Determination of the absorption length of CO_2 and high power diode laser radiation for a high volume alumina-based refractory material

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Abstract

The laser beam absorption lengths of CO_2 (10.6 μm wavelength) and a high power diode laser (HPDL) (810 nm wavelength) radiation for an Al_2O_3/SiO_2-based refractory have been determined through the application of Beer-Lambert's law. The findings revealed marked differences in the absorption lengths despite the material having similar beam absorption coefficients for both lasers. The absorption lengths for the Al_2O_3/SiO_2-based refractory of CO_2 and a HPDL radiation were calculated as being 345±22 μm and 198±15 μm respectively. Moreover, this method of laser beam absorption length determination, which has hitherto been used predominantly with lasers operated in the pulsed mode, is shown to be valid for use with lasers operated in the continuous wave (CW) mode, depending upon the material being treated.

Keywords: laser, absorption, refractory, alumina, silica

1. Introduction

Over recent years the high power diode laser (HPDL) has shown itself to be a viable tool for the processing of many materials. It is therefore imperative that a variety of comparative studies between the HPDL and other industrial lasers are conducted. This paper essentially compares the effects of wavelength differences between a CO_2 and a HPDL and the effects thereof on the lasers' absorption lengths in an Al_2O_3/SiO_2-based refractory material. Previously Schmidt et al. [1] compared the performance of CO_2, excimer and HPDL in the removal of chlorinated rubber coatings from concrete surfaces, noting wavelength dependant differences in the process performance. Additionally, Bradley et al. [2] compared the CO_2 and HPDL for the treatment of Al_2O_3-based refractory materials in terms of microstructure, observing wavelength dependant microstructural characteristics unique to each laser. In more comprehensive investigations, Lawrence et al. compared the effects of CO_2, Nd:YAG, excimer and HPDL radiation on the wettability characteristics of a SiO_2/Al_2O_3-based ceramic [3, 4] and a mild steel [5, 6], noting that in all instances, changes in the wettability characteristics of the material varied depending upon the laser type.

The quantity of published literature to date attests to the fact that the laser surface treatment of ceramic materials is an active field of research. The treatment of both bulk ceramics [7-11] and ceramic coatings [12-15] has been reported. The knowledge of how far a laser beam is absorbed by a material's surface is of fundamental interest, since the outcomes of many laser processing procedures are intrinsically influenced

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by this parameter. Indeed, such information is essential to scientists and engineers interested in the laser processing of ceramic materials. Notwithstanding this, only a limited amount of published work exists pertaining to the determination of the absorption length of laser beams in ceramic materials. Although not directly using the method described in this paper to determine laser beam absorption length, namely the application of Beer-Lambert's law, the fundamental theory behind the method was employed by a number of workers. Andrew et al. [16] used the method to ascertain the minimum fluence required to etch polymeric materials. Schmidt et al. [1] utilised the method to calculate the thermal loading of chlorinated rubber during CO_2 and HPDL treatment.

This paper describes for the first time the determination of the absorption length of CO_2 and HPDL radiation in an Al_2O_3/SiO_2-based refractory through the application of Beer-Lambert's law. The refractory material studied is used commercially as a lining in industrial furnaces and incinerators. Moreover, the method of employing Beer-Lambert's law for the determination of laser beam absorption length, which has hitherto been used predominantly with lasers operated in the pulsed mode, is shown to be valid for use with lasers operated in the continuous wave (CW) mode depending upon the material being treated.

2. Experimental procedures

In order to obtain results of a practical and useful nature, the material used in the experiments was an Al_2O_3/SiO_2-based refractory containing various impurities. The composition by weight of the refractory is as follows: Al_2O_3 (83.5%), SiO_2 (9%), Cr_2O_3 (4.5%), P_2O_5 (1.8%), Fe_2O_3 (0.4%), TiO_2 (0.3%), MgO (0.3%), NaO_2 (0.2%), CaO (0.1%) and K_2O (0.1%). The refractory material studied is used commercially as a lining in industrial furnaces and incinerators. The refractory was obtained (from Cleanaway Ltd.) in the form of blocks (200 x 200 x 100 mm^3). For the purpose of experimental convenience the as-received refractory blocks were sectioned into small cubes (20 x 20 x 10 mm^3) prior to laser treatment. The refractory was treated with both lasers at room temperature and in normal atmospheric conditions.

The work was completed using a CO_2 laser (Rofin-Sinar GmBh) emitting at 10.6 μm with a maximum output power of 1 kW and a HPDL (Diomed Ltd.) emitting at 810±20 nm with a maximum output power of 120 W. The CO_2 laser beam was delivered to the work surface by focusing the beam through a 150 mm focal length KC1 lens to give a stable diverging beam. The HPDL beam was delivered to the work area by means of a 4 m long, 600 μm core diameter optical fibre, the end of which was connected to a 2:1 focusing lens assembly. In both instances the laser optics were protected by means of a coaxially blown Ar shield gas jet a rate of 5 l min^{-1}. Both lasers produced a multi-mode beam. The laser fluences were set such that no melting occurred. The absence of melting was verified by subjecting the irradiated areas to an x-ray diffraction (XRD) to ensure the refractory retained its crystallinity.

3. Results and discussion

As one can see from Fig. 1(a) and Fig. 1(b), the ablation depth rate per shot, h, for the surface of the refractory irradiated with both lasers was seen to exhibit a logarithmic dependence on the laser fluence, E. An optical profiling system (ProScan) was employed to determine the values of h for the various values of E. It is evident from both Fig. 1(a) and Fig. 1(b) that a threshold for discernible material removal exists, with the minimum required fluence being approximately 91 J cm^{-2} for the CO_2 laser and approximately 142 J cm^{-2} for the HPDL.

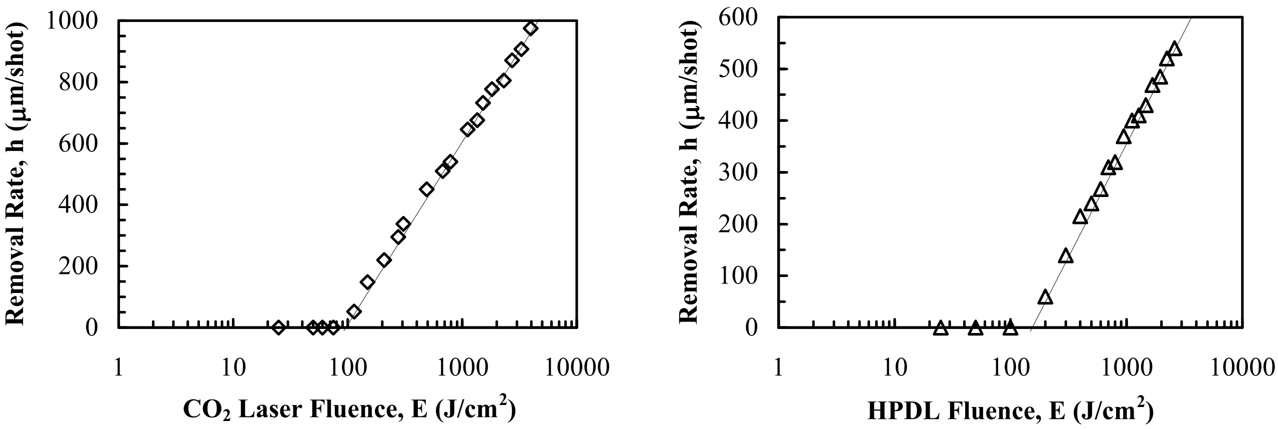

Fig. 1. Removal rate per shot, *h*, as a function of (a) CO_2 and (b) HPDL laser fluence, *E*.

Although this approach has been adopted previously to examine pulsed lasers (excimer) and shown to be sound [16], the technique has also been used to investigate CW lasers [1, 17]. Moreover, the distinct linearity of the data points further validates the use of this approach for the examination of CW lasers. It is important to note that this would assume a minimum conduction loss. However, the Al_2O_3/SiO_2-based refractory has relatively low thermal conductivity (3.25 W/mK), thus it is reasonable to suppose the laser power densities used were high enough and the pulses short enough to minimise the thermal conduction loss.

Since the energy deposition profile will be governed by the optical absorption coefficient, α, then the depth of material removed per shot, *h*, is given by Beer-Lambert's law:

$$h = \frac{1}{\alpha} \ln\left(\frac{E}{E_t}\right) \tag{1}$$

where, E_t, is the threshold value of the fluence at which significant material removal occurs and is defined as [16]

$$E_t = \frac{H + \rho C_p T_d}{\alpha(1 - R)} \tag{2}$$

Here, *H* is the latent heat of fusion, ρ the density, C_p the specific heat and *R* the reflectivity. T_d is some critical temperature at which rapid thermal degradation of the material occurs leading to the production of volatile fragments within the thermal time scale of the experiments. It is important to note that Eq. (1) takes no account of absorption of incident radiation by the plume of removed material and likely changes in the material's level of absorption as removal progresses. Nonetheless, as the work of Andrew et al. [16] and Schmidt et al. [1] demonstrated, this simple form of the expression is quite adequate as a first approximation. By rearranging Eq. (1) in terms of the absorption length, $1/\alpha$, thus:

$$\frac{1}{\alpha} = \frac{h}{\ln\left(\frac{E}{E_t}\right)} \tag{3}$$

then it is possible to determine the absorption length of both CO_2 and HPDL radiation into the surface of the Al_2O_3/SiO_2-based refractory. By introducing the ablation depth rate per shot, *h*, and the corresponding value of laser fluence, *E*, for each data point into Eq. (3) it was possible to calculate the average absorption length for each laser under the actual experimental conditions. These were found to be $1/\alpha=345\pm22$ μm for the CO_2 laser and $1/\alpha=198\pm15$ μm for the HPDL.

The principal factors that may influence the melt depth differences are arguably the absorption length and the actual absorptivity of the surface of the Al_2O_3/SiO_2-based refractory. But, absorptivity measurements made at room temperature using a comparative technique detailed elsewhere [18] revealed that the surface of the Al_2O_3/SiO_2-based refractory absorbed around 62% of CO_2 laser radiation and around 58% of HPDL radiation.

4. Conclusions

By employing Beer-Lambert's law, the laser beam absorption lengths of CO_2 and a high power diode laser (HPDL) radiation for the Al_2O_3/SiO_2-based refractory were determined. The absorption lengths for the Al_2O_3/SiO_2-based refractory of CO_2 and a HPDL radiation were 345 ± 22 μm and 198 ± 15 μm respectively. The principal factors that may influence the melt depth differences are arguably the absorption length and the actual absorptivity of the surface of the Al_2O_3/SiO_2-based refractory. But, absorptivity measurements made at room temperature using a comparative revealed that the surface of the Al_2O_3/SiO_2-based refractory absorbed around 62% of CO_2 laser radiation and around 58% of HPDL radiation. Thus, since these figures are similar, it is reasonable to assume that absorption length is the principal influence on the melt depth.

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