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Absorption of Nd:YAG laser beam by metallic alloys

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The development of high power laser systems has enabled the industrial use of lasers in the area of materials engineering, e.g laser cutting and welding, laser transformation hardening, laser alloying and cladding. In particular, laser surface treatment has attracted a great deal of attention because the possibility to heat the surface locally without affecting the material bulk, and the high cooling rates generating novel microstructures. For these applications, CO_2 and Nd:YAG lasers are often used.

Laser processing depends on set of variables of the laser source (wavelength, operation mode, power and diameter of the laser beam) and of the material (geometry, physical properties and laser absorption). If the process of laser treatment is to be useful in industry it is necessary to select, for a given material, their best combination of these parameters [1].

During laser processing the temperature of the metal surface varies over a wide temperature range where melting and even evaporation can be reached. The absorbed energy is transformed very rapidly into lattice vibrations, that is, into heat. Absorption of the laser light is different by solid or liquid. Other factors can affect the material absorptivity beam [2, 3] such as beam polarization and formation of oxide layers that increase the absorption of the laser.

All heat transfer calculations on laser material processing require knowledge of laser beam absorption. Once the temperature profile is known, it is possible to predict the depth of the heat-affect zone, the phase composition and the hardness profile of the laser-irradiated material. Thus, the effect of temperature on the absorption is very important [4].

Investigation of the dynamic variation of the metals absorptivity during laser processing is a topic of scientific and practice interest. Theoretical approaches, such as the Drude model [5], or empirical ones, for example, that of Bramson [6] can be used to predict the absorption in a solid state. Different methods have been developed for experimental determination of absorption, using either calorimetry [7] or ellipsometry [8], which is used to yield data for the liquid state but under conditions very different from the usual laser processing conditions. However, the absorption value for the solid state is certainly the main parameter in laser transformation hardening.

The purpose of this work is to study the laser beam absorption by two metallic alloys, a grey cast iron and an aluminum-silicon alloy, under conditions of transformation hardening using the calorimetry method and electrical resistivity measurements. Gray cast iron and aluminum-silicon alloy have been used in automotive cylinders and pistons fabrication. The laser treatment results in a reduction in wear and better cooling rates, which consequently allows the design of smaller engines or improve their performances.

Calorimetric experiments were conducted on samples ($5 \times 5 \times 0.5$ mm) of both metallic materials. The chemical compositions (wt. %) are given in Tables I and II, respectively. The sample surface without additional absorption coatings was polished with SiC 1000 grid paper, and then ultrasonically cleaned in ethanol in order to obtain the same surface quality for all experiments. Surface roughness was measured to be approximately 1 μm R_a (maximum roughness).

The experimental setup to the calorimetric tests is shown schematically in Fig. 1.

For the temperature measurements, a K-type thermocouple (wire diameter 0.5 mm) was fixed onto the back of the sample. The information of the temperature

TABLE I Chemical composition of the gray cast iron in wt. %

Element (wt.%)						
C	Si	P	Mn	Cu	Cr	Fe
3.45	2.4	0.65	0.75	0.66	0.38	Rest

TABLE II Chemical composition of the aluminum-silicon alloy in wt. %

Element (wt.%)		
Si	Cu	Al
12	1.5	Rest

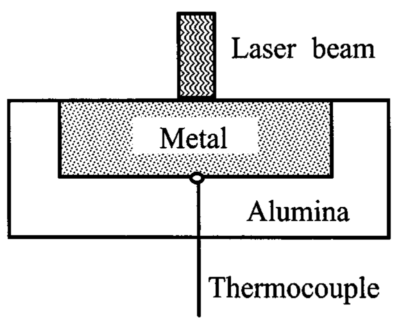

Figure 1 Experimental setup for the absorption measurements.

TABLE III Laser process parameters used for the absorption measurements

Parameter	Value
Pulsed energy [J]	4.55
Beam diameter [mm]	0.74
Repetition rate on sample [Hz]	1.2
Temporal width [ms]	10

variation was led to a signal electronic converter system composed by an amplifier, a lock-in and a computer.

A pulsed Nd:YAG laser ($\lambda = 1.06\ \mu$m) was chosen as a power source. Laser process parameters used for the absorption measurements are summarized in Table III. Under these processing conditions, no liquid phase or visible plasma was observed.

The sample is used as a calorimeter and the mean absorption $\bar{\beta}$ is calculated using the following equation:

$$\bar{\beta} = \frac{m \times c_{\mathrm{p}} \times (T_{\max} - T_{\mathrm{r}})}{E_i} \quad (1)$$

Where m is the mass of the sample in kg, c_{p} is the specific heat in J/kg · K, $T_{\max}$ is the maximum temperature reached by the sample in K, T_{r} is the room temperature in K and E_i is the energy for a number "i" of pulses ($1 \leq i \leq 5$).

For the $\bar{\beta}$ calculations, the specific heat values of the metals were obtained using the Thermocalc Data Base [9]. The temperature dependent specific heat can be calculated by Equation 2, for the gray cast iron, and by Equation 3, for the aluminum silicon alloy.

$$c_{\mathrm{p}} = 650.06 - 0.21014 \times T \quad (2)$$

$$c_{\mathrm{p}} = 548.69 - 0.44629 \times T \quad (3)$$

where T is the temperature in K.

The metal absorptivity was also estimated from an electrical resistivity data of the substrate using the empirical relationship proposed by Bramson:

$$\varepsilon_\lambda = 0.365 \times \sqrt{\frac{\rho}{\lambda}} - 0.0667 \times \frac{\rho}{\lambda} - 0.006 \times \sqrt[3]{\frac{\rho}{\lambda}} \quad (4)$$

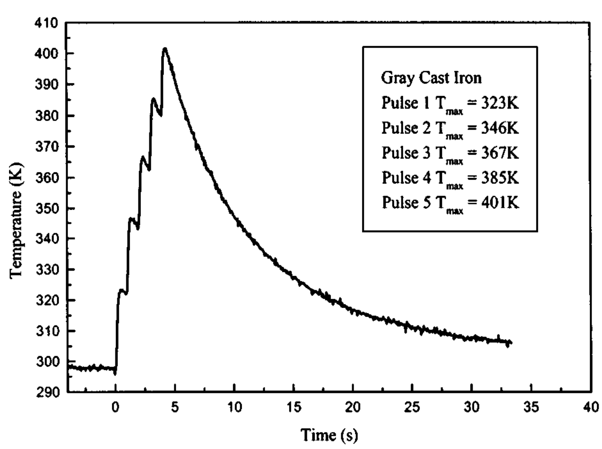

Figure 2 Experimental time-temperature curve obtained for gray cast iron.

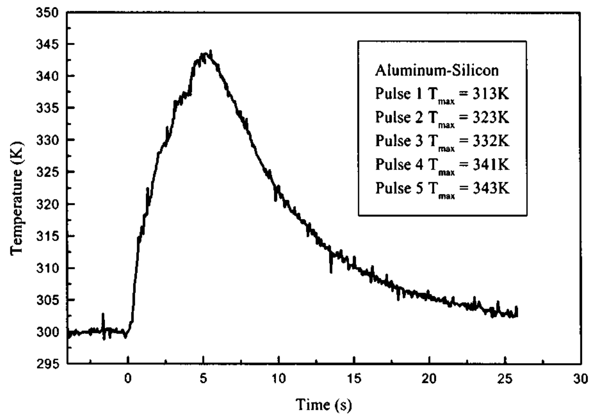

Figure 3 Experimental time-temperature curve obtained for aluminum-silicon alloy.

where ε_λ is the emissivity of substrate, ρ is the substrate electrical resistivity in Ω-m and λ is the wavelength of the laser beam in m.

The resistivity of metal was calculated based on resistance value. For its determination, four samples with different dimensions of each material were used. A digital micro-ohmimeter working with a Kelvin-type bridge system was used to take the resistance value.

The raise of temperature with the application of five pulses is shown in Figs. 2 and 3 for the gray cast iron and the Al-Si alloy samples, respectively.

The $\bar{\beta}$ values found of the metal alloys after application of one until five pulses are presented in Fig. 4. A little $\bar{\beta}$ diminution as the number of pulsed increased is observed, even with the temperature increase. The reasons are that the mean absorption is inversely proportional to the energy provided by each pulsed, according to Equation 1, and also heat runaway by thermal conduction happen.

Considering the wavelength of the laser and the obtained mean values for the metals resistivity, 10.2×10^{-7} Ω-m for the gray cast iron and 5.02×10^{-8} Ω-m for the Al-Si alloy, the mean absorption calculated through the Equation 4 was 30% and 7%, respectively. These values are in good agreement with the mean absorption calculated by calorimetry method. In conclusion, a semi-analytical method was developed to obtain the values of laser-matter absorption of two metallic

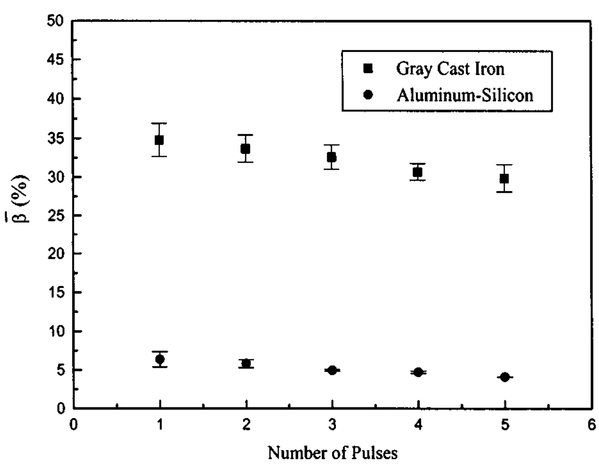

Figure 4 Mean absorption by metallic alloys after application of one until five laser pulses.

alloys during pulsed laser treatment. The absorption of Nd:YAG in metallic samples obtained experimentally by calorimetric method was in good agreement with the theoretical value estimated using electrical resistivity data. The average absorption in the gray cast iron and the Al-Si alloy were 32 and 5%, respectively.

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