Simulation of induction chemical-thermal treatment of titanium disks in a massive refractory container

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Abstract. The results of numerical simulation of chemical-thermal treatment, namely, heating of a massive metal container with a working medium and a small-sized titanium disk sample, are presented. To study the heating kinetics of this system, the effect of the parameters of chemical-thermal treatment, in particular the inductor current from 3.4 to 8 kA at a frequency of 90 kHz, was determined.

1. Introduction
Titanium and its alloys are widely used in industry for the production of critical items in aircraft and machine building, medicine and the chemical industry. However, titanium alloys have low values of hardness and coefficient of friction and this structural material is characterized by a tendency to contact setting and tear. These problems can be solved by the use of surface modification [1–4]. One of the effective methods is chemical-thermal treatment (CTT), e.g. carburization [5,6]. The developed process of carburization is applied in order to increase the hardness and wear resistance of small-sized titanium products (disks, cylinders, bushings and fasteners). This process is usually implemented in a sealed container, inside which the working medium is poured and a modified sample is placed. When heating the "container – working medium – sample" system the temperature on the outer surface of the technological chamber (container) differs from the internal temperature values [7,8]. The presence of the modifying medium also reduces the allowable temperature of treatment, which is determined by the "Ti–C" state diagram.

Thus, the aim of this work is to determine the temperature field in the working area of the container with the given CTT parameters due to the use of numerical simulation by the finite element method.

2. Methodology
To obtain functional coatings of titanium carbide (TiC) with high mechanical and chemical resistance, it is necessary to know the conditions of interaction between the modified metal (titanium) and carbon. The stoichiometry of titanium carbide was determined by the conditions (temperature and duration) of induction chemical-thermal treatment (ICTT). Based on the data of the "C – Ti" state diagram, the necessary temperature for the cementation of titanium is about 730–750 °C. This process will proceed most efficiently at a temperature about 1500 °C.

The heated "container – working medium – sample" system consisted of a container 4 with a lid 1 made of refractory metal. Inside the container there was a titanium sample 2 and a working medium 3 in the form of graphite powder. Next, the container with the load was located in the active region of the inductor 6, which was cooled by water 7. Between the container and the inductor there was a quartz tube 5, which served as thermal and electrical insulation. The rest of the system was air atmosphere 8 (Figure 1).
Figure 1. A model of the "container – working medium – sample" system.

Numerical simulation was carried out using the "Elecut" software. During simulation, the inductor current \( I \) varied from 3.4 to 8 kA at a fixed frequency \( f \) equal to 90 kHz. The current values from 3.4 to 5.5 kA were basic and corresponded to the conditions for chemical-thermal treatment with an exposure of about 480 s. The highest value of the inductor current \( I = 8 \) kA was used for accelerated heating of the system to the required temperature of exposure. The duration of the numerical experiment was \( t = 1000 \) s to achieve the stationary cementation temperature.

The simulation results were pictures of the Joule heat field \( Q \) and temperature \( T \) depending on the current of inductor \( I \). Three characteristic points were chosen at which the dynamics of temperature changes were analyzed, namely, the "center of the titanium sample", "the area of the working medium near the sample" and "end face of the container lid".

3. Results

The picture of the Joule heat field in the "container – working medium – sample" system showed that the largest value \( Q \) occurred in the surface layer of the container equaling \((0.1–0.2) \times 10^9\) W/m\(^3\) at \( I = 3.4 \) kA (Figure 2a). At an inductor current \( I = 8 \) kA the value \( Q \) reached \((0.7–1.0) \times 10^9\) W/m\(^3\) (Figure 2b).

Figure 2(a,b). The picture of the heat release field in the "container – working medium – sample" system.

Previously performed work on numerical simulation of the cementation process in a container of a smaller diameter (about 14 mm) showed that an excess of heat was accumulated in the working
carbon-containing medium compared to the titanium sample [7,8]. When using a container with a larger diameter (about 30 mm), a different situation was observed – there was no excess heat in the reaction medium and the temperature field in the active region of the container was uniform (Figure 3).

![Figure 3](image3.png)

**Figure 3.** The picture of the temperature field in the "container – working medium – sample" system.

At an inductor current $I = 3.4–5.5$ kA, an average temperature from 1050–1080 to 1350–1380 °C was reached in the working area of the container. This temperature range was sufficient for chemical-thermal treatment (cementation) to occur. The highest values of the calculated temperature were observed in the working medium and titanium sample (Figure 4).

![Figure 4](image4.png)

**Figure 4.** The diagram showing the heating kinetics of the "container – working medium – sample" system.

The temperature of the end face of the container in all cases was lower by 30–50 °C. At the current value of 8 kA, it was possible to quickly heat the active region of the system to a temperature about 1900 °C (which exceeds the melting temperature of titanium).
The heating kinetics at an inductor current of 3.4 kA had a minimum speed required to reach the stationary temperature of the exposure at $t = 700–900$ s. At the inductor current of 4.5 kA, the heating rate increased to 650–850 s and to 500–600 s at 5.5 kA. The value of 8 kA was characterized by a high heating rate of the system, namely, to the melting temperature ($T = 1670 \, ^{\circ}C$) in $t = 150–160$ s.

4. Conclusions
Thus, the theoretical results of the heating kinetics of the "container – working medium – sample" system showed that the application of the considered values of the inductor current in the range of 3.4–5.5 kA ensured the required conditions for the ICTT process in the carbon containing medium (graphite). The use of an increased inductor current of 8 kA made it possible to accelerate the heating of the active part of the system elements and, thereby, to increase the productivity of the carburization process.

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