Numerical simulation of induction heating considering the surface oxidation of cp-Ti samples

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Abstract. Induction heating and oxidation of cp-Ti samples surface using high frequency currents are studied. The dependency of heating up to the temperature from 800 to 1500 ºC is determined depending on the current values from 1.5 to 3 kA on the inductor at 90 kHz. Experimental results are compared to the data of numerical simulation of heat transfer in titanium samples.

1. Introduction

Induction heating is widely used in the treatment of metals, e.g. in heat treatment of ferromagnetic (steel) and some paramagnetic materials (aluminium, titanium) [1-3]. There is experimental data on hardening and surface modification with induction heating on titanium and its medical alloys [4,5]. Simulation of the physical processes is frequently applied when it is necessary to assess the distributed parameters in the elements of the studied products (sensors, medical products) [6,7]. In the description of fast processes of electromagnetic emission the development of models is an important task [8-10].

Control of technological parameters, temperature in particular, is important in the course of treatment with high-frequency currents (HFC) of metal products. In the accelerated mode of heating of metal products, the application of non-contact temperature control methods, infrared (IR) pyrometry and colorimetry (by colors of burning) in particular, is considered to be the most appropriate [4]. During the treatment of small-sized products using HFC the temperature measurement is significantly complicated by a number of factors:

– the characteristic size of the products is equal or smaller than the area where the temperature data are recorded using IR pyrometry (which is a constructive feature of pyrometers);
– the heated product is located in the treatment area (heating and heat treatment chamber), the access to which is limited;
– when the heating temperature exceeds 1200 ºC, the application of colorimetry is not effective as the heated product is characterized by a bright light yellow or white color of burning.

According to the factors mentioned above, it is necessary to develop a complex calculation procedure for the reliable analysis of temperature and heating rate based on experimental data on heating kinetics and analysis of the processes of changing the structure of metals occurring during the high temperature treatment. The last statement is related to the fact that many metals when heated up to more than 600 ºC, are characterized by intensive formation of an oxide coating [4].

Medical products from titanium alloys are machined, e.g. they are subjected to turning or abrasive blasting (Figure 1a). According to the obtained experimental results on the analysis of surface morphology of commercially pure titanium (Grade VT1-00) porous crystalline coatings with nanograins and nanopores of various shapes are formed on its surface due to the high temperature treatment with HFC [4] (Figure 1b).
Figure 1(a, b). Macrostructure of the surface after grinding (left) and abrasive blasting (right) (a); nanostructure of the oxide coating treated with HFC at the temperature of 800 °C (×200,000) (b).

Thus, at a high temperature of treatment the actual surface area $S$ of the article, where heat exchange with the environment occurs, is several orders of magnitude higher than its ideal area determined by macrogeometry, e.g. a flat disc surface (Figure 1a).

As the choice of treatment parameters for the samples appears to be difficult numerical simulation of distribution of AC magnetic field and heat transfer can be used to make it easier. Thus, the aim of this study is to establish the dependency of heating $T(I,t)$ of commercially pure titanium samples by induction heating on the current values from 1.5 to 3 kA of the inductor $I$ and to compare the experimental results of heating to the temperature $T$ values from 800 to 1500 °C with numerical simulation data.

2. Methodology
Numerical simulation was performed using software "Elcut 6". In this program the geometry of the system "inductor – sample" was drawn, further a finite element mesh was generated and AC magnetic field distribution and non-stationary heat transfer were modeled depending on the peculiarities of heat source and heat loss, due to convection, radiation, and oxidation. Main elements of the studied system comprised an inductor (1), water (4), air (5), a quartz camera (3), a titanium sample (2) with its central part [0; 0] and periphery [0; Y] (Figure 2a). The model of the system "inductor – sample" also contained boundary elements, on which heat exchange with the environment (7, 8) took place, and the boundary of the considered system (6). The boundary of the sample (8) was characterized by several processes – convective and radiant heat exchange, as well as the formation of a morphologically heterogeneous oxide coating.

A thin oxide layer at the initial stage of treatment with HFC (up to 500–600 °C) of titanium samples practically did not affect the heating kinetics $T(t)$. However, in the course of further treatment with constant current on the inductor $I$ the heating efficiency decreased sharply (Figure 2b). This was reflected in a significant (about 650–700 °C) difference in temperatures of high temperature exposure during the treatment with HFC (above 800 °C). Thus, intensive high temperature oxidation and the formation of the TiO$_2$ coating were associated with the appearance of an additional heat sink caused by a change in the actual area of the sample and an intensification of the convection and radiation processes. The mentioned heat sink can be associated with volumetric heat losses $q_v$. The volume $V$ of
this sink was determined by the increased (by several orders) surface area $S$ and the depth $h$ that can equal the thickness (from 0.5–2 to 5–50 µm) of the oxide coating as well as the energy cost $Q$ depending on the inductor current $I$ (Figure 3a). This circumstance is particularly important for small-sized products such as titanium implants (dental implants and bone screws), the characteristic size $D$ (wall thickness or diameter) of which varies from 2 to 6 mm.

![Figure 2(a, b). Model of the system "inductor – sample" (a); temperature differences between the experimental 1 and the calculated 1* data (b).](image)

The laboratory apparatus for induction heat treatment included power supplies with rectified high (up to +300 V) and stable low (+15 V) voltage, a generator unit, and an induction heating unit. It comprised a filter, AC-DC and DC-AC converters, and load – the system "inductor – sample". The generator unit included an oscillator with adjustable frequency in the range of 89.5±0.2 kHz [11].

The temperature of titanium samples with the diameter of 14 mm and length of 2 mm was measured using a non-contact method. For this purpose infrared pyrometer "MS6550B" with the upper limit of 1650 °C was used. To study high temperature area of the samples characterized by the radiance from light yellow (around 1000–1050 °C) to dazzling white (1200–1400 °C) an optical camera with a filter was applied, which enabled to extend the study area [4]. Hence, the exact blackness coefficient, which mainly depends on the surface state in case of commercially pure titanium and other metals, was not necessary.

3. Results

When the heat transfer problem was solved the curves of heating of a titanium sample in its central part and periphery – the hottest area of the skin-layer (Figure 3b) were built. The calculation results $I'-3'$ were compared to the experimental data $I-3$ at current values on the inductor 1.5, 2, and 3 kA, respectively.

In order to solve the heat transfer problem the influence of the oxidation process was considered. The power of the source $q_V$ was negative and it depended on the current in the inductor and the corresponding temperature of the heated titanium sample.
4. Conclusions
Thus, the experimental data on heating $T(I,t)$ at 1.5–2 kA correspond to the simulation results. At the maximum current of $I = 3$kA there was a significant difference between the mean temperature of a titanium sample and the calculated temperature in the central part of the sample. The presented simulation results prove that oxidation can be considered within the temperature values around $T = 1150–1200^\circ$C.

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