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Modelling of laser welding of biological tissues using focused radiation

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Abstract. Laser welding is an alternative technology for biological tissue reconstruction. The laser weld is small, liquid-tight and does not cause mechanical stress. However, thermal necrosis of the joined living tissue occurs during suture formation, and the depth of suture formation may be much less than required. This paper proposes the use of laser radiation with dynamically varying focusing parameters to reduce the area of thermal necrosis of the attached living biological tissue and increase the depth of suture formation. The influence of laser focusing parameters was evaluated by simulation. Absorption by biological tissue and braze was calculated according to the Beer-Lambert law. The degree of protein conversion in biological tissue and solder was determined using chemical kinetic methods and the Arrhenius equation. Heat transfer was calculated using the thermal conductivity equation.

Keywords: mathematical modeling, laser soldering, tissue reconstruction

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Моделирование лазерной сварки биологических тканей с использованием сфокусированного излучения

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Аннотация. Лазерное сваривание — это альтернативная технология реконструкции биологических тканей. Лазерный шов имеет небольшие размеры, герметичен и не вызывает механического напряжения. Однако, во время формирования шва происходит термический некроз соединяемы живых тканей, а глубина формирования шва может быть гораздо меньше, чем требуется. В данной работе предлагается использовать лазерное излучение с динамически изменяемыми параметрами фокусировки для уменьшения площади термического некроза присоединенной живой биологической ткани и увеличения глубины формирования шва. Влияние параметров фокусировки лазерного излучения оценивалось путем моделирования. Поглощение биологической тканью и пайкой рассчитывалось по закону Бера-Ламберта. Степень превращения белка в биологической ткани и припое определялась с помощью химико-кинетических методов и уравнения Аррениуса. Теплопередача рассчитывалась с помощью уравнения теплопроводности.

Ключевые слова: математическое, моделирование, лазерное сваривание, реконструкция тканей

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Introduction

Laser welding provides an alternative method of joining biological tissues. Laser welding provides advantages over traditional joining techniques by creating small sutures that are impermeable to fluids and cause no mechanical stress.

Laser suture formation involves heating the joining area and adjacent tissues. The heat generated results in thermal necrosis of the fused living tissue. This study aims to minimize the area of thermal necrosis of biological tissues during welding by modelling and optimizing the process.

Materials and Methods

The absorbed energy of the laser radiation was determined according to the Beer–Lambert law [1]:

$$I = I_0 e^{-\int_0^L \mu(\vec{r})dl}, \tag{1}$$

where I is the intensity of laser radiation after the beam passes through a layer with a thickness L, I_0 is the power of the incident laser radiation, $\mu(\vec{r})$ is the absorption coefficient.

The degree of suture formation and thermal necrosis of the living tissue was determined by the conversion α at time t [2]:

$$\alpha(\tau) = \frac{C_\tau}{C_0}, \tag{2}$$

where C_τ is the concentration of denatured protein at time t, C_0 is the initial concentration of native protein. The degree of weld formation and thermal necrosis was taken into account $\alpha = 0.63$.

The conversion was calculated according to the Arrhenius equation:

$$\alpha(\tau) = 1 - e^{-\int_0^\tau A e^{-\frac{E_a}{RT(t)}} dt}, \tag{3}$$

where A is the dimensionless pre-exponential factor of the Arrhenius equation E_a is the activation energy, R is the universal gas constant, T is the temperature, and t is the time [3–5].

Heat transfer has been calculated using the heat transfer equation:

$$\frac{\partial T(\vec{r},t)}{\partial t} - \nabla(a(\vec{r},t)\nabla T(\vec{r},t)) = f(\vec{r},t), \tag{4}$$

where T is the temperature, a is the thermal diffusivity, f is the function of heat sources, t is the time.

Results and Discussion

A simulation of the effects of laser radiation on the skin was performed. An area of 1·1·1 mm was simulated. Diameter of laser radiation beam area in the area of contact with tissue was $d_{laser\_beam} = 1$ mm. Spatial discretization of the simulation area was $d = 2\cdot10^{-5}$ m.

Laser weld formation occurs as a consequence of thermal denaturation of proteins. Bovine serum albumin was used as a protein in this work. Thermal denaturation is initiated by heating the proteins in the laser solder. The denaturation rate is defined as the derivative of the concentration of the denatured albumin by time. An acceptable albumin denaturation rate is achieved at temperatures above 55 °C. At lower temperatures, the rate will be so low that it will take more than 1 minute to form a 1 mm long suture. Such a long formation time is not acceptable for surgical applications.

When irradiating biological tissue and laser braze, the laser intensity decreases according to the Beer-Lambert law. This leads to uneven heating of the solder. In this case, overheating will occur in the upper layers, while in the deeper layers the solder temperature will not be sufficient to form a suture. The solution to this problem can be the use of focused laser radiation. A simulation of the heating process of solder and biological tissue using focused laser irradiation was carried out (Fig. 1).

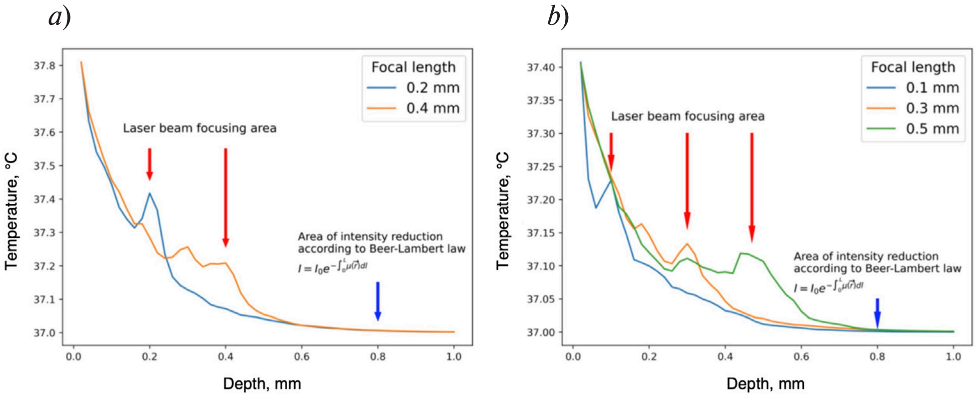

Fig. 1. Dependence of solder temperature along the optical axis of laser radiation at focal lengths of 0.2, 0.4 mm (*a*) and 0.1, 0.3, 0.5 mm (*b*)

The curves in Fig. 1 clearly show the general nature of the temperature distribution, which is inversely proportional to the exponent. However, local maxima corresponding to the depth of focus of the laser radiation can be distinguished. The presence of local maxima indicates the possibility of heating the solder deeper than the surface layers. In this simulation, the heating temperature of the solder in the focal area was not significantly higher than in the case of heating with collimated radiation. However, this limitation can be overcome by using laser radiation with a large cross-sectional radius in the area of contact with the surface of the biological tissue.

Fig. 2 shows temperature distributions in the biological tissue and suture when exposed to laser radiation with a focusing depth from 0.2 to 0.8 mm.

Fig. 2 clearly shows that the main heating takes place in the upper layers of the solder. In the deeper layers the heating temperature decreases. However, there is an increase in temperature in the focal zone. It can be seen that the area of biological tissue exposed to the laser radiation is not significantly heated. The increase in temperature of the biological tissue is mainly due to heat exchange with the hotter solder. The area of contact between the biological tissue and the solder is the riskiest in terms of thermal necrosis formation. Biological tissue necrosis occurs at a lower temperature than laser weld necrosis. This is an additional negative factor that increases the risk of significant thermal necrosis formation. The use of focused laser radiation can partially neutralize this effect. In this case, the heating is localized rather than along the entire length of the weld.

Fig. 2 shows that the solder areas around the perimeter of the weld are heated more than the solder areas inside the weld. The energy is delivered to the braze by photons passing through the biological tissue at an angle to the surface of the braze. In this way, the outer walls of the future weld and the top of the braze exposed to direct irradiation are formed first. Then, as the inner parts of the braze are heated by heat exchange, the inner part of the braze is formed. The rate of weld formation is therefore inversely proportional to the width of the weld.

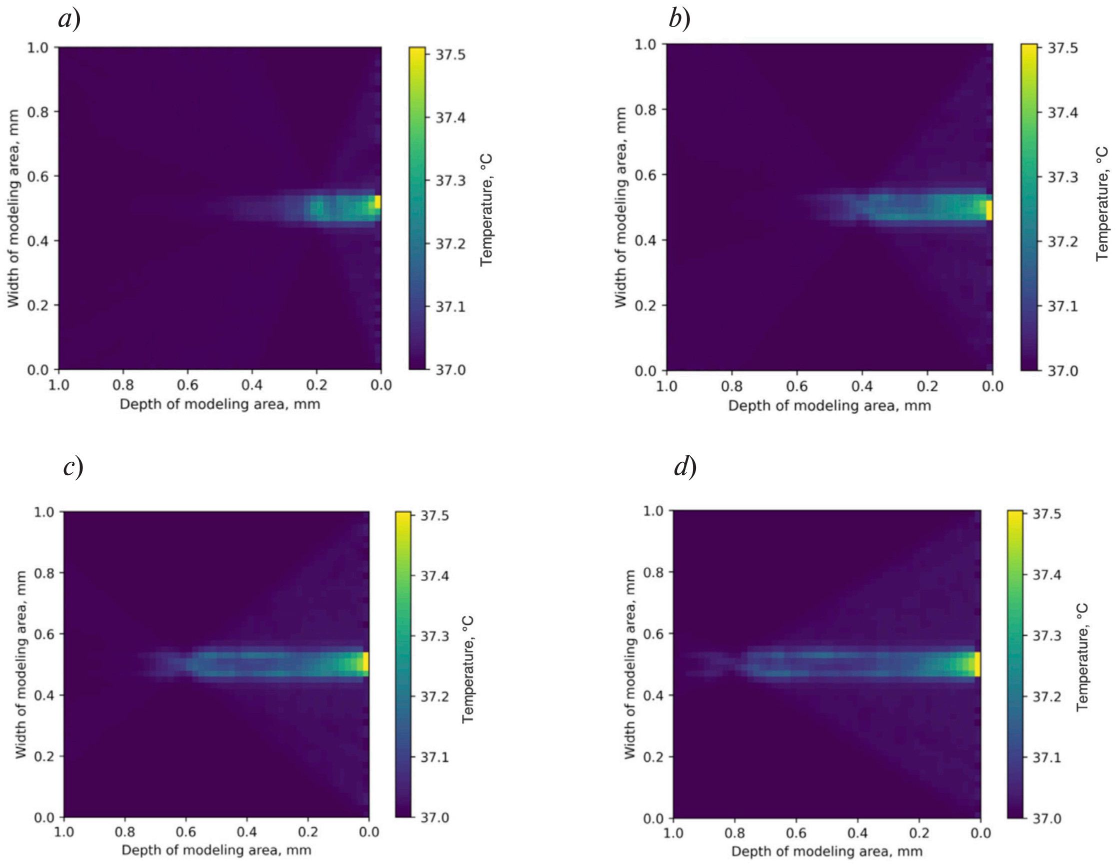

Fig. 2. Temperature distribution in biological tissue and solder in the area exposed to laser radiation with depth of focus 0.2 (*a*), 0.4 (*b*), 0.6 (*c*), 0.8 mm (*d*)

The overheating of the weld in the area of direct radiation exposure and the formation of a zone of thermal necrosis of the biological tissue can be reduced by cutting off the part of the laser radiation that falls on the weld and does not pass through the biological tissue.

Reducing overheating of the suture in the area of direct exposure to radiation and the formation of a zone of thermal necrosis of biological tissue is possible by cutting off the part of the laser radiation that falls on the solder, not passing through the biological tissue.

Conclusion

Studies have shown that the use of focused laser radiation allows more energy to be delivered deep into biological tissue. In the future, it will be possible to use laser radiation with a variable focal length. With this approach, the suture is formed only in the area where the laser radiation is focused. Increasing the diameter of the laser beam reduces the intensity of the irradiation.

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