Experimental data and numerical modelling of heating of titanium implants using high-frequency currents

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Abstract. High temperature heating of experimental titanium samples using high frequency currents is studied. The velocity of heating is determined depending on the current value on the inductor. Experimental results are compared to the data of numerical modeling of heat transfer in metallic products. The peculiarities of the heating of cylindrical designs of two types: I (diameter - 3.75 mm, length - 10 mm) and II (diameter - 3.95 mm, length - 62 mm) implanted into the bone tissue were studied. The temperature of the constructional elements of different implant parts was calculated.

1. Introduction
Heating with high-frequency currents (HFC) is widely used in the treatment of metals, e.g. in heat treatment of steel. However, this technology is not practically used in the treatment of titanium products. There is experimental data on strengthening and modifying effect of HFC on titanium and its medical alloys [1]. Various intraosseous and transosseous implants, e.g. dental implant, osteofixation devices and more complex designs, such as components of endoprostheses of large joints, are fabricated from titanium and its alloys.

In order to develop technological recommendations on heat modifying treatment with HFC different geometries of the system “inductor – sample” should be considered. As the choice of treatment parameters for the products with complex geometry appears to be difficult numerical modeling of physical distribution of AC magnetic field and non-stationary heat transfer can be applied to make it easier. Thus, the aim of this study is to establish the dependency of heating of commercially pure titanium samples and implants using HFC on the current values of the inductor and to compare the experimental results with numerical modeling data.

2. Methodology
2.1. Titanium samples
Titanium samples are have the disc shape, the diameter of 14 mm, thickness of 2 mm and are fabricated from commercially pure (CP) titanium. The samples served as control ones and were used to build the temperature curves of heating and cooling using the optical imaging techniques and infrared pyrometer. The samples corresponding to the geometry of the actual implant designs were cylinders of two types: I (diameter - 3.75 mm, length - 10 mm) and II (diameter 3.95 mm, length - 62.5 mm). There were threaded elements of complete and incomplete profiles, conical and wedge elements on the cylindrical parts.
2.2. **HFC heating device**

The laboratory apparatus for induction heat treatment includes power supplies with rectified high (up to +300 V) and stable low (+15 V) voltage, a generator unit and an induction heating unit. It includes an filters, an AC-DC and DC-AC converters, and load – the system "inductor – sample". The generating unit includes an oscillator with adjustable frequency in the range from 50 to 150 kHz. During the heating process power consumption did not exceed 550 W and changed by autoconnected transformer. The heating efficiency is determined by two factors: the amount of voltage supply and resonance. The peculiarities of the heating device performance were related to the geometry of both the product and the inductor. The inductor is a tool for power supply of AC magnetic field and has a shape of a single-layer coil (sometimes it has two or more layers), spiral or more complex geometry.

2.3. **Temperature measurement**

The temperature of titanium samples with the diameter of 14 mm and length of 2 mm was measured using a non-contact method (Figure 1). For this purpose we used infrared pyrometer "DT-8828" with the limit of -50…1100 °C. The figure shows: a copper inductor (1), a ceramic chamber (2), a control titanium sample (3), PTFE insulation (4), a sample holder (5), a water cooling tube of the inductor (6) and an IR pyrometer (7).

![Figure 1. Temperature measurement by infrared and optical methods.](image)

To study high temperature area of 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 used, which enabled to extend the study area. Hence, the exact blackness coefficient, which mainly depends on the surface state in case of commercially pure titanium and other metals, was not necessary.

2.4. **Numerical modelling**

Numerical modeling was performed using software "Elcut 6.1". 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 all types of heat loss (Figure 2a). Main elements of the studied system are: inductor (1); water (2); quartz camera (3); titanium sample (4) with its central part and periphery; ceramic holder (5) and locking (6) of the sample; lines of magnetic field potential (7).
3. Results

3.1. Heating of control titanium samples
Field images are the result of modeling, e.g. current density $j$ and magnetic field strength $H$ (Figure 2a). 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 were built (Figure 2b).

![Figure 2(a, b). System “inductor – sample” and modelling results (a); heating curves (b).](image)

The calculation results 1-3 were compared to the experimental data I-III at current values on the inductor 2000, 1700, and 1100 A, respectively. The differences between the experimental results and the calculation values were observed at low heat duration of 60±30 s.

3.2. Peculiarities of heating of titanium implant designs
The peculiarity of heating of implant samples with more complex shape was the presence of internal cylindrical and conical holes (Figure 3a). At the end part with the hole there was an area, which has a small thickness of about 0.2-0.3 mm. These areas were unevenly situated with regard to the inductor windings, which affected their bakeout temperature. The presence of the thread on the surface had no substantial effect on the temperature field inside the implant. The most significant temperature nonuniformity across the section was caused by the presence of internal cylindrical and conical holes, which lead to the temperature difference in areas II and III of about 200-250 ºC (Figure 3b). Therefore, the hole must be insulated with metal (titanium) plug, which would "level" the picture of the magnetic field potential and its other characteristics.
When the heating of the 62.5 mm long implant was performed in the inductor of the same design and at the current of 180 A several areas were observed in it. The hottest area was in the central part of the inductor at coils 3 and 4 (Figure 4). The temperature outside the inductor fell by 250-400 °C towards the end with the metric thread depending on the duration of heating.

**Figure 3(a, b).** The picture of the temperature field at t = 150 s (a); heating curves at points I-III (b).

**Figure 4.** Heating of the osteofix device and picture of the current density field in it.

**4. Conclusions**

Thus, experimental data on heating at 2200 A correspond to the modeling results. At lower current the results start to converge in the quasi-stationary area of heat treatment when the treatment duration is at least 100 s. According to the numerical calculation and experimental results, the temperature uniformity for the implants can be achieved if the functional elements are located in the central part of the inductor and if construction parts (plugs) are used to minimize the magnetic field inhomogeneity. The results are necessary to determine the inductor current and the treatment duration as these parameters define the biomechanical qualities of implants surface.

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**References**

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