Laser induced damage threshold on metallic surfaces during laser cleaning

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Abstract

In view of the importance of material degradation during laser irradiation, which can have deleterious effects on mechanical and chemical properties of a component, a study was initiated to determine a threshold at which damage takes place during laser paint removal. Laser induced damage on 316L stainless steel was studied, with the target subjected to single and multiple pulse irradiations using a Q-switched Nd:YAG, with fluences between 0.15 and 11.8 J/cm^2. Several different damage morphologies were observed during scanning electron microscope investigations. The information obtained from these investigations was used to quantify the onset of damage caused to the substrate when various laser parameters were used for paint removal.

Keywords: Laser induced damage, AISI 316L, Q-switched Nd:YAG, Scanning Electron Microscopy

Introduction

The laser paint removal process has been demonstrated to be an efficient cleaning method for artworks, statues and aircraft [1,2,3]. The main thrust of this research is based on paint removal from metallic substrates using an Nd: YAG laser. Besides the optimization of laser parameters required for surface cleaning, this work focuses on the possible substrate material degradation after the laser cleaning process. The possibility of substrate damage during the cleaning process is of considerable concern since this can result in premature failure of the cleaned component.

Laser cleaning with Nd:YAG lasers is based on thermal evaporation of the paint substance. There is a minimum laser energy density i.e. threshold fluence, required before any paint can be evaporated from a substrate, without causing any visible damage on the surface. The onset of the material damage was studied as a function of laser fluence. The damage morphologies were studied using optical and scanning electron microscopy. A brief overview of laser surface interaction, types of damage morphologies, experimental methods and results are discussed.

1.1 Laser surface interaction in relation to laser surface cleaning

When a target surface is irradiated with a high intensity laser beam it can be melted and vaporized. Lasers with intensities in the order of 10^{10} W/cm^2 or more are readily available, making it possible to produce a wide range of different laser matter interactions. The dominant laser matter interactions are dependent on the characteristics of the target surface and the laser parameters.

At the time of the interaction of the laser beam with the target surface, the amount of absorbed laser energy is determined by the absorptivity of the surface. The other laser parameters which have a significant influence on the interaction are the laser wavelength and the pulse duration. The absorption coefficient α of the surface at the laser wavelength determines the thickness of the surface layer which will be affected by the radiation. This can be expressed as shown in equation (1).

$$L = \tfrac{1}{\alpha} \ln(\tfrac{I_0}{I}) \qquad (1)$$

where L is the affected layer thickness, α is the absorption coefficient, I_0 is the incident intensity and I is the transmitted laser intensity.

The pulse duration influences the thickness of the thermally affected depth. This depth is approximately proportional to the square root of the pulse duration.

The relationship between this thermal depth and the thermophysical properties of the target surface is expressed by equation (2).

$$L_d = \sqrt{2\,D\,\tau} \qquad (2)$$

where, D [$m^2\,s^{-1}$] is thermal diffusivity, τ [s] is the pulse duration.

During laser paint removal, a portion of the incident laser beam energy is absorbed by the paint inducing a temperature gradient that depends on its absorptivity. The laser threshold fluence necessary for ablation can be expressed by rewriting equation (1) in terms of the incident and transmitted laser intensities. When small fluences are used for ablation, the surface temperature reached is too low for bulk material evaporation. The energy absorbed at these low fluences is just sufficient to ablate small particulates. At very high intensities, bulk material ablation takes places. This is accompanied by the generation of a strong plasma propagating normal to the target surface. The effect of surface melting and thermal stress generation has been observed to dominate with increase in laser fluences.

1.2 Laser substrate damage morphologies

The many advantages of laser paint removal could be compromised by the adverse side effects such as substrate damage. The surface damage on laser cleaned components has not received much attention. There is however a considerable body of literature on surface damage of laser optical components [4]. A number of laser induced damage morphologies were identified in the study of single crystal metals when subjected to single and multiple pulse irradiation [5]. The forms of damage that were identified in the literature include roughening, melting, boiling, crater formation, pits, cracks, fracture and slip line formation. Furthermore, it was found that in metal mirrors multiple pulse damage can occur even far below the single shot damage threshold.

In general, the nature of damage will depend on the laser characteristics, that is, fluence, number of shots, wavelength and the mechanical properties of the material. In the present paper the forms of substrate damage are mainly thermally induced.

The laser energy normally used for paint removal is marginally above the threshold fluence of the paint to be removed. At these fluences the energy of the laser is too low for any gross surface melting or boiling of the substrate. Experimental work shows the formation of slip lines and surface cracks. These forms of surface damage result from thermally induced strains and stress [5, 6, and 7]. The heating and cooling of the substrate induces compressive and tensile strains on the material due to thermal gradients established. The transient temperature distribution on the metal surface can be approximated from a one dimensional heat flow equation. This temperature distribution is then used to approximate the thermal stress in the material as shown in equation (3).

Stress induced by uniform heating:

$$\sigma = S\,\frac{E\,\varepsilon\,\Delta T}{(1-\upsilon)} \qquad (3)$$

E = Young's modulus, S = factor depending on the stress, υ = Poisson's ratio, ΔT temperature change, ε = expansion coefficient.

Any failure, i.e. slip line or crack, will occur when ΔT is sufficiently large such that equation (3) exceeds a critical yield stress, this condition is given by equation (4)

$$\sigma > \sigma_\gamma \qquad (4)$$

The threshold intensity where plastic yield will occur is given by equation (5).

$$I = \frac{\sigma(1-\nu)}{S\,\varepsilon\,E}\cdot\frac{\sqrt{\pi\,K\,C\rho}}{2(1-R)\sqrt{\tau_P}} \qquad (5)$$

K = Thermal conductivity, C = specific heat, ρ = density, R = reflectivity, τ_p = pulse duration.

Equations (3) to (5) can be used to predict, to first order, the type of optical damage that might be induced on the substrate, provided that the various physical parameters are known. In general the surface absorption, thermal conductivity etc, are temperature dependent making extrapolation of the data difficult. Moreover, the situation can be worse in multiple pulse irradiations where the first shot can change the surface leading to change in absorptivity for subsequent laser pulses, viz. cleaning and roughening.

Experimental details

1.3 Laser equipment and specimens

AISI 316L stainless steel was used as substrate material in the experiments. The specimens were 27 mm in diameter, 1.6 mm thick, fully annealed and metallographically polished to a 1 μm surface finish before a 20 μm layer of matt black paint was sprayed on the surface.

A Q-switched Nd:YAG laser with a maximum energy output of 800 mJ. was used for the irradiation of the specimens.

1.4 Evaluation

The damage caused to the substrate was studied for two laser parameters: (a) the number of pulses and, (b) the energy per pulse (fluence). In order to observe the influence of each parameter, one parameter was kept constant while the other was varied. The number of laser pulses was increased from 1 to 50. The laser fluence was increased from 0.15 to 11.80 J.cm^{-2} with regular intervals, using the same spot size.

The influence of the laser on the paint removal process was evaluated using a low magnification stereo type microscope with a maximum magnification of 40 times. The specimens were further examined and evaluated, using a high resolution variable pressure SEM (JEOL 5800LV).

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Results

1.5 Macro examination

Fig. 1 shows a specimen that was irradiated at a low fluence, i.e. 1.44 J.cm^{-2} using different number of pulses. The paint was only partially removed after 4 pulses. Low magnification light microscope investigations at 5X magnification showed no structural damage on the underlying microstructure. Progressive irradiation from the 20th pulse onwards resulted in surface discoloration. But the scenario changed as the fluence was increased, discoloration occurred at progressively fewer pulses.

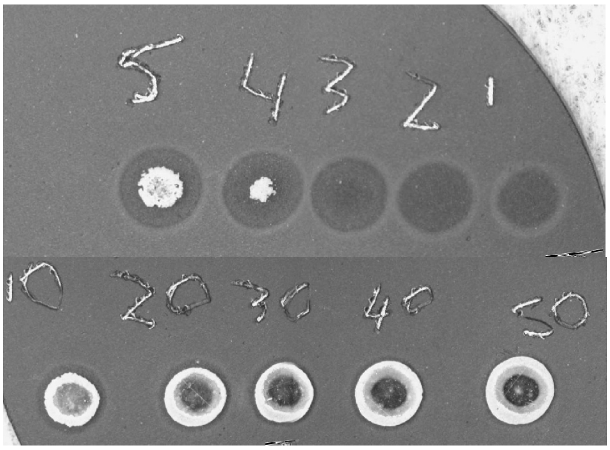


Fig. 1. Macro photograph of the specimen showing the effect of the laser after different number of pulses. The spot diameter is 2 mm.

1.6 Micro examination

SEM investigations were conducted to determine the possible forms and degree of laser induced microstructural damage caused by the various laser parameters.

Fig. 2 shows the degree of microstructural damage caused with a laser fluence of 8.15 J.cm^{-2} after 2 pulses. The damage mechanism observed at higher laser fluence was predominantly mechanical deformation resulting in slip lines. A major concern was the formation of micro cracks, following the grain boundaries but also trans granular.

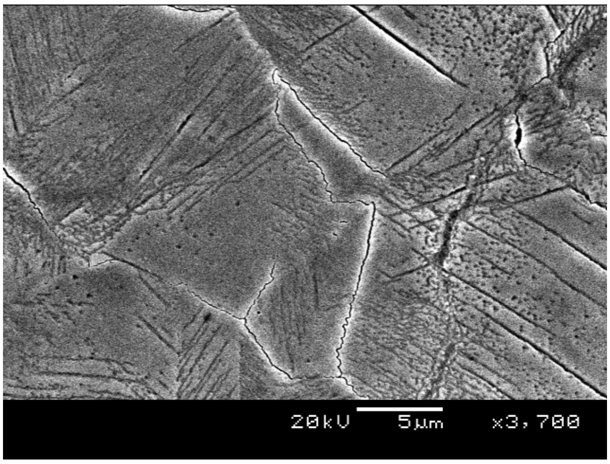


Fig.2. SEM micrograph showing structural damage caused during high laser fluence.

1.7 Damage quantification

The microstructural damage as observed with the SEM at various magnifications was classified in four categories, depending on the severity of the damage observed, see **Tab. 1.**

Tab. 1: *Damage categorization*

Category	*Description of damage category*
0	No paint removal, typically as seen at low magnification in **Fig.1** after **1, 2** or **3** shots.
1	Only paint removal, no discoloration or microstructural damage visible on substrate, typically as seen at low magnification in **Fig.1** after **4** shots. Only un-distorted grain boundaries were present at high magnification as shown in **Fig. 3.**
2	Paint removed with visible discoloration of the substrate, typically as seen at low magnification in **Fig.1** after **5** to**10** shots. Higher magnifications revealed the presence of slip bands see **Fig. 2**.
3	Paint removed with the presence of a re-melted zone near the centre of the substrate, as seen in **Fig. 1** after **20** shots and more. Melting with a ripple effect occurs in the centre with ablation and exposure of the grain boundaries near the edges. See **Figures 4 & 5.**

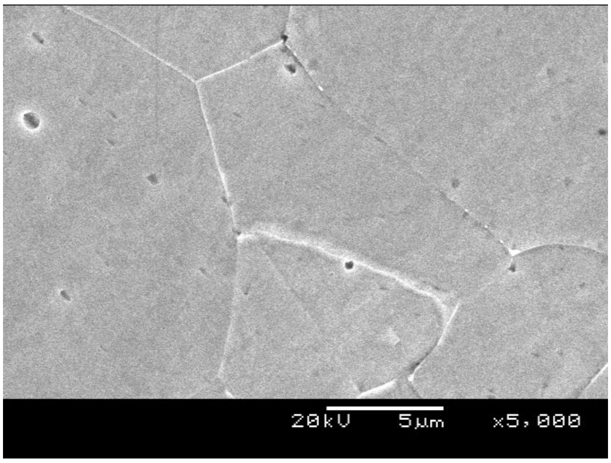


Fig.3. SEM micrograph showing un-distorted grain boundaries after paint removal, near the centre of the irradiated zone.

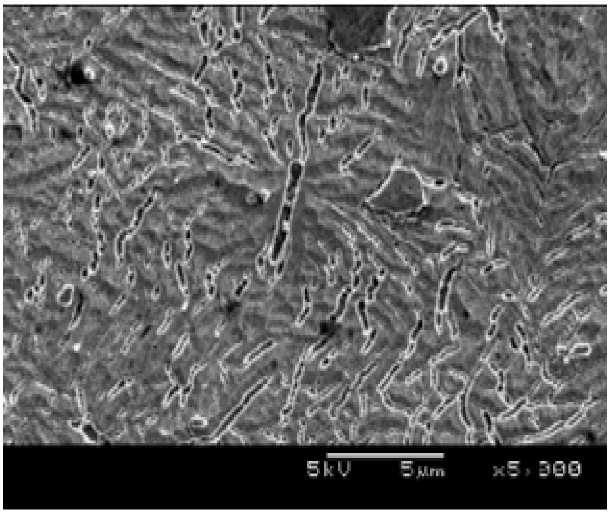


Fig.4. SEM micrograph showing structural damage in the form of melting caused during low laser fluence after 50 shots, near the centre of the irradiated zone.

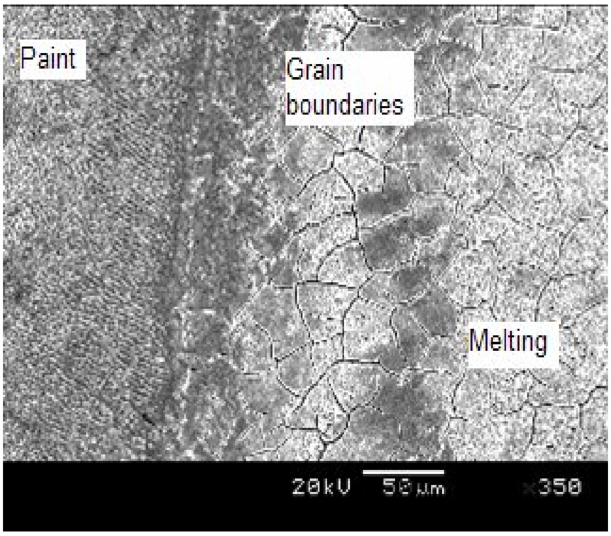
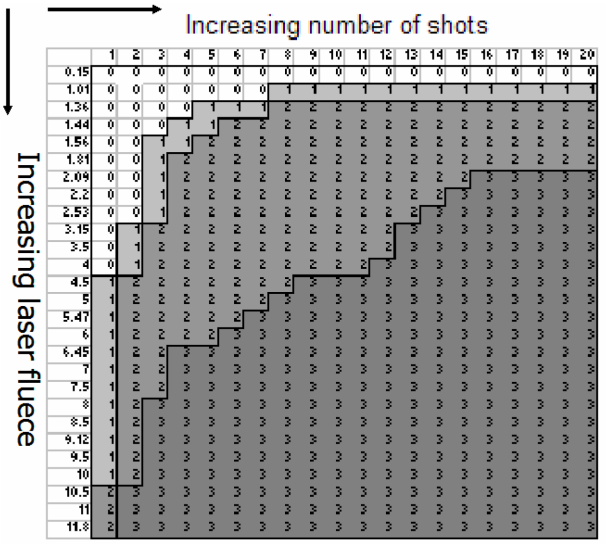


Fig.5. SEM micrograph showing structural damage caused during low laser fluence after 50 shots, near the edge of the irradiated zone.

A diagram shown in **Fig.6** was constructed using the damage criteria as categorized in **Tab.1** to indicate the onset of the damage on the specimens as a function of the number of shots versus the laser fluence



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
0.15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.01	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
1.36	0	0	0	0	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2
1.44	0	0	0	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
1.56	0	0	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
1.81	0	0	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
2.09	0	0	1	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3
2.2	0	0	1	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3
2.53	0	0	1	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3
3.15	0	1	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3
3.5	0	1	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3
4	0	1	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3
4.5	1	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3
5	1	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3
5.47	1	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3
6	1	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
6.45	1	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
7	1	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
7.5	1	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
8	1	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
8.5	1	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
9.12	1	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
9.5	1	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
10	1	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
10.5	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
11	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
11.8	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

Fig.6. Damage diagram showing the onset of laser damage as a function of the number of shots versus the laser fluence.

Conclusion

Laser induced damage on a metallic surface is dependent on the number of pulses as well as the fluence of the laser. Metallographic examinations showed that substrate damage only occurs after paint removal with subsequent heat build-up in the substrate.

A diagram was constructed to show the onset of damage on the substrate when using various laser parameters for the removal of a 20 µm thick paint layer. The threshold range for substrate damage at low fluence i.e. 2.09 J.cm^{-2}, is less than 16 pulses and at higher fluence i.e.11.80 J.cm^{-2}, is less than 2 pulses.

The degree of paint removal is highly dependant on the type of paint used as well as the thickness of the paint layer. A safe working window for paint removal without substantial damage caused to the substrate can be derived from the damage diagram in **Fig.6** for the current experimental parameters. Similar diagrams can be constructed for various other paint qualities, layer thicknesses and substrates for the determination of safe paint stripping regimes.

Bibliography

[1] Cooper, M.: Laser Cleaning in Conservation. Butterworth-Heinemann (1998)

[2] Kautek, W., König, E.: Lasers in the Conservation of Artworks. Wien. Mayer-Verlag (1997)

[3] http://www.adapt-laser.com

[4] Wood, R.: Laser damage in optical materials. The Adam Hilger Series on Optics and Optoelectronics (1986).

[5] Benz, R., Naoumidis, A. and Nickel, H.: Thermal shock testing of ceramics with pulsed laser irradiation, J. Nucl. Mat. Vol.150, (1987), 128-139

[6] Glenny, E.: Thermal fatigue, Metallurgical Rev. 6, (1961), 387

[7] Figueira, J. F., and Thomas, S. J.: Damage thresholds at metal surfaces for the short pulse IR lasers, IEEE J. QE 18, (1986), 1381