

Theoretical and Experimental Study of the Hair Bonding by Continuous Laser Radiation with a Wavelength of 980 nm

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Abstract. The possibility of hair bonding by continuous laser radiation with a wavelength of 980 nm has been studied. A computer optical model of a laser system for bonding of human hair has been created. Using the Monte Carlo method, the distribution of the power of the absorbed laser radiation in the contact area of two hairs during their laser irradiation was obtained. The power distribution of the absorbed laser radiation obtained in the optical model is used in a computer thermophysical model of the laser bonding of human hair, the calculation in which is carried out by the finite element method. The maximum values of the temperature and the Arrhenius function of a pair of hairs in the area of their contact are calculated for different laser radiation power (1–10 W) and scanning speed of the laser beam along the area of hair contact (1–10 mm/s). It is shown that the temperature slowly decreases with increasing scanning speed, at the same time the Arrhenius function demonstrates a sharp decrease, while the values of both the temperature and the Arrhenius function increase with increasing laser radiation power. The power of laser radiation and the scanning speed at which the temperature of hair denaturation is reached, and the value of the Arrhenius function becomes equal to one were determined. Assuming that for the bonding of hair it is necessary that the temperature in the irradiation area exceeds the temperature of hair denaturation, and the Arrhenius function is less than one, the region of optimal laser radiation powers and scanning speeds is determined. In an *in vitro* experiment, the possibility of hair bonding by radiation from a continuous diode laser with a wavelength of 980 nm was studied and the validity of the optimal parameters of laser exposure selected at the stage of theoretical research was demonstrated. The results of the study can be used to develop a device for laser hair extension. © 2023 Journal of Biomedical Photonics & Engineering.

Keywords: diode laser; power; scanning speed; hair bonding; absorption; heating; temperature; denaturation; Arrhenius function.

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1 Introduction

Currently, laser technologies are increasingly used in dermatology and cosmetology [1–3]. In the field of hair care, laser hair extensions are gaining popularity [4]. Hair extensions are a highly sought-after cosmetic procedure, the essence of which is to attach donor hair (natural or artificial) to human hair in one way or another [5]. Hair

extension methods can be divided into two large groups: “hot” and “cold”, that is, with and without heating, respectively [6]. Each of the existing extension methods has its advantages and disadvantages. Thus, “cold” methods allow to connect hair without heating it, however, they are distinguished by a long procedure duration and a limited set of hairstyle options [7]. As for the “hot” methods, the most well-known is capsule

extension, which consists in attaching donor hair with keratin capsules to human hair by melting these capsules using special thermal tongs [7]. This method of extension due to its speed, efficiency and flexibility is the most popular now. However, capsular extensions are not without drawbacks, mainly due to the keratin capsules themselves, which can cause discomfort during the first days after the procedure and require caution when caring for hair, which is associated with the risk of damage to the capsules. Currently, laser hair extension is a variant of the capsular extension technology, only in this case, the capsules are melted not with the help of special thermal tongs, but with the help of laser radiation [7]. The limitations associated with the use of capsules stimulate the search for new laser hair extension technologies without the use of capsules.

The subject of tissue bonding by laser radiation has been actively studied almost from the moment of the discovery of lasers. The mechanisms of laser bonding of biological tissues are considered in sufficient detail in literature [8–10]. Among these mechanisms laser welding and laser soldering are distinguished. In the first case, the bonding is carried out directly by laser radiation, while in the second case, the bonding occurs due to the action on the bonding substance – solder [11]. Thus, the existing technology of laser capsule extension is one of the options for laser soldering. The advantages of using laser soldering to connect biological tissues are, firstly, the reduction of heating and thermal damage to the biological tissue itself and, secondly, the creation of a joint that allows the biological tissue to successfully undergo the healing process [12, 13]. If the first advantage is important for laser hair extension, then the second one is not important, since the hair in the joint area does not regenerate [14]. In this regard, considering the inconvenience associated with the use of keratin capsules, it is of interest to study the possibility of hair extensions by welding them with laser radiation.

The connection of biological tissues is carried out by both continuous and pulsed laser radiation [11–13]. The main idea of using laser pulses is to reduce the thermal load on the biological tissues being joined [15]. The connection of biological tissues is possible both with a stationary laser spot and with a laser spot moving along the connection area. The choice between possible connection options occurs mainly based on the features of a particular procedure. When connecting biological tissues with continuous radiation, the fundamental

parameters of laser exposure are the power of laser radiation and the exposure time (with a stationary laser spot) or scanning speed (with a moving laser spot) [16]. The choice of laser wavelength is very important. Hair consists of water, keratin, lipids, and melanin [14]. Hair components have specific absorption spectra [17]. According to Ref. [17], hair absorption in the region $>2.7\ \mu\text{m}$ is due to the absorption of water and keratin, while in the region $<2.7\ \mu\text{m}$, it is due to the absorption of melanin. While extending hair, it is important that laser radiation is evenly absorbed throughout the entire volume of hair bundle, the size of which can vary from 50–60 μm (a single hair in a pair of connected hairs) to 1–2 mm or more (hair bundle). In this regard, the light attenuation coefficient at the wavelength of laser radiation should be in the range from 160–200 cm^{-1} (for bonding single hairs) to 5–10 cm^{-1} or less (for bonding hairs in a bundle). The absorption of a hair at a wavelength of 980 nm is 36.6 cm^{-1} [17], which makes it possible to use this radiation for bonding both single hairs and hairs in a bundle. Unfortunately, the hair welding by continuous laser radiation with a wavelength of 980 nm has not been studied.

Based on the foregoing, the main goal of the study was to theoretically and experimentally study the possibility of bonding (extending) human hair by welding them with continuous laser radiation with a wavelength of 980 nm and to determine the optimal combinations of laser radiation power and laser beam scanning speed for this procedure.

2 Materials and Methods

A computer optical model of a laser system for bonding of human hair was created using the TracePro Expert ver. 7.0.1 software package (Lambda Research Corporation, USA). The optical model of the system consisted of a laser radiation source, a lens, an optical fiber, and a sample (Fig. 1a).

The laser radiation source was an emitting area with a diameter of 300 μm . At the output of the source, the laser beam had a numerical aperture $\text{NA} = 0.22$. The spatial distribution in the laser beam was set to Gaussian. The laser radiation power at the output of the source was set equal to 1 W. The design parameters and optical properties of the lens and optical fiber are presented in Table 1.

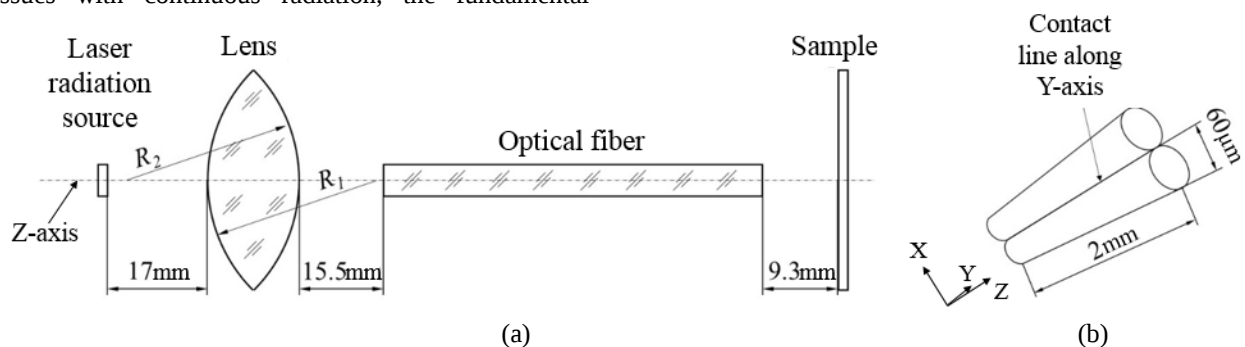


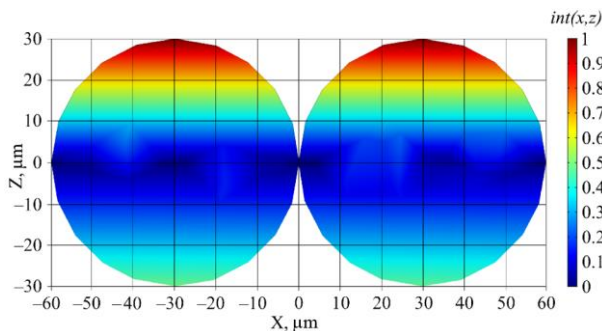
Fig. 1 Scheme of a laser system for bonding of human hair (a) and 3D model of the sample (b).

Table 1 Design parameters and optical properties of lens and optical fiber of a laser system for bonding of human hair [18, 19].

Component of laser system	Design parameters	Optical properties		
		Wavelength, nm	Refractive index	Absorption coefficient, mm ⁻¹
Lens	$R_1 = 9$ mm; $R_2 = -9$ mm; diameter 5 mm	980	1.5111	2×10^{-4}
Optical fiber	core diameter = 400 μ m; cladding diameter = 440 μ m; length = 1 m	980	1.457 (core); 1.439 (cladding)	1×10^{-5}

Table 2 Optical properties of human hair [20, 21].

Wavelength, nm	Refractive index	Absorption coefficient, mm ⁻¹	Scattering coefficient, mm ⁻¹	Anisotropy factor
980	1.55	3.66	1.345	0.79

Fig. 2 Spatial power distribution of the absorbed 980 nm laser radiation in the sample (function $int(x, z)$ in the X Z plane).

The sample consisted of two cylinders (hairs) with a diameter of 60 μ m and a length of 2 mm each located in air, parallel to each other and in perfect contact (Fig. 1b). The components of a laser system for bonding of human hair were located in such a way that the center of the laser spot was on the line of contact of the hair, and its diameter in the plane passing through the axis of symmetry of the hair was 1 mm. Such a construction of the optical scheme was carried out considering the specifics of the experiments (see below), so that it would be possible to adequately compare their results with the results of theoretical simulation. The optical properties of human hair used for modeling are presented in Table 2.

The calculation of the propagation of laser radiation in the optical model of the laser system for bonding of human hair was carried out by the Monte Carlo method [22]. The result of optical modeling was the interpolating function $int(x, y, z)$ describing the spatial distribution of the power of the absorbed laser radiation in the sample. When calculating this distribution, the sample was divided into many cubic elements with a side of 4 μ m (grid cell size). An example of the spatial power distribution of the absorbed 980 nm laser radiation in the sample in the X Z plane is shown in Fig. 2.

The $int(x, y, z)$ was used for subsequent calculations in a computer thermophysical model of laser bonding of human hair.

A computer thermophysical model of laser bonding of human hair was created using the COMSOL Multiphysics ver. 6.0 software package (COMSOL Inc., USA). The geometry of the sample in the computer thermophysical model was the same as in the computer optical model described above. The thermophysical and kinetic properties of human hair used for modeling are presented in Table 3.

The frequency factor A denotes the frequency of molecular collisions [25]. The simulation of the thermal effect of laser radiation was carried out on the basis of the power distribution of the absorbed laser radiation in the sample obtained as a result of optical simulation (see Fig. 2). The computational area was a parallelepiped with sides $120 \times 2000 \times 120$ μ m (X, Y, Z). Data on the power distribution of absorbed laser radiation in the sample, presented in tabular form, were linearly interpolated by software tools built into COMSOL Multiphysics ver. 6.0. Based on the obtained interpolating function, according to Ref. [26], an equation was compiled and applied to calculate the distribution of the volumetric power density of heat sources in the sample:

$$Q = int(x, y, z) \times \frac{P}{V}, \quad (1)$$

where Q is the volumetric power density of heat sources, $int(x, y, z)$ is the interpolating power distribution function, P is the power of laser radiation at the output of the source, V is the volume of the grid cell of the calculation.

Here, it should be noted that since the laser power at the output of the source was set equal to 1 W in the optical simulation, the multiplication of the interpolating function by the changing value of the laser power when specifying the heat source made it possible to easily scale the calculation of Q for different values of the laser power.

Table 3 Thermophysical and kinetic properties of human hair [23, 24].

Density ρ , kg/m ³	Coefficient of thermal conductivity k , W/(m·K)	Specific heat c , J/(kg·K)	Frequency factor A , s ⁻¹	Activation energy E_a , J/mol
1.31×10^3	0.37	1×10^4	2.49×10^{13}	1.47×10^5

In thermophysical modeling in the COMSOL Multiphysics ver. 6.0, the finite element method [27] was used to solve the standard heat transfer equation for the physical interface “Heat transfer in solids” [28]:

$$\rho c \left(\frac{\partial T}{\partial t} + \mathbf{v} \times \nabla T \right) + \nabla (q + q_r) = Q, \quad (2)$$

where ρ is the density of the sample, c is the specific heat capacity of the sample, T is the temperature of the sample, t is the time, $\mathbf{v}$ is the translational velocity vector of the sample, q is the heat flux density of the heat transfer, q_r is the heat flux density of the radiation, Q is the volumetric power density of heat sources.

To implement the finite element method, the sample was divided into elements. Splitting was done automatically with element size “Finer”. With such a division, the side of the element was no more than 16 μm . Trial calculations showed that a decrease in the size of the elements did not lead to a significant change in the results. It is important to note that the translation velocity vector of the sample was responsible for the velocity of the sample, the movement of which simulated the movement of the laser spot along the line of contact of the hair, thus, the calculation was carried out for different values of the scanning speed. For the correct operation of the thermophysical model, the coordinate systems in the optical and thermophysical models were matched. The initial conditions were established: an initial temperature of 298.15 K, a pressure of 101 kPa, and the presence of natural convection of the air surrounding the sample. In the COMSOL Multiphysics ver. 6.0, the convection heat flux in air q_0 for both hairs was calculated as:

$$q_0 = h \cdot (T_{\text{ext}} - T), \quad (3)$$

where h is the heat transfer coefficient, T_{ext} is the ambient temperature (air), T is the hair temperature.

The heat transfer coefficient was calculated for the case of a thin cylinder as:

$$h = \frac{k}{H} \left(\frac{4}{3} \left(\frac{7\text{Ra}_H \text{Pr}}{5(20 + 21\text{Pr})} \right)^{1/4} + \frac{4(272 + 315\text{Pr})H}{35(64 + 63\text{Pr})D} \right), \quad (4)$$

where k is the thermal conductivity of air, H is the cylinder (hair) height, Ra_H is the Rayleigh number, Pr is the Prandtl number of air, D is the cylinder (hair) diameter. In this case, the Rayleigh number was given as:

$$\text{Ra}_H = \frac{g\alpha_p |T - T_{\text{ext}}| H^3}{k\mu}, \quad (5)$$

where g is the acceleration of gravity, α_p is the coefficient of thermal expansion of air, μ is the dynamic viscosity of air [28].

The hairs in the model are in contact along the line of contact (see Fig. 1), no additional boundary conditions have been specified for this area due to the negligible hair contact area. The contribution of boiling and evaporation of water was not considered in the approximation that the water content in dry hair is low (in what follows, dry hair was used in the experiment).

As a result of thermophysical modeling, the maximum values of temperature and the Arrhenius function were calculated at the line of hair contact in the sample. The Arrhenius function is used to assess the degree of thermal damage to a biological tissue (the relative concentration of damaged molecules) and is calculated as [29]:

$$\Omega = \int_0^t A e^{-\frac{E_a}{RT}} dt, \quad (6)$$

where Ω is the value of the Arrhenius function, t is time, A is the frequency factor, E_a is the activation energy, $R = 8.31 \text{ J/(mol·K)}$ is the universal gas constant; T is the temperature.

The degree of thermal damage Λ is calculated as [30]:

$$\Lambda = \frac{C_0 - C(t)}{C_0} = 1 - \exp(-\Omega), \quad (7)$$

where C_0 is the initial concentration of molecules or cells, $C(t)$ is the concentration of molecules or cells at a time t .

At $\Omega = 1$, the degree of thermal damage Λ becomes equal to $1 - e^{-1} \approx 0.63$, and the temperature reaches a value sufficient for denaturation (irreversible change) of the biological tissue [31].

In the calculations, the laser radiation power was varied from 1 W to 10 W, and the laser spot scanning speed was varied from 1 mm/s to 10 mm/s.

In an *in vitro* experiment, the possibility of bonding two human hairs by welding them with 980 nm continuous laser radiation was studied. Dry dark uncolored hair of one person (volunteer) was used in the study. Before the experiment, a fragment 10–15 cm long was mechanically cut off from a hair 50–60 cm long and stored for 14 days in a dry, dark, unlit, air-conditioned room at a temperature of $23 \pm 1^\circ\text{C}$. A total of 20 fragments were obtained from 20 neighboring hairs. It

was these hair fragments that were used to create samples for research. The scheme of the experimental setup is shown in Fig. 3. The sample was a pair of hairs $60 \pm 10 \mu\text{m}$ in diameter and $20 \pm 2 \text{ mm}$ long, fixed in a holder so that their surfaces were in contact with each other along the line of contact parallel to the hair axis. An Alta-ST diode laser (Dental Photonics Inc., USA) with a wavelength of 980 nm operating in a continuous mode was used as a source of laser radiation. Laser radiation was delivered to the sample via an optical fiber, the output end of which moved along the sample fixed in the holder. The movement of the fiber was provided by a scanning system controlled by a computer.

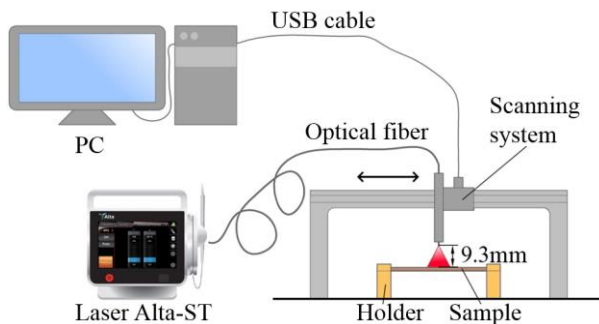


Fig. 3 Scheme of an experimental setup for *in vitro* study of the possibility of bonding two human hairs by welding them with continuous laser radiation at a wavelength of 980 nm.

The design parameters and optical properties of the materials were identical to those used previously in optical modeling. After laser exposure, the samples were photographed using an AxioScope A1 optical microscope (Carl Zeiss, Germany) equipped with an AxioCam camera (Carl Zeiss, Germany) and the appearance of the samples was analyzed for visible changes, bonding (welding) or irreversible thermal damage.

3 Results and Discussion

The dependences of the maximum temperature and the maximum value of the Arrhenius function at the line of contact of the hairs in the sample on the scanning speed obtained as a result of modeling at various values of the laser radiation power are shown in Fig. 4(a) and Fig. 4(b), respectively.

It can be seen that with an increase in the scanning speed at a constant laser radiation power, the maximum temperature at the line of hair contact in the sample decreases. In this case, the higher the laser radiation power, the higher the maximum temperature that can be achieved at a constant scanning speed. The melting point of a Caucasian hair of 508.95 K is not achieved for all combinations of power and speed, which is obviously due to the competition between heating and cooling processes.

It can also be seen that with an increase in the scanning speed at a constant laser power, the maximum

value of the Arrhenius function at the line of hair contact in the sample decreases. At the same time, the higher the laser radiation power, the higher the scanning speed at which $\Omega_{\max} = 1$. The maximum value $\Omega_{\max} = 1$, at which irreversible thermal damage to the hair occurs, is not achieved for all combinations of power and speed, which is due both to the competition between heating and cooling processes and with the contribution of the rate of the denaturation process.

The analysis of the dependences presented in Fig. 4 made it possible to determine the combinations of scanning speed and laser radiation power at which the melting temperature is reached at the hair contact line in the sample and at which $\Omega_{\max} = 1$ (see Fig. 5).

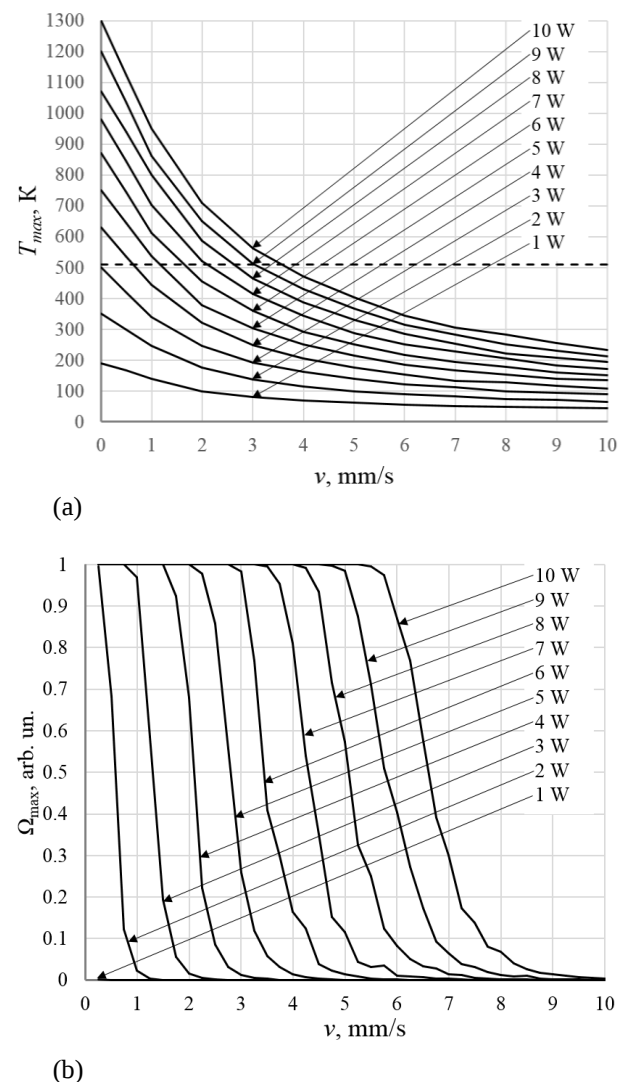


Fig. 4 Dependence of the maximum temperature $T_{\max}$ (a) and the maximum value of the Arrhenius function $\Omega_{\max}$ (b) at the line of hair contact in the sample on the scanning speed v at different powers of laser radiation at a wavelength of 980 nm (dashed line corresponds to the melting temperature of a Caucasian hair of 508.95 K [32]).

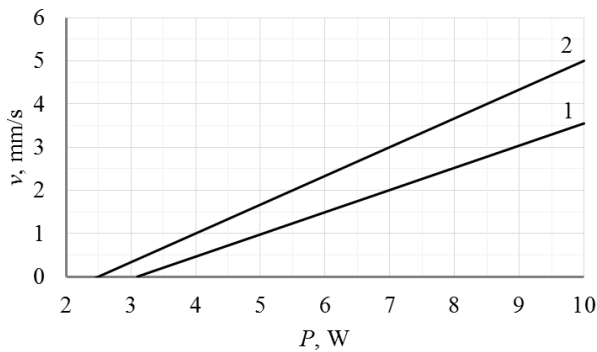


Fig. 5 Dependence of the scanning speed v at which the temperature at the line of hair contact in the sample reaches the melting point of a Caucasian hair of 508.95 K (line 1) and at which $\Omega_{\max} = 1$ (line 2) on the power of laser radiation P at a wavelength of 980 nm.

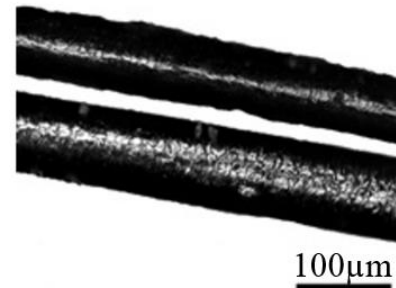
Achieving the melting temperature of the hair at the line of contact of the hair in the sample leads to a reversible thermal change in the hair shell (cuticle), which consists mainly of keratin, and does not affect the hair as a whole. This change makes it possible to connect the hairs to each other. At the same time, reaching the value $\Omega_{\max} = 1$ by the Arrhenius function leads to irreversible thermal damage to the hair, which should be avoided.

Thus, based on the simulation, it can be assumed that hair welding can be achieved by heating them to the melting temperature and the optimal combinations of laser radiation power with a wavelength of 980 nm and laser beam scanning speed for bonding (extension, welding) hair lie above line 1 and below line 2 in Fig. 5.

In the *in vitro* experiment, the impact on the sample was carried out at three combinations of the scanning speed of the laser spot and the power of the laser radiation. Combination #1 ($P = 3.5$ W and $v = 4$ mm/s) lies above line 1 and line 2 in Fig. 5 and, according to the previously formulated assumption, should not cause melting and irreversible thermal damage to the hair, therefore, should not lead to welding. Combination #2 ($P = 5.0$ W and $v = 1.5$ mm/s) lies below line 1 and above line 2 in Fig. 5 and, according to the previously formulated assumption, should lead to welding along the line of hair contact in the sample. Combination #3 ($P = 6.5$ W and $v = 1$ mm/s) lies below line 1 and line 2 in Fig. 5 and should lead to irreversible thermal damage to the hair. In total, 10 samples were studied in the experiment for each of the three combinations of the laser spot scanning speed and the laser radiation power. Typical photographs of samples after laser exposure with each of the three combinations are shown in Fig. 6.

It can be seen that laser exposure with Combination #1 did not change the appearance of the hair and did not lead to their bonding. Combination #2 did not change the appearance of the hair and led to their bonding along the line of contact. Combination #3 changed the appearance of the hair (they increased in diameter and collapsed) and did not lead to their bonding along the line of contact.

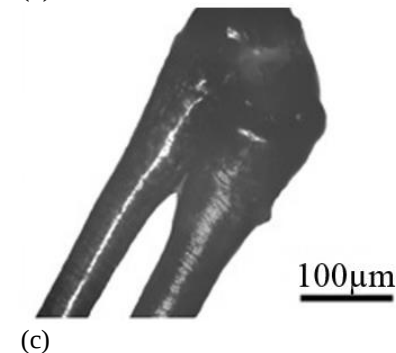
Thus, the results observed in the experiment confirm the conclusion made on the basis of modeling about the possibility of hair welding and the validity of the recommendations on choosing the optimal combinations of the power of continuous laser radiation with a wavelength of 980 nm and the scanning speed of the laser beam for their bonding (extension).



(a)



(b)



(c)

Fig. 6 Typical photographs of samples after exposure to continuous laser radiation with a wavelength of 980 nm: (a) Combination #1, (b) Combination #2, and (c) Combination #3.

4 Conclusion

In the course of the study, a computer optical model of a laser system for bonding of human hair and a computer thermophysical model of laser bonding of human hair were created. As a result of modeling, the dependences of the maximum temperature and the maximum value of the Arrhenius function at the line of contact of hairs in the sample on the scanning speed of the laser beam were obtained at different powers of laser radiation with a wavelength of 980 nm. The optimal combinations of laser radiation power and laser beam scanning speed for bonding (extension) of hair were determined. *In vitro* experiments were carried out on bonding hair with laser

radiation with a wavelength of 980 nm. The results of the experiments confirmed the possibility of bonding (extension) hair by welding with continuous laser radiation with a wavelength of 980 nm and showed a satisfactory agreement with the simulation results.

Disclosures

All authors declare that there is no conflict of interests in this paper.

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