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A model to calculate the laser absorption property of actual surface

Hongze Wang [a,*], Yosuke Kawahito [a,*], Ryouhei Yoshida [b], Yuya Nakashima [c], Kunio Shiokawa [c]

[a] Joining and Welding Research Institute (JWRI), Osaka University, 11-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan
[b] Graduate School of Engineering, Osaka University, Suita, Osaka 567-0871, Japan
[c] Fuji Electric Corporation, Tokyo 191-8502, Japan

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ABSTRACT

Research on absorption rate could contribute to better understanding laser processing. In this paper, a mathematical model was developed to calculate the laser absorption rate of actual surface considering the fractal characteristic. Fractal parameters were determined based on the measured characteristic of surface roughness, surfaces that met the fractal nature were then built. A light tracing algorithm was developed to trace the route of light in multiple reflections through the surface rough structure, and the Fresnel equation was used to calculate the fraction of the absorbed light at each reflection. The experiment system to measure the absorption rate of blue laser in hardening based on the water calorimetric method was developed. The experimental absorption rate fit well with the theoretical value, verifying the model as a tool to calculate the absorption rate in laser hardening.

1. Introduction

Laser processing has been widely used in industry because of the advantage in quality, stability, efficiency and flexibility [1–3]. Absorption rate of laser light determines the interaction behavior between the laser light and the material. Research on absorption rate could contribute to better understanding the mechanisms of laser processing. Various researchers have focused on the experimental method to measure the absorption rate [4–12]. Water calorimetric method was reported to be an effective method [5,7,13,14], and had been used to measure the absorption rate in laser hardening and welding. Wang [10] investigated the effect of surface roughness on the absorption rate in laser surface treatment by experiment, and the results showed that the absorption rate increased with surface roughness. However, there was no obvious theoretical progress in the method to calculate the absorption rate in the last years.

Fresnel theory, which described the behavior of light when moving between media of different refractive indices, has been widely used to calculate the light absorption rate [15]. In this theory, the optical properties of the material, wave length and incidence angle of light were considered, while the characteristic of surface roughness of the actual material wasn't. Fig. 1 shows the schematic of the interaction between light and a rough surface. The flat surface in macro scale with the calibration equal to 1 mm appeared to be fluctuant when the calibration was equal to 1 μm, and this fluctuation characteristic was further enlarged when the calibration was equal to 0.1 μm. When laser was irradiated on the surface of material, multiple reflections might happen in the rough tiny structure. Characterizing this tiny structure of the rough surface was the key procedure to estimate the absorption rate accurately. Bergström [16] supposed that the peak of the rough surface met Gaussian distribution, and developed a model to calculate the effect of roughness and slope on absorption rate, and the results showed that the coupled function of roughness and slope would significantly affect the absorption rate. However, the actual rough surface was much more complicated, and the Gaussian distribution assumption might not describe the surface characteristic accurately.

Fractal theory has been widely used to describe the repeating pattern displayed in the world [17]. The rough surface, which appears random and infinitely self-similar, can be viewed to meet the fractal rule [18]. Majumdar et al. [19] characterized the rough surface with fractal theory and developed the model to calculate the thermal contact conductance. Pohrt [20] used the fractal theory in the field of calculating the normal interfacial stiffness. However, the fractal theory hasn't been previously used to calculate the absorption rate.

In present work, the actual rough surface was built based on fractal theory. The ray applied on this actual surface was traced with a designed algorithm and absorption rate of the rough surface in laser hardening can thereby be calculated. Effect of incidence

* Corresponding authors.
E-mail addresses: wanghz@jwri.osaka-u.ac.jp (H. Wang), kawahito@jwri.osaka-u.ac.jp (Y. Kawahito).

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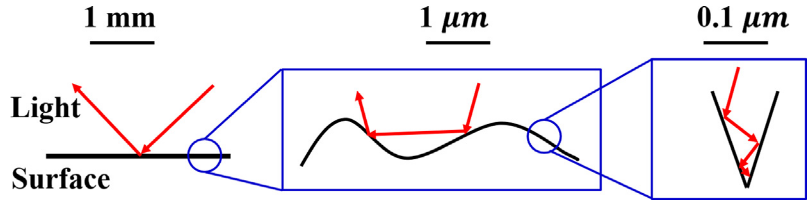

Fig. 1. Schematic of the interaction between light and a rough surface.

angle on the absorption rate was also investigated. This paper provides a method to calculate the laser absorption rate of actual surface in hardening.

2. Fractal surface

2.1. Measurement of surface roughness

Characteristic of surface roughness of steel SUS420 was measured by confocal laser scanning microscope, KEYENCE VK-X250. The representative rough profile is shown in Fig. 2. The surface was rough, both the height and the location of the embossment varied randomly. This rough surface was thought to meet the fractal law [21,22], and this measured rough data will be used to extract the fractal parameters.

2.2. Fitting fractal parameters

Weierstrass-Mandelbrot (WM) function could be used to characterize the rough profile that met the fractal law [23,24], and the equation to describe the profile was:

$$z(x) = G^{(D-1)} \sum_{n=n_1}^{\infty} \frac{\cos 2\pi\gamma^n x}{\gamma^{(2-D)n}}, \ 1 < \mathrm{D} < 2, \ \gamma > 1 \tag{1}$$

where G and D were the fractal roughness and fractal dimension, respectively. γ^n controlled the density of frequency of the surface roughness and $\gamma = 1.5$ was a typical value for rough surface [23], n was the number of the wave, and $\gamma^{n_1} = \frac{1}{L}$, L was the length of the measured surface, here 30 μm (the length in X direction as shown in Fig. 2). Roughness of the surface would then be decided by parameters G and D.

The power spectrum method was usually used to calculate the fractal parameters based on the measured rough profile by fitting. The power spectrum of the W-M function was expressed as [19]:

$$S(\omega) = \frac{G^{2(\mathrm{D}-1)}}{2\ln\gamma} \frac{1}{\omega^{(5-2D)}} \tag{2}$$

The structural function of the profile was defined as [19]:

$$S(\tau) = \left\langle [z(x+\tau) - z(x)]^2 \right\rangle = \int_{-\infty}^{+\infty} S(\omega)(e^{jw\tau} - 1)d\omega \tag{3}$$

By submitting Eq. (2) into Eq. (3), and computing this integral, the integrated equation could be:

$$S(\tau) = CG^{2(D-1)}\tau^{(4-2D)} \tag{4}$$

where

$$C = \frac{\Gamma(2D-3)\sin[(2D-3)\pi/2]}{(4-2D)\ln\gamma} \tag{5}$$

For the rough profile, the fractal dimension D met the range of $1 < D < 2$, and C was constant.

The linear relationship between $S(\tau)$ and τ was obtained on the double logarithmic coordinate axis, and the slope of the line is defined to be K_s. If $0 < K_s < 2$, then this profile could be viewed to meet the fractal law. The fractal dimension D was:

$$D = \frac{4 - K_s}{2} \tag{6}$$

The fractal roughness G could be calculated based on the intercept K_I on the $\log_{10}(S_\tau)$ axis, and the equation was:

$$G = \left(\frac{10^{K_I}}{C}\right)^{\frac{1}{2(D-1)}} \tag{7}$$

Fig. 3 shows the relationship between $\log_{10}\tau$ and $\log_{10}S(\tau)$, both the experimental and fitted results are presented. For each profile (as shown in Fig. 2), one group of $S(\tau)$ could be obtained. Ten profiles from different positions of the surface were obtained, and the average of $S(\tau)$ from these profiles was calculated, representing the average of the rough information of the surface. The fitted coeffi-

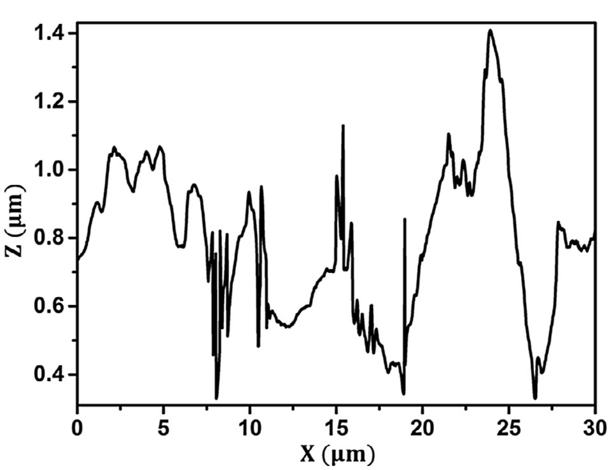

Fig. 2. Characteristic of the measured rough profile.

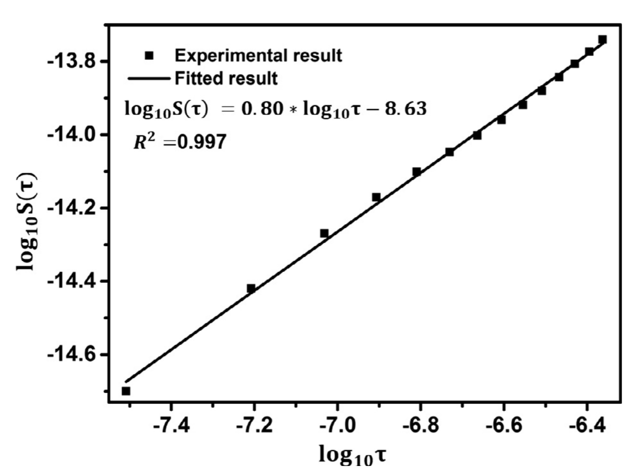

Fig. 3. Relationship between $log_{10}S(\tau)$ and $log_{10}\tau$.