Research on mechanism and process of paint removal with pulsed fiber laser

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Abstract. Compared with the traditional cleaning technology, laser cleaning, as a new type of industrial technology, has the advantages of high cleaning rate, green pollution-free and low cost. So laser cleaning is widely used in the fields of paint removal. This paper analyzes that the mechanism of paint removal and heat transfer process in the paint layer and substrate, also determines the process parameters of affect the laser paint removal. The removal of paint from steel substrate with fiber laser of frequency adjustable 20 to 500kHz at 1064nm is reported, researching impact that laser energy density,scanning speed and line width on the paint removal effect. The results show that, the 100μm paint layer can be removed completely while keeping the substrate undamaged with the laser energy density of 10.19J/cm^2 and speed of 4200mm/s and width of 0.02mm. In order to get better results, the cleaning efficiency can be improved by increasing the power, speed and spot size under the right energy density.

1 Introduction

As a new surface cleaning technology, laser cleaning technology has opened up a new field of laser technology in industrial applications. Laser paint removal is a green cleaning method, which will reduce the pollution to the environment, and decrease the damage to the substrate. Because of advantages of laser cleaning technology, laser paint removal has drawn great attention from researchers and companies all over the world in the past few years [1]. Experiment show that the paint,which have thickness of 14μm and area of 1m^2, can be removed by the Q-switched Nd: YAG laser with the average power of 15W and frequency of 50Hz in about 10 minutes [2]. Researchers used an 2KW TEA CO_2 laser with a single-pulse energy of 9J and frequency of 330Hz for paint removal of aircraft, the results show that it needs 15 pulses to remove the aircraft paint layer with a thickness of 100μm [3]. Used a Q-switched Nd: YAG laser at 1064 nm to remove four different paint layers on the stainless steel surface,the energy density was increased from 0.1J/cm^2 to 7J/cm^2, laser ablation was used to evaluate the efficiency of the paint removal,the best parameters of paint removal were determined [4]. Used QCW Nd: YAG laser with frequency of 0.5-50kHz at 1064nm to remove 50μm paint layer, the results show that the paint cleaning threshold of 5.31*106W/cm^2, spot overlap of 80% can completely remove the paint without damaging the substrate [5]. Studied the paint removal mechanism with the low-frequency

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YAG pulsed laser,paint can be completely removed under the condition that scanning speed of 249mm/s and overlap 0.6mm, the efficiency can be up to 15.5mm^2/s.

In recent years, the development of laser technology has promoted the rapid improvement of laser performance. At present, fiber laser have the advantages of small volume, low cost, better beam quality and higher conversion efficiency [6-8]. The largest single pulse energy of the pulsed fiber laser in this experiment is 1mJ, the frequency is adjustable 20-500kHz, and the pulse duration is 100ns. In this paper, the physical process of paint removal was analyzed based on the pulse laser cleaning mechanism, including the heat conduction process of paint layer and substrate layer, the effects of laser energy density, scanning speed and line width on the paint removal are researched experimentally, the paint removal experiment are done for different parameters,it provides some guidance for determining the best laser paint removal process parameters.

2 Analysis and calculation of laser paint removal

2.1 Determination of laser heat source model

The laser beam is normally considered as a uniform heat source, *i.e.* temperature distribution of heat effect zone is slightly affected by light intensity distribution. However, the pulsed fiber laser is adopted as the laser source in practical application, and its laser beam, as the heat source, is not featured with absolutely uniform light intensity distribution but Gaussian distribution. The heat flow distribution function is as equation (1):

$$q_{(r)} = \frac{2AP}{\pi R^2} \exp\{-\frac{2r^2}{R^2}\} \tag{1}$$

where A refers to absorption coefficient of material to laser, P refers to laser power, R refers to spot diameter, r refers to distance from observation point to spot center.

The laser heat source model determined and thermal parameters of laser and material will be very useful to analyze temperature distribution of paint layer surface at different moments and in different locations, so as to determine the optimal laser cleaning parameters according to actual material features.

2.2 Analysis for heat conduction process

A geometrical model of bilayer ablative vibration is established to analyze heat conduction processes of surface and substrate during paint removal. The paint removal model is as shown in figure 1, and z=0 in the coordinate refers to the contact plane between paint layer and metal substrate; L_1 refers to thickness of paint layer, L_2 refers to thickness of substrate, and L_2 is drastically greater than L_1, $1/\alpha$ refers to absorption length (α refers to absorption coefficient of material).

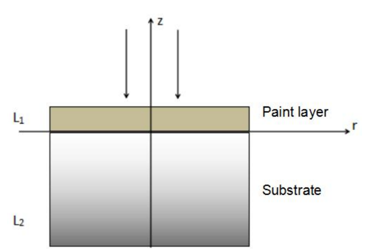

Fig. 1. Schematic diagram of painting-substrate.

Since power density of pulsed laser vary with time and space, the energy density is related to time and space accordingly. When the energy density of incident laser beam pulse is I_0, the formula of pulse featured with Gaussian distribution is equation (2)

$$I(r,t) = I_0 s(r) g(t) = I_0 \exp(-\frac{r^2}{{r_0}^2}) \frac{t}{\tau^2} \exp(-\frac{t}{\tau}) \tag{2}$$

where, I_0 refers to the initial light intensity of incident laser, s(r) and g(t) refer to time distribution and space distribution forms of Gaussian laser respectively, τ refers to the full width at half maximum of pulsed laser function. During paint removal, the incident laser is absorbed by the paint layer, and then part of laser is also absorbed after being transmitted to substrate. After absorption, heat effect will appear in the paint layer, which can be considered as the heat conduction process. The equation of heat conduction in paint layer can be expressed as equation (3)

$$\rho_p c_p \frac{\partial T(r,z,t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}[r k_p \frac{\partial T(r,z,t)}{\partial r}] + \frac{\partial}{\partial z}[k_p \frac{\partial T(r,z,t)}{\partial z}] \tag{3}$$

ρ_p and c_p refer to density and heat capacity of paint layer material; k_p refers to heat conduction coefficient; range of z is $0 \sim L_1$.

At the initial status, i.e. T=0, the temperature of paint layer is equal to ambient temperature, as shown in equation (4):

$$T_p(r,z,0) = T_0 \tag{4}$$

After passing through the paint layer, power density of laser pulse is equation (5)

$$I(r,0,t) = (1-R) I(r,z,t) A_p(T) I_0 s(r) g(t) \exp(-\alpha L_1) \tag{5}$$

where, R refers to the reflection ratio of material surface to laser and A_P refers to the absorption ratio of paint layer to laser.

As indicated by above analysis, power density of incident laser on substrate surface is not equal to the initial power density but to that of laser passing through the paint layer, and temperature distribution of substrate surface can be known accordingly, so as to prevent from damaging substrate surface due to excessive laser energy. In addition, temperature distribution is known, the paint layer is removed and substrate damage is avoided, and then an optimal cleaning threshold is acquired.

Through comparing heat conduction processes of paint layer and substrate, the heat conduction equation of substrate can be also acquired, as shown in equation (6):

$$\rho_s c_s \frac{\partial T(r,z,t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}[r k_s \frac{\partial T(r,z,t)}{\partial r}] + \frac{\partial}{\partial z}[k_s \frac{\partial T(r,z,t)}{\partial z}] \tag{6}$$

where ρ_s, c_s and k_s refers to density, heat capacity and heat conduction coefficient of substrate material; T refers to temperature distribution and absolute value range of z is $0 \sim L_2$.

2.3 Physical quantity affecting paint removal effect

Cleaning effect is affected by laser and scanning parameters in the paint removal test, and energy density of laser, scanning speed and width of scanning line are analyzed in tests of this paper.

The point light source, after being scanned by two-dimensional laser galvanometer, will be converted into the surface light source loaded on paint layer, and the cleaning efficiency and quality will be directly affected by scanning speed and width of scanning line. The scanning speed affects moving speed of single pulsed laser in the direction of X; the width of scanning line, defined as the distance between spot centers of two adjacent laser pulses, directly affects the scanning overlap rate between light spots in the direction of Y. They can be directly set through control system software. Specific conditions are simplified in figure 2.

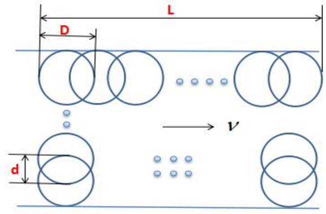

Fig. 2. Simplified Schematic of Pulsed Laser Scanning.

L refers to the scanning length; D refers to spot diameter; d refers to width of scanning line (also considered as the spot overlap length); v refers to the scanning speed. The spot overlap rate can be expressed as equation (7):

$$n = \frac{d}{D} * 100\% \quad (7)$$

3 Experiment structure

The experimental system includes a pulsed fiber laser, control system, a two-dimensional scanning mirror system, focusing system,cleaning system and worktable,etc. The laser beam irradiated by pulsed fiber laser, and then scanned into a surface by a two-dimensional scanning mirror system, finally through the focusing system to focus on the paint sample surface, the control system controls the working state and parameter setting of the whole laser and scanning system,the vaporized pain is sucked away by the cleaning system. The system structure is shown in figure 3.

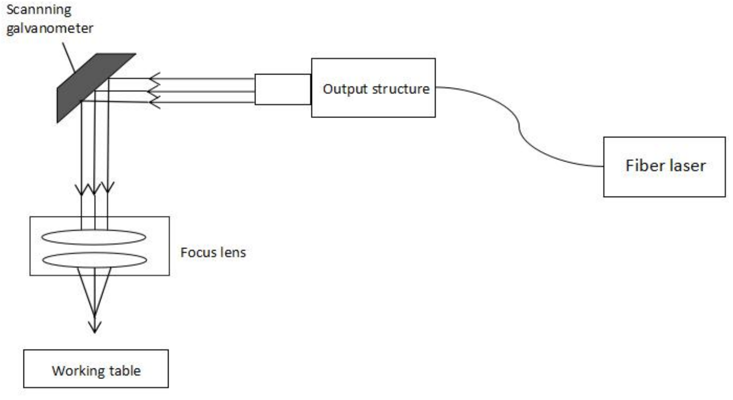

Fig. 3. Laser paint removal experimental structure diagram.

The maximum single pulse energy is 1mJ, the frequency is 20-500kHz adjustable,and pulse duration is 100ns in this experiment.The output spot size is 6 mm, it is compressed to about 0.05mm through the focusing lens with focal length of 160mm.

4 Experiment results and discussion

4.1 The effect of energy density on the paint removal

In this experiment, the substrate adopted for the cleaning sample is stainless steel, and the paint layer is gray alkyd paint with the thickness of about 100 µm. The spot size at working time is a constant value, which is 0.05mm approximately. The scanning area is set to be 15mm*15mm, scanning speed is 5000mm/s, and the frequency is 500kHz.

In order to effectively distinguish the coating removal effects, it is defined as the best cleaning effect when the metal substrate is clearly visible and the coating removal rate (n) measured and calculated by thickness tester is above 90% (table 1)(Coating removal rate (n) is defined as the ratio between the coating thickness difference before and after the cleaning and the coating thickness before cleaning, that is n=△/100*100%).

Table 1. Cleaning effects with different laser energy densities.

$F/(J/cm^2)$	n	Cleaning effects
2.04	26.75%	The surface becomes rough,leave a superficial trace
4.08	56.63%	The paint began to vaporize and surface carbonation black
8.15	89.13%	There are some residual paint layer
10.19	95.52%	Paint layer is vaporized fully and no damage to substrate

When the laser energy density is 2.04J/cm^2, as shown in figure 4, it can be seen in the scanning area that there is almost no change in the surface of the coating layer. That is because the laser energy density is so low that the temperature produced by energy density of pulse laser injected to coating surface can't reaches the vaporization temperature of coating layer. With the increase of laser energy density to 10.19J/cm^2, there is a highly significant vaporization phenomenon during the process of scanning. And the coating layer is completely sprayed out from the substrate layer and the shiny metal substrate can be seen. The removal rate of the coating layer reaches 95.52%. Therefore, it is considered that the coating removal effect is the best when the laser energy is 10.19J/cm^2.

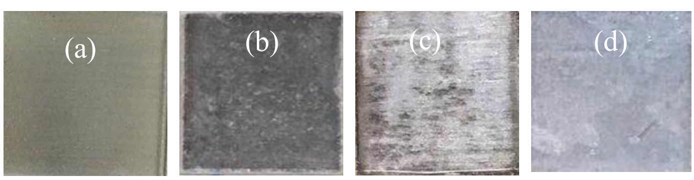

Fig. 4. Cleaning results with different laser energy densities at(a) 2.04J/cm^2, (b) 4.08.15J/cm^2, (c) 8.15J/cm^2,(d) 10.1J/cm^2.

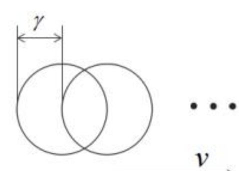

Fig. 5. Overlap diagram of adjacent laser spots.

4.2 The effect of scanning speed on the paint removal

Different from the continuous laser, the laser emits pulsed laser beam. The pulsed fiber laser used in this experiment has a high frequency, and the energy distribution is Gaussian,therefore, it is necessary to ensure that there is an appropriate overlap between each adjacent spots in the X-direction. Controlling the scanning speed can change the overlap,too low speed can damage substrate because of the energy accumulation.The pulsed fiber laser used in this paper has high energy density, so we need to set faster scanning speed to prevent damage substrate and achieve the requirement of paint removal.

As shown in figure 5, the scanning length of adjacent two single pulse spots in the x-direction is expressed in γ, and the scanning speed v in this direction can be expressed as equation (8), the f is the frequency of pulse laser.

$$v = \gamma \bullet f \tag{8}$$

According to the experimental results above, we set the frequency is 200kHz, and the power is 40W. The cleaned samples work at the focus, Therefore, the spot size in the scanning area is 0.05mm, and the laser energy density is 10.19J/cm^2. The scanning speed can be set directly in the control software, as the scanning length γ increases with the scanning speed. As shown in table 2, it can be seen that the paint removal effect can change greatly with different speed.

Table 2. Cleaning effects with different scanning speed.

$v/(mm/s)$	γ/mm	Cleaning effects
2100	0.0105	Metal substrate was completely damaged with sparks
3300	0.0165	Damage of metal substrate is decreased
4200	0.021	Paint layer is removed fully
5600	0.028	The surface has residual paint
6900	0.0345	Some paint can be removed and reticulate crack

When the scanning speed is 2100mm/s,the overlap of adjacent two spots is large, so there are a lot of metal sparks splashing out, and the substrate is seriously damaged. With the increase of scanning speed, the damage will be gradually reduced,when the scanning speed is 4200mm/s, the paint layer is completely vaporized and be able to see bright metal substrate. It is considered that the scanning speed is the best under the setting condition. Continue to increase the scanning speed, the spot overlap becomes smaller, the paint can not be removed and form reticulate crack. As shown in figure 6. On the basis of the experimental data and phenomena, it is found that when the scanning speed is 4200mm/s, the effect of paint removal is the best, and the spot overlap in the X-direction is about 58%.

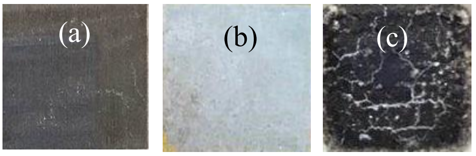

Fig. 6. Cleaning effects with different scanning speed at (a) 2100mm/s, (b) 4200mm/s, and (c) 6900mm/s.

4.3 The effect of line width on the paint removal

The line width is also an important parameter to control the spot overlap in Y-direction. The distance between the two rows of lines is determined by line width, different line width affects the paint removal. The sample is in focus, so the spot size is 0.05mm. The results of experiment are shown in figure 7.

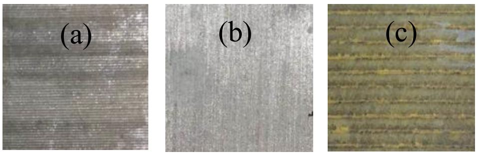

Fig. 7. Cleaning effects with different line width at (a) 0.01mm, (b) 0.02mm, and (c) 0.03mm.

The frequency for 200kHz and the scanning speed of 4200mm/s in this experiment. It can be seen from the results that when the line width is 0.01mm, the paint layer is removed, but the substrate is seriously damaged because of too narrow line width. When the line width is 0.02mm, the paint is completely removed, the substrate is glossy and there is no damage. When the line width is 0.03mm, most paint layer in the scanning area can be vaporized, but the surface has residual paint stripes, this is because there is too little overlap between the scanning lines. In conclusion, it can be considered that the 100μm paint layer can be effectively cleaned with the line width of 0.02mm, the spot overlap is about 60% in Y-direction.

5 Conclusion

This paper briefly analyzes the heat conduction process between paintcoat and basal layer through laser cleaning mechanism, and through the experiment of laser cleaning to the 100μm thick paintcoat sample using high-frequency impulse fiber laser, the papers researches the main influences of laser energy density, scanning speed and the line width on the paint removal effectiveness. The experimental results show that, at three different repetition frequencies, the optimal cleaning effect can be obtained when the laser energy density is 10.19 J/cm^2, and the value is considered as the complete cleaning threshold. Under the conditions of 40W of output power and 200kHz of frequency, the cleaning effect is the best when the scanning speed is 4200mm/s, and the scanning speed can be accelerated by increasing the laser's output power or repetition frequency, thereby to improve the cleaning effect and efficiency. At the optimum cleaning threshold, the paintcoat can be completely cleaned without any damage to substrate when the scanning line width is 0.02mm. From the scanning area we can see from this experiment that, no matter the scanning speed or the overlapping ratio determined by the line width, the cleaning effect is the best when the overlapping ratio of the facula in both the X and Y direction are about 60%.

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