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Development of a water-jet assisted laser paint removal process

Yuvraj K. Madhukar, Suvradip Mullick, Ashish K. Nath*

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

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ABSTRACT

The laser paint removal process 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 water-jet assisted laser paint removal process has been investigated. The 1.07 μm wavelength of Yb-fiber laser radiation has low absorption in water; therefore a high power fiber laser was used in the experiment. The laser beam was delivered on the paint-surface along with a water jet to remove the paint and residual ashes effectively. The specific energy, defined as the laser energy required removing a unit volume of paint was found to be marginally more than that for the gas-jet assisted laser paint removal process. However, complete paint removal was achieved with the water-jet assist only. The relatively higher specific energy in case of water-jet assist is mainly due to the scattering of laser beam in the turbulent flow of water-jet.

1. Introduction

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]. Different types of continuous wave (CW) and pulsed lasers of wavelength ranging from infrared to ultraviolet and pulse duration ranging from ms (millisecond) to fs (femtosecond) range have been employed for paint removal [4–14]. The most notable lasers are the CW and pulsed TEA CO_2 lasers, free-running pulsed and Q-switched Nd:YAG (1.06 μm and its higher harmonics) lasers, excimer lasers and high power diode laser. Tsunemi et al. used pulsed TEA CO_2 laser at 10.6 μm wavelength to remove paint from metallic substrates [4]. They observed a small amount of paint/residual layer left on the surface and they demonstrated its effective removal by dimethyl formamide liquid assisted laser irradiation. Brygo et al. employed nanosecond laser pulses of Q-switched Nd:YAG laser and investigated the effect of various process parameters like laser fluence, repetition rate in 1–10,000 Hz range and pulse durations of 5 ns and 100 ns [5]. They observed that laser pulses of 100 ns duration yielded higher process efficiency than 5 ns duration pulses at high laser fluences. The best efficiency reported were 0.3 mm^3/J, 0.22 mm^3/J and 0.16 mm^3/J for the laser pulse duration and repetition frequency combinations of 100 ns and 10 kHz, 100 ns and 20 Hz, and 5 ns and 20 Hz, respectively. Dyer and Sidhu [6], and Galantucci et al. [7] investigated the ablation of different polymeric materials with excimer lasers of different UV wavelengths. Liu and Garmire studied the paint removal with a CW CO_2 laser at 10.6 μm wavelength, Q-switched Nd:YAG laser at 1.06 μm with 2.5 ns and 8 ns pulse widths, $XeCl^*$ excimer laser at 308 nm with 130 ns pulse-width and an Er:YAG laser at 2.94 μm with 1.2 ms pulse duration [8]. They established a universal engineering curve for the time needed for paint removal from nonconductive substrates which was valid over 10^2–10^8 W/cm^2 power density range. Among the various lasers they used, Q-switched Nd:YAG laser was found to be the most efficient in removing paint from metallic and non-metallic surfaces. Schmidt et al. employed an RF excited CO_2 laser operating at 10.4–10.8 μm wavelengths and modulated at 1 kHz [9], a continuous wave (CW) diode laser emitting at 810 nm wavelength [10] and also an ArF^* excimer laser at 193 nm wavelength [11] to remove chlorinated rubber and epoxy resin type of paints, and compared the results of different lasers. They found that the thermal loading (J/cm^3) for paint removal was comparable for the diode and excimer lasers; however, for CO_2 laser this was an order of magnitude smaller. The paint removal rate increased linearly with laser power [12]. They confirmed involvement of combustion in laser paint removal process and also found higher efficiency with oxygen as an assist gas than nitrogen and argon [9,10]. Barletta et al. also used CW diode laser to remove epoxy polyester from aluminium substrate [13]. They found that an optimum range of laser power and interaction time combination could remove paint without any damage to the substrate surface; however, excess and reduction of both led to subsequent substrate damage and

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* Corresponding author. Tel.: +91 3222 281784/+91 9932199975; fax: +91 3222 255303.
E-mail addresses: aknath@mech.iitkgp.ernet.in, nath.ashishk@gmail.com (A.K. Nath).

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insufficient removal, respectively. Madhukar et al. [14] investigated the laser paint removal behavior with both CW beam and repetitive pulses using an Yb:fiber laser. They found that there is a range of process parameters irrespective of the mode of laser operation that could cause complete removal of paint without any damage to the substrate surface. However, the process efficiency was found to be higher in case of pulsed mode having considerably long time interval between two successive pulses. The relatively long time interval between pulses allowed the laser produced plume to decay down and this reduced the absorption loss of laser power in plume. More recently, with the advent of ultrafast (sub-ps and fs) lasers, paint removal has been attempted with fs Ti–sapphire and fiber lasers. Gaspard et al. examined the modifications induced by 120 fs pulses at 795 nm from a Ti:sapphire laser in unvarnished aged model temperas constituted by unpigmented, cinnabar and chrome yellow paints, and found that the fs laser had better control than ns laser in restoring paintings [15]. Pouli et al. investigated the effect of laser pulse duration in ns–fs range with 500 fs, 248 nm wavelength KrF* excimer pumped dye laser, 100 fs, 800 nm Ti–sapphire laser and ns pulse duration 248 nm KrF* excimer in cleaning varnish over paintings [16,17]. They found that fs, UV laser pulses had better resolution, smaller ablation threshold, and caused little change on the sub-surface compared to 800 nm, fs laser pulses. During ultrashort duration laser irradiation, there is a very short time for heat to conduct, therefore; there is little heat affected zone and no deleterious thermal effects, which is important especially in cleaning of light-sensitive substrates such as artistic paintings. The process efficiency is also one of the important concerns during laser paint removal. It depends on various factors such as laser fluence, laser pulse duration or interaction time, laser operating mode (continuous or pulsed), type of paint to be removed and laser generated plume in the laser–paint interaction zone [9,10,12,13].

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 [9,10,12] or wiping out by some mechanical means [5,13,14]. 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 [9,10,12]. 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 [18].

The use of a high pressure water-jet is also one of the well established processes to remove paints [19–21]. Several investigations on the effects of water-jet kinetic energy, stand-off distance [19], flow characteristics of water-jet in air [20], nozzle design, orifice diameter, and target parameters [21] 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 [22,23]. This utilizes a narrow nozzle opening of the order of 150 μm diameters and a very high water-jet velocity in 200–300 m/s range to remove the molten material from narrow kerfs effectively.

From the above review it can be concluded that the laser paint removal process leaves some amount of residual ashes on the substrate surface; however, the high pressure water-jet can remove the ashes very effectively.

In order to remove the paint completely without any trace of ashes, a hybrid laser process which utilizes a water-jet along with the laser beam, has been developed. A coaxial water-jet at about 20 m/s velocity along with a high power fiber laser beam removed the paint and residual ashes very effectively. The results are compared with the gas assisted laser paint removal process [14]. The specific energy required to remove paint was found marginally higher in case of water-jet assisted laser paint removal process. However, complete removal of paint without any trace of ash could be achieved with water-jet assist only.

2. Background: Laser paint removal mechanisms

Paint is essentially a mixture of a binder, pigments, and solvents. Binder sticks the paint to the surface, pigments give colour to the paint and make it opaque, and solvents make the paint spreadable. Binder is a polymeric substance such as drying oils, alkyd resins, epoxy resins or vinyl and acrylic emulsions. These are long molecules containing simple atoms like carbon, hydrogen, nitrogen, oxygen and chlorine. Pigments are inorganic and organic substances and they not only give the paint its colour and finish, but also serve to protect the surface underneath from corrosion and weathering. The solvent used for resin-based paints is a variety of organic compounds, the most common being mineral turpentine, and for emulsion paints this is simply water [24].

Since paint is a multi-components polymeric material its interaction with laser beam and subsequent removal mechanisms are rather complex. Laser interaction with polymeric materials and their ablation mechanisms have been extensively studied in the last couple of decades because of its importance in laser paint stripping and thin film deposition [25–30]. For efficient laser paint removal coating should absorb laser energy effectively. When laser beam is incident on paint coating, a part of laser energy is reflected, a part is absorbed in paint and remaining energy is transmitted to the substrate. Paints are basically dielectric materials and they do not have relatively-free electrons like metals. Therefore, they cannot absorb laser radiation of all wavelengths. They usually have absorption bands in mid-infrared and near UV radiation originating from vibrational and electronic excitations, respectively [12,17,31]. Pigments added in binder to give the desired colour reflect the light of that colour and absorb the complementary wavelengths.

IR laser energy absorbed by vibrational modes gets dissipated as heat raising the temperature of paint coating. As the temperature rises beyond certain threshold paint undergoes melting, sublimation, vaporization, combustion (charring), and decomposition by bond breaking, the so-called photo-thermal or pyrolytic process. On the other hand UV laser energy absorbed in electronic excitation may either dissipate as heat leading to photo-thermal decomposition or cause direct bond breaking which is classified as photochemical or photolytic process. The decomposed volatile fragments can also undergo combustion in air forming a plume over the paint during laser irradiation. The exothermic combustion process provides addition energy to the process. The laser-induced photochemical process is mainly non-thermal, i.e. the temperature rise during the process is not significant. If both thermal and non-thermal mechanisms are significant, the process is denoted as photo-physical [30].

At high laser intensities (>GW/cm^2), which can be readily produced by ns and shorter duration laser pulses, nonlinear processes such as multiphoton absorption, dissociation and ionization can occur. Through multiphoton ionization process a few free seed electrons are produced and these electrons are further multiplied by avalanche ionization process in presence of the intense electric field of high intensity laser beam and form plasma at the paint surface [30,32,33]. Plasma can absorb laser energy by inverse Bremsstrahlung process and thereby its temperature can rise to very high values. High temperature plasma can heat the paint coating by thermal conduction. Thus, the high intensity laser pulses can be absorbed even in transparent materials through the nonlinear multi-photon process.

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