Selection the measuring system for registering the metal parts temperature at microarc heating and its thermophysical analysis

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Abstract. Measuring the temperature of metal parts during thermal and thermochemical treatment is necessary for the control of the correctness of the technological process. Currently, new methods of thermochemical processing of parts under high-energy conditions, such as microarc surface alloying, are proposed. Heating is carried out by the action of microarc discharges on the surface of parts immersed in coal powder when an electric current flows. It reduces the processing time from a few hours to a few minutes, but makes it difficult to measure the temperature, because heating occurs in dynamic mode. The aim of the work was to select a measuring system for recording the metal parts' temperature during microarc heating, and the thermophysical analysis of the heating process. The S-type sensor was selected. The measuring system also includes a digital multimeter and a personal computer. The density of the electric current on the surface of the samples was 0.53 A/cm². The registered heating curve consists of several stages. At the first stage the heating speed was about 8 °C/s. At the second stage it increases to 16 °C/s, but then decreases to 3.5 °C/s. Then the temperature increases monotonously with an average speed of 9 °C/s. At the fourth stage the sample temperature is stabilized at 1250 °C. The thermophysical process' model of the heating metal parts under the influence of microarc discharges was proposed. The analysis showed that the calculated data coincide with the experimental data.

1. Introduction

Measuring the temperature of metal parts during their heating is the most important technical problem of thermal and thermochemical treatment. Traditional thermal hardening processes are energy-intensive and their duration is several hours [1-5]. Methods of high-energy influence on the material (laser, plasma, ion, etc.) are proposed for heating intensification [6-10].

Microarc surface saturation is one of the methods that use high-energy effects on the material. The parts' heating is carried out as a microarc discharges impact result on their surface that occur in the coal powder, in which the parts are immersed when an electric current flows. Carbon monoxide is released during thermal decomposition of coal, which leads to carburization of the part's surface. Using of coatings containing carbide-forming elements makes it possible to form high-hard carbide coatings. As a result, the hardening treatment duration is reduced from several hours to several minutes [11-15].

Thus, the microcurrent effect can significantly reduce the processing time of parts, but the high heating speed requires special attention to the choice of a temperature measuring device. Also, the
dependence of the sample temperature on the surface current density and microarc heating duration is of interest. Therefore, the work aimed to choose a measuring system for recording the metal parts temperature during microarc heating and its thermophysical analysis.

2. Methods of study
Technological processes of thermal and chemical-thermal steels and alloys parts processing made are usually carried out at a temperature up to 1300 °C, and for its measurement, thermoelectric measuring instruments are used. Their work is based on the thermoelectrical effect (the Seebeck effect), which consists in the fact that in a closed electrical circuit consisting of dissimilar conductors, a thermoelectric motive force occurs if the temperatures of their contacts are different [16, 17].

It is known that any two conductors create an electrical voltage in a pair, but only a limited number of the thermoelectric electrode are used to create thermoelectric sensors, because their materials have several requirements: stability and reproducibility of thermoelectric properties, the thermowell linear dependence on temperature, heat resistance, and mechanical strength, chemical inertia; manufacturability, cheapness. None of the modern available materials fully meets all the requirements. Experimentally, most suitable metal pairs were selected for use in thermoelectric devices. These are pairs of chromel-copel, chromel-alumel, copper-constantan, iron-constantan, platinum-platinorodium, rhenium-tungsten, and others. Each of them is used for specific tasks. Some types of thermocouples that are most commonly used in measurement practice are shown in table 1.

Table 1. Types of temperature sensors

| Type of thermocouple | International designation according to the IEC standard | Material of thermoelectric electrode positive | Material of thermoelectric electrode negative |
|----------------------|---------------------------------------------------------|---------------------------------------------|----------------------------------------------|
| Chromel - Kopel       | L                                                       | The alloy Chromel                           | The alloy Kopel                              |
| Chromel - Alumel      | K                                                       | The alloy Chromel                           | The alloy Alumel                             |
| Copper - Constantan   | T                                                       | Copper                                      | The alloy Constantan                         |
| Chromel - Constantan  | E                                                       | The alloy Chromel                           | The alloy Constantan                         |
| Iron - Constantan     | J                                                       | Iron                                        | The alloy Constantan                         |
| Platinorhodium - platinum | S, R                                              | The alloy platinum - rhodium               | Platinum                                    |
| Platinorhodium - platinorhodium | B                                           | The alloy platinum - rhodium               |                                             |
| Tungsten - rhenium - tungsten - rhenium | A-1, A-2, A-3 | The alloy tungsten - rhenium               |                                             |

90,5%Ni+9,5%Cr  94,5%Ni+5,5%Al

90,5%Ni+9,5%Cr  60%Cu+40%Ni

60%Cu+40%Ni  95%W+5%Re

87%Pt+13%Rh  95%W+5%Re

90%Pt+10%Rh  80%W+20%Re

94%Pt+6%Rh
The most common thermocouples types are L (chromel-copel), K (chromel-alumel), and S (platinum-platinorodium). The L-type thermocouples are used for precise temperature measurements and has the highest differential sensitivity of all industrial thermocouples. This type has an exceptionally high thermoelectric stability, because changes in the thermopower of the chromel and copel thermoelectrodes compensate for each other. However, its application temperature range is limited and usually does not exceed 600 °C.

The K-type thermocouples have a high heat resistance and is the most common for industrial measurements and scientific research. This type is designed to measure temperatures up to 1100 °C, but can be used up to 1300 °C for short-term heating.

The S-type thermocouples are used for industrial and laboratory measurements in the temperature range up to 1600 °C. This type's main advantages are high heat resistance, high melting point, and a fairly large thermal thermoelectric power. When choosing the thermocouple type, it was taken into account that under the action of microarc discharges, the parts surface is heated to a temperature exceeding 1000 °C, and the individual microarcs temperature, according to some estimates, can reach several thousand degrees. Therefore, S-type thermocouples were used for experimental studies. The thermocouple characteristics: tolerance class 2 with tolerance limits of 1.5 °C in the range from 0 °C to 600 °C and 0.0025 t in the range from 600 °C to 1600 °C by GOST R 8.585-2001.

When measuring the metal surface temperature using thermocouples, possible sources of measurement errors should be taken into account: insufficient thermal contact the thermocouple working junction with the metal and the presence of an air gap between them, as well as the interference influence that occurs when heating the metal by passing an electric current [18-20]. In our experiments, we used a thermocouple with a wire diameter of 0.3 mm, which was welded to the sample's surface. The electric current density on the sample's surface was 0.53 A/cm², which provided a heating rate of no more than 20 °C/s, which makes it possible to ignore the current flowing influence through the sample on the thermal EMF produced by thermocouples. For experiments, cylindrical samples with a length of 35 mm and a diameter of 12 mm were used, to the surface of which the working junction of the thermocouple was welded. Samples were immersed vertically for half the length in a metal container filled with coal powder with a particle size of 0.4-0.6 mm. Contact wires were connected to a digital multimeter APPA-305, connected to a personal computer using an RS-232 interface. The WinDMM 300 software was used for processing the measurement results.

3. Results and Discussion

Based on the analysis, a measuring system is proposed for recording the temperature of metal samples during heating, the scheme of which is shown in figure 1.

![Figure 1. Scheme of the measuring system used in experimental studies](image)

To evaluate the dynamic heating mode, the dependence of the sample surface temperature on time was recorded. To construct a kinetic curve using the APPA-305 device, the temperature measurement mode was first selected (figure 2, a), then the time interval between individual measurements was set (1 second was selected, figure 2, b). Then the device was switched on and the supply voltage was simultaneously applied to the experimental unit. The readability of the multimeter was 0.1 °C.
Figure 2. APPA-305 multimeter interface

The registered heating curve is shown in figure 3. There are several stages that differ in the mechanism of influence of heating on the sample temperature.

![Graph showing the dependence of sample surface temperature on duration of heating.](image)

Figure 3. Dependence of the sample surface temperature $T$, °C on duration $t$, s of heating, surface current density 0.53 A/cm$^2$

The first stage begins when the supply voltage is applied and microarc discharges occur simultaneously. The temperature increases to $(70 - 80)$ °C at a rate of about 8 °C/s. Microarc discharges are distributed evenly in the volume of coal powder. Increasing the current density in the direction from the container to the sample surface gradually leads to the significant dissipated electrical power proportion release in the volumes of powder adjacent to the sample.

As a result of these processes, the second heating stage occurs, in which microarc discharges are concentrated around the sample surface. This leads to a rapid increase in temperature to 200 °C at a rate of about 16 °C/s, after which the heating rate decreases and in the range $(200 - 270)$ °C is equal to 3.5 °C/s, which is explained by endothermic processes in the coal structure in this temperature range.

At the third heating stage, microarc discharges concentrated around the sample surface form a zone of local gas discharge in the microarc halo form. As a result, the sample temperature increases monotonously at an average rate of about 9 °C/s.

Further, the heating rate slowly decreases due to the gradual burning out of the carbon particles around the sample.
At the fourth stage the formation of the microarc discharge around the sample gradually stops as the coal particles, which adjacent to the sample are burn out, in the rest part of the coal powder microarc formation and coal particles combustion continues, and the sample temperature is stabilized at 1250 °C.

When studying heat transfer in the microarc heating process, it is advisable to describe the heating source as a combination of instantaneous point sources \[20\] The further heat propagation through the body is described by the thermal conductivity differential equation.

The concept of an instantaneous point source reflects the actual process physical picture in microarc heating, since the surface is heated as a result of multiple microarc discharges. When describing the microarc heating process, it was assumed that the powder medium consists of spherical particles, set located in a container by analogy with the simple cubic lattice packing density, and the sample is heated due to microarc formation at the contact points of its surface with the first carbon particles layer.

The surface temperature of a cylindrical sample depending on its size and heating time described by the solution of the differential equation subject to the conditions of a uniform temperature distribution of the sample in the initial time and constant heat flux at the surface (boundary condition II, equation (1) \[20\]):

\[
T(t, R) = 2T_0 + \frac{qR}{\lambda} \left( \frac{2at}{R^2} + 0.25 \right)
\]

where \(T_0\) – the sample temperature at the initial time; \(q\) – the heat flux density; \(R\) – the sample radius, \(\lambda\) – the thermal conductivity coefficient; \(a\) – the coefficient of thermal conductivity; \(t\) – the heating duration.

The steel microarc heating such thermophysical parameters estimation was calculated as the power generated by the electric current on the steel product surface, the heat flux density, as well as the single microarc discharge energy (table 2).

| Surface current density, A/cm² | Allocated power, Vt | Heat flux density, \(\cdot10^5\) Vt/m² | The energy of a single discharge, \(\cdot10^3\) Dj |
|--------------------------------|---------------------|--------------------------------------|-----------------------------------------------|
| 0,45                           | 96,88               | 1,71                                 | 4,31                                          |
| 0,49                           | 117,22              | 2,07                                 | 5,21                                          |
| 0,53                           | 139,50              | 2,47                                 | 6,20                                          |

Equation (1) can be used to calculate the steel product temperature depending on its size, microarc heating energy parameters, steel grade, and process duration.

Such results are not available in the published literature \[1-8\].

As an example, figure 4 shows the sample surface temperature calculating result with a radius of 6 mm depending on the time in the range of \(t\) values from 30 s to 150 s at the second microarc heating stage. The calculation takes \(T_0 = 270 ^\circ\)C, \(\lambda = 27\) W/(m•°C).

You can see that the temperature increases linearly. The heating rate is 8.2 ° C/s, and the temperature reaches a value of about 1250 ° C, which almost coincides with the experimental values on the heating curve (figure 3) and indicates the adequacy of the selected model.
4. Conclusions
1. A measuring system for recording the metal parts temperature during microarc heating is proposed. It is advisable to use a thermoelectric sensor of type S as a sensitive element.
2. The registered heating curve contains several sections that differ in the heating speed.
3. A thermophysical model is proposed that adequately describes the nature of changes in the surface temperature of a steel product depending on its size, energy parameters of heating, steel grade, and duration of the diffusion saturation process.
4. The steel microarc heating thermophysical parameters estimation calculated was performed. When the surface current density increases from 0.45 to 0.53 A/cm², the heat flux density increases from 1.71 to 2.47 (×10⁵) W/m², the energy of a single discharge – from 4.31 to 6.20 (×10⁻³) J.

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