Removing paint from a metal substrate using a flattened top laser*

Shi Shu-Dong(施曙东)[a)d)], Li Wei(李 伟)[a)], Du Peng(杜 鹏)[a)], Wang Meng(王 萌)[a)], Song Feng(宋 峰)[a)†], Liu Shu-Jing(刘淑静)[b)], Chen Nian-Jiang(陈念江)[c)], Zhao Hong(赵 鸿)[c)], and Yang Wen-Shi(杨文是)[c)]

[a)] *School of Physics, Nankai University, Tianjin* 300071, *China*

[b)] *Department of Physics, College of Basic Medical Sciences, Tianjin Medical University, Tianjin* 300070, *China*

[c)] *Science and Technology on Solid-State Laser Laboratory, Beijing* 100015, *China*

[d)] *Electricity Department, Patent Office, Beijing* 100088, *China*

(Received 22 March 2012; revised manuscript received 8 April 2012)

In this paper, we investigate laser cleaning using a flattened top laser to remove paint coating from a metal substrate. Under the irradiation of a flattened top laser, the coating paint of the metal substrate can be removed efficiently by laser induced ablation, stress, and displacement force. The temperature distribution, stress, and displacement are calculated in the coating layer and substrate using finite element analysis. The effects of a Gaussian laser and a flattened top laser and the results of different diameters of laser spot are compared. The investigation shows that the flattened top laser can reduce the substrate damage and enhance the cleaning efficiency. This method meets the need of large area industrial cleaning applications by optimizing the flattened top laser parameters.

Keywords: laser cleaning, laser ablation, finite element method, flattened top laser beam

PACS: 42.62.–b, 52.38.Mf, 79.20.Eb **DOI:** 10.1088/1674-1056/21/10/104209

1. Introduction

Laser cleaning is an environmentally friendly cleaning technique and has attracted much attention in the industry. Due to its superior characteristics,[1] laser cleaning has proved to be very successful in the cleaning of polymers,[2] rubber tire molds,[3,4] large mirrors,[5] magnetic head sliders,[6] artworks and historical heritage pieces,[7] and semiconductor chips with surface particles.[8−11] However, the early application of laser cleaning techniques had a relatively low cleaning efficiency. Although there has been successful applications of laser cleaning to remove paint from a metal surface, the technique has its disadvantages. For example the cleaning speed is relatively slow due to the small cleaned area, owing to small laser spot size. In addition, overexposure of the Gaussian laser pulses may result in substrate damage due to its high energy density beam.

Therefore, a more effective laser cleaning technique requires not only a high cleaning efficiency but also no damage to the substrate. Chen *et al.*[12] found that the cleaning efficiency of removing a paint coating from a substrate was dependent on the laser power and overlap ratio. Daurelio *et al.*[13] demonstrated that the paint removing efficiency was related to the laser power and the paint type. However, utilization of a conventional Gaussian beam laser for cleaning has its own disadvantages because the substrate can easily be damaged especially in the centre of the beam spot while the paint at edge of the area cannot be removed, which reduces the efficiency. If a higher energy laser is used, more serious damage to the substrate is induced by a laser beam. Therefore it is necessary to investigate the laser cleaning techniques not only for improving the cleaning efficiency but also to minimize the damage to critical surfaces in the cleaning process. Schweizer and Werner[14] mentioned that a flatten top beam profile is better than a Gaussian beam during paint stripping of aircraft using a TEA CO_2 laser. However they did not do experimental and theoretical studies on the influence of the beam profile in the work. Francois *et al.*[15] investigated experi-

*Project supported by the Industrial Technology Development Program, China (Grant No. A1120110023) and the National Key Laboratory of Solid-State-Laser Technology, China (Grant No. 9140C040201100C04).

†Corresponding author. E-mail: fsong@nankai.edu.cn

© 2012 Chinese Physical Society and IOP Publishing Ltd

mentally the influence of laser fluence, repetition rate and pulse duration effects in the laser cleaning paint process.

In this paper, we investigate the effect of flattened top laser cleaning and compare the efficiencies when using a flattened top laser and a Gaussian profile laser. In order to meet the requirements of industrial large surface cleaning applications, we numerically optimize the laser cleaning control method to enhance the coating cleaning rate and reduce the substrate damage in the two-layer coating-substrate system. In the experiment an efficient laser cleaning strategy is presented by studying the iron surface modifications induced by the irradiation of a laser in air.

2. Numerical simulations

2.1. Thermal conduction theory

The geometry coordination of laser irradiation on a coating-substrate system is schematically shown in Fig. 1. The system includes two layers, a paint coating and a substrate, which can be analysed by the thermal stress in the layer. The coating is paint deposited on an iron substrate. The spatial mode of the laser beam is assumed to be a nearly flattened top distribution. The temperature distribution in the x and y direction is symmetrical, so we discuss only the x direction in the next analysis for simplicity. The thermal conductive equation is described as[16]

$$\rho c\frac{\partial T}{\partial t}=\frac{1}{x}\frac{\partial}{\partial x}\left[xk\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial z}\left[k\frac{\partial T}{\partial z}\right], \tag{1}$$

where ρ, c, and k are the density, thermal capacity, and thermal conductive coefficient respectively; T represents the temperature distribution at time t. In the coating layer and substrate the thermal equations are the same.

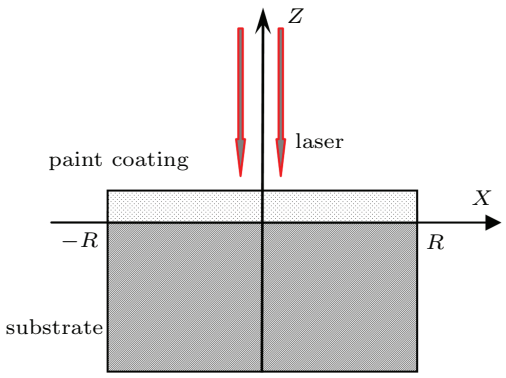


Fig. 1. (colour online) Schematic diagram of the coating-substrate and coordinate system.

The boundary conditions are set as follows. The laser irradiation can be a surface heat source, so the boundary conditions at the surface of the coating layer and substrate can be written as follows:

$$-k_{\text{coat}}\frac{\partial}{\partial z}T_{\text{coat}}\left(x,l_{\text{c}},t\right)=\frac{I_{\text{c}}A_{\text{c}}}{\pi\cdot w_0^2}, \tag{2}$$

$$-k_{\text{sub}}\frac{\partial}{\partial z}T_{\text{sub}}\left(x,0,t\right)=\frac{I_{\text{s}}A_{\text{s}}}{\pi\cdot w_0^2}, \tag{3}$$

where I_{c} and I_{s} are the incident laser power densities of the coating layer and substrate, A_{c} and A_{s} are the optical absorption coefficient of the paint and substrate respectively, w_0 is the waist radius of the laser, and l_{c} is the thickness of the coating layer. The flattened top laser power density can be written as[17]

$$I=E(x,z)E^{*}(x,z). \tag{4}$$

The temperatures of the coating and substrate interface are the same and can be assumed to be in ideal thermal contact, i.e.,

$$T_{\text{sub}}\left(x,0,t\right)=T_{\text{coat}}\left(x,0,t\right). \tag{5}$$

The two side walls of the two-layer system have the same boundary conditions according to the thermal insulation conditions, i.e.,

$$k\frac{\partial T}{\partial n}\bigg|_{x=\pm R}=0. \tag{6}$$

The back surface of the substrate opposite to the laser irradiation direction can be assumed to be of thermal insulation, so the boundary condition of back face can be written as

$$T_{\text{sub}}\left(x,l_{\text{s}},t\right)=T_0, \tag{7}$$

where l_{s} is the thickness of the substrate, T_0 is the ambient temperature of 293 K. When $t=0$, the initial condition is

$$T(x,z,0)=0. \tag{8}$$

2.2. Finite element method

In order to study the temperature and strain distribution in the coating-substrate system, caused by the flattened top laser irradiation, the Comsol Multiphysics software is adopted due to its comprehensive solution ability between multiple fields of physics. In this simulation, the coating and the substrate each are considered as a stress-free layer. The two-layer system is then irradiated by the pulsed laser, which induces thermal stresses in the coating/substrate assembly.

The system is symmetric, which makes it possible to use the two-dimensional (2D) plane strain application model. This model contains only one thermal load which is induced by the laser irradiation, and it is introduced into the constitutive equation according to the following equations:[18]

$$\sigma = D\varepsilon_{e1} + \sigma_0 = D(\varepsilon - \varepsilon_{\rm th} - \varepsilon_0) + \sigma_0, \quad (9)$$

$$\varepsilon_{\rm th} = \alpha_{\rm vec}(T - T_0), \quad (10)$$

where σ is the stress vector, D is the elasticity matrix, $\alpha_{\rm vec}$ are the thermal expansion coefficients, T is the actual temperature, and T_0 is the ambient temperature of 293 K.

The finite element method (FEM) is used to analyse the temperature distribution, deformation, and stress in the laser cleaning process. The heat-affected zone is smaller than the domain of the material and the thickness of the coating is in the order of μm. Figure 2 shows the mesh model for a two-layer absorption system using the FEM method. The study of meshing size reveals that a further decrease in the element does not change the result significantly. Therefore, very fine meshes are required to resolve the temperature distribution in the coating layer and irradiated region. Varying fine meshes are shown in Fig. 2, which are close to the boundary of the heat flux and expand gradually away from it. Then, good accuracy can be obtained with a reasonable calculation time.

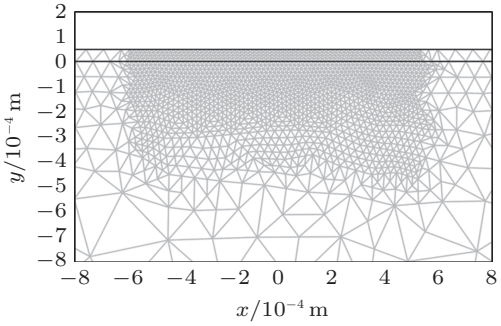


Fig. 2. Schematic diagram of mesh used in the finite element method software.

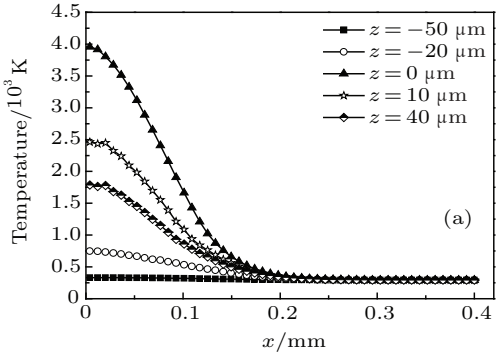
2.3. Results and discussion

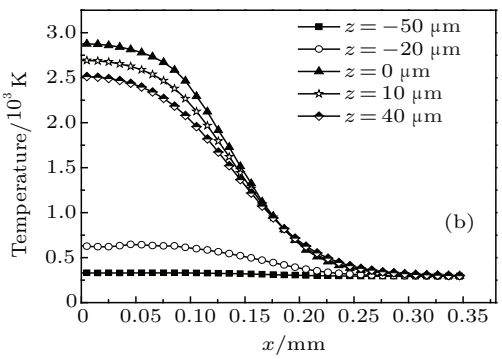
In the numerical simulation of the two-layer system, the thickness of the paint coating layer is assumed to be 50 μm, and the thickness of the metal substrate is 5 mm. The diameter of the coupon is 5 mm. The parameters of the substrate and coating layer material properties are listed in Table 1. We compare three circumstances, including the nearly flattened top laser spot with diameters of 0.4 mm, 0.7 mm, and 1.0 mm. Temperature distribution and strain distribution are shown in Fig. 3.

Table 1. Material-thermal properties and mechanical properties of two-layer systems.

	k/W·m^{-1}·K^{-1}	$c_{\rm p}$/J·kg^{-1}·K^{-1}	ρ/kg·m^{-3}
Iron	80	4600	7800
Paint coating	0.3	2510	1300
	Y/Pa	γ/K^{-1}	A
Iron	1.9×10^{11}	1.27×10^{-5}	0.3
Paint coating	1.0×10^{10}	1.0×10^{-6}	0.17

In the three embodiments, the numerical simulation results of coating layer removal suggest that the flat top laser can substantially induce even temperature and strain distribution in the middle of the flattened area. The results reveal that the temperature peak is present in the centre of spot. However, near the edge of the flat top of the spot, there is an increasing stress near the surface of the substrate. When the flattened top laser irradiation lies on the surface of both the coating layer and the substrate, part of the coating layer is selectively vaporized from the surface because the temperature is higher than the melting and vaporizing point of the coating and substrate materials. The absorption is also induced in the substrate, and in the shallow surface the local temperature of the substrate rapidly





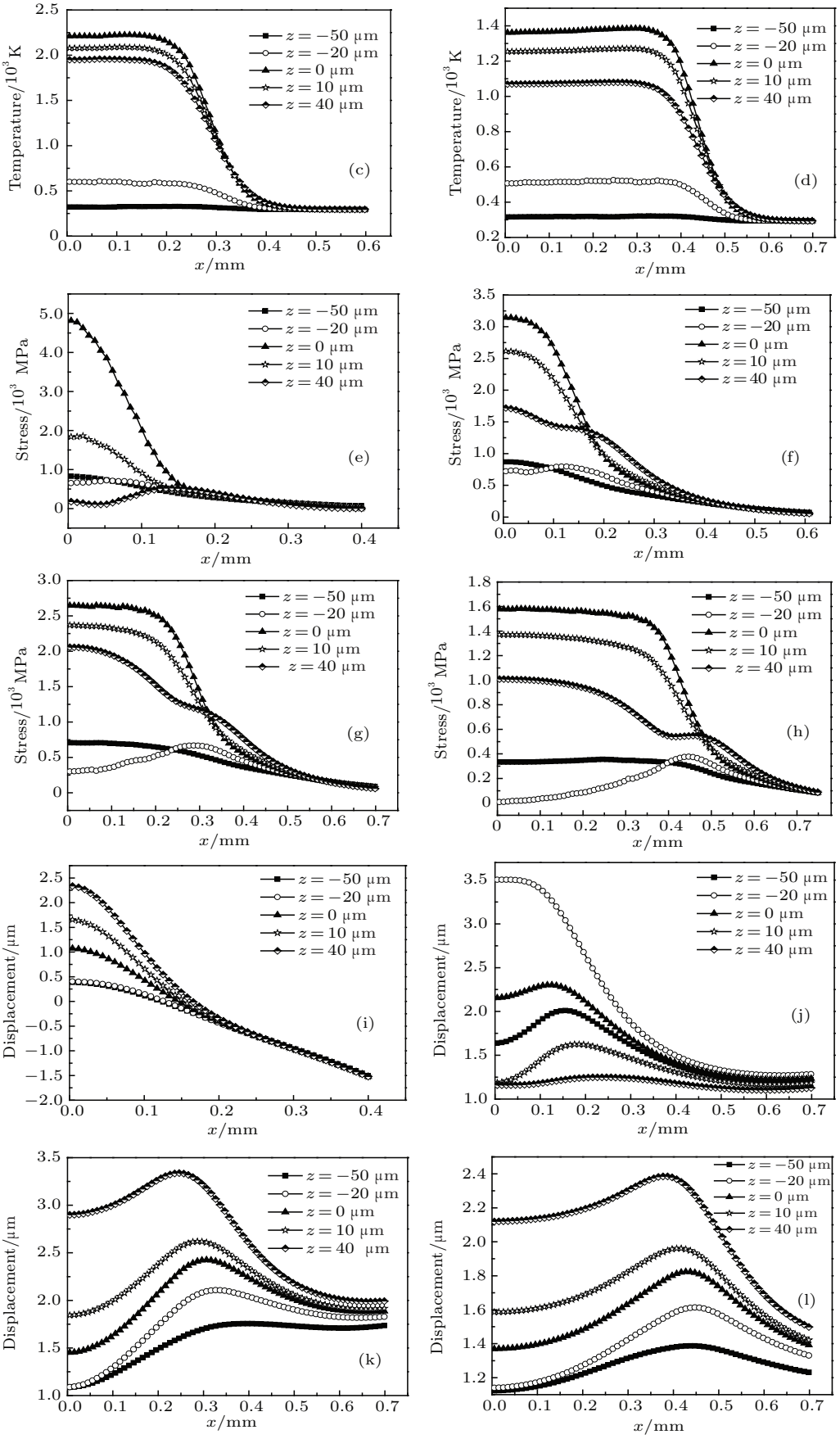


Fig. 3. Temperature distributions, stress distributions, and displacements numerically simulated by the FEM software, in the cases of Gaussian laser irradiation (panels (a), (e), (i)), and nearly flattened top laser irradiation, with spot diameters being 0.4 mm (panels (b), (f), (j)), 0.7 mm (panels (c), (g), (k)), and 1.0 mm (panels (d), (h), (l)).

increases. In the first and second embodiments the temperature distribution indicates that the temperature of the substrate is higher than the melting point of iron. Whereas the third embodiment shows that the peak temperature of the substrate is less than its melting point due to the decreased intensity with the larger diameter of the spot. The numerical simulation on stress reveals a high stress ring along the flattened top edge.

3. Experiment

3.1. Experimental setup

A schematic diagram of the experimental set-up for the laser cleaning system is depicted in Fig. 4. The acousto–optic Q-switched Nd:YAG laser is used with a 1064-nm wavelength and 25-mJ pulse energy. The pulse duration is 200 ns–400 ns and the repetition rate can reach 3 kHz. In order to obtain a generally flattened top laser beam, in the optical path we lay lenses each with a spherical aberration, and then set an aperture to make the centre of the beam pass through. The lens system comprises lens with a negative spherical aberration. Different lenses with different coefficients may be selected to adjust the diameter of the laser spot.

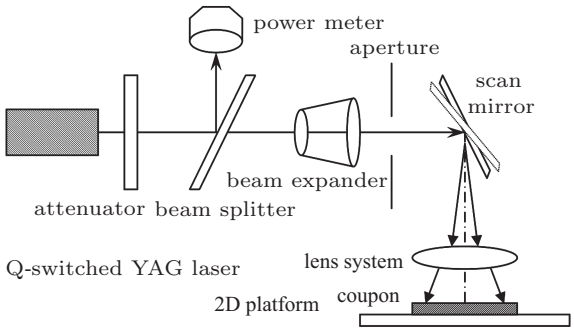


Fig. 4. Experimental set-up of medium repetition acousto–optic Q-switched laser cleaning system.

Laser cleaning is carried out to remove the surface paint coating from an iron substrate. The iron substrate used in this experiment has a generally smooth surface with micro texture. By observing the changes of surface texture the influence of laser irradiation can be identified. In other words, the substrate damage level can be detected. The surface coating is painted with a thickness of about 50 μm, which is sprayed evenly. The repetition rate is relatively high, so the scanning mirror apparatus is utilized to separate the laser spot. The coupon is fixed on the mechanical platform which can move in the X and Y directions on the 2D platform.

3.2. Experimental results

The cleaning results of Gaussian laser irradiation and nearly flattened laser irradiation are shown in Fig. 5, respectively. The micrographs of the experimental results show that the surface of the coupons after laser irradiation is restructured with different levels. Figure 5(a) shows that the central area of the Gaussian laser spot is seriously damaged, which results from the unevenness of the laser profile. A concave in the centre of the laser spot can be obviously seen. These illustrate that near the centre of the laser spot, the temperature of substrate is higher than the melting point of iron, so a melting and re-solidifying ring can be observed. Meanwhile at the edge of the laser spot the coating layer is vaporized or vibrated. However, due to the uniform intensity central region of the flattened laser, the surface of the substrate is cleaned uniformly, so that there is no obvious substrate damage in Figs. 5(b)–5(d). There is no obvious vaporizing area in the central spot.

We also ran experiments using flattened laser spots with different diameters (0.4 mm, 0.7 mm, and 1.0 mm) separately. Comparing the three experimental results of the different flattened laser spots, different phenomena can be observed as shown in Fig. 5. Due to the difference in thermal expansion between the coating layer and the substrate, the heating and cooling rate of the substrate are faster than those of the coating layer. Hence the transient surface heating and cooling can provide a compressive shock force on the coating layer and remove the coating layer away from the substrate. In the first experiment of diameter 0.4 mm, the area near the spot centre is clean and is patterned into ring grooves. Meanwhile the substrate is melted and re-solidified. In the second experiment of diameter 0.7 mm, almost all of the substrate surface is covered with micro convexes. In the third experiment of diameter 1.0 mm, the micro structures of surface are not changed apparently. Moreover, the surface colours are also different in the three embodiments. In the first experiment the exposed substrate area near the centre of laser spot has clear colour. On the contrary, the colours of the latter two experiments are dark due to oxidation. This dark is a mixed colour of yellow Fe_2O_3 and black FeO and Fe_3O_4. In the first experiment of a flattened top laser, due to the fact that the melting iron is rapidly solidified, a ring structure can be recorded under the effect of stress and edge intensity peak. The ring structure is shown in Fig. 5(b). However, in the experiments of 0.7 mm diameter and

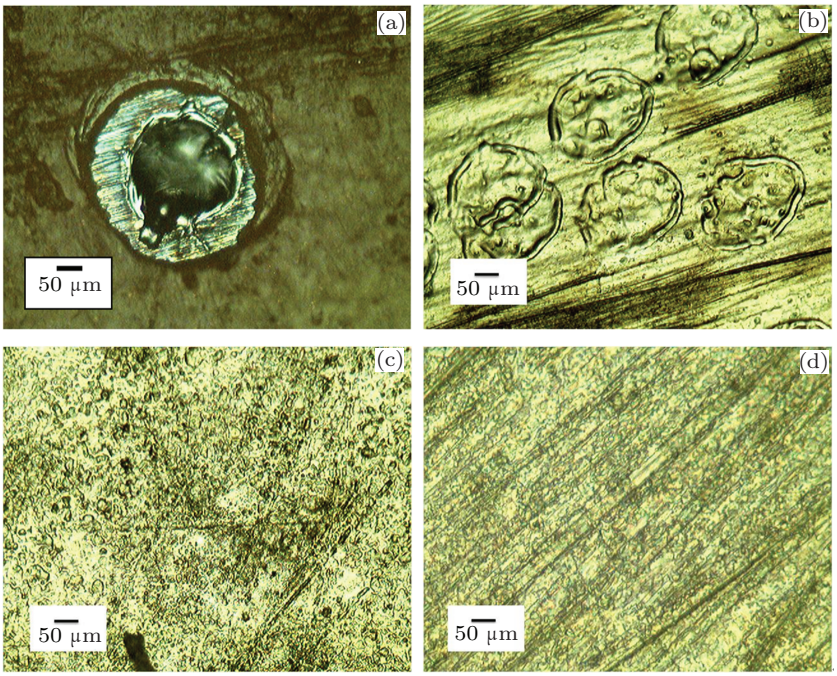


Fig. 5. (colour online) Experimental comparison of surface profiles after being irradiated by different profile lasers. Panel (a) shows the consequence by Gaussian laser irradiation; Panels (b)–(d) exhibit the results by nearly flattened top laser irradiation. The spot diameters are 0.4 mm (b), 0.7 mm (c), and 1.0 mm (d).

1.0 mm diameter, the ring structure does not appear. This can be explained as follows. In experiment of 0.7 mm diameter the laser power intensity is lower than that of the experiment of 0.4 mm diameter. The substrate can melt, but the melting deepness is very shallow, and the laser induced stress cannot form the ring structure. Only some re-solidified dots are left. Furthermore in the experiment of diameter 1.0 mm, the temperature of substrate iron is lower than the melting point. The micrograph shows that the surface of the iron substrate after laser irradiation is covered with a dark layer. The dark layer is an oxide layer which actually acts as a passivation protection layer.

The effective cleaning area can be obtained at the position of maximum displacement according to the data in Fig. 3. Based on the experimental results, the relative cleaning efficiency can be deduced, which is shown in Table 2. By adjusting the laser spot, the cleaning area obtained by the flattened laser is larger than that obtained by the Gaussian laser. The cleaning results show different efficiencies in four experiments, the effective cleaning area apparently increases with increasing diameter. The cleaning efficiency can be enhanced by about seven times at an appropriate scanning rate. Moreover the laser induced damage to the substrate can be reduced to a minimal degree. This meets the needs of sensitive substrate cleaning.

Table 2. Effective area irradiated by single pulse laser.

Spot diameter/mm	Laser type	Effective area/mm^2	Relative efficiency
0.3	Gaussian	0.064	1
0.4	flattened	0.102	1.59
0.7	flattened	0.246	3.84
1.0	flattened	0.477	7.45

4. Conclusions

We investigated the effect of flattened laser cleaning, and numerically simulated the temperature distribution and strain distribution of a two-layer coating-substrate system. The results show that the finite element method can be applied to the thermal analysis of the coating-substrate system. From the numerical and experimental data, the nearly flattened laser can obtain a more optimal effect than the Gaussian laser, which indicates that the flattened top laser has a better ability to remove the paint from the metal substrate. Therefore, in view of the uniformity of the near flattened laser intensity, the thermal effect on the substrate can be minimized, so that the damage to the substrate can be effectively reduced and the cleaning efficiency can be enhanced.

References

[1] Song F, Liu S J and Yan B X 2004 *Cleaning World* **20** 43 (in Chinese)

[2] Fourrier T, Schrems G, Mühlberger T, Heitz J, Arnold N, Bäuerle D, Mosbacher M, Boneberg J and Leiderer P 2001 *Appl. Phys.* A **72** 1

[3] Lu Y F, Song W D, Lukyanchuk B S, Hong M H and Zheng W Y 2000 *Mater. Res. Soc. Symp.* 617 (Singapore: Materials Research Society)

[4] Zhou G L and Zhao H X 2003 *Special Purpose Rubber Products* **24** 39 (in Chinese)

[5] Mann K, Wolff-Rottke B and Muller F 1996 *Appl. Surf. Sci.* **96** 463

[6] Lu Y F, Song W D, Hong M H, Chong T C and Low T S 1995 *Mater Res. Soc. Symp. Proc.* **397** 329

[7] Siano S and Salimbeni R 2010 *Acc. Chem. Res.* 43 739

[8] Zapka W, Ziemlich W, Leung W P and Tam A C 1993 *Micro-electron. Eng.* **20** 17138

[9] Hills M M 1995 *Vac. Sci. Technol.* A **13** 11830

[10] Lmen K, Lee S J and Allen S D 1991 *Appl. Phys. Lett.* **58** 20347

[11] Tam A C, Leung W P, Zapka W and Ziemlich W 1992 *J. Appl. Phys.* **71** 3515

[12] Chen G X, Kwee T J, Tan K P, Choo Y S and Hong M H 2010 *Appl. Phys.* A **101** 249

[13] Daurelio G, Chita G and Cinquepalmi M 1999 *Appl. Phys.* A [suppl.] **69** S543

[14] Schweizer G and Werner L 1994 *Proc. SPIE* **2502** 57

[15] Brygo F, Dutouquet C, Guern F Le, Oltra R, Semerok A and Weulersse J M 2006 *Appl. Surf. Sci.* **252** 2131

[16] Xu B Q, Shen Z H, Lu J, Ni X W and Zhang S Y 2003 *Heat and Mass Transfer* **46** 4963

[17] Pu J X 1999 *Laser Technology* **23** 42 (in Chinese)

[18] William B J Z 2007 *COMSOL Multiphysics Finite Element Method*: *Model and Analysis* (Beijing: China Communications Press) (in Chinese)