Application of thermal stress model to paint removal by Q-switched Nd:YAG laser*

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In this paper, we demonstrate that thermal stress is the main mechanism in the process of paint removal by Q-switched Nd:YAG laser ($\lambda = 1064$ nm, $\tau = 10$ ns). A theoretical model of paint removal by short-pulse laser is established from the perspective of thermal stress. Thermal stress is generated by thermal expansion, and the temperatures of different samples are calculated according to the one-dimensional (1D) heat conduction equation. The theoretical cleaning threshold can be obtained by comparing thermal stress with the adhesion of paint, and the theoretical damage threshold is obtained by calculating the temperature. Moreover, the theoretical calculations are verified by experimental results. It is shown that the thermal stress model of the laser cleaning is very useful to choose the appropriate laser fluence in the practical applications of paint removal by Q-switched Nd: YAG laser because our model can validly balance the efficiency of laser cleaning and the safety of the substrate.

Keywords: laser cleaning, thermal stress, cleaning threshold, damage threshold

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1. Introduction

Laser cleaning can be used in many fields, such as culture, microelectronics, oxide layers, and organic contamination, *et al*.[1] Paint removal by laser has attracted increasing attention among scientists and engineers. It is a dry process in air. It is effective to evacuate and collect by sucking and filtering, which offers an environmentally compliant way of deposing waste materials. It is feasible by optical power delivery with mirrors or optical fibers. There are no secondary contaminated materials, which is usually a very serious problem appearing in the chemical removal and particle blasting method.

The mechanism of laser cleaning is dependent on object and condition. The theory of particle removal has been mainly reported.[2–5] However, most of the studies about paint removal by laser have only focused on the factors influencing the cleaning effect in experiment.[6–14] At present, there are few reports about the quantitative analyses of the theoretical mechanism of cleaning paint with a Q-switched laser. In this paper, we construct a theoretical model of the laser removal of paint from the perspective of thermal stress.

The physical mechanism of paint removal by short-pulse laser is different from that with a long-pulse laser. The ablation effect is the main cleaning mechanism in a long-pulse laser.[6] According to our theoretical calculations and experiments, we find that paint removal by nanosecond pulse laser is attributed to the thermal stress. The quantitative analysis of thermal stress is discussed. The thermal stress is obtained from the one-dimensional heat conduction equation. The cleaning condition is obtained by comparing thermal stress with adhesion. The laser irradiation experiments are performed with a Q-switched Nd:YAG laser to verify the theoretical model. This study sheds light on how to choose the suitable laser fluence to remove paint by nanosecond pulse laser.

2. Experiment

The experimental setup for measuring paint removal consists of a Q-switch laser, a convex lens, beam splitter, optical microscope and the sample of paint, as shown in Fig. 1. The Q-switched laser is used as a laser source and produces a laser beam which has a wavelength of 1064 nm, a pulse width of 10 ns, a repetition rate of 1Hz, and maximum pulse energy of 600 mJ. A suitable energy can be achieved by regulating the voltage of a laser power supply. The focal length of the convex lens is 30 cm. Firstly, the laser beam is focused by a convex lens. After the laser beam passes through the beam splitter, one part enters into an energy meter and the other vertically irradiates the sample of paint. The surface of the paint and substrate before and after laser cleaning can be observed by the optical microscope. No additional gas is employed in the process of paint removal during experimental tests as it would have produced further uncertainty in the understanding of the leading paint stripping mechanisms.

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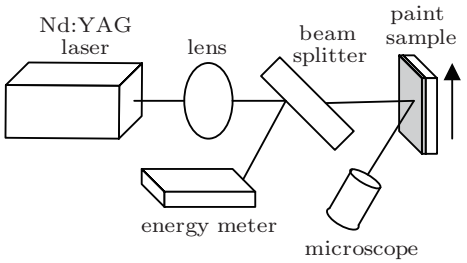


Fig. 1. Simplified experimental setup for paint removal, energy measurement, and sample surface detection.

Paint in our experiments is mainly composed of an epoxy polyester hybrid and its color is orange, which is widely used in the market. Paint is sprayed on the Fe and Al substrates evenly. The specific parameters of three samples are shown in Table 1. The values of reflectivity and transmissibility of paint and substrate are obtained by the device of double integrating sphere at a wavelength of 1064 nm. From the data in Table 1, sample II and sample III have almost the same paint on the different substrates. The adhesion f between paint and substrate is very complex. It is difficult to interpret the formation of adhesion from a single theory. Therefore, we measure the sample adhesion by the method of pull-off tests and combining scratch tests. The average values of adhesion are given in Table 1.

The energy E is obtained by an energy meter and the diameter of the laser spot D is obtained by micrometer. The laser fluence can be calculated from the formula $e = E/[\pi(D/2)^2]$. The laser fluence varies from 0 to 2.5 J/cm^2. Hence, the cleaning efficiencies at different laser fluences can be compared and the cleaning threshold at which the paint began to be removed can be obtained. The damage threshold can be acquired by observing the optical micrograph of the substrate.

3. Results and discussion

3.1. Effects of laser fluence

The thermal,[15,16] optical and mechanistic parameters[16,17] of three samples are given in Table 1. The thermal parameters of paint and substrate are obtained at the temperatures of 340 K and 293 K, respectively.

Table 1. Thermal, optical, and mechanistic parameters of samples I, II, and III.

	Sample I		Sample II		Sample III	
	Fe substrate	Paint	Fe substrate	Paint	Al substrate	Paint
Thickness $l/10^{-3}$ m	1	4.0×10^{-2}	1	6.3×10^{-2}	1	6.3×10^{-2}
Thermal conductivity λ/w·m^{-1}·k^{-1}	78.48	0.3	78.48	0.3	205.8	0.3
Density $\rho/10^3$kg·m^{-3}	7.87	1.30	7.87	1.30	2.696	1.30
Specific heat $c/10^3$J·kg^{-1}·k^{-1}	0.452	2.51	0.452	2.51	0.879	2.51
Thermal diffusivity $a_t/10^{-8}$ m^2·s^{-1}	2206	9.19	2206	9.19	8684	9.19
Linear thermal expansion coefficient $\gamma/10^{-6}$·k^{-1}	12.3	1.00	12.3	1.00	23.8	1.00
Absorptivity α	0.360	0.500	0.363	0.611	0.642	0.614
Reflectivity r	0.640	0.410	0.637	0.202	0.358	0.193
Transmissibility t	0	0.090	0	0.187	0	0.193
Absorption coefficient $A/10^4$m^{-1}	5240	4.29	5240	1.88	10000	2.27
Elastic modulus $Y/10^{10}$N·m^{-2}	19	1.0	19	1.0	7	1.0
The approximate value of adhesion $f/10^7$N·m^{-2}		4.0–4.5		4.2–5.0		4.8–6.1

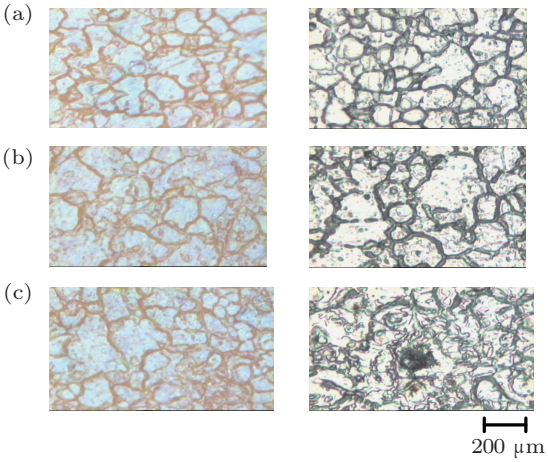


Fig. 2. (color online) Left micrographs of panels (a)–(c) are the optical micrographs of paint of sample I. Right micrographs of panels (a)–(c) are the optical micrograph of substrate of sample I for the cases: (a) before laser irradiation, (b) laser irradiation at a laser fluence of 1.0 J/cm^2, and (c) laser irradiation at a laser fluence of 2.2 J/cm^2.

Figure 2 shows the optical micrograph of sample I. From the optical micrographs it can be found that the surface of the paint has no damage after laser cleaning, nor does the surface of Fe substrate, at a laser fluence of 1.0 J/cm^2 (Fig. 2(b)). However, it is damaged when the laser fluence is 2.2 J/cm^2 (Fig. 2(c)).

The above-mentioned laser cleaning setup is used to measure the energy and the laser spot size, when the paint can be just removed and the substrate is broken. Hence, the cleaning and damage thresholds of different samples can be obtained (Table 2).

Table 2. Cleaning thresholds and damage thresholds of samples I, II, and III.

	Experimental cleaning thresholds/J·cm^{-2}	Experimental damage thresholds/J·cm^{-2}
Sample I	0.54	2.2
Sample II	0.27	2.0
Sample III	0.18	1.0

3.2. Thermal stress model

When the laser irradiates onto the paint, it will be reflected, absorbed, and transmitted. Figure 3 shows that the paint and substrate are irradiated by laser beam and the Cartesian coordinate systems are set up on the paint (x,y,z) and on the substrate (x',y',z').

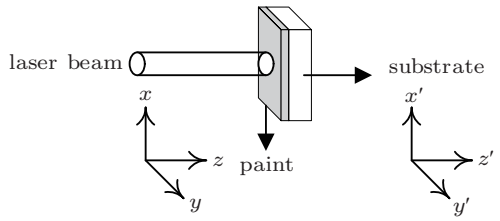


Fig. 3. Simplified schematic diagram of paint removal by laser.

The temperature of paint rises after absorbing the laser energy. Then, the laser transmitting the paint irradiates on the substrate and makes its temperature rise. The change of temperature obeys the heat conduction equation.

The following equation of heat conduction is established on the assumption that: (i) the laser intensity is top-hat shape on the x–y plane, (ii) the laser intensity of z direction follows the absorption law, (iii) x–y plane is taken for infinite plane approximately, and (iv) two sides of paint and substrate are insulated,

$$\rho c\frac{\partial T(z,t)}{\partial t}=\lambda\frac{\partial^2 T(z,t)}{\partial z^2}+\alpha I_0 A\,\mathrm{e}^{-Az},\quad 0\le t<\tau,\ \ 0\le z\le l, \tag{1}$$

where the temperature $T(z,t)$ is a function of depth z and time t. The physical meanings of parameters $(\rho,c,\lambda,\alpha,A)$ in Eq. (1) are indicated in Table 1.

The pulsed laser is set to have a constant energy per pulse and I_0 is the initial laser intensity, which is obtained by dividing the energy with laser beam area S and pulse width τ, i.e., $I_0=E/(S\cdot\tau)$. The boundary and initial conditions of Eq. (1) are given by

$$\begin{cases}\lambda\dfrac{\partial T}{\partial z}\Big|_{z=0}=0,\\ \lambda\dfrac{\partial T}{\partial z}\Big|_{z=l}=0,\end{cases} \tag{2}$$

$$T(z,0)=300\ (\mathrm{K}). \tag{3}$$

The equation, and its boundary and initial conditions hold true for the paint and substrate. Solving Eqs. (1)–(3), we can obtain

$$\begin{aligned}T(z,t)\ =\ &\sum_{n=1}^{\infty}\frac{C_n I_0}{a_t}\left(\frac{l}{n\pi}\right)^2\cos\left(\frac{n\pi}{l}z\right)\left[1-\mathrm{e}^{-a_t(\frac{n\pi}{l})^2 t}\right]\\ &+C_0 I_0 t+300\ (\mathrm{K}),\quad n=1,2,3,\ldots,\\ &0\le t<\tau,\quad 0\le z\le l.\end{aligned} \tag{4}$$

Let ΔT be the increment of temperature, then we will have

$$\begin{aligned}\Delta T(z,t)\ =\ &T(z,t)-T(z,0)\\ =\ &\sum_{n=1}^{\infty}\frac{C_n I_0}{a_t}\left(\frac{l}{n\pi}\right)^2\cos\left(\frac{n\pi}{l}z\right)\left[1-\mathrm{e}^{-a_t(\frac{n\pi}{l})^2 t}\right]\\ &+C_0 I_0 t\ (\mathrm{K}),\quad n=1,2,3,\ldots,\\ &0\le t<\tau,\quad 0\le z\le l,\end{aligned} \tag{5}$$

with

$$C_n=\frac{2\alpha}{\rho c l}\frac{(1-\cos n\pi\,\mathrm{e}^{-Al})}{1+(n\pi/lA)^2},\quad n=1,2,3,\ldots, \tag{6}$$

$$C_0=\frac{\alpha}{\rho c l}\left(1-\mathrm{e}^{-Al}\right). \tag{7}$$

When the object absorbs the laser energy, its temperature will rise and the object will begin to expand. The thermal expansion produces thermal stress in the object. The thermal expansion length of z direction is given by

$$\Delta l=l\gamma\Delta T, \tag{8}$$

where γ is the linear thermal expansion coefficient. Parameters ρ, c, λ, a_t, γ generally vary with temperature. However, in the paper they are assumed to be constants because from the later analysis the temperatures of paint and the substrate change little, when the laser energy density value is near the cleaning threshold (see Section 3.3.2). Hence, the assumption is reasonable.

The object is taken as an homogeneous elastic mass, so the thermal stress of paint per unit area at $z=l$ is given by

$$\sigma_{\mathrm{p}}=Y_{\mathrm{p}}\varepsilon_{\mathrm{p}}=Y_{\mathrm{p}}\frac{\Delta l_{\mathrm{p}}}{l_{\mathrm{p}}}=Y_{\mathrm{p}}\gamma_{\mathrm{p}}\Delta T_{\mathrm{p}}(l,t), \tag{9}$$

and the thermal stress of substrate at $z'=0$ is as follows:

$$\sigma_{\mathrm{s}}=Y_{\mathrm{s}}\varepsilon_{\mathrm{s}}=Y_{\mathrm{s}}\frac{\Delta l_{\mathrm{s}}}{l_{\mathrm{s}}}=\mathrm{Y}_{\mathrm{s}}\gamma_{\mathrm{s}}\Delta T_{\mathrm{s}}(0,t), \tag{10}$$

where Y is the elastic modulus. The force making the paint separate is mainly the thermal stress at the interface between the paint and substrate.

Because the two sides of paint and substrate are considered as insulators, only the transmitted laser can heat the substrate, so when equation (1) is used to calculate the thermal stress of substrate, I_0 needs to be replaced by $I_0'(I_0'=t_{\mathrm{p}}I_0$, where t_{p} is the transmissibility of paint), and there is the relation of $t_{\mathrm{p}}+r_{\mathrm{p}}+\alpha_{\mathrm{p}}=1$, where r_{p} and α_{p} are the reflectivity and absorptivity of paint, respectively.

The condition of laser removal of paint is $\sigma\ge f$. The thermal stress model is used to simulate the laser removal of paint on the metal substrate and to analyze the theoretical results.

3.3. Discussion

3.3.1. Cleaning threshold

From Eq. (5), we know that ΔT and thermal stress reach their maximal values at the end of the laser pulse. The maximum thermal stress varies with the laser fluence. When the maximum thermal stress is equal to the adhesion, the corresponding laser fluence is the cleaning threshold of laser removal of paint.

Figures 4 and 5 show that the maximum thermal stress increases linearly as laser fluence increases, and comparing Fig. 4 with Fig. 5, we find that the thermal stress of substrate σ_s is far larger than that of paint σ_p. Thus, the thermal stress of paint is considered to be negligible in the process. When the laser fluence is greater than the adhesion, the paint can be removed by laser.

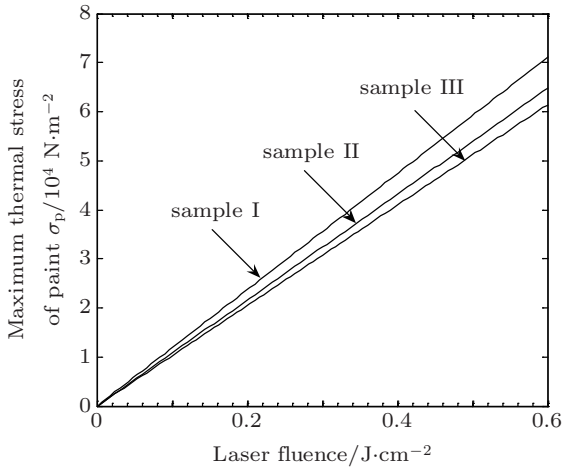


Fig. 4. Computed maximum thermal stresses of paint at a wavelength of 1064 nm and at the end of pulse ($\tau = 10$ ns) versus laser fluence.

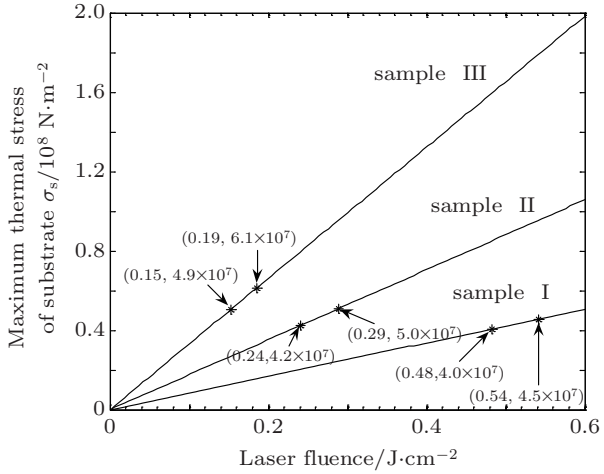


Fig. 5. Computed maximum thermal stresses of substrate at a wavelength of 1064 nm and at the end of pulse ($\tau = 10$ ns) versus laser fluence. The asterisks refer to the cleaning thresholds.

According to our theoretical computation (see Fig. 5), we note that the ranges of theoretical cleaning thresholds of sample I, sample II, and sample III are (0.48–0.54) J/cm^2, (0.24–0.29) J/cm^2, and (0.15–0.19) J/cm^2, respectively, which are in accordance with the experimental results 0.54 J/cm^2, 0.27 J/cm^2, and 0.18 J/cm^2 as shown in Table 2. We also find that the cleaning threshold depends on the type of substrate. The cleaning threshold of the Fe substrate is greater than that of the Al substrate.

3.3.2. Damage threshold

3.3.2.1. Irradiation time required for paint removal

In the preceding section, the thermal stress at the end of laser pulse has been analyzed. In this subsection, we continue to discuss the thermal stress in the period of laser pulse time of the substrate of sample I. Figure 6 illustrates the thermal stress of Fe substrate varying with laser pulse time. The two lines represent laser fluences of 1.0 J/cm^2 and 2.0 J/cm^2, respectively.

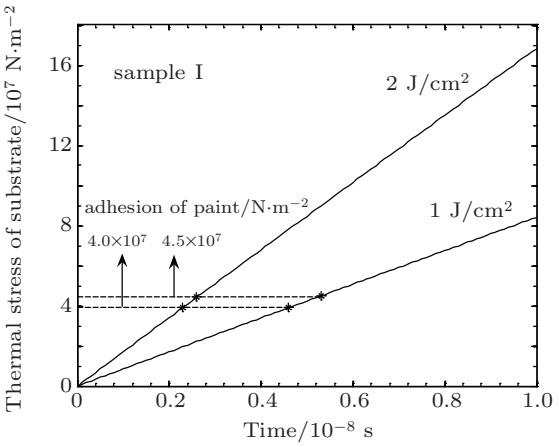


Fig. 6. The two solid lines stand for the thermal stress of substrate changing with the duration of laser ($\tau = 10$ ns) for sample I at the laser fluences of 1 J/cm^2 and 2 J/cm^2. The two dotted lines stand for thermal stress equal to adhesion of paint 4.0×10^7 N·m^{-2} and 4.5×10^7 N·m^{-2}, respectively.

Figure 6 indicates that the thermal stress increases linearly with the increase of the laser pulse time and at the end of laser pulse it reaches a maximum. At the same time, the higher the laser fluence, the larger the thermal stress will be. Therefore, when the laser pulse width is fixed, the laser fluence needs to be raised to remove the paint for the case of larger adhesion of paint. Figure 6 also shows that the irradiation time depends on laser fluence when the thermal stress is equal to the adhesion. When the adhesion of paint is 4.0×10^7 N·m^{-2}, the irradiation times are 4.6 ns and 2.3 ns at the laser fluences of 1.0 J/cm^2 and 2.0 J/cm^2, respectively. The higher the laser fluence, the shorter the irradiation time is. When the adhesion of paint is 4.5×10^7 N·m^{-2}, the irradiation times are 5.3 ns and 2.7 ns at the laser fluences of 1.0 J/cm^2 and 2.0 J/cm^2, respectively. At the same laser fluence, paint with greater adhesion will require a longer irradiation time for paint removal. When the laser fluence is higher than the cleaning threshold, the paint will be lifted off from the substrate before the laser

pulse ends ($\tau = 10$ ns) and in the remaining time of laser pulse the substrate will be directly irradiated by the laser.

3.3.2.2. Temperatures of paint and substrate

The temperature of the paint will rise with the increase of irradiation time of pulsed laser until the paint has been detached from the substrate, as shown in Fig. 7. The initial temperature of the paint is 300 K. From Fig. 7, the solid lines show the temperature of paint rises with the increase of laser irradiation time before the paint is removed. The dotted lines in Fig. 7 indicate that the paint has dropped. Although the laser pulse still irradiates, the paint has already been separated from the substrate. The temperature of the paint does not rise any more after the it has been separated from the substrate. Hence, the maximum temperature of the paint is the temperature at the moment of its removal. Figure 7 only shows the varying trend of the curve of sample I, but this trend holds true for samples II and III. The higher the laser fluence, the faster the paint is detached. The temperature of the paint at position $z = 0$ changes with laser fluence, as shown in Fig. 8. The paint is just removed at the moment of inflection point. The values of horizontal ordinate, which the inflection points in Fig. 8 correspond to, are the cleaning thresholds. Figure 8 shows that the temperature of paint is far lower than the melting point of paint 500 K. Therefore, the phase transition of paint will not happen, which is consistent with the previous experimental results (see Fig. 2).

The temperature variation of substrate is different from that of the paint layer, which is due to the fact that the laser still irradiates the substrate after the paint layer has been away from the substrate.

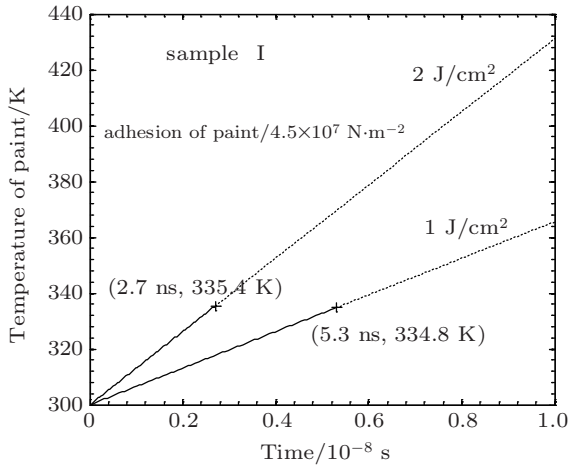


Fig. 7. Temperatures of paint changing with the duration of laser ($\tau = 10$ ns) for sample I at the laser fluences of 1 J/cm^2 and 2 J/cm^2, respectively (solid lines). The plus signs (+) refers to the time paint removal. The two dotted lines represent the simulation results in the case that the paint has been removed from substrate, in fact the temperature will not continue to increase any more.

The preceding results showed that when the paint is lifted off the substrate, the substrate will be directly irradiated by the laser. The temperature of the substrate at position $z' = 0$ changes with the laser fluence, which is indicated in Fig. 9. The paint is just removed at the moment of inflection points. The values of horizontal ordinate, which correspond to the inflection points in Fig. 9, are the cleaning thresholds. After the moment, the temperature of substrate rises quickly. At the end of the laser pulse the temperature of substrate reaches a maximum. Before the Fe substrate reaches the melting point 1808 K, the Fe substrate has been rapidly oxidized at 900 K temperature. Then, the substrate is broken. So, from Fig. 9 the damage thresholds of samples I and II are 2.0 J/cm^2 and 1.7 J/cm^2, respectively, which are approximate to the experimental results 2.2 J/cm^2 and 2.0 J/cm^2, respectively (see Table 2). The melting point of Al is 879 K. The Al substrate is just broken at a laser fluence of 0.75 J/cm^2, which is approximate to the experimental result 1.0 J/cm^2 (see Table 2). From the comparison between the theoretical and the experimental damage thresholds, we can find that there are some deviations

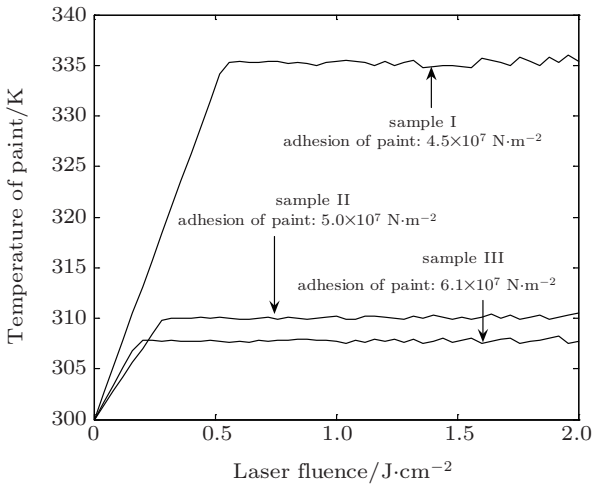


Fig. 8. Computed temperatures of paint of samples I, II, and III irradiated at a wavelength of 1064 nm and pulse time of 10 ns versus laser fluence.

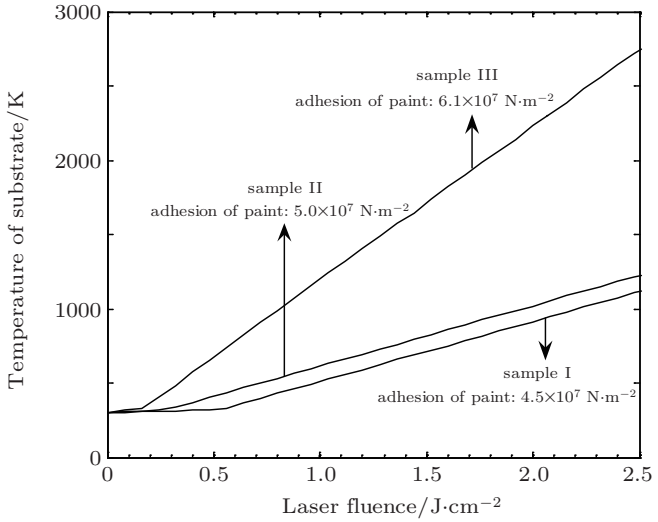


Fig. 9. Computed temperatures of substrate of samples I, II, and III irradiated at a wavelength of 1064 nm and pulse time of 10 ns versus laser fluence.

between them, which is because the parameters (ρ, c, λ, a_t, γ) of substrate will change when the laser fluence rises up to the damage threshold. According to the above analysis, we can conclude that the laser fluence should not be increased blindly and the heat effect must be considered. An appropriate laser fluence must be chosen in order to balance the efficiency of paint removal and the safety of the substrate.

4. Conclusions

In this paper, paint removal from Fe and Al substrate by Q-switched Nd:YAG laser is studied. The research results indicate that the same paint is easier to be removed from Al substrate than from Fe substrate. According to our theoretical model, the calculated theoretical cleaning and damage thresholds are in accordance with the experimental results. Hence, thermal stress can be used to explain the paint removal by short pulse laser. If the laser fluence is higher than cleaning threshold, the paint will be detached from the substrate before the pulse ends. After which, the temperature of the paint will not rise any further. Therefore, no matter how high the laser fluence is, the temperature of the paint changes little, which is different from that of the substrate because it will be directly irradiated by the laser after the paint has dropped off. The increase of the substrate temperature will lead to the changes of parameters and so the theoretical damage threshold is slightly different from the experimental result. On the whole, it is significant to set up this model for choosing an appropriate laser fluence in the practical application of paint removal by Q-switched Nd:YAG laser.

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