Study on the optimal process parameters for stripping the X-ETFE insulation layer of aviation wires by a small semiconductor laser

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Abstract
A reasonable laser wire stripping process parameter set is a prerequisite for high-quality and high-efficiency wire stripping. For the X-ETFE insulated wire used in aviation, this study explores the method of obtaining the optimal stripping process parameters based on a 405 nm wavelength semiconductor laser. Build energy conversion model, mobile heat source model, and finite element simulation numerical model of the laser stripping insulating layer process. Based on the single-factor analysis method, simulate the effect of laser power, scanning speed, and processing time on the kerf width, heat-affected zone width, and cutting seam depth of the insulating layer. The results show that increasing the laser power to improve the stripping efficiency will also increase the width of the kerf and heat-affected zone, and increasing the scanning speed can effectively reduce the kerf width. A reasonable combination of laser power and scanning speed can improve stripping efficiency while ensuring quality. According to the single-factor simulation analysis results, select the possible value levels for each parameter to carry out the actual laser wire stripping orthogonal test. There is a good correspondence between the range analysis results of the test data of each stripping quality evaluation index and the conclusions obtained from the single-factor simulation, which verifies the reliability of getting the optimal combination of laser stripping process parameters through the orthogonal test.

Keywords
X-ETFE insulation layer, laser wire stripping, process parameters, finite element simulation, orthogonal test

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Introduction
Laser wire stripping is generally considered to be the most efficient and best quality wire stripping method in the market. It plays an important role in the processing of the wiring harness end and is widely used in cutting-edge technology industries such as aerospace, microelectronics, etc. The essence of laser wire stripping is shown in Figure 1. The focused high heat flux laser spot is applied to the surface of the insulating layer made of high molecular polymer, and the spot and the wire keep a relative rotation. When the temperature of

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the insulating layer material in the ablated area is greater than a certain critical threshold under the effect of heat conduction, it will rapidly decompose and vaporize.\textsuperscript{1,2} The temperature distribution generated within the insulating layer, which determines the cutting seam depth, kerf width, and heat-affected zone (HAZ) width of the insulating layer, depends on the deposition energy distribution and thermal diffusion rate during laser irradiation. Among them, the width of the kerf and HAZ, as the key evaluation indexes for the quality of laser wire stripping, should meet the specific requirements of the standard SAE-AIR6894.\textsuperscript{3} For continuous lasers, the main factors affecting the index level are the action time, power and scanning speed of the laser. The energy absorbed by the insulating layer per unit time is proportional to the power and inversely proportional to the scanning speed. A reasonable combination of laser power and scanning speed can shorten the laser action time while ensuring the stripping quality, thereby improving the stripping efficiency.

At present, the research on laser wire stripping technology is mainly distributed in the aspects of processing mechanism,\textsuperscript{4-9} processing technology design,\textsuperscript{10-13} and process parameters. Through experimental comparison, Brannon et al.\textsuperscript{4} found that the absorption coefficient of polyurethane insulating material for ultraviolet band laser is much higher than that of the infrared band. They pointed out that the insulating material’s intense energy absorption capacity and the short laser pulse duration are the key factors in achieving good wire stripping results. The stripping test of the polyurethane insulating layer doped with rhodamine dye was carried out by them using a pulsed laser with a wavelength of 532 nm. It was found that the absorption coefficient of polyurethane material to this wavelength laser can be improved by doping rhodamine dye, and a better stripping effect can be obtained by adjusting parameters such as dye concentration, doping amount, pulse duration, and pulse number. For the first time, the method of stripping the acrylate jacket of optical fibers using a laser was proposed by Barnier et al.\textsuperscript{6} They pointed out that the good matching between the energy absorption band of polymer material and the laser wavelength is the key requirement for successful laser stripping. In the research of laser stripping process parameters, the effects of laser pulse energy density and pulse number on the thickness of SMF28 fiber coating removal were experimentally studied by Peng et al.,\textsuperscript{14} Peng and Zhou,\textsuperscript{15} and Zhu et al.\textsuperscript{16} using TEA CO\textsubscript{2} infrared laser and KrF excimer ultraviolet laser respectively. It is found that the removal thickness of the coating layer increased logarithmically with the increase of laser pulse energy density, changed logarithmically with the increase of infrared laser pulse number, and changed linearly with the increase of ultraviolet laser pulse number. A transient temperature field finite element simulation model for the laser stripping process of thermal barrier coatings was established to predict the size of the ablation profile under different laser powers and scanning speeds by Marimuthu et al.\textsuperscript{17} And under the same process variables, the validity of the simulation model was verified with an experimental result based on nanosecond pulsed laser. Yang et al.\textsuperscript{18} and Chen et al.\textsuperscript{19} studied the process method of cutting metal shielding layer with YAG laser on the basis of cutting the outer insulating layer of fine wire with CO\textsubscript{2} laser. They performed numerical simulation analysis on the process of YAG laser cutting RG113 metal shielding layer, and obtained the laws of the influence of laser power, scanning speed, pulse number, and defocusing amount on the kerf width and depth of the metal shielding layer and surface quality, but did not further test to explore the optimal laser cutting process parameters of the metal shielding layer under this method. Based on the single-factor test method, the effects of laser power and scanning speed on the stripping quality and efficiency of the polyimide insulation layer of aviation wires were studied by Tang\textsuperscript{20} and Zhang\textsuperscript{21} using a CO\textsubscript{2} laser. It is found that under the same stripping quality condition, the scanning speed has a greater influence on the stripping efficiency than the laser power. Lazov and Snikeris\textsuperscript{22} conducted a study on the possibility of stripping the PVC insulation of fine wires with a low-power continuous CO\textsubscript{2} laser. Based on the single-factor test method, the functional relationship between the kerf width and cutting seam depth of the PVC insulation layer and the main process parameters such as laser power and scanning speed was obtained.
However, most of the previous studies focused on exploring the influence of various process parameters on the quality and efficiency of wire stripping, but there are few elaborations on how to obtain the optimal combination of laser wire stripping process parameters. In addition, at present, there are few pieces of research on the laser stripping process of the X-ETFE insulation layer of aviation wire. Moreover, the lasers traditionally used for wire stripping are generally larger and the supporting facilities are relatively cumbersome. The existing laser wire stripping tools cannot meet the lightweight and desktop-level production requirements in the field of aviation wire harness processing. Therefore, based on small lasers, exploring high-quality and efficient stripping process parameters of the X-ETFE insulation layer of aviation wire is an important production problem that needs to be solved urgently.

In this paper, to study the effects of laser power, scanning speed, and processing time on the kerf width, HAZ width and cutting seam depth of the insulating layer, the laser stripping process of the X-ETFE insulation layer of aviation wire was simulated. And on this basis, the optimal combination of laser stripping process parameters for the X-ETFE insulation layer was further explored through the orthogonal test, to improve the quality and efficiency of laser wire stripping.

### Modeling of temperature field in laser stripping of X-ETFE insulation layer

#### Energy conversion model and uniqueness conditions

During the stripping process, the laser focused spot acts on the surface of the insulating layer, and part of the spot energy is absorbed by the surface of the insulating layer, causing the surface temperature to rise rapidly. At the same time, the surface energy is continuously transferred to the inside of the insulating layer. In addition, the laser stripping process of the insulating layer is in a natural environment, there is a large temperature difference between the surface of the insulating layer and the surrounding environment, and part of the surface energy is lost in its thermal radiation to the surrounding space and natural convection heat transfer with the surrounding air. Therefore, in summary, the following energy conversion model for laser stripping of the insulating layer can be established:

\[
Q_1 + Q_2 + Q_3 + Q_4 = Q_{\text{laser}},
\]

where \(Q_1\) represents the energy that increases the temperature of the laser ablation area on the surface of the insulating layer, referred to equation (2). \(Q_2\) represents the energy transferred to the inside of the insulating layer, referred to equation (3). \(Q_1\) represents the energy of convective heat transfer between the surface of the insulating layer and the surrounding air, referred to equation (4). \(Q_4\) represents the energy of thermal radiation on the surface of the insulating layer, referred to equation (5). \(Q_{\text{laser}}\) represents the focusing laser energy effectively absorbed by the insulating material, which is described in Section 2.3.

\[
\begin{align*}
Q_1 &= \rho c_p \frac{\partial T}{\partial t}, \\
Q_2 &= -\lambda \cdot \text{grad}T, \\
Q_3 &= h(T - T_f), \\
Q_4 &= \alpha(T^4 - T_f^4),
\end{align*}
\]

where \(\rho\), \(c_p\), and \(\lambda\) represent the density, specific heat capacity, and thermal conductivity of the insulating material, respectively, \(h\), \(\varepsilon\), and \(\alpha\) are the heat transfer coefficient of natural convection of air, the emissivity of the insulating material and the Stefan-Boltzmann constant, respectively. \(T\) is the temperature of the laser ablated surface of the insulating layer, and \(T_f\) is the ambient temperature.

To study the heat conduction process of laser stripping X-ETFE insulation layer, it is necessary to further supplement the energy conversion model shown in equation (1), that is, to add uniqueness conditions. Among them, the geometric condition is described in Section 2.2, and the remaining conditions are as follows:

1) Physical conditions: Assuming that the thermophysical parameters of X-ETFE insulation materials are constants, the values are shown in Table 1 below.

| Thermophysical parameters   | Value  |
|----------------------------|--------|
| Density \((\rho)\) (kg m\(^{-3}\)) | 1700   |
| Specific heat capacity \((c_p)\) (J kg\(^{-1}\) K\(^{-1}\)) | 1172   |
| Thermal conductivity \((\lambda)\) (W m\(^{-1}\) K\(^{-1}\)) | 0.23   |
| Emissivity \((\varepsilon)\) | 0.89   |

2) Initial conditions: The essence of laser stripping the insulating layer is a transient heat conduction process, the temperature inside the object changes with time. Therefore, the temperature distribution inside the insulating layer at the initial time should be explained. The process of laser stripping the insulating layer is carried out at room temperature. Here, the initial temperature of the overall insulating layer is set to be the same as the ambient temperature, that is, \(T|_{t=0} = T_0 = T_f = 293.15K\).
3) Boundary conditions: For the transient heat conduction process, it is necessary to clarify the heat flux value $Q_s$ on the boundary surface of the object at any time. Therefore, we should first determine the heat flux distribution over time and space of the mobile laser heat source applied on the surface of the insulating layer, which is described in Section 2.3. Secondly, the heat loss on the outer surface of the insulating layer is mainly caused by air convection and thermal radiation shown in equations (4) and (5). Here, the convective heat transfer coefficient $h$ takes an empirical value of $5 \text{ W} / (\text{m}^2 \cdot \text{K})$, the emissivity $\varepsilon$ can be obtained from Mainini et al.,26 and its value is shown in Table 1.

Finite element model and meshing

According to the energy conversion model and uniqueness conditions described in Section 2.1, the finite element method is used to numerically calculate the temperature field of the laser stripping X-ETFE insulation layer in the time domain. To simplify the simulation process, the following assumptions are made:

1) It is assumed that the insulating material is isotropic and does not chemically react with other substances in the processing environment during the ablation process.
2) Since X-ETFE is a thermoset material,27 there is no flow of molten material in this simulation. Therefore, the splashing and bulging phenomena caused by fluid dynamics are not considered.
3) Ignore the change of the thermophysical parameters of X-ETFE insulation material with temperature.
4) The simulation does not include thermal-mechanical stress and the fracture of insulating materials, where the removal of material elements is only affected by the decomposition and gasification mechanism.

In the simulation, the geometric model will be established concerning the real insulating structure of the 20 AWG wire. Considering that the wire insulation layer is approximately cylindrical, to improve the simulation efficiency, a one-fourth model of the 3D insulating layer with a length of 2 mm, an inner diameter of 0.96 mm, and an outer diameter of 1.48 mm was established. Two major regions for meshing were given to the model, namely the fine and coarse mesh regions. The fine mesh region was applied to the laser irradiation and heat-affected area, and the coarse mesh region was applied outside the heat-affected area, as shown in Figure 2. In general, as the mesh density increases, the accuracy of the calculation results improves, but this also increases the computational cost. In addition, when the mesh is refined to a certain extent, the increase in the accuracy of the calculation result will become very small. Therefore, in order to improve the simulation accuracy and improve the calculation efficiency as much as possible, here the fine mesh element size was empirically set to one-fifth of the spot diameter, and the size is $0.02 \text{ mm}$. Regarding the formation of the cutting depth, the elements whose temperature is greater than the material decomposition and gasification threshold in the simulation are removed, and the laser beam will further irradiate the downward elements, thereby increasing the cutting depth.

Mobile laser heat source loading

In this study, a continuous laser with a wavelength of 405 nm was used. The laser focused spot was circular and its intensity was Gaussian. Because the X-ETFE insulation material has a low laser transmittance to this wavelength, and the laser energy is mainly surface absorption, the Gaussian surface heat source model is chosen in the simulation. The effective laser intensity distribution acting on the surface of the insulating layer can be expressed as follows:

$$Q_{\text{laser}} = \frac{2AP}{\pi \omega_0^2} \exp \left( -2 \frac{r^2}{\omega_0^2} \right),$$

where $A$ is the absorptivity of X-ETFE insulation material for the laser with a wavelength of 405 nm. This value is obtained from the laser absorption spectrum curve of the X-ETFE insulation material doped with other impurities provided by the wire supplier, which is about 0.45. $P$ is the laser power, the maximum is 1 W. $\omega_0$ is the radius of laser focused spot, its value is obtained according to the laser wire stripping test platform described in Section 3.2, about 0.05 mm, and $r$ is the distance from a point in the laser loading area on
the surface of the insulating layer to the spot center. According to the above equation (6), the average power density of the laser is about 127.3 W/C\(^2\) mm\(^2\).

To further realize the simulation of the process of laser moving and cutting the insulating layer, it is also necessary to add a time-varying motion control equation to the distance \(r\) between the laser loading point and the center of the spot in the laser heat source model shown in equation (6). The starting point, path, and coordinate system position of the laser movement in the simulation are shown in Figure 2. The established motion control equation is as follows:

\[
r^2 = [x - 1.48 \sin(2\pi n \cdot t)]^2 + [y - 1.48 \cos(2\pi n \cdot t)]^2 + (z - 1)^2
\]  

(7)

After substituting equation (7) into equation (6), the mobile laser heat source model obtained was applied to the simulation. As shown in Figure 3, the temperature field near the moving track of the spot is like a comet tail, the temperature in the center area of the spot is the highest, and the temperature of the area flowing through the spot gradually decreases.

### Materials and methods

#### Experimental materials and tools

In the laser wire stripping experiment, the wire adopted 20 AWG aviation-use 19-strand soft silver-plated copper core X-ETFE insulated wire that complies with the US military standard MIL-W-22759, which was purchased from Quanxin Cable Technology Co., Ltd., Nanjing, China. The laser is a semiconductor laser with a wavelength of 405 nm and a power range of 0–1 W (model MDL-III-405nm-1W-BH81498), which was purchased from New Industries Optoelectronics Technology Co., Ltd., Changchun, China. The focusing lens group consists of two K9 plano-concave lenses with different diameters (6 and 50.8 mm) and two K9 plano-convex lenses with a diameter of 12.7 mm, both of which were purchased from Hengyang Electronic Technology Co., Ltd., Guangzhou, China. The wire-rotating drive motor (model SM2-310L) and driver (model SD253) were purchased from MOTEC Technology Company, China. The stepper motor speed regulator (model YF-18) was purchased from Haoxin Digital Technology Studio, Guangzhou, China. The XY-axis feed slide (travel 80 × 80 mm) used to adjust the position of the facula was purchased from Huasen Hardware Electronics Co., Ltd., Shenzhen, China. The microscope (model XY-M) used to observe the laser stripping effect of the X-ETFE insulation layer was purchased from Sunny Optical Technology Co., Ltd., Yuyao, China, and was equipped with a 3-megapixel industrial camera (model MER-310-12UC).

#### Experimental scheme and platform construction

In this experiment, the possible value range of each process parameter will be determined based on the single-factor finite element simulation results of laser stripping X-ETFE insulation layer with respect to laser power, scanning speed, and processing time. Then, based on the laser wire stripping experimental platform shown in Figure 4, to improve efficiency and determine the optimal process parameter combination for stripping X-ETFE insulation layer with a small semiconductor laser, the orthogonal test analysis is carried out on the laser stripping effect of the insulating layer under different process parameter combinations.

The experimental platform is mainly composed of laser, focusing lens group, wire rotation driving mechanism, focusing spot locating device, and speed regulator. The focusing lens group was built after optical design, and the radius of focusing spot is about 0.05 mm. By adjusting the XY axis feed slide, the
focusing spot can be accurately located at different positions of the wire. The speed regulator controls the stepper motor to drive the wire to rotate at different speeds, to achieve the effect of laser circumferential cutting of insulating layer at different scanning speeds.

**Results and discussion**

According to the thermogravimetric analysis of X-ETFTE insulation materials for aviation in Morelli et al., Zen et al., and Zhang et al., the X-ETFTE insulation materials begin to decompose when the temperature reaches 350°C, and slight discoloration occurs on the surface of the material. When the temperature reaches 550°C, the decomposed insulating material is almost completely gasified. Therefore, in the following simulation of the temperature field of the laser stripping insulating layer, to facilitate the observation of the changes in the kerf width, HAZ width, and cutting seam depth of the insulating layer, the area where the insulating layer temperature is between 350°C and 550°C is set as the HAZ, and the area where the temperature is greater than 550°C is the material removal area.

**Single-factor finite element simulation analysis of each processing parameter**

Single-factor simulation is a method of analyzing only one factor while keeping other influencing factors unchanged. Next, based on this method, the influence of laser power, scanning speed, and processing time on the stripping quality of the X-ETFTE insulation layer will be explored respectively.

**Laser power.** The laser power is the most significant parameter that affects the stripping quality of the insulating layer. In this simulation, based on experience, the laser scanning speed was initially set to 3 r·s⁻¹, the processing time was 4 s, and the laser power was set to 0.6, 0.7, 0.8, 0.9, and 1 W for analysis. The temperature field distribution in the laser cutting area of the insulating layer at each power is shown in Figure 5(a)–(e) below. The red area represents the insulating material that has been completely decomposed and gasified, and the yellow area represents the incompletely decomposed insulating material, that is, the HAZ. With the increase of laser power, the size changes of the kerf width, HAZ width, and cutting seam depth of the insulating layer are shown in Figure 5(f).

As can be seen from Figure 5(f), the kerf width, HAZ width, and cutting seam depth of the insulating layer all increase with the increase of laser power. When the laser power was 0.6 and 0.7 W, due to the relatively small heat flux acting on the surface of the insulating layer, the cutting seam depth reached within the same time was smaller, and the insulating layer was not completely cut through. This means that lower laser power will result in lower stripping efficiency.

**Scanning speed.** In the single-factor finite element simulation for laser scanning speed, the laser power and processing time were set to 0.8 W and 4 s respectively, and the scanning speed was valued as 1–5 r·s⁻¹ respectively for analysis. The temperature field distribution of the laser cutting area of the insulating layer at each scanning speed is shown in Figure 6(a)–(e) below, and the color definition is the same as that in Figure 5. With the increase of scanning speed, the size changes of the kerf width, HAZ width, and cutting seam depth of the insulating layer are shown in Figure 6(f).

As can be seen from Figure 6(f), although the kerf width of the insulating layer decreased obviously with the increase of the scanning speed, the insulating layer was not completely cut through when the laser scanning speed was 1, 4, and 5 r·s⁻¹. The reason is that when the scanning speed is high, although the laser action frequency is increased, the smaller action period reduces the energy obtained inside the insulating material, thereby reducing the diffusion range of heat, so the material removed by vaporization is reduced. This shows that increasing the laser scanning speed can improve the stripping quality, but it will also reduce the stripping efficiency.

**Processing time.** In the single-factor finite element simulation for laser processing time, the laser power and scanning speed were set to 0.8 W and 3 r·s⁻¹ respectively, and the processing time was valued as 2–6 s respectively for analysis. The temperature field distribution of the laser cutting area of the insulating layer at each processing time is shown in Figure 7(a)–(e) below, and the color definition is also the same as that in Figure 5. With the increase of processing time, the size changes of the kerf width, HAZ width, and cutting seam depth of the insulating layer are shown in Figure 7(f).

As can be seen from Figure 7(f), when the action period of the laser on a single point on the insulating layer remains unchanged, the laser action frequency increases with the increase of processing time, and then the amount of material gasification removal increases. Therefore, the insulating layer is not completely cut through when the laser processing time is relatively short (2 and 3 s). In addition, the change of processing
Figure 5. Single-factor finite element simulation results of the influence of laser power on the stripping quality of the X-ETFE insulation layer: (a) 0.6 W, (b) 0.7 W, (c) 0.8 W, (d) 0.9 W, (e) 1 W, and (f) as the laser power increases, the size change curves of the kerf width, HAZ width, and cutting seam depth of the insulating layer.

Figure 6. Single-factor finite element simulation results of the influence of laser scanning speed on the stripping quality of the X-ETFE insulation layer: (a) 1 r/s⁻¹, (b) 2 r/s⁻¹, (c) 3 r/s⁻¹, (d) 4 r/s⁻¹, (e) 5 r/s⁻¹, and (f) As the laser scanning speed increases, the size change curves of the kerf width, HAZ width, and cutting seam depth of the insulating layer.
time does not affect the size of the laser heat flux. Therefore, in the three groups of simulation results in which the insulating layer is completely cut through, as the processing time increases, the changing trend of the kerf width is relatively slow, and the HAZ width does not change significantly.

**Orthogonal test analysis**

Orthogonal test method is a mathematical statistical method that uses orthogonal table to arrange and analyze the test of multi-factor and multi-level problems. Using this method can not only make the factor level distribution uniform, get the primary and secondary influence relationship of various factors on the test result, but also reduce the number of tests and improve the test efficiency.

From the single-factor finite element simulation of each process parameter in Section 4.1, it can be found that the laser power and scanning speed have a greater impact on the kerf width and HAZ width of the insulating layer. A reasonable arrangement of laser power and scanning speed can ensure the stripping quality and efficiency of the insulating layer, three possible value levels were selected for each parameter, namely, laser power (0.7, 0.8, and 0.9 W), scanning speed (2–4 r·s⁻¹), and processing time (3–5 s). Obviously, it was a three-factor and three-level test, so the L₉(3⁴) orthogonal table could be used to arrange nine sets of process parameters for the test. After the test, the morphology of the cutting seam of each group of insulating layer was observed successively with a microscope, and the kerf width, cutting seam depth, and HAZ width of the X-ETFE insulation layer under each group of process parameters in the orthogonal test was accurately captured and measured through the size measurement module in Galaxy, the exclusive image acquisition software of industrial camera matched with the microscope. The orthogonal test arrangement and size measurement results are shown in Table 2, and the laser stripping effect of the insulating layer under different process parameter combinations is shown in Figure 8.

Table 3 shows the results of the range analysis for the evaluation index of the stripping quality of the insulating layer. Among them, Aᵢⱼ represents the average value of the i index in each group of responses at the j level of a parameter, and Rᵢ represents the difference between the maximum value and the minimum value of Aᵢⱼ, that is, the range value. The larger the Rᵢ, the greater the influence of its corresponding parameter on
The influence degree of each parameter on each index in Table 3 can be analyzed intuitively as follows:

1) Kerf width: laser power ⇒ scanning speed > processing time.
2) Cutting seam depth: laser power > processing time > scanning speed.
3) HAZ width: laser power ⇒ scanning speed > processing time.

The above analysis is basically consistent with the influence law explored in the single-factor simulation of each processing parameter in Section 4.1, which verifies the reliability of the established finite element model of the laser cutting of the insulating layer and the obtained orthogonal test results.

To obtain the optimal combination of processing parameters for 20AWG wire, the test results in Table 2 were analyzed. The index of cutting seam depth should be considered first, and the test group whose cutting seam depth reached the thickness of the insulating layer (260 μm) is the qualified group. It can be seen that the width of the kerf and HAZ of the insulating layers

Table 2. Orthogonal test arrangement for laser stripping of the X-ETFE insulation layer of 20AWG aviation wire and measurement results of relevant stripping indexes.

| Group no. | Laser power (W) | Scanning speed (r·s⁻¹) | Processing time (s) | Kerf width (μm) | Cutting seam depth (μm) | HAZ width (μm) |
|-----------|----------------|------------------------|---------------------|-----------------|------------------------|----------------|
| 1         | 0.7            | 2                      | 3                   | 92              | 180                    | 99             |
| 2         | 0.7            | 3                      | 4                   | 91              | 215                    | 78             |
| 3         | 0.7            | 4                      | 5                   | 81              | 231                    | 76             |
| 4         | 0.8            | 2                      | 4                   | 125             | 260                    | 121            |
| 5         | 0.8            | 3                      | 5                   | 96              | 260                    | 107            |
| 6         | 0.8            | 4                      | 3                   | 87              | 243                    | 95             |
| 7         | 0.9            | 2                      | 5                   | 135             | 260                    | 126            |
| 8         | 0.9            | 3                      | 3                   | 112             | 260                    | 104            |
| 9         | 0.9            | 4                      | 4                   | 101             | 260                    | 100            |

Table 3. Range analysis results of laser stripping quality evaluation index of X-ETFE insulation layer of 20AWG aviation wire.

| Evaluation indexes | Parameters | Laser power | Scanning speed | Processing time |
|--------------------|------------|-------------|----------------|-----------------|
| Kerf width (μm)    | A₁₁        | 88          | 117.33         | 97              |
|                    | A₁₂        | 102.67      | 99.67          | 105.67          |
|                    | A₁₃        | 116         | 89.67          | 104             |
|                    | R₁         | 28          | 27.67          | 8.67            |
| Cutting seam depth (μm) | A₂₁   | 208.67      | 233.33         | 227.67          |
|                    | A₂₂        | 254.33      | 245            | 245             |
|                    | A₂₃        | 260         | 244.67         | 250.33          |
|                    | R₂         | 51.33       | 11.67          | 22.67           |
| HAZ width (μm)     | A₃₁        | 84.33       | 115.33         | 99.33           |
|                    | A₃₂        | 107.67      | 96.33          | 99.67           |
|                    | A₃₃        | 110         | 90.33          | 103             |
|                    | R₃         | 25.67       | 25             | 3.67            |
corresponding to all qualified groups is less than 150 μm, which fully meets the laser stripping requirements of the standard SAE-AIR6894 for the insulating layer of aviation wires. Next, considering the processing efficiency, the laser wire stripping time is the shortest under the eighth group of processing parameters among all qualified groups, that is, the stripping efficiency is the highest under this parameter combination. Therefore, it can be concluded that the optimal combination of laser stripping parameters for the X-ETFE insulation layer of 20.4WG aviation wires is: laser power 0.9 W, scanning speed 3 m/s, and processing time 3 s.

For optimizing the laser stripping process of other insulation types of wires, the above method of obtaining the optimal combination of laser stripping parameters for the insulation layer through single-factor simulation of the laser cutting insulation layer combined with the orthogonal test is also applicable. In addition, the author believes that in the numerical simulation of the laser stripping insulating layer, coupling the thermal stress generated inside the insulating material to study the thermal expansion of the insulating material at the kerf can better guide actual production.

Conclusion

Based on the single-factor analysis method, the current work simulated the effects of laser power, scanning speed, and processing time on the temperature field distribution in the laser ablation area of the X-ETFE insulating layer, respectively. The study found that increasing the laser power can speed up the removal rate of insulating material and increase the width of the kerf and HAZ of the insulating layer. However, a change in the laser scanning speed has the exact opposite effect of the above.

The single-factor simulation results selected three possible value levels for laser power, scanning speed, and processing time respectively. Then, based on the 405 nm wavelength semiconductor laser wire stripping experimental platform, a 3-factor and 3-level laser wire-stripping orthogonal test was carried out on the 20.4WG X-ETFE insulated aviation wire. The range analysis of the orthogonal test data show that the influence degree of each processing parameter on each stripping quality evaluation index is in good agreement with the single-factor simulation results, which also shows the reliability of the established laser wire-stripping finite element model and orthogonal test. Combined with the requirements for the quality and efficiency of insulation stripping, the optimal combination of laser wire stripping process parameters can be quickly obtained from the orthogonal table.

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