

Study of processes of induction heating of steel billets with melting of corrosion-resistant coating considering two Curie points

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Abstract. A technology has been developed for melting a sprayed corrosion-resistant coating during induction heating of a steel cylindrical billet with the specified coating under rotational conditions. The current frequency and other parameters of the high-frequency induction unit were chosen to ensure maximum heat release in the corrosion-resistant coating during its melting on the surface of a steel cylindrical billet. Calculations and studies of the surface distributions of the current density and temperature along the length of the billet during induction heating have been carried out. Calculation and experimental studies of induction heating, thermal and thermally stressed state of a steel billet with a coating are given. The calculated and experimental curves for heating the surface of a steel billet with a coating are compared taking into account two Curie points. An analysis of the results shows that the thermal stresses that arise in the billet do not affect the technological process of induction heating of the billet with coating melting.

1 Introduction

The problem of protecting metals from corrosive processes does not lose its relevance. The pace of development in many industries is slowed by unresolved corrosion control issues. This makes it necessary to search for technologies that would provide a significant increase in the service life of metal parts in aggressive environments [1-15]. The application of coatings on the surface of metal, improving their performance characteristics - one of the most promising and effective ways to combat corrosion. The use of corrosion-resistant coatings increases the durability of metal, provides protection for metal structures working in the atmosphere, water [5, 6] and other environments [1, 2, 7-15].

Today, such technologies as electrolytic deposition, gumming, gas-thermal spraying, etc. are used to prevent the effects of corrosion on metal structures and to effectively extend the service life of the product. Analysis shows that one of the easiest to implement, most efficient and cost-effective methods is gas-flame powder spraying [1, 12].

The coating obtained by spraying is largely porous in structure. In some cases, this property can be used, but more often dense coatings with low pore content are required, including for hardening the part and increasing wear resistance [1]. A significant disadvantage of gas-flame coatings is also their relatively low adhesive strength. These factors are effectively influenced by

subsequent additional high-energy impact with a concentrated energy source on the sprayed coatings to improve their quality indicators.

2 Research results

The comparative analysis allowed us to establish that in the conditions of combined processing the most preferable way of temperature influence on the sprayed coatings is induction heating by currents of medium and high frequency. It has a characteristic advantage: melting occurs directly in a narrow zone of adhesion between the surface and the coating [1].

The protective coating technology proposed by the authors is divided into two stages: powder spraying with a special gas-flame burner (fig. 1) and its subsequent melting for fixation on the parts with the help of induction heating.

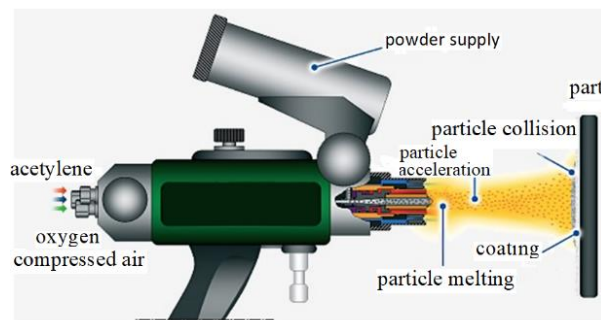


Fig. 1. Scheme of gas flame spraying.

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The process of melting the applied corrosion-resistant coating using an induction unit, in which the rotation of the product and the movement of the inductor were carried out using asynchronous motors, was considered.

When melting the applied corrosion-resistant powder, the powder-coated workpiece must rotate around its axis at 200 rpm and the inductor must move exactly within the area of the applied powder.

The Department of Electric Power Supply of Industrial Enterprises and Electrical Technologies at the MPEI created an induction unit with stepper motors (fig. 2), one of which moves the inductor and the other rotates the coated product. Synthesis of the control system and programming of controllers of electric drive control boards were carried out. The used solutions allow to increase the accuracy of technological process control, reduce the size and reduce the cost of the installation. The unit consists of: inductor, flexible current lead, power source, stand with fixed inductor, workpiece, stepping motor, mechanical converter, control cabinet.



Fig. 2. Experimental setup.

Cylindrical billets of different sizes made of steel 45 with a gas-flame sprayed coating Castolin Eutalloy RW 12496 (fig. 1) were used in the studies. The choice of steel 45 and corrosion-resistant coating material is due to their effective use in the rods of hydraulic cylinders of industrial mechanisms. The selected coating will increase the wear resistance of hydraulic cylinder rods.

Implementing the technology requires solving the electrical and thermal objectives simultaneously, and then the mechanical objectives.

The algorithms for calculating the electromagnetic and thermal objectives were considered [4]. This paper considers the solution of electromagnetic and thermal problems in a software package COMSOL Multiphysics, and to calculate and study the thermal stresses arising in the steel billet during induction melting of the coating and its rotation by a stepper electric motor, software package.

The whole process of solving a problem in COMSOL Multiphysics can be divided into the following stages: defining the physical interface and the problem type; selecting the type of investigation; defining the global model parameters; defining the model geometry, its parameters, model element materials, physical interface parameters and

multiphysics relations; setting calculation grid parameters; calculating the problem; visualizing and analyzing calculation results.

The construction of a finite element model begins with a description of the geometry and materials. The selected geometry consists of three rings of the inductor coil (to which the electric voltage is applied), a coated steel blank in the form of a cylinder 12 mm in diameter (with a coating applied with an average thickness of 1 mm) and a significant finite element domain to simulate the electromagnetic field in the environment surrounding the blank. The finite-element grid of the billet inductor system is shown in fig. 3.

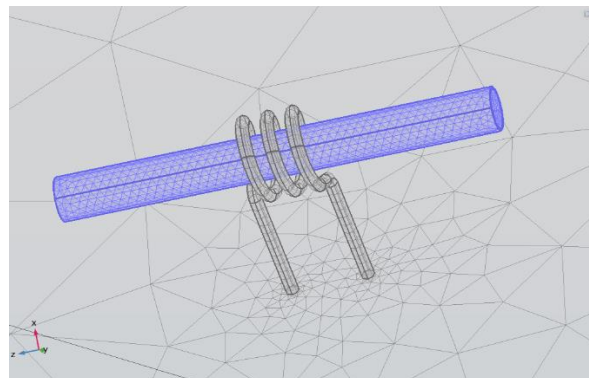


Fig. 3. Finite-element grid of the billet inductor system.

Based on the analysis of current penetration depth Δ into the corrosion-resistant coating as a function of current frequency (fig. 4), a current frequency of 66 kHz and an induction set-up corresponding to this frequency was selected. In this case, the maximum heat release will be observed inside the coating with a thickness of 1 mm along its depth.

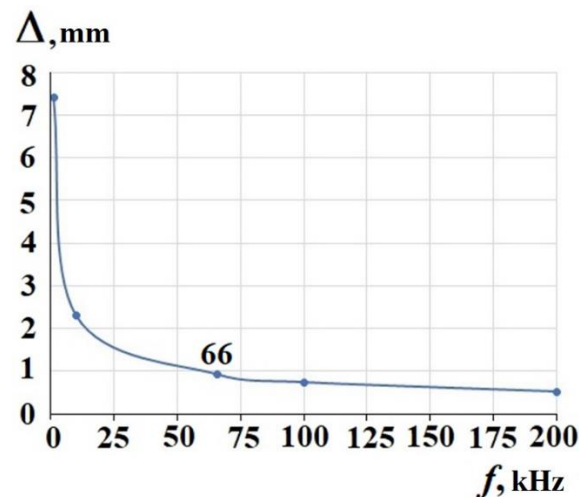


Fig. 4. Dependence of the depth of penetration into the coating material (at its melting) on the frequency of current.

In this work, simulation is carried out with the following parameters: length of the blank – 200 mm, diameter of the blank – 10 mm, thickness of the sprayed layer – 1 mm, inductor current – 380 A, current frequency – $f = 66$ kHz, heating temperature $T = 250-1100$ °C.

Figure 5 shows a drawing of the system "inductor - load", where 1 - inductor, 2 - steel workpiece, 3 - sprayed coating, h - thickness of sprayed coating, d - diameter of the billet.

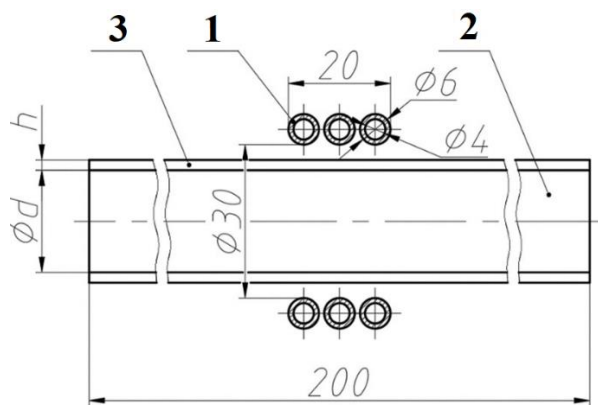


Fig. 5. Sketch of the calculated area of the set-up and the coated workpiece.

Based on the solution of the electromagnetic problem in the Comsol package, the calculated distribution of current density at a selected frequency of 66 kHz in a steel billet located inside a three-core inductor was obtained (fig. 6). The current density maximums on the surface of the workpiece are in the inductor area. The results of solving the thermal problem are shown in fig. 7.

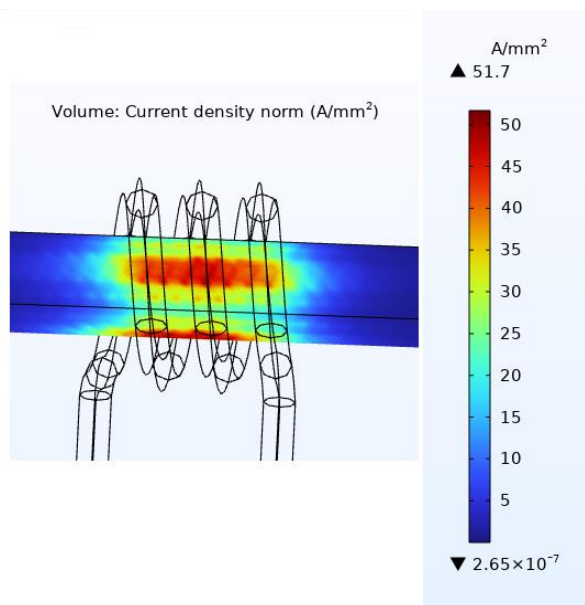


Fig. 6. Current density distribution in the steel billet in the inductor area.

Experimental studies of induction heating of steel billets with melting of corrosion-resistant coating (1 mm thick) were carried out on this setup at a frequency of 66 kHz and the heating curve 1 in fig. 8 with two Curie points. The experimental curve 1 is obtained in fig. 8 when measuring temperatures using an XL Stcok XE-165 thermal imager with a measurement accuracy of $\pm 1 \div 2\%$. The peculiarity of the experimental curve 1 is the presence of the first Curie point (point A) in fig. 8 (temperature - 358 °C), which is associated with the loss of ferromagnetic properties of the coating at a thickness of 1 mm. When heating beyond point A, there is a slight decrease in temperature and then a gradual increase. In addition, on the experimental curve 1 at higher temperatures there is a second Curie point (point B), which is associated with the loss of ferromagnetic

properties of the base material of the steel header. After experiments with reflow, the uniformity of the coating thickness was controlled on cut samples with an analysis of the microstructure. This control showed that the surface of the cylindrical billet is homogeneous and the coating thickness is uniform.

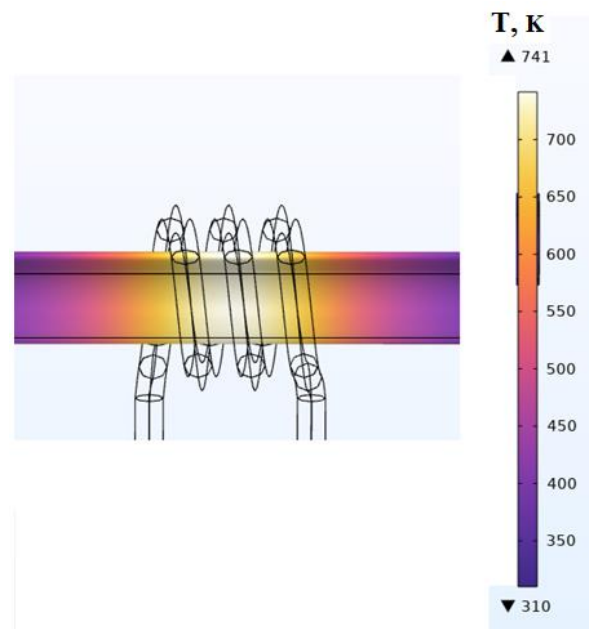


Fig. 7. Distribution of the steel billet surface temperature in the inductor area.

In Fig. 8, using a software package [4], a calculated curve 2 of a coated steel billet also with two Curie points was obtained. The temperature levels of the calculated curve 2 in Fig. 8 turned out to be slightly higher than the experimental curve 1, because it is difficult in the calculation to take into account all the real heat losses during heating of the coated steel billet, as well as the influence of rotation conditions. The calculations took into account the heat losses during convective heat transfer and heat transfer by radiation. It was difficult to take into account convective heat transfer during the rotation of a cylindrical billet. The heat losses from the billet to the mounting shaft of the installation were not taken into account.

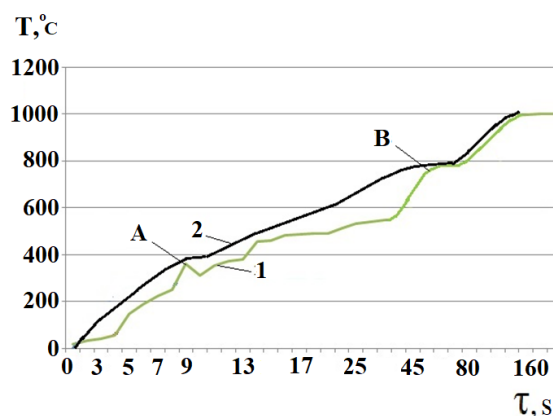


Fig. 8. Experimental curve 1 of heating and calculated curve 2 of heating of steel billets with corrosion-resistant coating: A - first Curie point, B - second Curie point.

In accordance with the calculated curve 2 in fig. 8 (at a temperature of up to 700 °C) was obtained average temperature difference of 20-25 °C between the surface temperature of the curve and the center of the steel billet, and it was slightly larger at the beginning of heating. With increasing temperature above 700 °C this temperature difference gradually decreased to zero and the process of melting of metal coating at 1000 °C was carried out with uniform heating of the steel billet (fig. 8). Taking into account the obtained calculated thermal state of the steel billet, the thermal stresses in it were calculated using a software package [4]. Based on these results, axial thermal stress (curve 1) and circumferential thermal stress (curve 2) curves were plotted in fig. 9. Analysis of the calculated thermal stress state (fig. 9) shows that the thermal stresses have small values (much less than the yield point of the material) and do not affect the technological process of heating the steel billets with melting of the corrosion-resistant coating.

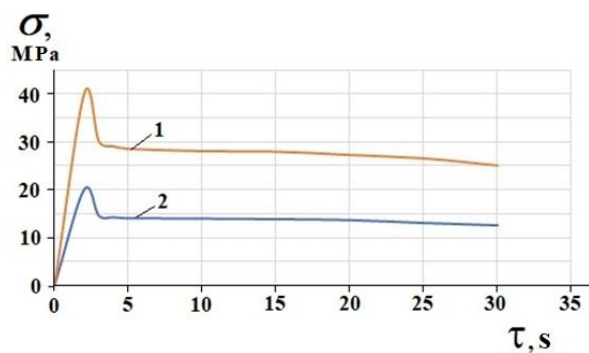


Fig. 9. Calculated curves of axial 1 and circumferential 2 thermal stresses in the center of a cylindrical billet.

3 Conclusion

A technology has been developed for melting a sprayed corrosion-resistant coating during induction heating of a steel cylindrical billet with the specified coating under rotational conditions. The current frequency and other parameters of the high-frequency induction unit were chosen to ensure maximum heat release in the corrosion-resistant coating during its melting on the surface of a steel cylindrical billet. Calculations and studies of the surface distributions of the current density and temperature along the length of the billet during induction heating have been carried out. Calculation and experimental studies of induction heating, thermal and thermally stressed state of a steel billet with a coating are given. The calculated and experimental curves for heating the surface of a steel billet with a coating are compared taking into account two Curie points. An analysis of the results shows that the thermal stresses that arise in the workpiece do not affect the technological process of induction heating of the billet with coating melting. Application of induction heating using an over-frequency unit provides the following advantages: uniformity of heating along the working length of the part, absence of thermal stresses, automatization of the technological process, reduction of human factor influences on the final result. A repeatable technology has been developed in terms of

obtaining a given coating hardness and a uniform chemical composition over the working surface of the part.

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