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Laser removal of lubricating oils from metal surfaces

D. Ahn, D. Jang, T. Park, D. Kim *

Department of Mechanical Engineering, POSTECH, Pohang 790-784, Republic of Korea

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ABSTRACT

This work analyzes the laser cleaning process used to remove lubricating oil from metal surfaces. In an experiment, mineral oil is removed from carbon steel, stainless steel, or copper surfaces using near-infrared (Nd:YAG) laser pulses that are weakly absorbed by the oil. The results are compared with those from a strongly absorbing case in which a commercial lubricant is removed from carbon steel surfaces using ultraviolet (excimer) laser pulses that are relatively strongly absorbed by the lubricant. The removal process is visualized using laser flash shadowgraphy. Numerical computations are conducted to estimate the temperatures of the oil and substrate, and the results are discussed in comparison with the experimental data. The removal mechanism has been found to depend critically on the optical properties of the oil. In the case of Nd:YAG laser cleaning where the oil is almost transparent to the incident laser beam, it is effectively removed by the laser pulses. The removal efficiency is independent of the oil film thickness up to 150 μm, revealing that the removal occurs by explosive vaporization of the oil at the oil–substrate interface followed by bulk hydrodynamic flow. On the other hand, removal of an opaque oil film is well explained using a surface ablation of organic ingredients in which the removal rate is substantially lower than the removal rate under the explosive vaporization mechanism. The optimal conditions for oil removal are discussed based on the experimental results.

1. Introduction

Removal of oil from solid or liquid surfaces is important in various applications, including steel manufacturing [1–4], surface coating technology [5,6], semiconductor fabrication [7,8], and environmental restoration [9–11]. The removal of lubricating oil from metal surfaces is particularly essential in high-quality steel production because it critically affects the quality of a coating process [12]. Several chemical and electrolytic degreasing methods have been developed and have proven to be effective for removing oils from metal surfaces [13]; however, these methods typically consume large amounts of toxic chemicals and generate a substantial environmental load. Therefore, the development of environmentally friendly techniques that are free from chemical agents, such as laser beam [14] or plasma [15,16] techniques, has become an important issue.

Previous studies have demonstrated that pulsed laser ablation can effectively remove oils and oil-based organic contaminants from a variety of surfaces [17,18]. Lafargue et al. investigated a cleaning process for low-carbon steel sheets using two laser sources operating at wavelengths in the UV (ultraviolet) to visible range, and they reported the successful removal of carbonaceous pollutants [1]. Durbin et al. used a UV laser to demonstrate that oil-based contaminants trapped in the microcavities of a steel surface can be removed by laser irradiation [19]. Kim et al. showed that a near-infrared (near-IR) laser pulse provides an effective tool for removing lubricants from carbon steel surfaces [12]. More recently, Mateo et al. suggested laser cleaning as an alternative method for removing contaminants generated by oil spill accidents [11,20,21]. They found that irradiation with UV pulses can remove the oil from steel surfaces as well as the coastal rocks.

Despite the above-mentioned studies, no unified understanding of the physical processes underlying laser removal of oil films from solid surfaces is yet available. Although laser ablation of organic materials, such as polymers, has long been the subject of intensive studies [22–25], the process underlying the laser removal of thin lubricant films in the liquid state is complicated by several additional parameters, including the thermal and optical properties of the lubricant and the hydrodynamics of the oil film during pulsed laser ablation. Accordingly, the role of such parameters as the laser wavelength, pulse width, and oil film thickness δ_{oil} remains unclear in the context of laser-based oil removal processes.

In this work, a combined experimental and numerical analysis was performed to reveal the mechanisms underlying the laser removal of mineral oil or lubricant from typical metal surfaces, including carbon steel, stainless steel, and copper surfaces. Mineral oil, weakly absorbing the NIR laser light with an optical penetration depth δ_{opt} on the order of 10 mm, was selected because it is a major component of most commercial lubricants. For comparison,

* Corresponding author. Tel.: +82 54 279 2179; fax: +82 54 279 5899.
E-mail address: dskim87@postech.ac.kr (D. Kim).

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commercial lubricant which is relatively strongly absorbing the UV laser light ($\delta_{opt} = 11$ μm) was tested. The experimental data were compared with the results of numerical simulations to reveal the physical mechanisms underlying the oil removal process, which suggested optimal conditions for removal.

2. Theory

The removal of oil depends strongly on the absorption properties of the oil. Under conditions of strong laser absorption by the oil, direct photothermal and/or photochemical ablation of the oil occurs at the surface because the major ingredients of commercial lubricants are organic components [26–28]. The removal of a transparent liquid film is governed by the phase changes that occur at the liquid–solid interface. Previous studies showed that a nanosecond laser pulse can superheat the liquid above the boiling point (approaching the spinodal limit), leading to explosive vaporization at the interface [29–31]. The spinodal limit is the upper limit for superheating of liquid determined by mechanical-stability requirement, i.e.,

$$\partial p/\partial v\Big|_{T=T_{sp}} = 0, \tag{1}$$

where T_{sp} is the spinodal temperature, p is the pressure, and v is the volume [32]. The explosive vaporization generates sufficient momentum to remove a thin liquid film; therefore, we postulate that an oil film of thickness smaller than a critical value is removed via explosive vaporization, i.e., by the indirect heating of the oil at the solid–liquid interface. Accordingly, the case of transparent oil removal was modeled by solving the heat conduction equation Eq. (2) with laser heat source Eq. (3) to estimate the critical temperature, and the oil film was assumed to evaporate instantaneously when the temperature reached the spinodal limit T_{sp} ($\approx T_c$: thermodynamic critical temperature).

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + S, \tag{2}$$

$$S = (1-R)I_0 \exp(-\alpha z)F(t), \tag{3}$$

$$F(t) = \begin{cases} -\dfrac{1}{t_p}\left|t-t_p\right| + 1 & 0<t<2t_p \\ 0 & 2t_p<t \end{cases}, \tag{4}$$

where T is the temperature, t is the time, z is the axial coordinate, k is the thermal conductivity, ρ is the density, c_p is the specific heat, S is the heat source term for laser heating, α is the absorption coefficient, R is the reflectance, I_0 is the irradiance at the surface, $F(t)$ is the dimensionless temporal pulse shape (triangular type), and t_p is the pulse width. All exterior boundary conditions were assumed adiabatic. The initial temperature over the calculation domain and the ambient temperature were assumed to be 25 °C. The above-described model required various material properties as input data; however many of these values were not available and/or were ill-defined in the case of the commercial lubricant as it is a mixture of many ingredients. Consequently, the optical properties of the oils and the substrates were measured through separate experiments because they were critical for determining the characteristics of laser ablation. The properties of the metal and oil samples are summarized in Tables 1 and 2, respectively.

3. Experimental

The metal samples were prepared by cutting 2 mm thick metal plates into 15 mm × 15 mm pieces and mechanically polishing the surfaces. In the case of carbon steel and stainless steel, sandpaper with CAMI (Coated Abrasive Manufacturers Institute) designation 220 was used for polishing. Similarly, the copper samples were prepared using CAMI 1200 polishing paper. Because the reflectance change depending on the surface roughness was not negligible, all the samples were polished to eliminate the sample-to-sample variation. After polishing, the mineral oil and the lubricant oil were spin-coated onto the sample to form oil films with two different thicknesses, 10 and 150 μm. The lubricant was a cold rolling oil (Yushiroble 200TP(S), Buhmwoo Chemical Inc.). Because the surfaces were not optically smooth, literature values for the optical properties could not be used in the analysis. Therefore, the normal reflectance R of the metal sample was measured by measuring the energy of the incident and reflected laser beams (Table 1). The optical properties of the mineral oil and commercial lubricant were measured using a UV/visible spectrometer (Table 2). Two laser sources were used in the experiment: a KrF excimer laser (λ = 248 nm, full width at half maximum FWHM = 25 ns) and a Q-switched Nd:YAG laser (λ = 1064 nm, FWHM = 6 ns). In both cases, a square-shaped mask was used to form a 1 mm square beam spot with a flat-top energy distribution on the sample surface. The Nd:YAG laser scanned the entire sample surface at variable frequencies up to 10 Hz, which adjusted the number of pulses, N, delivered to a spot. Use of the excimer laser to remove the commercial lubricant resulted in strong absorption of the laser beam by the oil, and a very low removal rate was obtained compared with the case of the transparent oil. It was, therefore, necessary to irradiate a single spot with up to 1000 pulses to quantify the removal rate.

Table 1
Thermal and optical properties of the metal samples.

Property	Carbon steel	Stainless steel	Copper
Density (kg/m^3)	7860 [37]	7900 [37]	8960 [37]
Specific heat (J/kg·K)	434 [38]	477 [38]	384 [37]
Thermal conductivity (W/m·K)	52 [37]	15 [37]	401 [37]
Reflectance (λ = 1064 nm)	0.47	0.68	0.85
Reflectance (λ = 248 nm)	0.32	0.25	0.2
Melting temperature (°C)	1515 [37]	1425 [37]	1085 [37]

Table 2
Thermal and optical properties of the mineral and commercial lubricant.

Property	Mineral oil	Lubricant oil
Density (kg/m^3)	834 [39]	900 [40]
Specific heat (J/kg·K)	2255 [39]	2000 [41]
Thermal conductivity (W/m·K)	0.15 [39]	0.15 [41]
Flash point (°C)	150–200 [41]	200–310 [41]
Reflectance (λ = 1064 nm)	0.04	0.04
Absorption coefficient (m^{-1}, λ = 1064 nm)	~0	~0
Reflectance (λ = 248 nm)	0.04	0.04
Absorption coefficient (m^{-1}, λ = 248 nm)	3×10^2	9×10^4

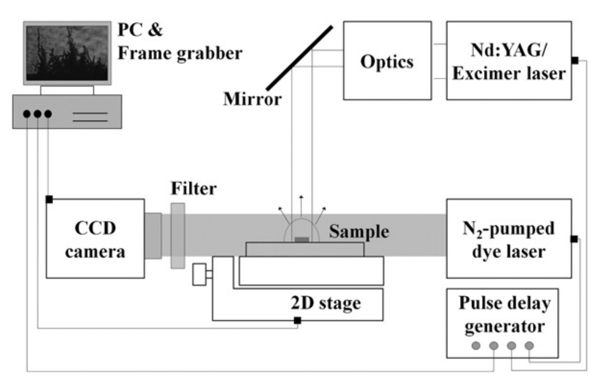

Fig. 1. Experimental setup for the oil removal and in situ shadowgraphic visualization.