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Effect of water-jet on laser paint removal behaviour

Yuvraj K. Madhukar, Suvradip Mullick, Shitanshu S. Chakraborty, Ashish K. Nath*

Department of Mechanical Engineering, IIT Kharagpur, Kharagpur-721302, India

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Abstract

The laser paint removal behaviour with water-jet assist laser has been investigated using Yb- fiber laser. The conventional laser paint removal process with gas-jet assist usually leaves behind traces of combustion product i.e. ashes on the surface. An additional post-processing such as light-brushing or wiping by some mechanical means is required to remove the residual ash. In order to strip out the paint completely from the surface in a single step, a hybrid laser process which utilizes a water-jet along with laser beam has been developed. A coaxial water-jet along with a high power fiber laser beam removed the paint and residual ashes very effectively. The specific energy, defined as the laser energy required removing a unit volume of paint was found to be marginally higher than that for the gas-jet assisted laser paint removal process. However, complete paint removal was achieved with the water-jet assist only.

Key words: Paint removal; fiber laser; water-jet

Nomenclature

E_s	specific energy
P_l	laser power
v	scan speed
t	total paint layer thickness (red oxide + black paint)
w	cleaned track width
P_p	laser power incident on the paint surface
α	absorption coefficient
l	length of plume in the direction of laser beam
α_L	linear absorption coefficient in water
β, γ	constants
M^2	beam quality parameter
L_1	focal point distance from water surface
L_2	focal point distance from the painted surface
ω_s	beam waists at water surface
ω_0	beam waists at focal plane
λ	wavelength of the laser

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* Corresponding Author*: Tel: +91 - 3222 – 281784; fax: +91-3222-255303*

E-mail address: aknath@mech.iitkgp.ernet.in

Postal address: Department of Mechanical Engineering, IIT Kharagpur, Kharagpur-721302, India

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1. Introduction

Now-a-days, lasers are being increasingly used in various industrial applications such as cutting, drilling, welding, etching, cladding etc. The controlled irradiation by laser and its tunability make the laser applicable to precision applications also, such as removal of coatings and restoring the paintings and sculptures. The use of paint for making barrier between the environment and the surface is for preventing atmospheric contamination. But, in many cases often paint needs to be removed from the surface for various reasons. Laser paint removal is an attractive technique to remove paints and coatings in a controlled manner without any damage to the surface as associated with the conventional methods such as mechanical and chemical removal processes [1-3]. Laser in paint removal has many advantages over the conventional techniques. Specifically, selective removal, no substrate damage, and fast rate of cleaning are the key favourable factors in laser paint removal. It can serve the purpose efficiently in hazardous places like in nuclear and marine industries, large size bridges and walls, and also in paint stripping from aircraft and automobile bodies, storage tank, rail cars etc. However, in laser paint removal, often a thin layer of residual ashes remains stuck on the surface and this needs further post-processing like light-brushing [4-6] or wiping out by some mechanical means [7-9].

Paint can be removed from the surface with laser by one or more of the process such as vaporisation, ablation, combustion, multi-photon absorption, shock removal etc. All the processes can be operative individually or in combinations depending on the characteristics of laser beam utilised. The basic task is to deliver a control amount of laser energy on the paint for its removal. This requirement can be fulfilled with either a pulsed laser beam or with a rapidly scanning continuous wave (CW) laser beam [4, 8, 17].

Two approaches have been demonstrated to take off the ashes during paint removal by laser. First is to employ a high pressure gas jet from coaxial and lateral directions. Though it improved the process to a great extent, the complete removal of ashes could not be achieved [4-6]. Second patented approach is associated with the irradiation by laser beam in a conical chamber, along with a chilled gas flowing coaxially at a high velocity. The high pressure gas jet shattered and striped out the ashes and this was taken out by evacuating the chamber [10].

The use of a high pressure water-jet is also one of the well established processes to remove paints [11-13]. The water pressure utilised is in the range of hundreds of bar. Several investigations on the effects of water-jet kinetic energy, standoff distance [11], flow characteristics of water-jet in air [12], nozzle design, orifice diameter, and target parameters [13] were carried out experimentally and through modelling. Recently, a hybrid process called water micro-jet guided laser cutting has been developed with which fine cutting of thin metal sheets and silicon wafers, and cutting and grooving of hard materials like cubic boron nitride (CBN), and silicon nitride have been reported [14,15].

From the above review it can be concluded that the laser paint removal process leaves some amount of residual ashes on the substrate surface. In order to remove the paint completely without any trace of ashes, a coaxial water-jet at about 20m/s velocity along with a high power fiber laser beam was employed and this hybrid process removed the paint and residual ashes very effectively. The results are compared with the gas assisted laser paint removal process [9]. The specific energy, which is defined as the amount of laser energy needed to remove unit volume of paint prior to the onset of substrate damage, has been chosen as a measure of the process efficiency.

2. Experimental details

The experiments were carried out with a 2 kW Yb-fiber laser (IPG photonics, Model no.YLR-2000) operating at 1.07 µm wavelength. The laser power can be modulated in 50–1000 Hz frequency range at 5–100% duty cycle (DC). The laser beam delivery system is mounted on a CNC work station capable to move at speeds up to 25 m/min. The substrate material of stainless steel AISI 304 of 85 mm×25 mm×1.5 mm were first polished with the abrasive paper of 1000 grade and then cleaned with ethyl alcohol before painting. Two layers of different paints, a first layer of red oxide (primer) and after drying the second layer of synthetic enamel of black colour were put by spray painting. The total thickness of paint layer (primer + synthetic enamel) was within 40±5 µm range (measured by a flat tip digital micrometer of 1 µm least-count, Mitutoyo 293-811). A hybrid processing head which allows water to flow coaxially with the laser beam was made in-house to carry out the experiment. The experimental setup is schematically shown in Fig. 1. As the absorption of fiber laser power in water is a function of laser intensity, water column height and water temperature, their effects were investigated and reported elsewhere [16]. In order to minimize the absorption loss in water, the dimensions of the coaxial water-jet nozzle were so chosen that the laser beam has to travel a minimum distance before it is incident on the specimen.

The specific energy, E_s which a measure of process efficiency is determined with the knowledge of laser power, P_l and scan speed, v as the following

$$E_s = P_l / v.t.w \tag{1}$$

Here t and w respectively are the thickness of paint layer and the width of cleaned track from which paint has been removed by laser scan.

In an earlier study the authors had established that the specific energy in gas-assisted laser paint removal process is lower for the modulated laser beam than for CW beam [9], therefore the present experiments were carried out with modulated power laser beam. It was further observed that the specific energy was lower for higher laser scan speeds, therefore experimental runs were performed at maximum possible laser power and scan speed to ensure better process efficiency. In the present study the modulation frequency was varied from 50 to 1000 Hz and the duty cycle from 5 to 20%. SOD was varied in 1-3 mm range. Experiments were carried out varying one parameter at a time. As the laser beam travelled through the water jet it suffered some absorption and scattering losses before reaching the paint surface. The actual laser power incident on the paint surface was estimated by measuring the laser power with the help of a laser power meter (model-COMET-10K-V1ROHS OPHIR) for different lengths of water-jet through which the beam travelled.

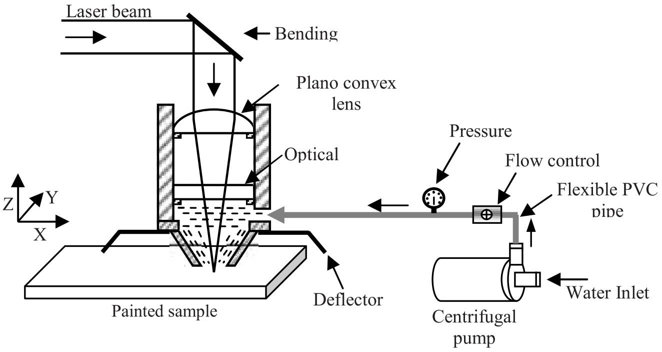

Fig. 1. Schematic of the water-jet assisted laser paint removal setup

3. Result and discussions

3.1 Water-jet assisted laser (WJAL) paint removal process

Experiments were carried out to determine the upper limits of laser peak power and scan speed for different laser modulation frequencies and duty cycles at which continuous clean tracks without any trace of paint, residual ashes, and surface melting were produced. The macrographs of the bare substrate surface and after paint removal by the water-jet assisted laser beam at different scan speeds are shown in Fig. 2a-c. In the first set of experiment, maintaining the SOD and water stagnation pressure at 2 mm and 2 bar respectively, the optimum laser processing parameters were determined for minimizing the specific energy. Thereafter, the effects of SOD and water pressure were investigated with these optimized laser parameters.

It may be mentioned that as the laser modulation frequency is increased at a given duty cycle, laser pulse duration decreases. The general trend for all duty cycles except 5%, is that the laser power and correspondingly the scan speed increased with increasing laser modulation frequency for complete paint removal. The corresponding specific energy reduced, which shows that the process efficiency improved with the increase of modulation frequency; in other words, with the reduction of laser pulse duration. The variations of specific energy with different laser modulation frequencies and DCs are plotted in Fig. 3. At 5% duty cycle the maximum laser power limit of 1800W reached at 150 Hz modulation frequency, and thereafter the variation deviated from the general trend. The paint could not be removed at 5% duty cycle at modulation frequency beyond 250 Hz. Similarly, at 10% DC the process became uncertain when the modulation frequency was increased beyond 800Hz. At 15% and 20% DC, the specific energy with increasing modulation frequency tends to saturate beyond 750 Hz. The minimum specific energy of 15.6 J/mm^3 was realized at 10% DC, 1800W peak laser power, 750 Hz modulation frequency and 15000 mm/min of scan speed.

Next set of experiments was conducted to investigate the influence of SOD on specific energy. The SOD was varied in 1-3 mm range. Experimental runs were performed at 500Hz and 750Hz modulation frequency and 10% DC at which the specific energy was in the lower range. Laser power and scan speed were optimized for different SOD's for these experimental conditions. The variation of specific energy with SOD is shown in Fig. 4. Specific energy increased with increasing SOD for both modulation frequencies.

The influence of water stagnation pressure was also investigated for three different values in 1-3 bar range. However, no significant variation in specific energy was observed for the variation of water pressure within this range.

Among all experimental runs, the minimum specific energy of 11 J/mm^3 was realized at 1mm SOD, 1800 W laser peak power, 750 Hz frequency, 10% DC and 21000 mm/min scan speed.

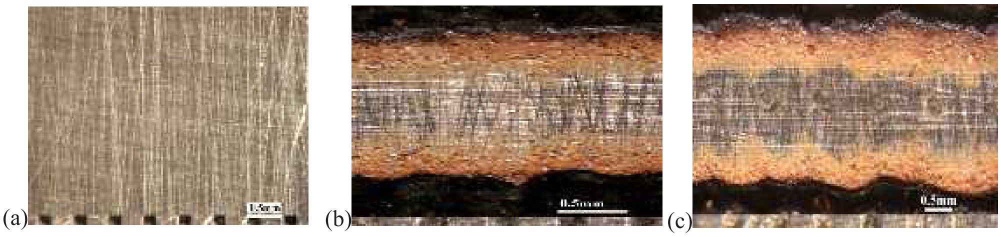

Fig. 2. Photographs of stainless steel samples (a) bare base metal, (b) complete removal of paint by the water-jet assisted laser beam, laser peak power = 1800 W, modulation frequency = 200 Hz, duty cycle = 10%, and scan speed = 7000 mm/min; (c) onset of melting in the central zone, scan speed = 6000 mm/min, other conditions same as (b).

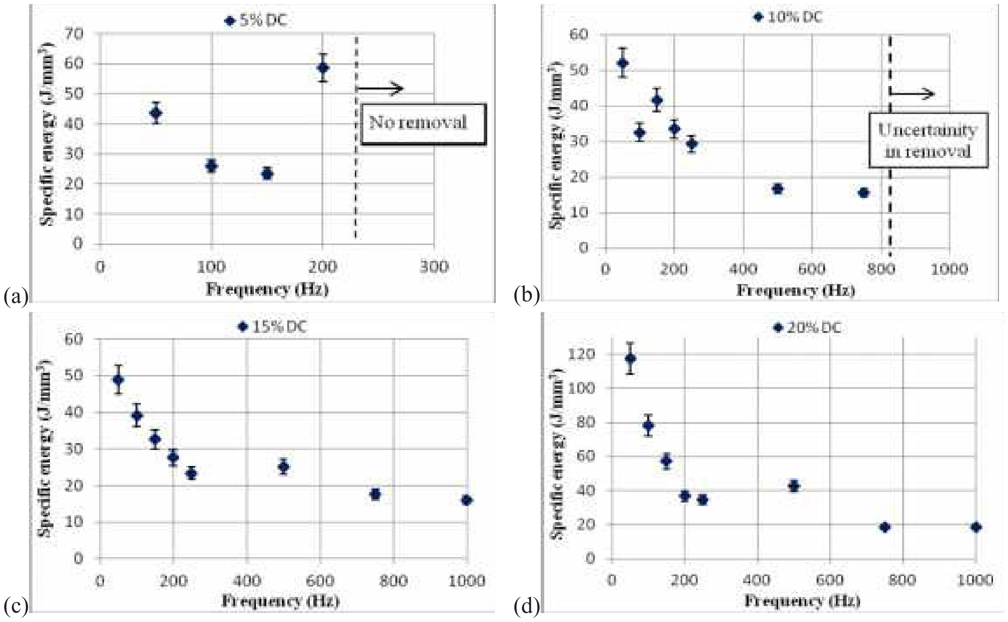

Fig. 3. Variation of specific energy with different modulation frequencies and duty cycles (CD)

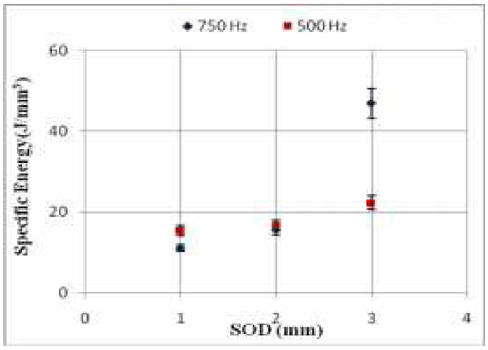

Fig. 4: Variation of specific energy with SOD at 2 bar water stagnation pressure and laser modulation frequency of 500 Hz and 750 Hz.

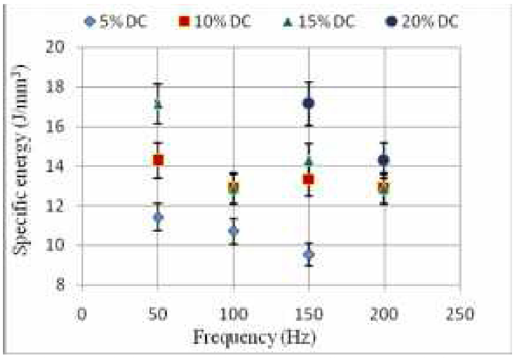

Fig. 5. Variation of specific energy for different DC in lower frequency ranges.

3.2 Gas-jet assisted laser (GJAL) *paint removal process*

An extensive study on the effect of laser operating mode on paint removal for different frequencies and duty cycles has been reported earlier [9]. Compressed air (~4.5 bar) flowing from the lateral direction served as the assist gas. The maximum process efficiency as determined by the minimum specific energy of 9.5 J/mm^3 was obtained at 5% DC, 150Hz modulated frequency and 50% overlap between two successive pulses as shown in Fig. 5 [9].

A comparison of the experimental data indicates that the specific energy in GJAL paint removal process is slightly lower than that in WJAL paint removal process, i.e. the efficiency of the former process is higher than the present process. However, the GJAL process always left a residual combustion product in the form of ash on the surface. Some post processing such as light brushing or wiping out by some mechanical means was required for its removal.

In WJAL process little ash remains on the substrate. In this respect this process can be considered to be more effective and equally efficient. The optimum values of operating parameters (modulation frequency and DC) giving maximum process efficiency was different for different processes. But, the laser energy requirement is expected to be constant to promote combustion and remove a unit volume of paint, irrespective of the mode of operation or process. This is also reflected in the specific energy obtained in both the processes. Therefore, different sets of optimum parametric values yielding the minimum specific energy in WJAL and GAJL paint removal processes could be because of the different loss mechanisms in them.

Plume formation is a common phenomenon during laser interaction with polymer based materials like paint [17]. This was observed during the experiment as shown in Fig. 6(a). The loss of laser energy can occur due to absorption in the laser produced plume [17] and this will depend on the fume particle density and its extent in the direction of laser beam. The absorption loss was modelled using the Beer-Lambert's law as the following [9],

$$P_p = P_l e^{-\alpha l} \tag{2}$$

Where P_l and P_p are the laser power incident on the plume and paint surface respectively, α and l are the absorption coefficient and the length of plume in the direction of laser beam. The absorption coefficient, α and the plume length, l will depend on the fume particle density and the laser interaction time respectively, therefore, the αl product can be expressed as $\alpha l \propto P_l/v$, where v is the laser scan speed [9]. By ignoring the laser energy loss in the plume, the specific energy E_s was estimated to be 6±0.6 J/mm^3 [9].

In WJAL paint removal process the extension of plume was restricted by the continuous flow of water-jet as can be seen in Fig. 6(b). Therefore, the absorption loss of laser energy in the plume was relatively less compared to that in GJAL process. However, the absorption and scattering losses in water inside the nozzle and in water-jet can be significant. The absorption of 1.07μm wavelength in water was investigated for different laser intensities and focal point position inside water [16]. The absorption becomes nonlinear at high laser intensities, i.e. it depends on laser intensity. The nonlinear absorption coefficient can be expressed as [16]

$$\alpha = \alpha_L + \frac{\beta P_0}{\pi \omega_s^2} + \frac{\gamma P_0}{\pi L \omega_0^2}\left[\tan^{-1}\left(\frac{M^2 \lambda L_1}{\pi \omega_0^2}\right) + \tan^{-1}\left(\frac{M^2 \lambda L_2}{\pi \omega_0^2}\right)\right] \tag{3}$$

Where, P_0 is the laser power, L ($=L_1+L_2$) is the total water column height, L_1 is the focal point distance from water surface, L_2 is the focal point distance from the painted surface, ω_s and ω_0 are the beam waists at water surface and focal plane respectively, α_L is the linear absorption coefficient, M^2 is the laser beam quality factor, and λ is the laser wavelength (1.07μm). The value of α_L, β and γ were experimentally determined as 0.135 cm^{-1}, 2.5×10^{-6} cm/W and 1.65×10^{-8} cm^2/W respectively [16]. The absorption coefficient was calculated using Eq. 3 for the present experimental conditions, P_0=1800 W, L_1=1.35 cm, L_2= 0.05 cm, ω_s=0.31cm, and ω_0= 0.03 cm, and this came out to be $\alpha = 0.156$ cm^{-1}. Putting this value of 'α' in Eq. 2, the laser power reaching at the paint surface, P_p is calculated to be ~1447 W. This shows an unavoidable loss of laser power of about 20% in water. If this loss is excluded, the specific energy will reduce to 8.9 J/mm^3 from 11 J/mm^3.

It has been also observed that the water-jet tends to entrap air and transform into a spray as the distance from the orifice increases, as shown in Fig. 7. Due to this the laser beam propagating through the water-jet undergoes scattering and the laser energy reaching at the paint surface reduces. The above calculated specific energy does not include this scattering loss. Therefore, the total loss (absorption + scattering) of laser power was experimentally measured for different lengths of water-jet through which laser beam travelled. Fig. 8 shows the laser power loss as a function of water-jet length. For comparison, the loss calculated using Eq. 3 is also plotted. The loss increased with the water-jet length and this was almost independent of laser intensity.

The increase of specific energy with increasing SOD was also reflected in Fig. 4. If this scattering loss is also excluded, the specific energy required to remove paint through combustion in WJAL paint removal process may fall in a range similar of

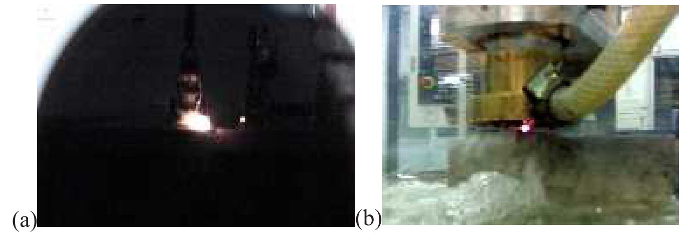
(a) (b)

Fig. 6. (a) Plume generation during GJAL paint removal process, photograph taken with a neutral density filter to eliminate bright light coming from the interaction zone, (b) Plume generation in the water-jet assisted laser paint removal process (without any optical filter).

GJAL paint removal process.From the above experimental results and discussion it can be concluded that the dominant loss mechanisms in GJAL and WJAL paint removal processes are different; while it is the absorption loss in laser produced plume in the former case, the scattering in water-jet is in the later case. And, the optimum sets of operating parameters (modulation frequency and DC) in two cases are different because of the different phenomena of loss mechanisms. Essentially, the process efficiency is higher and specific energy is lower for shorter duration laser pulses or interaction i.e. smaller DC, higher modulation frequency, higher scan speed at higher laser power. However, the optimum modulation frequency in case of GJAL is lower than WJAL because of the detrimental effect of plume produced by the previous laser pulse, which is suppressed in case of WJAL.

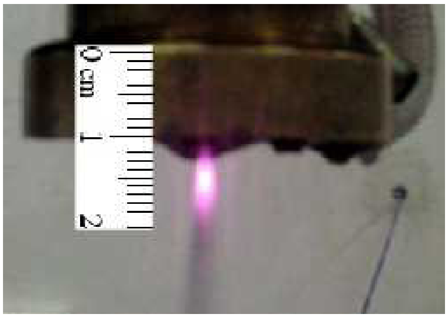

Fig. 7. Scattering of laser beam as it propagates through the water-jet at 3 bar water stagnation pressure.

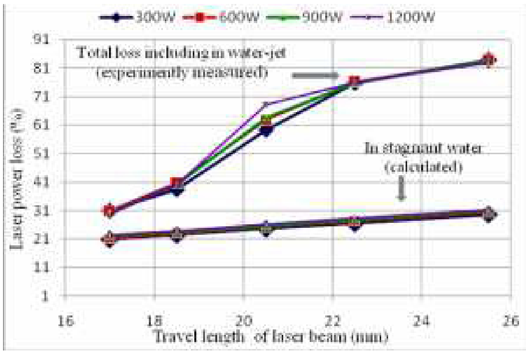

Fig. 8. Variation of laser power loss with travel length in stationary water and through water-jet.

4. Conclusion

The efficacy of the water-jet assisted laser paint removal process in complete removal of paint has been demonstrated.

- The water-jet tends to suppress the laser produced plume and corresponding absorption loss of laser energy in it, on the other hand it introduces scattering loss due to turbulence and air entrapment.
- The optimum sets of operating parameters (modulation frequency and DC) for the maximum efficiency in WJAL and GJAL paint removal processes were different, because of the different loss mechanisms dominating in the two cases.
- WJAL paint removal process has marginally lower (~16%) energy efficiency than GJAL process; however the water assisted process removes paint completely without any trace of residual ashes on the surface.

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