8	998.6	1000.2	1197.5	1199.0	1200.1	1201.8
7	0.4	24	13	400.6	400.8	401.9	402.1	601.3	601.4	601.0	601.3	801.1	801.5	800.3	800.7	998.7	1001.6	1001.8	1002.3	1200.1	1202.0	1198.3	1200.6
8	0.6	24	13	401.9	402.0	401.7	401.8	602.1	602.2	600.3	600.4	802.0	802.0	801.2	801.6	1000.2	1002.0	999.2	1001.4	1199.4	1200.8	1200.0	1202.0
9	0.8	12	0	400.0	400.1	399.8	399.9	600.1	601.2	599.9	600.8	799.4	800.2	799.6	800.8	1000.1	1001.4	1001.3	1002.0	1197.1	1197.9	1199.2	1200.2
10	0.4	18	0	400.1	399.9	400.1	400.1	600.1	599.4	600.3	600.0	801.3	801.2	800.4	800.3	1000.7	1000.7	1001.6	1001.4	1200.0	1200.6	1203.1	1202.3
11	0.6	18	0	400.2	400.3	399.9	400.0	600.7	601.0	598.8	600.5	799.1	800.8	799.8	800.1	999.4	1000.8	1001.3	1001.9	1199.5	1200.7	1201.0	1201.2
12	0.8	18	0	399.2	400.8	400.1	401.5	599.4	601.3	599.7	600.8	800.2	801.7	798.7	800.2	1000.2	1002.0	1000.6	1001.8	1200.2	1201.5	1198.8	1200.5
13	0.8	24	0	400.1	401.7	399.7	402.1	599.6	602.2	599.6	601.0	801.0	803.2	801.0	802.8	1000.3	1003.5	1002.1	1002.9	1200.1	1202.9	1198.5	1199.7
14	0.8	12	13	400.5	401.7	400.2	401.0	599.6	600.3	600.2	601.5	799.0	800.3	800.7	801.4	1000.1	1001.8	998.9	999.2	1199.2	1199.7	1199.2	1200.3
15	0.4	18	13	401.0	400.4	400.1	400.1	601.1	600.8	600.4	600.3	801.5	801.4	801.1	800.8	1000.9	1000.6	1001.5	1001.4	1199.6	1199.4	1200.2	1200.2
16	0.6	18	13	399.6	400.3	401.3	402.2	599.7	600.4	600.4	601.3	800.1	800.4	801.0	801.7	1000.9	1001.2	999.7	1000.4	1200.7	1201.1	1201.6	1202.4
17	0.8	18	13	399.8	401.1	400.1	401.8	599.9	602.1	600.0	600.8	801.4	802.6	801.2	803.0	1000.4	1002.7	1000.4	1000.9	1199.1	1200.9	1198.8	1199.8
18	0.8	24	13	400.1	402.4	400.5	402.2	599.6	601.8	600.4	602.2	799.9	802.9	801.7	802.7	1000.1	1001.8	1001.2	1003.5	1199.0	1200.8	1199.3	1201.5
19	0.4	12	28	401.3	400.1	402.3	401.5	600.9	600.1	600.6	599.4	802.3	801.1	802.1	801.3	1002.9	1001.3	1003.0	1002.6	1201.5	1201.3	1200.1	1200.1
20	0.6	12	28	400.4	400.3	401.1	401.0	600.9	601.0	601.3	601.2	800.6	800.5	801.2	801.1	1000.7	1000.7	1001.7	1001.5	1202.6	1202.5	1202.0	1201.9
21	0.8	12	28	400.3	400.8	399.7	401.2	599.9	600.3	599.4	601.0	800.9	802.3	799.5	800.1	1001.7	1002.8	999.3	1000.2	1201.8	1202.9	1201.4	1201.5
22	0.4	18	28	401.9	401.4	400.1	399.8	600.9	600.2	601.9	601.8	801.8	801.4	800.4	800.2	1000.3	999.8	1000.6	1000.5	1201.9	1201.7	1200.7	1200.3
23	0.6	18	28	400.2	401.5	400.1	400.4	600.4	600.8	601.4	602.0	801.0	801.7	800.5	800.8	1000.4	1000.7	1000.8	1001.5	1200.3	1200.8	1200.9	1201.4
24	0.8	18	28	399.8	401.1	400.6	402.3	600.1	602.2	600.8	601.3	801.3	802.5	800.5	801.9	999.6	1001.5	999.9	1000.6	1199.1	1199.7	1201.1	1202.9
25	0.4	24	28	400.1	399.9	398.9	400.1	600.2	600.5	600.6	600.9	801.4	801.7	799.9	800.2	1001.4	1001.7	1002.3	1002.4	1199.9	1200.4	1202.7	1202.8
26	0.6	24	28	399.6	400.4	399.9	401.1	600.1	600.9	599.8	601.4	799.1	799.6	799.3	800.8	1001.3	1002.1	999.5	1000.7	1200.5	1201.9	1199.8	1200.4
27	0.8	24	28	399.2	401.4	399.0	400.8	599.5	601.9	599.7	601.3	799.2	800.7	799.4	801.9	999.4	1001.8	1001.0	1002.6	1198.1	1199.9	1198.6	1200.8

The samples heat transfer from the surface deep into the material increases with an increase in their mass due to an increase in diameter, and decreases due to a decrease in thermal conductivity as a result of chromium alloying [19].

For each influencing factor, accuracy studies have not been conducted before, so they were accepted as type A uncertainty sources. For this, following GOST R 8.736-2011, the studied factors values distribution laws were evaluated.

Coal particle diameters were measured with nominal values of 0.4, 0.6, 0.8 mm. Based on the three general aggregates obtained values results, weighing 100 g each, the coal particles sizes distributions selected values of this factor are obtained, shown in Figure 1.

To check the distribution normality, the Pearson criterion χ^2 was used with a criterion value of $\chi^2_{0.005} = 21.96$, the calculated values for the distributions (Figure 1*a*, *b*, *c*) are 21.67117, 21.95738 and 14.32143, respectively, so in all cases the normal distribution law is adopted.

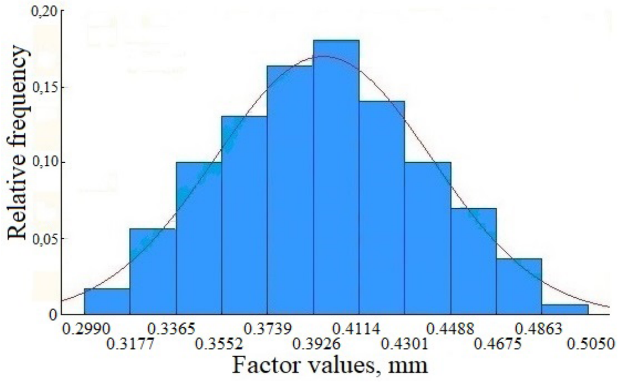
It can be seen from the histograms that for the distributions in Figure 1*a*, *b*, the kurtosis and asymmetry differ from the theoretical ones for the normal distribution. For both of these distributions, there is an asymmetry, for the histogram in Figure 1*a* – excess in excess. The histogram in Figure 1*c* is closest to the theoretical normal distribution. A certain smaller coal particles fraction excess relative to the nominal value does not have a noticeable effect on the microarc heating process dynamics.

The dispersion of the parameter values is estimated as the average value of the intra-group variance:

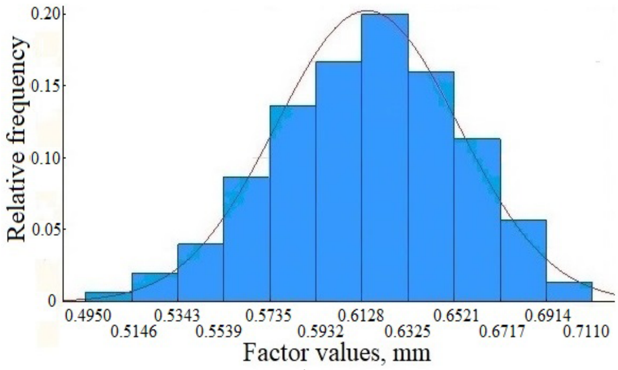
$$\sigma_{X1}{}^2 = \frac{\sigma^2_{0.4} + \sigma^2_{0.6} + \sigma^2_{0.8}}{3} = 0.000915 \ \ (\text{mm}^2).$$

To evaluate the distribution samples diameter values law, 3 batches of 75 pieces each were made. The size distributions in the samples are presented as histograms in Figure 2. It is established that the Pearson criterion χ^2, the calculated values of which for distributions (Figure 2*a*, *b*, *c*) are equal to 1.268285, 0.879434 and 5.530104, respectively, allows us to accept the compliance hypothesis with the normal distribution law, taking into account the criterion value $\chi^2_{0.05} = 9.488$.

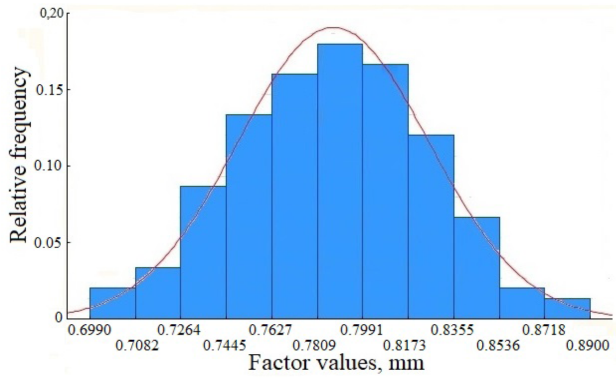
It can be seen from the histograms that there is a slight asymmetry for all three distributions.



a



b



c

Figure 1 – Coal particles distribution size histograms with a nominal size of 0.4 mm (*a*), 0.6 mm (*b*) and 0.8 mm (*c*)

This parameter values dispersion is estimated as the average value of the intra-group variance:

$$\sigma_{X2}{}^2 = \frac{\sigma^2_{12} + \sigma^2_{18} + \sigma^2_{24}}{3} = 0.004077 \ \ (\text{mm}^2).$$

To evaluate the chromium content distribution law in the samples from steels 20, 20Cr13, and 15Cr28, 5 measurements were performed on each of the 15 samples. The results are shown in Figure 3.

To test the compliance hypothesis with the theoretical uniform distribution, the Pearson criterion χ^2 was used [20].

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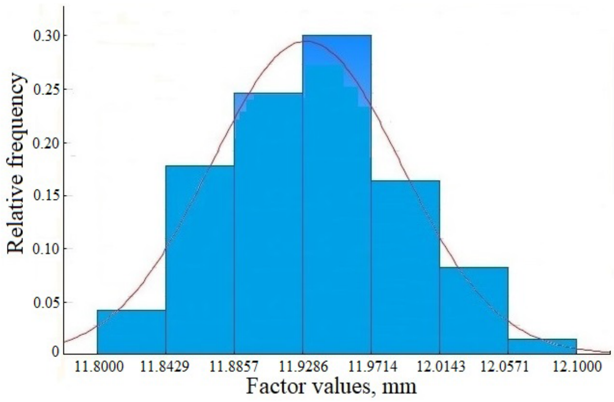
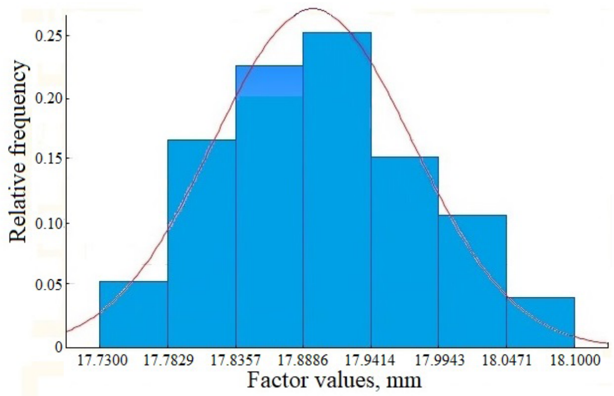
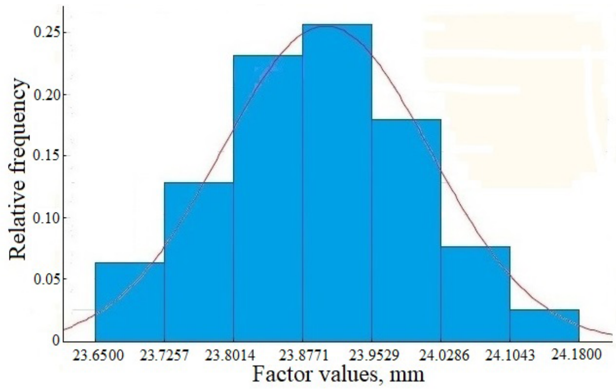


a

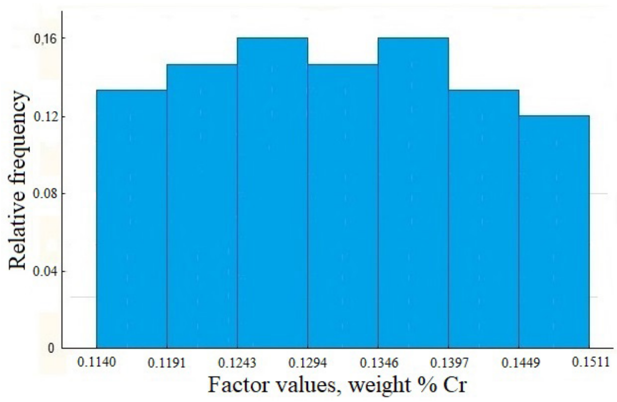


b

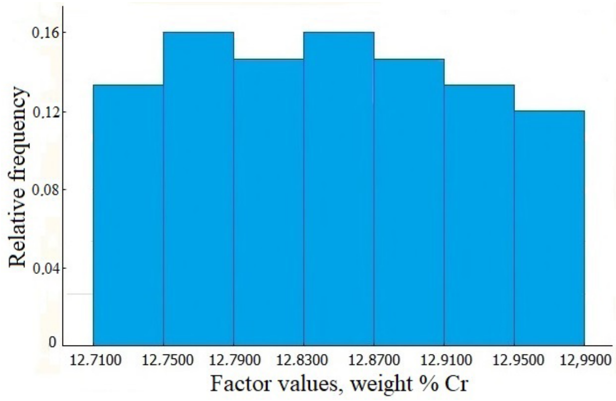


c

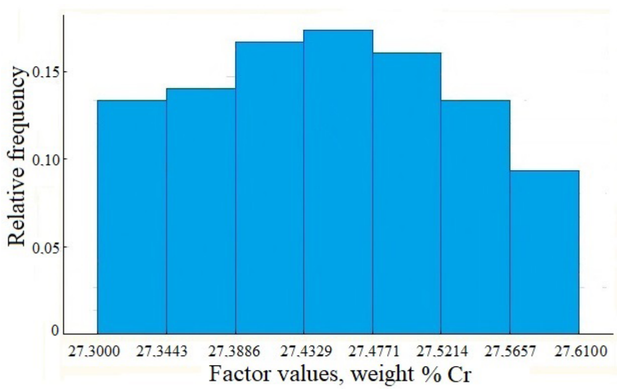
Figure 2 – Histograms of the distribution of the actual sizes of the sample diameters: *a* – 12 mm; *b* – 18 mm; *c* – 24 mm



a



b



c

Figure 3 – Chromium content distribution in steel samples 20 histograms (*a*), 20Cr13 (*b*), and 15Cr28 (*c*), wt. %

The calculated values of χ^2 for the distributions (Figure 3*a*, *b*, *c*) are 0.6933, 0.7145 and 0.8267, respectively, which, taking into account the criterion value of $\chi^2_{0.05}$ = 9.488, allows us to accept the compliance hypothesis with the uniform distribution law.

The parameter values dispersion is estimated as the average value of the intra-group variance:

$$\sigma_{X3}{}^2 = \frac{\sigma_0^2 + \sigma_{13}^2 + \sigma_{28}^2}{3} = 0.003445 \text{wt.\%}.$$

Taking into account the each factors influence coefficients of considered, an assessment of the total uncertainty introduced by them was performed:

$$U_c = \sqrt{(-4.03)^2\sigma_{X1}^2 + (-0.10)^2\sigma_{X2}^2 + 0.01^2\sigma_{X3}^2} = 0.122 \ (°C).$$

Taking into account the uncertainty established as a thermocouple calibration result, the reproducibility of SR standard deviation, and the total uncertainty found from the additional factors studied, it is possible to write:

$$U^2 = S_R^2 + U_c^2 + U_T^2.$$

For the thermocouple used in the experiment, according to calibration data, U_T = 0.57 °C, the reproducibility standard deviation S_R = 0.87 °C [12], uncertainty from additional factors U_C = 0.122 °C.

Then the overall uncertainty estimate is: U = 1.047 °C ≈ 1.1 °C.

It should be noted that the uncertainty from the studied factors was established based on the intra-group variances averaged values and proved to be commensurate with the reproducibility index. Thus, when assessing the temperature measurements results uncertainty, it is advisable to use the studied factors contributions estimates found to the total uncertainty and attribute them to the uncertainty of type B. The contribution from the thermocouple used, which is determined by its calibration results, also belongs to the uncertainty same type.

The reproducibility standard deviation value can vary significantly depending on the measured temperature and can be determined by the previously obtained mathematical model [18].

As a result, a detailed quantitative temperature measurement method accuracy assessment for microarc heating in the steel products surface alloying process was obtained, which allows taking into account all significant influencing factors.

Thus, the generalized uncertainty assessment takes into account the fullest possible factors influence acting in the measuring temperature measurement results accuracy process. At the measurement method reproducibility standard deviation determining stage, the following were taken into account: current in the circuit, thermocouple calibration, coal powder burnout degree, multiple measurements number, and thermocouple instance. Additionally, the factors considered: coal powder particle size, samples diameter, sample material chemical composition are taken into account by their influence on the measurement results uncertainty.

Such an assessment can be used to compare the temperature measurement methods quality in similar measuring and production tasks, when identifying and considering influencing factors, for periodic experimental measurement method correctness verification and the measuring installation functioning, taking into account metrological reliability indicators.

Conclusion

An increase in the coal powder particle size and the samples diameter leads to an increase in the temperature measurement error negative component during microarc heating, and an increase in the chromium content shifts the error towards positive values. To reduce the temperature measurement error, it is necessary to reduce the sample heating rate and increase the heat transfer intensity from its surface deep into the material.

During the microarc surface alloying technological process, the temperature measurements total uncertainty obtained value from the three studied factors can be used as a priori information as a type *B* uncertainty.

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