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# STUDY OF CHANGE IN SPECIFIC ELECTRICAL CONDUCTIVITY OF BIOLOGICAL TISSUES AS A RESULT OF LOCAL COMPRESSION BY ELECTRODES IN BIPOLAR WELDING

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The paper presents the results of mathematical modeling of anisotropy of specific electrical conductivity (ASEC) of a soft biological tissue and investigates the difference between the results of the process of welding biological tissues produced without and taking into account anisotropy of the specific electroconductivity of a biological tissue. The results of calculations of the tissue resistance, current density and impedance dispersion are compared. 14 Ref., 1 Table, 10 Figures.

*Keywords: welding of biological tissues, specific electrical conductivity, mathematical modeling, anisotropy of biological tissues*

Soft biological tissues (SBTs) consist of cells, conjunctive tissue and tissue fluid. The basic structural unit of all living things is cells. They consist of a membrane inside which a jelly-like cytoplasm with a large number of organelles is located. The basis of conjunctive tissue consists of collagen and elastin fibres. These fibres together with membranes form a spongy structure of the conjunctive tissue, in the cells of which tissue fluid is located. Due to such a structure, SBTs are much more elastic than any metal and even rubber. During compressing by an electrical welding tool, they are significantly deformed, which leads to significant changes in their electrical and thermophysical properties. Electric welding of SBTs differs from electrocoagulation by an obligatory application of a considerable force of electrodes compression [1, 2]. The electrodes pressure leads to destruction of cell membranes (possibly), transfer of an electroconductive tissue water from the centre of the electrodes to the periphery in the direction of decreasing pressure, increasing vaporization temperature and the maximum temperature of the tissue.

Currently, researchers are paying a considerable attention to improving the quality and reliability of welded joints of SBTs, expanding the range of types and thickness of welded tissues by studying the process of resistance electric welding of SBTs as an object of automatic control. They provide analytical calculations, computer modeling of welding process, experimental studies in laboratory installations, processing and analysis of the obtained results [3–10].

The publications on mathematical modeling of thermal processes in SBTs are known (for example, [11]). But all of them are devoted either to surface heating applying a focused power source such as a laser beam, or with the help of single-electrode electrosurgical instruments. In addition, SBTs are considered in them as solids with constant thermophysical and electrical characteristics. These assumptions can only be used as a first approximation for modeling electrocoagulation, but are not suitable for modeling electric welding.

Biological tissues are electroconductive due to the presence of an intracellular and tissue fluid with the salts dissolved in it. Ions are the main current carriers in them. The proteins, of which cell membranes, organelles, and structural tissues are built, are not electroconductive. Electroconductive of the tissue depends on its internal structure and it changes significantly in the welding process due to a local compression by the electrodes, phase transformations of water in the tissue, coagulation of proteins, thermal effects, etc. Consequently, the specific electroconductivity in each elementary volume of the tissue has a significant anisotropy. Joule heat, which is released in each elementary volume of the tissue during the flow of current, is proportional to the square of current and inversely proportional to its electroconductivity. In this case, in the literature sources the thermal processes are mainly described, the results of which were obtained using the values of the specific conductivity of an uncompressed tissue [12, 13].

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**Figure 1.** Laboratory welding unit: *1* — laser sensor of electrode movement; *2* — electrodes; *3* — weights; *4* — lever axis

Between the electrode clamps, where the tissue is compressed the most and has the greatest deformation, the main processes, characterizing bipolar welding of SBTs, take place. In this regard, the study of the anisotropy of the specific conductivity of a compressed SBT is relevant.

The aim of the work is to show the difference between the values of the parameters of processes of welding SBTs, obtained without taking and taking into account ASEC of biological tissues.

**Experimental studies.** The study of SBTs compression was performed in a laboratory welding unit (Figure 1). On it, laser sensor is mounted to move the upper electrode relative to the lower one. The movement of the laser point, which glows on the remote screen, corresponds to the movement of the upper electrode with a gain factor of several tens of times. Expansion of the upper electrode displacement measurement system is ±15 μm. At such sensitivity, the accuracy of measuring the thickness of a compressed tissue is already beginning to be affected by the deformation of the entire structure, which leads to some movement of the lower electrode with an increase in the load in the form of a weight. To minimize these errors, the dependence of the movement of the upper electrode on the value of the applied force without the tissue between the electrodes was previously determined. This dependence was used to correct the sensor values while measuring changes in the thickness of the tissue depending on the compression force.

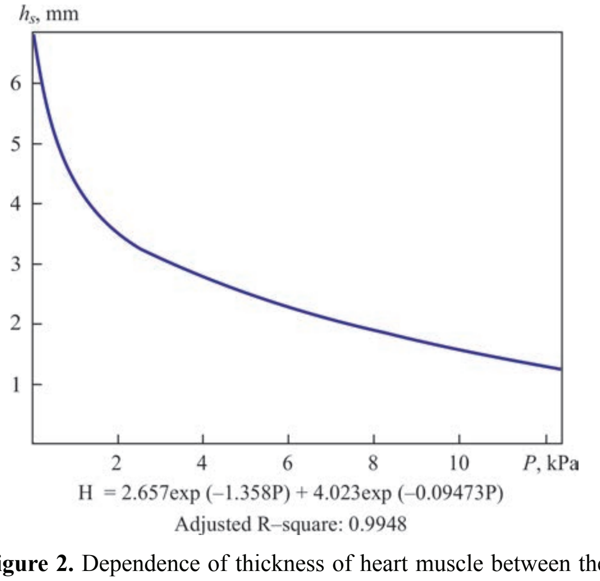


**Figure 2.** Dependence of thickness of heart muscle between the electrodes of electric welding unit $h_s$ on electrodes pressure $P$

The range of the set pressure of electrodes $P$ amounts to 15–1100 kPa. Since the actual pressure on the surface of the electrodes is nonuniformly distributed, in our case the average value of the pressure $P = F/S_e$ is meant, where F is the force applied to the electrodes; $S_e$ is the contact surface area of the electrodes.

The cross-section of the electrodes is 3×10 mm, i.e. $S_e = 30$ mm$^2$. The long sides of the electrodes, rectangular in the cross-section, are perpendicular to the longitudinal axis of the lever. This guarantees a uniform pressure distribution along the larger side of the electrode and a small nonuniformity along the smaller one. In the experiment the heart muscle of a pig was used, taken no later than three hours after slaughter. Before the study, the heart was stored at a temperature of +5 °C.

Figure 2 shows the dependence of the heart muscle thickness $h_s$ between the electrodes of the electric welding unit on $P$. The sizes of the heart muscle fragment are the following: thickness $m_s = 6.9$ mm, width $l_h = 35$ mm and depth $d_h = 25$ mm. The area of the heart muscle fragment is $S_f = 875$ mm$^2$.

Simultaneously with the measurement of $h_s = (P)$, the electrical resistance of the heart muscle fragment $R_f(P)$ was measured at a constant voltage $U_s = 6.9$ V through the resistance $R = 1$ kOhm. The voltage at the electrodes $U_{ind}$ was measured. There are many schemes for measuring the resistance of SBT and a common problem for them is the inaccuracy of maintaining the sizes of the specimens. However, in our case the measurement of the same specimen is carried out, but at a different local compression of the tissue. Therefore, under the condition $S_f >> S_e$, the set initial inaccuracy of the sizes of the heart muscle fragment is neglected.

The resistance $R_f$ of the heart muscle fragment is calculated by the formula:

$$R_f = \frac{U_{ind} R}{U_s - U_{ind}}.$$

The results of the experiments are shown in Table, where $h_1 = h_s/m_s$.

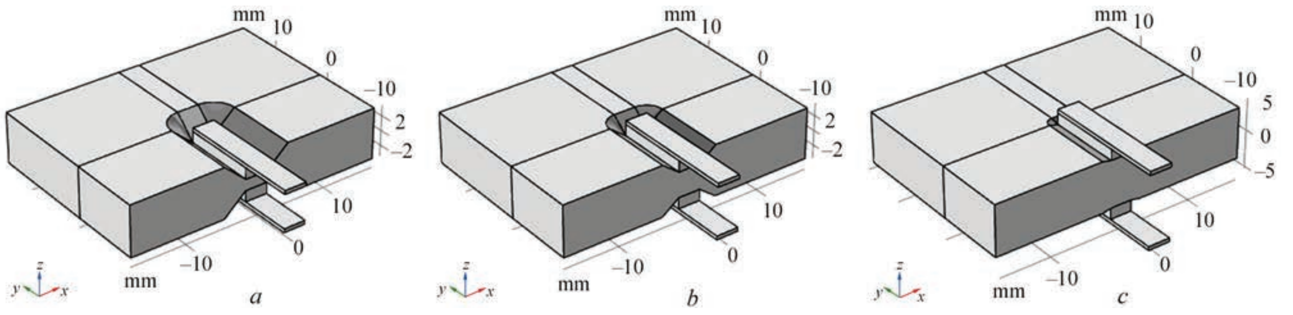

**Figure 3.** Geometric model of experiment at different values $h_s$: *a* — $h_s$ = 1.52 mm, $h_1$ = 0.2203; *b* — $h_s$ = 3.43 mm, $h_1$ = 0.4971; *c* — $h_s$ = 6,37 mm, $h_1$ = 0.9232

**Mathematical modeling.** The mathematical model of the experiment was built using the package COMSOL multiphysics 5.3a. The model includes the modules («Physics») «Electric Currents» and «Heat Transfer in Solids» with the solver «Multiphysics/ Electromagnetic Heating», which allows combining these different physics for solving problems of the model. Figure 3 shows a geometric model under different conditions for compression SBT. As materials used in the model, copper and pig's heart muscle are accepted. The main approach to modeling was to provide the best conformity of a geometric part of the model to geometric parameters of the physical experiment. It was necessary to use physical properties of SBT, which correspond to the pig's heart muscle. Based on the theory of similarity [14], such approach will determine the desired values of a specific electrical conductivity of the tissue applying the method of successive approximations, taking into account the data in Table and those calculated on the mathematical model.

In the model for simulating the force of SBT compression, a functional dependence between the compression force and the distance between the compression electrodes $P(h_s)$ is introduced, the inverse dependence of that is obtained experimentally (Figure 2).

The calculated component for «electrical conductivity» $\sigma(x)$ is a graphical interpretation of change in the specific conductivity $\sigma$ from the coordinate $x$ of the model and the specific intermediate conductivity $G_{inter}$, where $G_{inter}$ is the value of $\sigma(x)$ at $x = 0$ (Figure 4, *a*). $G_{inter}$ is called intermediate because its value is between the desired minimum value $G_{min}$ and the maximum $G_{max}$ value of the specific electrical conductivity of the tissue. At $h_{1min}$ $G_{inter} = G_{min,}$ at $h_{1max}$ $G_{inter} = G_{max.}$ In Figure 4, *a* the values $G_{max,}$ $G_{inter}$ and $G_{min}$ are taken arbitrarily for clarity of presentation.

Modeling in COMSOL multiphysics applying the method of similarity of geometric parameters of physical and mathematical models allowed determining ASEC in the zone of a local compression of SBT (Figure 4, *b*). As is seen from this diagram, the specific electroconductivity of the pig's heart muscle approximately twice decreases with a decrease in a

Results of experiments

| Number | $P$, kPa | $h_s$, mm | $h_1$, rel. un. | $R_f$(0.3 kHz), Ohm |
|---|---|---|---|---|
| 1 | 0 | 6.90 | 0.9999 | 778 |
| 2 | 16.4 | 6.37 | 0.9232 | 760 |
| 3 | 146.2 | 4.20 | 0.6087 | 635 |
| 4 | 271.2 | 3.43 | 0.4971 | 586 |
| 5 | 422.1 | 2.86 | 0.4145 | 568 |
| 6 | 557.9 | 2.53 | 0.3667 | 551 |
| 7 | 691.0 | 2.27 | 0.3290 | 551 |
| 8 | 825.0 | 2.06 | 0.2986 | 547 |
| 9 | 960.9 | 1.65 | 0.2391 | 546 |
| 10 | 1091.4 | 1.52 | 0.2203 | 542 |

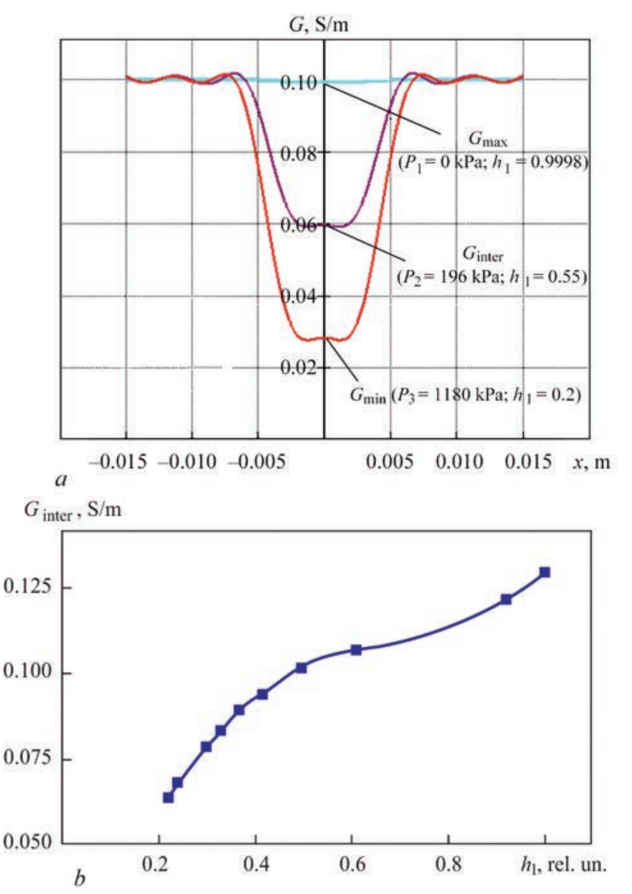


**Figure 4.** Graphical interpretation of change in specific electrical conductivity $\sigma(x)$ at the maximum value $h_{1max}$, intermediate value $h_{1iner}$ and the minimum value $h_{1min}$ (*a*) and ASEC at SBT compression (*b*)

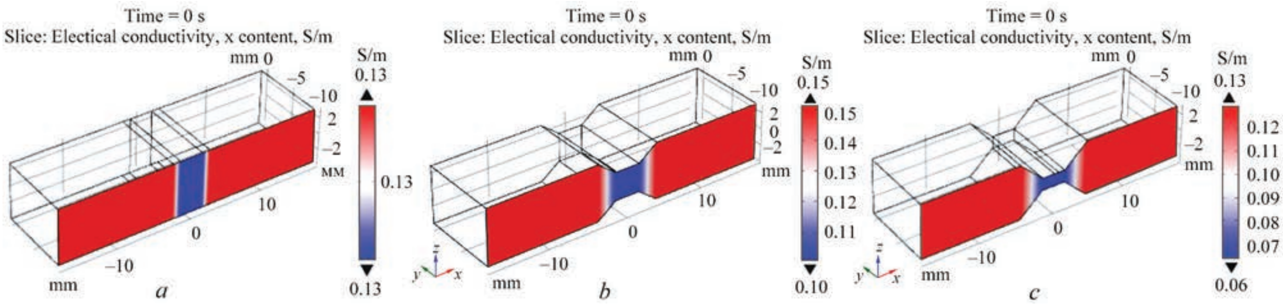


**Figure 5.** Distribution of specific conductivity in SBT fragment at different values of local compression by electrodes of the pig's heart muscle: *a* — $h_1$ = 0.999; *b* — 0.497; *c* — 0.22

relative compression of SBT. All the published data on specific resistance are obtained for uncompressed biological tissues and are not suitable for using in calculations and mathematical modeling of bipolar welding processes.

Figure 5 shows diagrams of the distribution of specific conductivity in the SBT fragment at different values of local compression. The diagrams show how specific conductivity decreases during compression at the place of local compression of SBT by the electrodes and how it increases at a distance from the place of a local compression of SBT.

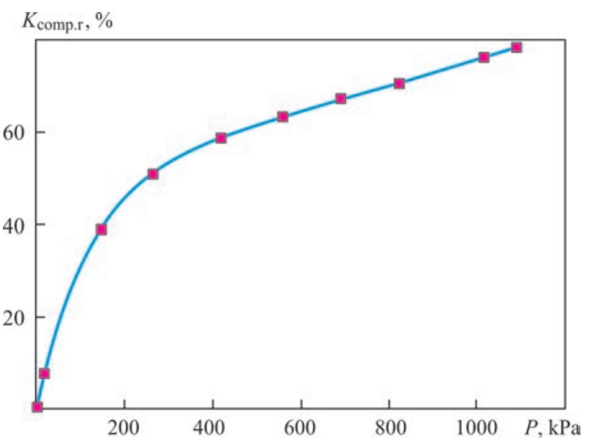


**Figure 6.** Dependence of compression ratio $K_{comp.r}$ on the pressure value during compression $P$

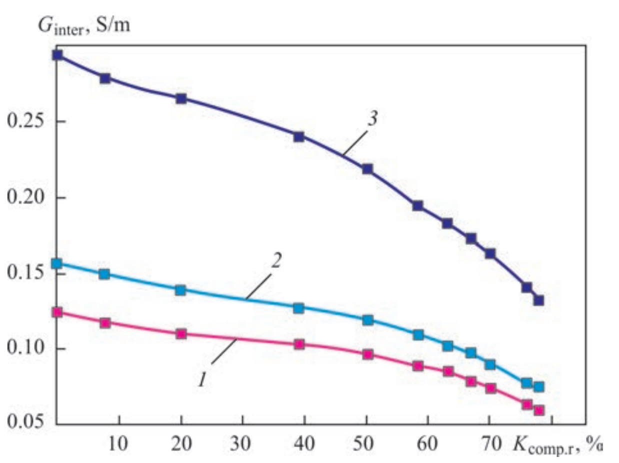


**Figure 7.** Dependence of specific conductivity of the pig's heart muscle $G_{inter}$ on compression ratio $K_{comp.r}$ for the frequencies of 0.3 (*1*), 30 (*2*) and 300 (*3*) kHz

As a result of experimental investigations in the laboratory conditions, the dependence of the degree of compression of the biological tissue $K_{comp.r}$ on the value of the load $P$ during compression was obtained (Figure 6). The compression ratio is calculated by the formula

$$K_{comp.r} = \left(1 - \frac{h_s}{m_h}\right) \cdot 100\,\%.$$

Figure 7 shows diagrams of dependence of a specific electroconductivity $G_{inter}$ in the zone of a local compression of SBTs on the compression ratio $K_{comp.r}$ for different frequencies of the applied voltage of 0.3, 30 and 300 kHz. $G_{inter}$ decreases with an increase both in $K_{comp.r}$ as well as in the frequency of voltage.

**Comparison of results. Calculation of complete resistance.** Based on the experimentally measured resistances of the SBT fragment of the pig's heart muscle, on the model the resistances with and without taking into account ASEC for different degrees of compression ratio at a frequency of 0.3 kHz were calculated (Figure 8). From this diagram we see that the measurement data, obtained during the experiment coincide with the results of calculations on the model obtained taking into account ASEC. The values of resistances calculated without taking into account ASEC differ from those obtained experimentally in the range of 0–50 %.

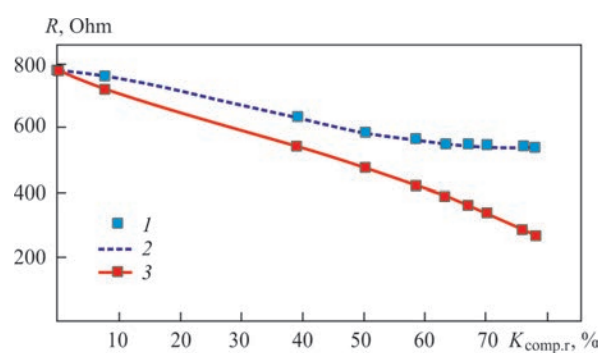


**Figure 8.** Results of SBT fragment resistance measurements obtained experimentally and calculated on the model taking and without taking into account ASEC: *1* — physical experiment; *2* — model taking into account ASEC; *3* — model without taking into account ASEC

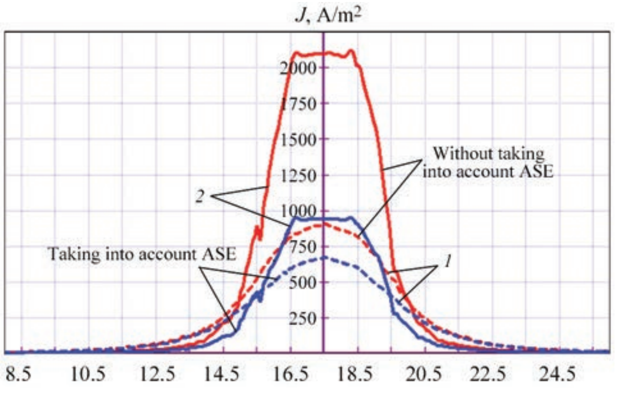


**Figure 9.** Distribution of current density $J$ according to the coordinate x of the model at different $K_{comp.r}$ at a frequency of 0.3 kHz, calculated taking and without taking into account ASEC: *1* — $K_{comp.r}$ = 50.3 %; *2* — 78 %

**Calculation of current density.** The current density $J$ along the coordinate $x = 0$ of the model, which is calculated without taking into account ASEC at $K_{comp.r}$ = 78 %, is twice higher than that calculated taking into account ASEC (Figure 9).

**Calculation of impedance dispersion.** The resistance of the tissue was determined by the voltmeter-ammeter method during passing a low stable current of different frequency through the tissue. As is seen from Figure 10, the resistance of the tissue to a greater or lesser extent depends on the frequency. For living tissues, this property, called impedance dispersion, is well known. As a result of a physical experiment, the resistance of the simulated fragment of a pig's heart muscle was measured at frequencies of 0.3, 1, 3, 10, 30, 100 and 300 kHz. The calculations of $R(F)$ on the model taking and without taking into account ASEC at the maximum compression of SBTs being 1100 kPa showed that the results obtained taking into account ASEC, coincide with those obtained experimentally. But the results of calculating $R(F)$, obtained without taking into account ASEC, differ from the results obtained experimentally, twice.

## Conclusions

1. The adequacy of the results of experimental studies of SBT resistance and the results of calculating SBT resistance obtained on the mathematical model taking into account ASEC is shown.

2. Comparison of the results of calculations without and taking into account ASEC showed, that the relative error of calculations of electrical parameters, such as the total resistance of SBT, current density and impedance dispersion can reach 50–100 %.


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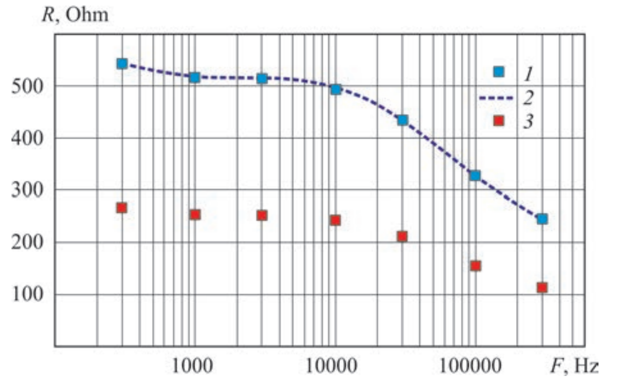


**Figure 10.** Calculations of resistance of SBT fragment, obtained experimentally on a mathematical model, taking and without taking into account ASEC: *1* — physical experiment; *2* — model taking into account ASEC; *3* — model without taking into account ASEC


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