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Design and implementation of laser-based equipment for aircraft skins cleaning

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Abstract: Aircraft skin structure is complex and plays a very important role in aircraft safety, which needs to be replaced regularly. Laser cleaning has the characteristics of pollution-free, high efficiency and high cost performance, and has advantages and application potential in laser cleaning of aircraft skin. Based on the need for rapid cleaning of aircraft skins, laser cleaning equipment was built and corresponding experiments were conducted. Research results show that the laser output power can be adjusted to remove the layers of aircraft skins without damaging the substrate, based on the different thermodynamic parameters of the top coat and primer. The laser cleaning equipment built has adjustable laser parameters and can be used to achieve accurate removal of aircraft skins.

Keywords: laser cleaning, aircraft skin, topcoat, primer, thermodynamic effects

I. Introduction

Aircraft surface paint, with its special properties such as resistance to oxidation, wear and corrosion, plays an important role in the flight safety of the aircraft, and the aging and performance degradation needs to be removed periodically. The removal of the skin is very difficult, and the main common cleaning methods are mechanical grinding method, high-pressure sandblasting method [1, 2] and chemical solvent method [3], but there are some problems insurmountable, such as pollution of the environment, easy to cause irreversible damage to the substrate, while laser paint removal technology has great potential for application in this field [4]. High-energy pulsed laser irradiates the surface of the paint layer, causing its temperature to rise rapidly and vaporize or peel off from the substrate to achieve the purpose of paint removal. Laser paint removal system has the advantages of easy control,high stability and low maintenance cost.

To order to improve the quality and efficiency of laser cleaning, scholars have conducted a lot of research and gradually improved the theory of laser cleaning, and established a system for laser cleaning. At present, relevant research mainly focuses on the cleaning mechanism of single-layer paint and the selection of optimal parameters, but it is not suitable for the multi-layer paint structure of aircraft skin. The main problems are as follows: Firstly, aircraft skin belongs to a multi-layer structure, with significant differences between layer structures and distinct removal mechanisms, which poses difficulties in establishing physical models for aircraft skin removal and determining laser cleaning methods [5]. Secondly, according to the characteristics of the paint, different laser parameters should be selected for optimized cleaning, which is the key to controllable cleaning. Parameter optimization needs to be achieved through the study of the mechanism of laser cleaning, especially for thicker paint or multi-layer paint structures, which is rarely studied [6]. Thirdly, due to the multi-layer structure of aircraft skin, it is necessary to adjust laser parameters for targeted layered paint removal, which requires laser equipment to have the ability to change parameters [7]. This article first built a laser cleaning equipment with variable parameters and achieved effective cleaning of aircraft skin.

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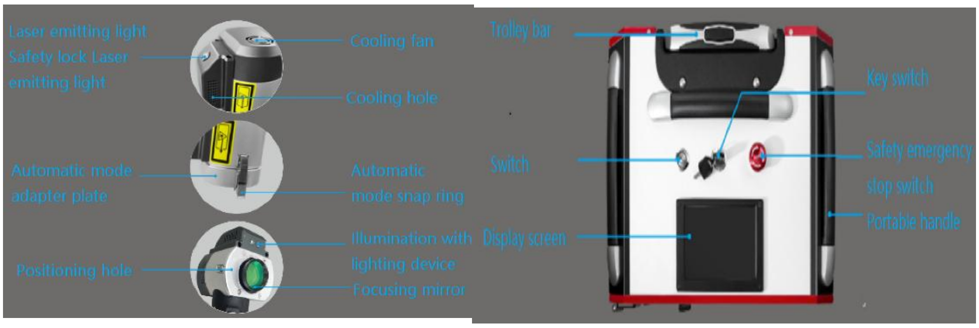
II. Construction of laser cleaning equipment

The architecture design of the laser cleaning equipment system we have built mainly includes three parts: mechanical system, optical system, and control system. Through the overall architecture design of mechanical and laser paint removal equipment, the selection of control system hardware, software architecture design, and electrical system design, a complete equipment architecture scheme can be formed. The mechanical system module is mainly responsible for the motion and auxiliary functions of laser cleaning lenses. The optical system mainly includes laser and lens systems, which are key components in laser cleaning work. The control system mainly undertakes the supply of strong and weak voltage, and uses microcontroller and FPGA controller to achieve logic operation, signal processing, signal output and other functions. Develop a dedicated device control system based on FPGA+STM32 for composite laser cleaning equipment, including sub modules such as mechanical motion control module, laser control module, controller communication module, etc., and develop human-machine interaction interface and electrical system construction based on C++. The laser cleaning equipment built is shown in Figure 1.

(a) Equipment appearance (b) Construction of laser cleaning equipment



(c) Laser head structure (d) luggage function key

Figure 1. Laser cleaning equipment

For the laser head construction, Indicator lights and safety locks that illuminate and ensure safe operation of the equipment. Cooling fan and heat dissipation through cooling holes to ensure stable operation of the laser head. Automatic mode adapter plate that allows switching between manual and automatic modes. Positioning holes can be assisted by the processing device in manual mode. Illumination unit can be used in poor lighting conditions. Focusing mirror focal length canbe changed and cleaning scanning route can be straight line, circle, spiral, distance shape, square, also can add the corresponding scanning graphics according to customer requirements. For the function keys of the cleaning machine, the pull rod makes the cleaning equipment's more convenient to carry and move. The key switch can prevent unrelated personnel from accidentally opening the safety emergency stop switch.

The laser of this equipment adopts MOPA pulsed fiber laser with a wavelength of 1064nm, a maximum power of 200W, an adjustable repetition frequency between 1 and 2000kHz, a mode of fundamental mode Gaussian, an M^2 value of about 1.3, and an adjustable pulse width from 10-400ns. The adjustability of laser pulse width, repetition frequency, etc. provides a choice of parameters for laser cleaning of aircraft skins, and the following experimental study of related cleaning is carried out.

III. Laser cleaning experiment of aircraft skin

3.1 Structure of aircraft skin

The sample used in this experiment is the Boeing 717 aircraft skin sample, whose metal substrate is 1 mm thick aluminum alloy, and the aluminum alloy surface has three layers of materials, namely, chartreuse chemical conversion coating, red polyurethane finish (80-90 μ m thick) and gray epoxy primer (100-110 μ m thick), as shown in Figure 2.

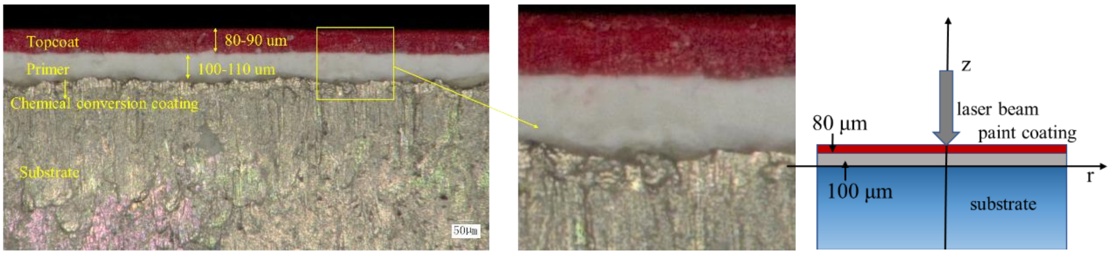


Figure 2. Model of multi-layer structure and layered cleaning of aircraft skin

There is a significant difference between the topcoat and primer, as shown in Table 1 for their laser absorption and thermodynamic parameters.

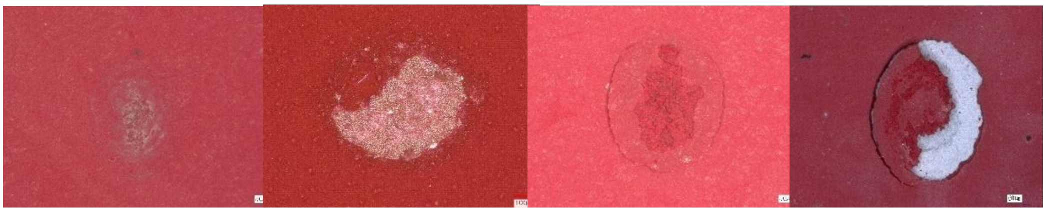
Table 1. The thermodynamic parameters of topcoat and primer

parameters	topcoat	primer
$\alpha/(m^{-1})$	4.29×10^4	1.49×10^5
$k/(W\ .\ m^{-1}\ .\ K^{-1})$	0.192	0.2
$c/(J\ .\ kg^{-1}\ .\ K^{-1})$	2.5×10^3	1.18×10^3
$\rho/(kg\ .\ m^{-3})$	1450	1800
Decomposition temperature/(K)	573	415

The surface coating of aircraft skin belongs to a multi-layer structure and must be removed sequentially from the topcoat to the primer. Firstly, the effects of output power and action time on the removal morphology of surface paint were studied. Then, increasing the output power and extending the action time were used to investigate the changes in the removal morphology of the primer.

3.2 Removal of the topcoat

We conduct cleaning experiments on the topcoat with an output power of 80 W, a focused spot diameter of 0.5 mm, a repetition frequency of 0.5 kHz, and a pulse width of 12 ns. As the application time progresses, the topcoat is gradually removed, as shown in Figure 3.



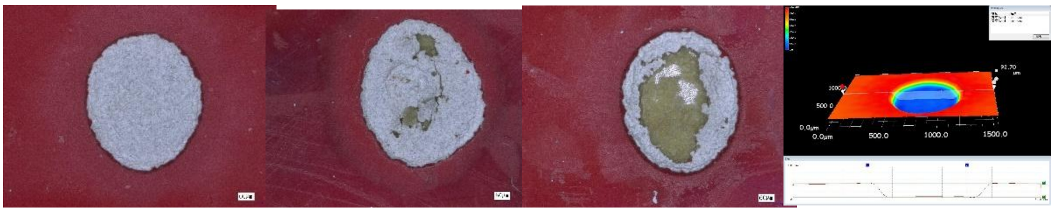
(a) 0.5s (b)1s (c) 1.5s (d) 3s

Figure 3. Cleaning process of aircraft skin topcoat

Laser cleaning experiments were conducted on the topcoat. With the increase of laser output power, the topcoat is gradually removed. When the laser action is 0.5 seconds, it is only the ablation of topcoat surface. When the action time is 1 second, the topcoat has a significant clearance. When 1.5 seconds, there is a significant edge fracture in the laser action area, and until 3 seconds, the topcoat is basically completely cleared. During the laser action process, ablated particles, dust, and particles will appear, which is mainly caused by the gasification phase transition caused by thermal ablation. With the increase of laser action time, thermal fracture occurs due to the difference in light intensity at the edge of the spot, and under the action of thermal stress, edge fracture occurs [9]. As the laser removal area increases, the ablation marks in the middle of the light spot become more obvious, at the same time cracks begin to appear around it, and even the entire circular topcoat directly cracks off the primer.

3.3 Removal of the Primer

On the basis of removal of the topcoat, cleaning of the primer was carried out. The laser output power is 150W, and other parameters remain unchanged. With the increase of time, the cleaning morphologies of the primer is shown in Figure 4.



(a) 0.8s (b) 1.5s (c) 2s (d) (2s) 3D image

Figure 4. Cleaning process of primer

As shown in Figure 4, with the increase of the laser action time, the color of the primer becomes brighter. With the removal of the topcoat, the oxide layer of the substrate gradually exposes. Due to the Gaussian pulse distribution of laser intensity, the highest energy is deposited at the center of the spot, and therefore the substrate is first exposed in the center area of the spot. The comparison of laser cleaning effects between topcoat and primer can be analyzed based on the differences in thermodynamic parameters between them. The difference in thermal conductivity and density is very small. The specific heat capacity of the topcoat is high, the density is low, and the decomposition temperature is high, but the thermal absorption coefficient is of high difference. Therefore, the topcoat is more likely to cause the deposition of laser energy, so the required laser output power is low [10]. Although the decomposition temperature of the primer is relatively high, due to its low laser absorption rate, it is necessary to increase the laser output power to achieve effective cleaning effect.

3.4 Aircraft Skin Layered Cleaning Model

The difference in the coefficient of laser absorption and thermal expansion between the topcoat and primer allows the topcoat to be removed through ablation and thermal fracture. The removal of the primer is based on the thermal stress difference between the primer and the substrate and the high-temperature decomposition of the primer. Their combined effect causes the topcoat to directly detach from the substrate and be removed. It can be seen that the difference in thermodynamic parameters between the topcoat and primer results in different cleaning mechanisms between the topcoat and primer, so we must carry out layered paint removal.

IV. Conclusion

We have built a laser cleaning equipment based on high repetition rate for cleaning aircraft skins. Cleaning experiments were conducted on the aircraft skin, achieving layered cleaning. For topcoat, due to its high laser absorption rate, it can generally be achieved with lower laser power, while for primer, higher power is required. The laser cleaning equipment designed in this article has the characteristic of variable laser parameters, which is suitable for layered cleaning of aircraft skin. Based on the multi-layer structure of aircraft skin, the removal mechanism and optimal removal parameters of topcoat and primer can be obtained.

V. Knowledge

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