Simulation of induction heating of a titanium sample in a container with a carbon-containing medium and determination of the amount of heat losses during chemical heat treatment

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Abstract. In this work, the process of induction heating of a container with a titanium sample in a carbon-containing medium was simulated using the finite element method. The dependence of the inductor current \( I \) and the duration of treatment on the heating kinetics \( T(I,t) \) of the "inductor – container – sample" system taking into account the heat losses \( Q_L(I,T) \) on the process of chemical-thermal treatment of titanium was established.

1. Introduction
In the manufacture of products from titanium and its alloys, methods of strengthening chemical-thermal treatment (CTT) are widely used, e.g. cementation, nitriding, oxidation, etc. [1,2]. As a result of this treatment, wear-resistant coatings with high values of hardness [3-5] and other functional qualities, such as morphological heterogeneity and porosity [6-8], are obtained on the surface of the products.

Among the enumerated CTT methods, the cementation process is considered to be efficient, since it is characterized by low costs and allows the production of wear-resistant coatings and diffusion layers [4]. In order to accelerate chemical processes, it is preferable to use induction heating, which is distinguished by high productivity [9,10]. Thus, when using a solid reaction medium, e.g. carbon-containing, the process of cementation of titanium samples should be performed in a refractory container.

In the proposed cementation method, there is the problem of measuring the temperature in the inner part of the container with the sample. It is known that mathematical modeling, in particular the finite element method (FEM), allows the study of the complex systems with numerous elements and interfaces, and where complex processes occur, such as diffusion and heat transfer [11,12]. Hence, it is proposed to use a combined approach consisting in the experimental determination of the temperature of the container surface and the numerical calculation of the temperature field inside the "inductor – container – sample" system.

2. Methodology
The object of study is a system comprising an inductor, a container, a titanium sample, and auxiliary elements (Figure 1). The refractory container (5) with the titanium sample (6) and the working medium (7) are placed inside a cylindrical three-turn inductor (1) with water cooling (2), a tubular quartz chamber (3) with locking dielectric elements (4).
In the simulation, the values of the current parameters were applied that were used in cementation, i.e. the inductor current $I$ from 2.4 to 5 kA and fixed frequency $f$ equaling 110 kHz.

Numerical 2D modeling was performed using the "Elcut" software. The computation duration $t$ did not exceed 400 s, which corresponded to the actual cycle of high-temperature cementation. The main parameters of the system were determined, in particular the nature of the heat source distribution $Q(x,y,I)$ and the thermal field $T(x,y,I,t)$ depending on the inductor current $I$, the geometry of the system elements, as well as corrections for heat losses $Q_L(I,t)$ at CTT.

3. Results

The simulation results showed that in the "inductor – container – sample" system the greatest amount of heat $Q$ was released in the area with carbon-containing medium. This value $(2.9–3.2) \times 10^9$ W/m$^3$ was 3–10 times higher than the heat release in the container equaling $(0.3–0.9) \times 10^7$ W/m$^3$ (Figure 2).

This non-uniformity of heat release was related to the peculiarity of induction heating at high frequencies (over 100 kHz). Apparently, high heat release $Q$ in the carbon medium was associated with reradiation of the alternating field inside the heated system.

The solution of the heat conduction problem for the considered system with a minimum inductor current $I \approx 2.4$ kA showed that the temperature of the container $T$ with heated samples exceeded their melting temperature. However, this phenomenon was not observed in the experiment. Thus, when the container material was heated, along with the known heat losses on convection and radiation, a heat sink of a different nature was acting. It was likely that during the heating of the container, the processes of formation of new phases (chemical compounds – refractory oxides and solid solutions of the oxygen diffusion into the metal) and changes in the structure (growth of crystalline grains) occurred.
To solve the thermal problem correctly, it was necessary to take into account the losses for the above mentioned processes, which was possible by introducing the function $Q_L$ in a graphical form (Figure 3). The shape of the graph of this function had an exponential form, which was associated with the values of the inductor current and temperature.

The solution of the heat conduction problem taking into account the heat losses $Q_L$ on the CTT process was in the form of parabolic curves with a saturation region (stationary exposure). Of greatest interest were the graphs for the periphery of the container and the titanium sample in the region of maximum field strength (in the center of the inductor coil).
Curve (2) corresponded to the temperature on the container surface in the zone of influence of the inductor, curve (3) to the temperature in the center of the titanium sample (Figure 3,a). The experimental curve (1) was characterized by a much lower heating rate to a maximum temperature of about 1200 °C at a minimum inductor current of 2.4 kA, since the temperature was measured at the end surface of the container. The temperature difference significantly decreased at a prolonged heating of more than 180 s. With high-temperature exposure, the difference of stationary temperature between the curves of the simulation and the experiment did not exceed 30-50 °C.

The characteristic form of the function $Q_L(T)$ at the minimum inductor current was shown in the figure (Figure 3,b). The function $Q_L$ had a minimum of $-0.8 \times 10^9$ W/m$^3$, which corresponded to the initial temperature of the container material. Further, the function $Q_L$ significantly increased in absolute value up to $Q_L = -1.25 \times 10^9$ W/m$^3$ at a temperature of about $T = 1000$ °C. At this point, an inflection of the function was noted, after which the function $Q_L(T)$ gradually increased linearly.

4. Conclusions

Thus, the experimental and theoretical results of the kinetics of heating the "inductor – container – sample" system were consistent when using the heat loss function $Q_L$ for the CTT process. During the simulation, it was shown that the maximum heat release was localized inside a container with a carbon-containing medium. In the simulation, it was established that inside the container a temperature was reached at which it was possible to efficiently perform a CTT process, in particular cementation. Further studies will be associated with an increase in the accuracy of simulation both the initial section of intensive heating and the stationary section of high-temperature exposure at higher values of the inductor current.

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References

[1] Chuang Y and Jing L 2019 Vacuum. 163, 52
[2] Burdovitsin V A, Golosov D A, Oks E M, Tyunkov A V and Zavadsky S M 2019 Surf. Coat. Technol. 358 726
[3] Fomin A, Dorozhkin S, Fomina M, Koshuro V, Rodionov I, Zakharevich A, Petrova N and Skaptsov A 2016 Ceram. int. 42 10838
[4] Fomin A, Egorov I, Shchelkunov A, Fomina M, Koshuro V and Rodionov I 2018 Compos. Struct. 206 467
[5] Koshuro V, Fomina M, Voyko A, Rodionov I, Zakharevich A, Skaptsov A and Fomin A 2018 Compos. Struct. 202 210
[6] Koshuro V, Fomina M, Fomin A and Rodionov I 2018 Compos. Struct. 196 1
[7] Fomin A A, Steinhauer A B, Rodionov I V, Fomina M A and Zakharevich A M 2013 Tech. Phys. Lett. 39 969
[8] Fomin A A, Steinhauer A B, Rodionov I V, Petrova N V, Zakharevich A M, Skaptsov A A and Gribov A N 2013 Biomed. Eng. 47 138
[9] Demidovich V B, Chmilenko F V and Rastvorova I I 2015 Acta Tech. CSAV. 60 107
[10] Kuvaldin A B, Lepeshkin S A and Lepeshkin A R 2014 Acta Tech. CSAV. 59 279
[11] Aman A, Majcherek S, Hirsch S and Schmidt B 2015 J. Appl. Phys. 118 164105
[12] Aman S, Aman A and Morgner W 2013 Compos. Sci. Technol. 84 58