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SKIN-EFFECT IN SOFT BIOLOGICAL TISSUE AND FEATURES OF TISSUE HEATING DURING AUTOMATIC BIPOLAR WELDING

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The skin-effect that occurs in the electric circuit at high-frequency electrosurgery, including electric welding of soft biological tissues (SBT) with electrodes for bipolar welding, is of interest to researchers as a possible source of considerably uneven heating of SBT in automatic welding. Mathematical study of electrical and thermal processes in automatic bipolar welding was performed, taking into account and ignoring the impact of skin-effect at the frequency of 300 kHz. It was determined that in biological tissue the skin-effect causes uneven heating to a smaller degree. The main reasons that influence the unevenness of heating are the presence of sharp ridges on the surface of electrodes that contact the tissue, degree of SBT compression by the electrode clamps, length of SBT compressed between the electrodes, and also duration of the process of SBT heating. 13 Ref., 6 Figures.

Keywords: skin-effect, bipolar electrodes, electric welding of soft tissues, biological tissue, anisotropy of specific conductivity

Electrosurgery with application of high frequency currents (HFC) of more than 200 kHz [1] became widely applied in medicine. Passage of HFC through the electric circuit of the conductors, which are the electrodes of electrosurgical instruments, and a section of soft biological tissues (SBT) being welded, generates a high-frequency electromagnetic field that leads to current density concentration near the conductor surface. So-called surface effect (skin-effect) arises [2]. Nonuniform distribution of current density results in nonuniform distribution of Joulean heat in the conductor cross-sectional plane. One of the quality requirements to electric welding of soft tissues is even heating of SBT section being welded. In this connection, a number of researchers in their work paid attention to the evenness of SBT heating during performance of electrosurgical operations, allowing for the skin-effect. Works [3, 4] analyze the influence of skin-effect arising at the frequency of 440 kHz in a thin cylindrical monopolar electrode at welding of the retina, which has detached, to the choroid. Coagulation rings as traces of current passage, are clearly visible under the microscope. The question of modeling the skin-effect in the electrode is considered in detail, but no analysis of the electric and thermal processes in SBT at appearance of coagulation rings on the choroid is given. In works [5–8] the main attention is paid to elimination of the nonuniformity of current density distribution in the electrodes in the presence of skin-effect, but without analyzing how this nonuniformity affects the distribution of Joulean heat in SBT.

The objective of the work is to show the results of mathematical analysis of running of the electric and thermal processes in SBT (pig heart muscle) at automatic bipolar welding with different degrees of tissue compression between the electrodes, taking into account the skin-effect at 300 kHz frequency, as well as in the assumption of absence of the skin-effect.

Model, used to conduct the mathematical experiment of skin-effect impact on SBT, was constructed using COMSOL Multiphysics 5.3a software package. The model includes «Electric Currents» and «Heat Transfer in Solids» («physics») modules with «Multiphysics/Electromagnetic Heating» solver which allows combining these different physics to solve the model tasks. Pig heart muscle and copper jaw plates (electrodes) were taken as materials used in the model. The range of the set electrode pressure was 15–1100 kPa. Electrode cross-section was 3×10 mm. Dimensions of the heart muscle fragment were equal to: initial thickness of uncompressed tissue $mh = 6.9$ mm, width — 35 mm and depth — 25 mm. The compression coefficient is taken into account by the following formula

$K_{\text{com}} = \left(1 - \frac{hs}{mh}\right) \cdot 100\ \%$, where hs is the thickness of SBT between the electrodes.

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Proceeding from the postulates of the theory of similarity [9], a model was created in COMSOL Multiphysics package that takes into account the similarity of its geometrical parameters to those of the physical model. Modeling allowed determination of the anisotropy of specific electric conductivity in the zone of SBT local compression (Figure 1) [10].

The main condition for modeling was to ensure the best correlation between the geometrical part of the model and geometrical parameters of the physical experiment. Here, it was necessary to use the physical properties of pig SBT that correspond to the heat muscle, taking into account the anisotropy of its specific conductivity at compression.

Mathematical experiment was conducted at the frequency of alternating harmonic current $f = 300$ kHz.

For a field that oscillates with frequency f, we have:

$$\Delta \sim 50\sqrt[3]{(\sigma\mu f)^{-1}} \qquad (1)$$

where Δ is the skin-layer thickness, m; σ is the specific conductivity, S/m; μ is the relative magnetic permeability, rel. un.

If the thickness of the skin-layer is great, compared to body dimensions ($\Delta >> lh$), the distribution of the magnetic field at each moment of time will be the same as in the stationary case at the specified value of the field outside of the body. Here, the vortex electric field and the resistive losses related to it, can be neglected [11].

Taking into account the anisotropy of specific conductivity in the zone of SBT local compression (Figure 1), we can calculate the dependence of Δ on K_{com}. Calculations show that the smallest thickness of the skin-layer for the conditions of our experiment is equal to 1.7 m (Figure 2). This is much more than the dimensions of that electromagnetic field, acting around the electrodes with 3×10 mm cross-section. As is known, SBT electric welding differs from electrocoagulation by mandatory application of a considerable force of electrode compression [12]. Electrode pressure leads to (possible) destruction of the cell membranes, to transfer of electrically conductive tissue water from the electrode center to the periphery in the direction of pressure lowering, to increase of vapour formation temperature and maximum temperature of the tissue. In this connection, at maximum degree of compression of the pig heart muscle $K_{com} = 78$ %, the skin-layer thickness (Figure 2) is 2.5 m.

Taking into account the above-said, it can be stated with a high degree of probability that the high-frequency current passing through SBT should cause practically no changes in current density distribution in SBT under the conditions of electrosurgical operations on soft biological tissues.

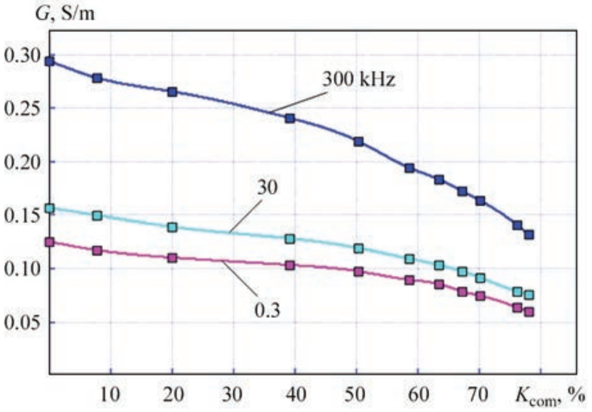

Figure 1. Dependence of specific electric conductivity of pig heart muscle G on the degree of compression K_{com} for frequencies of 0.3, 30 and 300 kHz

Hence the question: what is happening with distribution of current density on the electrode surface at their collision with SBT. As SBT is an element of the circuit where HFC flows, there should be no nonuniformity of current associated with the skin-effect, on the boundary of electrode contact with SBT. However, a reverse situation was observed with coagulation rings on the retina in work [3].

In our model the electrodes are represented by copper jaw plates. HFC flows from the voltage source through the copper plate of 3×10×1.5 mm size, then through a section of SBT, compressed by the electrodes, and then through the second copper plate. The electric circuit is closed to the voltage source.

Even for a round conductor calculation of the skin-effect involves considerable difficulties. In order to perform the calculation, many assumptions are used of the conductor straightness, infinity of its length, etc. For conductors of a rectangular cross-section, in work [13] calculation is based on the assumption that the conductor cross-section consists of sets of round conductors, the diameter of which is equal to doubled thickness of the skin-layer, and, accordingly, on the assumption of the conductor straightness and infinity of its length.

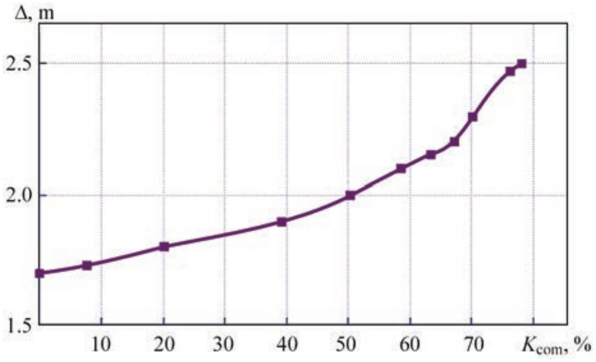

Figure 2. Thickness of the skin-layer in pig heart muscle at $f = 300$ kHz, depending on the degree of compression

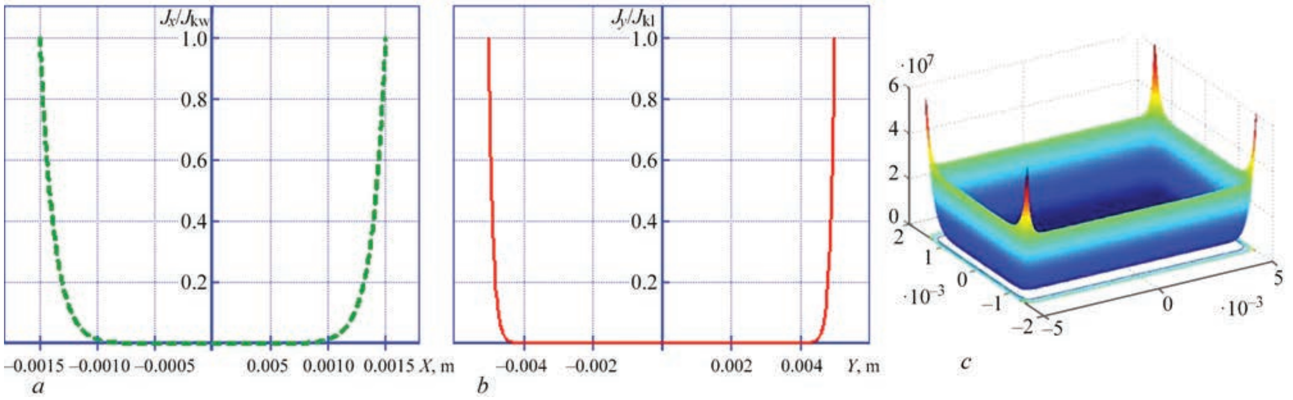

Figure 3. Graphs of distribution of relative current density along the width (*a*) and length (*b*) of the jaw copper plate and distribution of 3D specific conductivity in 3D image (*c*)

For our model we take the following assumptions, in order to simplify calculation of the skin-effect impact:

- skin-effect is present only in the jaw copper plates;
- as the skin-effect is manifested in the current density concentration on the conductor surface, we perform simulation of the skin-effect through assigned nonlinearity of specific conductivity along the length and width of the copper plate;
- dependence of reduction of the current density on frequency in copper when moving away from the surface is readily approximated by hyperbolic cosinus;
- skin-effect is manifested both along the width, and along the length of the copper plate, here the current density is averaged.

We will denote half-width of the copper plate as a_w, its half-length as b_l. Then, $a_w = 1.5$ mm, $b_l = 5$ mm. X coordinate of the plate with be in the range of $\{-a_w \ldots a_w\}$. Y coordinate of the plate will be in the range of $\{-b_l \ldots b_l\}$. Current density J_x along X coordinate is calculated by the following formula:

$$J_x = \mathrm{ch}(kf^{0.5}X), \qquad (2)$$

similarly, for

$$J_y = \mathrm{ch}(kf^{0.5}Y). \qquad (3)$$

On the left and right surfaces of the copper plate, limiting its width, current density will be $J_{kw} = \mathrm{ch}(kf^{0.5}a_w)$. Accordingly, on the opposite surfaces, limiting the plate length, current density will be $J_{kl} = \mathrm{ch}(kf^{0.5}a_a)$. Value of coefficient k is determined by inverse transformation of hyperbolic cosines in formulas (2) and (3) and substitution of the value of skin-layer thickness for copper at the frequency of 300 kHz, obtained using (1). As for copper $\Delta = 0.119$ mm, then $k = 15.36$.

In connection with the fact that current density J is proportional to specific conductivity σ of an elementary site of normal current vector, we assume that:

$$\sigma(X, Y) = 6E^7\left(\frac{J_x(X)}{J_{kw}} + \frac{J_y(Y)}{J_{kl}}\right)0.5.$$

Substituting σ(X, Y) in the calculation part of the model for the value of specific conductivity of copper, which is unchanged in each elementary volume of the copper plate ($\sigma = 6E^7$, S/m) for direct current, we obtain the current density distribution in the copper jaw plates, that corresponds to the distribution at the skin-effect for 300 kHz frequency. Figure 3 presents the graphs of distribution of the relative current density along the width and length of the jaw copper plates, as well as a 3D image of σ (X, Y).

To gain a more definite understanding of current density distribution at skin-effect inside the copper plate volume, including within the SBT, we will calculate the current distribution along lines A and B (Figure 4, *a*, *b*). Line A lies in the plane, which is the boundary between the copper plate and SBT (SBT not shown in the figure for simplification purposes), and it passes in the middle of the plate along its width. Line B passes between the center of the surface of the plate left side and center of the surface of the copper plate right side. In Figure 4, *a* we can see that the current density along line B decreases from the left surface of the copper plate from 28000 A/m^2 practically to zero, and then rises towards the right surface of the plate up to 28000 A/m^2. Distribution of current density along line A is repeated with the same regularity, but it has much smaller values at the ends (approximately 2000 A/m^2), while middle value of current density is higher than that for line B.

In order to refine the results, we will calculate the current density distribution along the secant segment connecting the centers of line B and line A (Figure 4, *c*), as well as the secant segment connecting the left ends of these lines (Figure 4, *d*).

It is obvious that when getting closer to SBT, the current density abruptly changes its values, the first

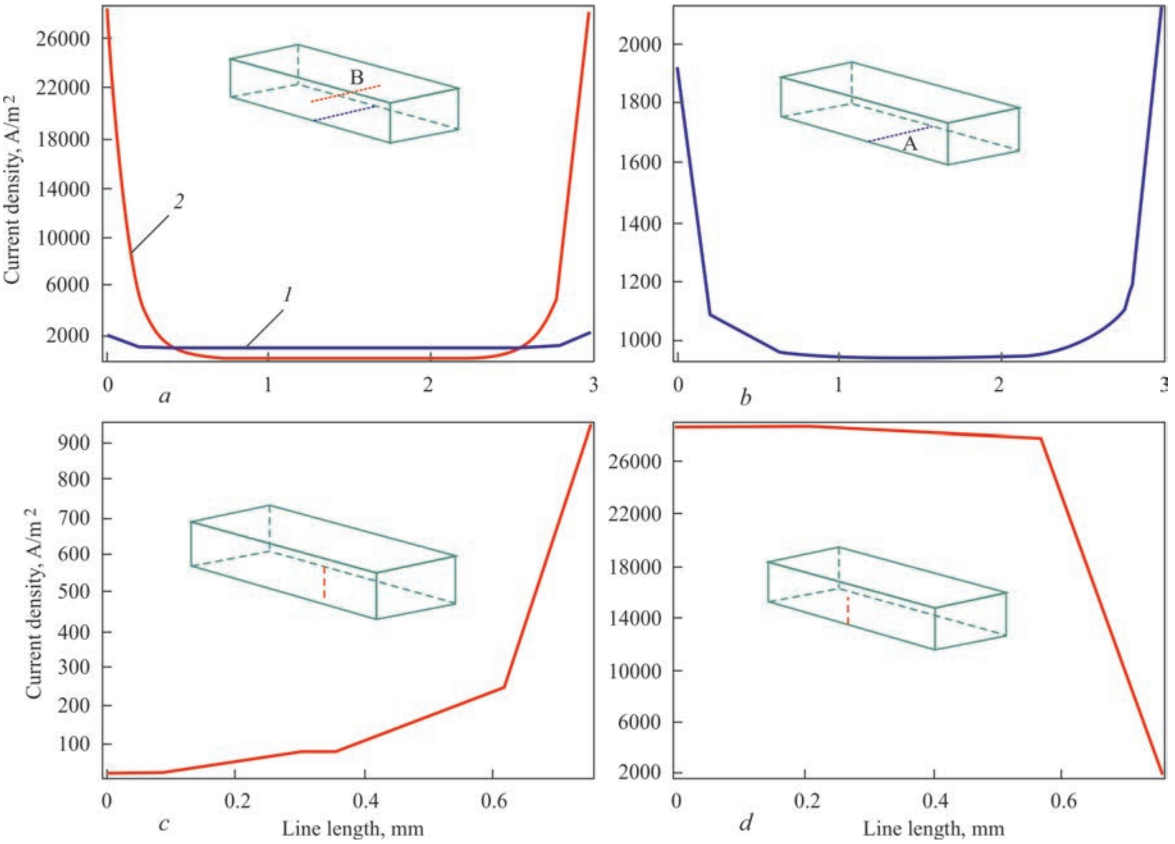

Figure 4. Distribution of current density at skin-effect within the copper plate along lines A and B (*a*) (*1* — distribution of current density along line A; *2* — along line B) and A (*b*). Distribution of current density at skin-effect within the copper plate along a vertical secant connecting the centers of lines B and A (*c*) and secant connecting the left ends of lines A and B (*d*)

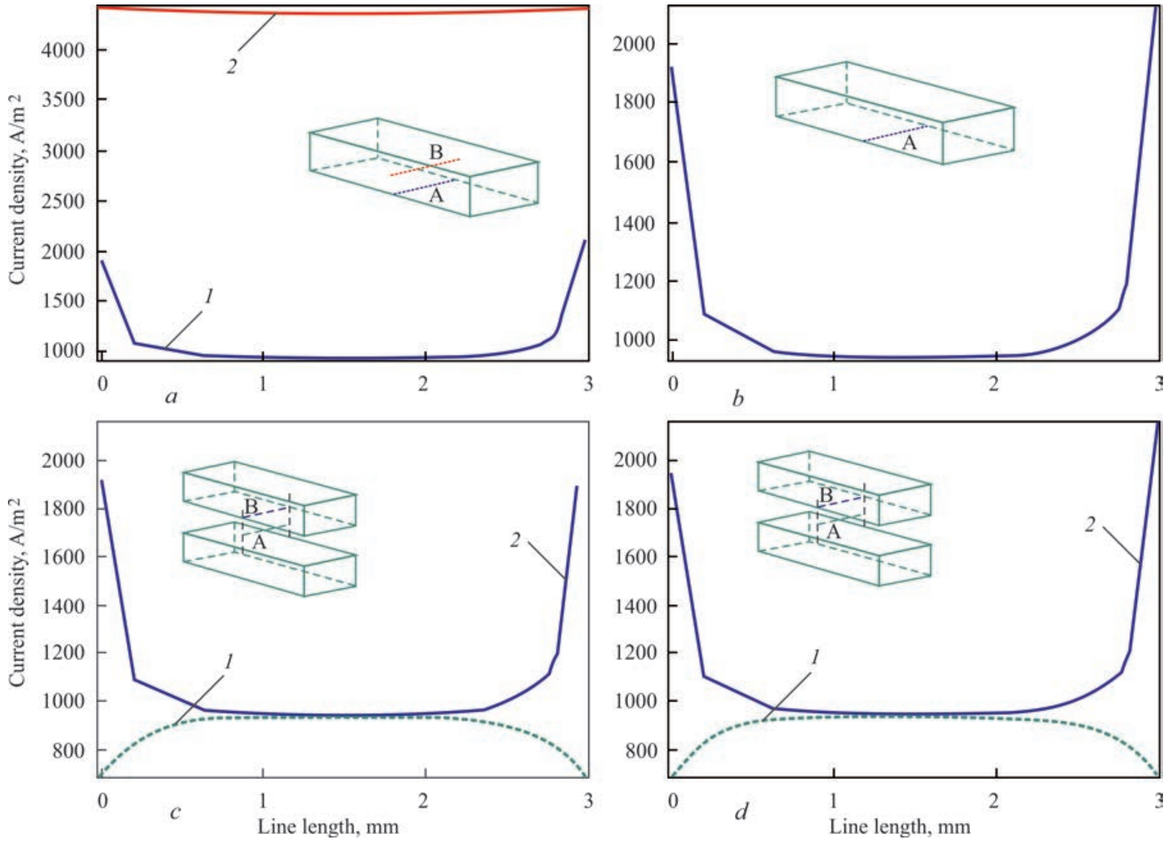

Figure 5. Distribution of current density without allowing for the skin-effect inside within the copper plate along lines A and B (*a*) and just line B (*b*). Distribution of current density with skin-effect inside SBT volume along lines A and B (*c*) and without allowing for skin-effect (*d*) (*1* — distribution of current density along line A; *2* — along line B)

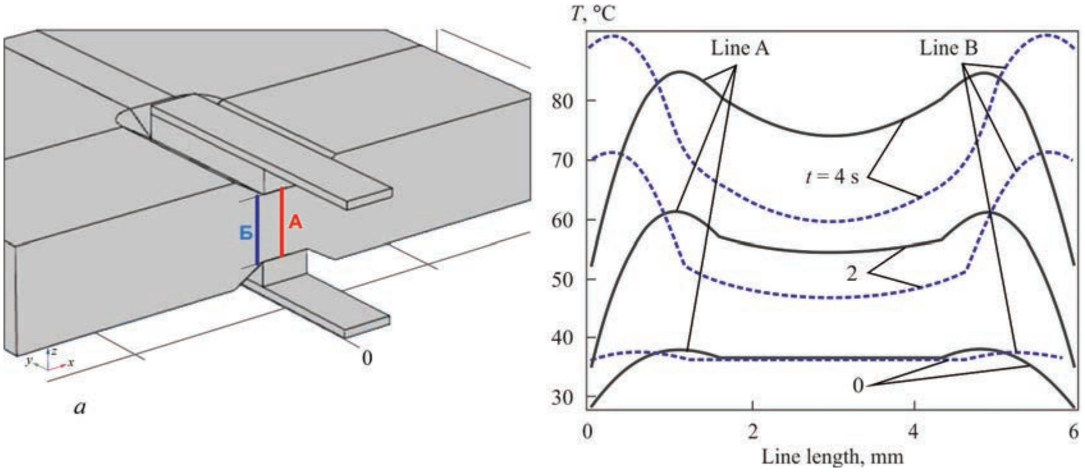

Figure 6. Vertical lines A and B on SBT surface (*a*). Temperature distribution in SBT along axis *Z* along vertical lines A and B at moments of time 0, 2 and 4 s (*b*)

(Figure 4, c) towards its increase, and the second (Figure 4, *d*) towards its decrease. This is indicative of the fact that the electric properties of SBT have a dominating impact on current density distribution in the copper plate near SBT.

Then we will calculate current distributions along the same lines, as in the previous calculations, but we will eliminate the simulation of the skin-effect (Figure 5, *a*, *b*). Distribution of current density along line B is practically uniform, and is equal to approximately 5000 A/m^2, while distribution of current density along line A is the same as current distribution, calculated at skin-effect (Figure 4, *b* and Figure 5, *b*).

Thus, we obtained one more confirmation that the skin-effect is practically absent in biological tissue at bipolar welding.

Further calculations of current density distributions inside the biological tissue along lines A and B with «included» skin-effect (Figure 5, *c*) and along the same lines without the skin-effect (Figure 5, *d*) showed complete identity of the results.

Note the fact that the current density in the middle of line A and in the middle of line B coincides (Figure 5, *c*, *d*). Therefore, SBT middle part, compressed between the electrodes, has the same specific electric conductivity along the vertical. At a distance from the middle to the left and right from line A the specific conductivity decreases, because of approaching the SBT sections with lower compression. With greater distance from the middle to the left and right along line B the current density grows, because of approaching the copper plate ridges, on which an increase of electric field density is observed, because of an abrupt increase of the conductor curvature. Such a nonuniform distribution of current density on electrode-SBT boundary results in appearance of a nonuniform distribution of the thermal field on the tissue surface.

Temperature distribution was calculated along vertical line A in SBT (Figure 6, *a*) between the electrode middles and along line B, which has equal length with line A and passes vertically to the left of the lower corner of the copper plate by 0.05 mm. Calculation was performed for three moments of heating time: 0, 2 and 4 s. The graph (Figure 6, *b*) shows that after 4 s of heating the temperature at the ends of line B has reached the critical value of ~90 °C, and the temperature inside SBT compressed section on line A was ~70 °C. Such a unevenness of SBT heating can lead at the stage of dehydratation in some sections of the tissue to unplanned coagulation processes, and as the polymerization stage tissue necrosis can occur in some sections.

Most probably, the coagulation rings on the retina, described in work [3], formed because of higher current density on the electrode ridges. It is envisaged that the rounding-off of the ridges on the electrode surface, located on the boundary with SBT, will allow partially eliminating the unevenness of heating distribution in SBT at mono- and bipolar welding.

Conclusions

1. The conclusion that the skin-effect, arising at HFC passage through the jaw copper plates, does not influence the processes of current flowing and SBT heating, is important for solving the tasks of automation of bipolar welding of SBT.

2. Nonuniformity of current density in SBT and running of the heating processes are affected by presence of sharp ridges on the surface of electrodes, contacting the tissue, coefficient of SBT compression by electrode clamps, length of SBT compressed between the electrodes, as well as time of running of SBT heating process.

3. The model developed during the mathematical experiments, using COMSOL multiphysics, will further allow studying the procedure of selection of the required ratios of geometrical parameters of the electrodes, selection of the laws of automatic change

of supply voltage (current) in time, in order to reach an optimum heating process at automated welding of soft biological tissues to improve the quality of the produced welded joints.

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