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Laser beam absorption depending on the angle of incidence on ground surfaces

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Abstract

Absorption of the laser beam energy on material surfaces depends on certain conditions, such as incident angle or surface roughness. During laser processing complex parts with machined surfaces, e.g. crankshafts, laser beams strike the surface under varied incident angles during the process. Therefore, an analysis of the laser energy absorption on angled polished surfaces becomes necessary. Surface hardening was done on micro-alloyed steel plates with a surface roughness of 0.5 µm. The angle of the laser beam relative to the plate surface was varied. The sizes of heat-affected zones in the material surface were measured and compared, showing that the absorptivity at incident angles of 10°, 20°, and 30° tends to be constant. However, changes of the incident angle affects the beam size and thus the value of power density and line energy, which can affect the process results. Therefore, the angle or curvature of the structure must be taken into consideration for process development since process parameters must be changed depending on the angle or curvature of the specimens.

Keywords: Absorption; laser surface treatment; angle of incidence; microalloyed steel.

1. Introduction

In the case of conducting materials, such as metals, propagation of the electromagnetic waves includes exchange of energy between the incoming electromagnetic waves and electrons in the surface. The electrons take the electromagnetic waves' energy to excite into higher energy levels, while the electromagnetic waves experience a decrement of the amplitude (Griffiths, 1999). This phenomenon is called absorption.

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The electromagnetic waves are then seen as a form of energy source that can develop its own dynamics depending on the specific electronics response. For example, near infrared high-power lasers can be seen as a thermal energy source for materials processing (Schaaf, 2010). The energy of an infrared laser is absorbed by the electrons in the surface of a specimen through inter- and intra-band electronic transitions. Therefore, the laser beam induces a non-equilibrium electronic distribution that thermalizes the specimen's surface via electron-electron and electron-phonon interactions (Indhu et al., 2018). Then, the heat created in the surface spreads in depth and sideways through conduction. The materials structure and properties can be altered in this way for engineering and industrial proposes. Consequently, the absorption takes an important role in the characteristics of the process.

The amount of laser beam energy being absorbed at the interface can be approximated through the Fresnel equations as

$$A_p = \frac{4n\cos\theta}{(n^2+k^2)cos^2\theta+2n\ \cos\theta+1} \tag{1}$$

$$A_s = \frac{4n\cos\theta}{n^2+k^2+2n\ \cos\theta+cos^2\theta} \tag{2}$$

p and *s* denotes the polarisation of the laser beam in parallel and perpendicular to the plane, respectively. θ is the angle of incoming laser beam to the normal plane. The absorptivity of unpolarised laser beam can be estimated as an average of the two polarisations.

$$A = \frac{A_p+A_s}{2} \tag{3}$$

The *n* and *k* are refractive index and extinction coefficient, which are related to the complex electrical permittivity of the materials as

$$k = \sqrt{\frac{-\varepsilon_1+\sqrt{\varepsilon_1^2+\varepsilon_2^2}}{2}} \tag{4}$$

$$n = \sqrt{\frac{\varepsilon_1+\sqrt{\varepsilon_1^2+\varepsilon_2^2}}{2}} \tag{5}$$

ε_1 and ε_2 correspond to the real and imaginary permittivity values. The permittivity that includes inter- and intra-band absorption has been derived (Roberts, 1959) as

$$\varepsilon = 1 - \frac{\lambda^2}{2\pi c\varepsilon_0}\sum_m \frac{\sigma_{Dm}}{\lambda_{Dm}-i\lambda} + \lambda^2 \sum_n \frac{K_{in}}{\lambda^2-\lambda_{in}^2+i\delta_{in}\lambda_{in}\lambda} \tag{6}$$

i denotes inter-band, D is the Drude terms, c is the velocity of light and ε_0 is the permittivity of vacuum. The Drude parameters σ_{Dm} and λ_{Dm} represent the conductivity and the damping, respectively. λ_{Dm} is calculated from the collision frequency in the same way as the laser wavelength can be calculated from the laser frequency. λ_{in} can be related to the resonance wavelength and δ_{in} to the damping coefficient.

These show that absorptivity depends on the incident angle of the laser beam, electronics properties of the materials and the wavelength of the laser beam. Dausinger (2008) calculated the refractive index and extinction coefficient for Iron at a laser wavelength of 1.06 µm. Accordingly, the absorptivity along different angle of incidence is shown in Figure 1.

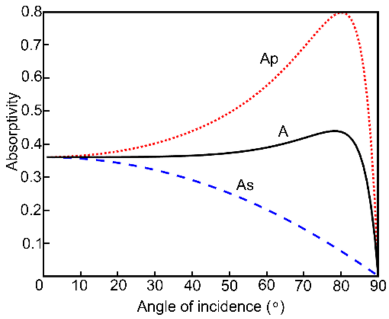

Fig. 1. Absorptivity of near infrared laser beam on steel depending on the angle of incidence.

The absorptivity of an unpolarised laser beam tends to be almost constant up to 40^{o}. It starts to increase and reach the peak at 78^{o}. This behaviour is called Brewster effect, where a certain angle of incidence gives the highest absorptivity. This also shows that the absorptivity can change according to the angle of incidence, which may affect the outcome of laser processing a complex structure, such as a crankshaft. Therefore, analysis and observation of this behaviour was carried out to improve the energy efficiency. Hence, this work evaluates the impact of the incident angle laser hardened zone after laser surface heat-treatment.

2. Methods

2.1. Experimental

Figure 2 illustrates the experimental set-up. A defocused Gaussian-like beam of 8 mm diameter from Yb:fibre laser by IPG photonics with a wavelength of 1070 nm was used to produce single straight surface treated lines at a length of 60 mm.

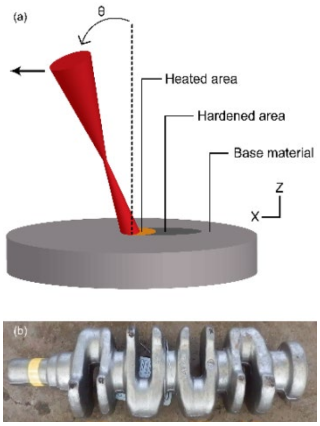

Fig. 2. (a) Illustration of the experimental set-up, showing an angled defocused Gaussian-like laser beam moves along x-axis, leaving a hardened area and (b) example of crankshaft's complex structure

38MnSiVS5 and 44MnSiVS6 microalloyed steels were used as specimens. The specimens were prepared as disks of 10 mm thickness and 110 mm in diameter. The disks' surfaces were grinded to 0.5 µm to 1 µm. Three different incident angles of the laser beam were investigated. The power was changed according the angle of incidence to achieve the same power density. The experiment was divided into two parts; the first part had constant scanning speed and was applied to both steel. The second part of the experiment used adjusted scanning speed to maintain the same line energy. This was done for the 44MnSiVS6 microalloyed steel. Entire investigated parameters in this work are shown in Table 1.

Table 1. Applied parameters on the two steels at three variations of incident angle with constant scanning speed as the first part of the experiments and adjusted scanning speed to maintain the same line energy as the second part of the experiment.

Angle of incidence (^{o})	Laser power (W)	Laser scanning speed (mm/s) I	Laser scanning speed (mm/s) II
	44MnSiVS6		
10	7300		60
20	7767	60	64
30	8424		70
	38MnSiVS5		
10	7300		
20	7767	60	-
30	8424		

2.2. Analysis of the treated cross-section area

Polished cross sections of the samples with the treated surfaces were etched using 5% Nital. Microstructure images were taken using an optical microscope with 1.2 times magnification. The area of the treated zone was approximated by counting the amount of pixels in the treated zone using ImageJ. The region of interest was selected from the original image in Figure 3a. The background was removed and the image colour was blacken as shown in Figure 3b.

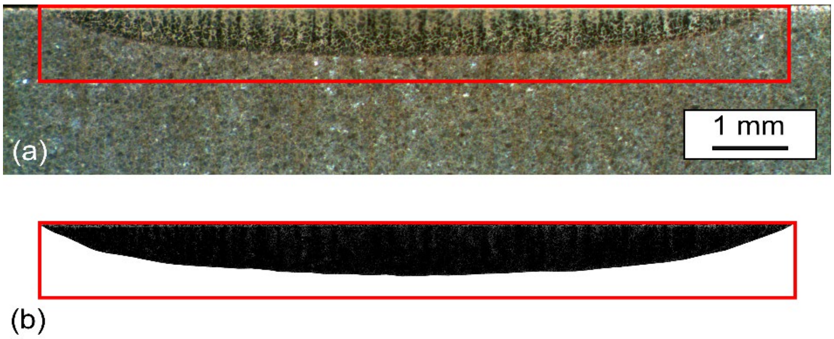

Fig. 3. Measurement of the treated area cross section showing (a) an example of the optical microscope images with rectangular marking of the evaluated area and (b) region of interest from Figure 3a with removed background and blackened treated area

3. Results

The geometry of the heat-treated zone was evaluated and the area of the heat-treated zone was measured. Figure 4 shows that steeper angles of incidence produces larger areas of the heat-treated zones during the first part of experiments (experiments at constant scanning speed), while the areas of the heat-treated zones are relatively constant for the second part of experiments (44MnSiVS6 experiments, adjusted scanning speed). 38MnSiVS5 microalloyed steel samples show higher amount of pixels in the heat-treated area compared to the 44MnSiVS6 samples.

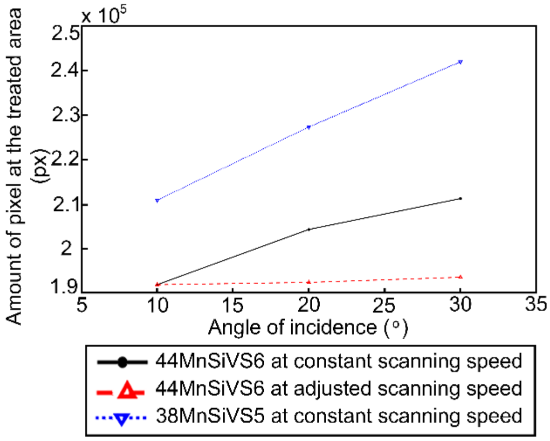

Fig. 4. Results of the treated area analysis as a function of incident angle for all parameters where the solid and dash line corresponds to 44MnSiVS6 samples and the dot line to the 38MnSiVS5 samples.

4. Discussion

When changing the incident angle of the laser beam from a perpendicular illumination, the laser beam shapes are elongated along the tilted direction. This means that steeper incident angles produce a larger laser beam area on the material surface. Since the power density is the ratio between power input and the area of the laser beam, the power input for steeper incident angles will become higher when the power density is kept constant. However, this does not guarantee to give the same energy input along the scanning track. If the ratio between laser power input and the scanning speed is considered, steeper incident angles will have higher energy input along the track when the scanning speed is constant. Therefore, the treated area increases as the incident angle increases in the first experiment of this paper, where the scanning speed was constant at varied incident angle.

Therefore, both power density and energy input along the track should be kept constant to examine the impact of the incident angle on absorptivity. The second part of the experiments shows that the treated area is relatively constant for steeper incident angles. This follows the theoretical model in Figure 1 where the absorptivity value at incident angles of 10^{o} to 30^{o} degree is nearly constant.

Additionally, the observed larger areas of the treated zone for 38MnSiVS5 microalloyed steel samples might occur due to different thermal conductivity of the two materials.

5. Conclusion

The absorptivity of the laser beam is relatively constant along incident angle of 10^o, 20^o, and 30^o. However, change of the incident angle results in a change of laser beam area on the material surface that affects the value of power density and energy input along the track. This is important to note for laser processing complex structures. The angle or curvature of the structure can change the laser beam area, which can interrupt the process outcomes. Hence, the angle or curvature of the structure must be taken into consideration when applying the process parameters. They must be adjusted depending on the angle or curvature of the specimens.

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