Determination of absorption length of CO_2 and high power diode laser radiation for ordinary Portland cement and its influence on the depth of melting

J. Lawrence, and L. Li

Manufacturing Division, Department of Mechanical Engineering, University of Manchester Institute of Science and Technology (UMIST), Manchester, M60 1QD, UK.

Correspondence

Dr. Jonathan Lawrence
Manufacturing Division,
Department of Mechanical Engineering,
University of Manchester Institute of Science and Technology (UMIST),
Manchester,
M60-1QD,
UK.
Tel : (+44) 161 236-3311
Fax : (+44) 161 200-3803
e-mail : j.lawrence@stud.umist.ac.uk

Abstract

The laser beam absorption lengths of CO_2 and a high power diode laser (HPDL) radiation for concrete have been determined. By employing Beer-Lambert's law the absorption lengths for concrete of CO_2 and a HPDL radiation were 470±22 μm and 177±15 μm respectively. Indeed, this was borne out somewhat from a cross-sectional analysis of the melt region produced by both lasers which showed melting occurred to a greater depth when the CO_2 laser was used.

Keywords: Laser; Cement; Concrete; Absorption; Melting; Vitrification

1. Introduction

A great many laser processing procedures are intrinsically influenced by the depth to which a laser beam is absorbed by a material's surface. It is therefore essential for both scientists and engineers to have knowledge of how far a particular laser beam is absorbed by a certain material. Such information is clearly necessary for those interested in the laser processing of cement and concrete. To date, many studies have been carried out to investigate the laser processing of concrete. Most of the research, however, has concentrated on the laser cutting of concrete and reinforced concrete using high power CO_2 lasers [1-3], the sealing/fixing radioactive contamination onto concrete surfaces [4-7] and the production of novel surfaces [8-10] by means of CO_2 laser glazing of the ordinary Portland cement (OPC) surface of the concrete. In all of these studies, however, spallation and excessive cracking and porosity formation were found to be major problems undermining the performance of the laser glazed region. In contrast, the treatment of the OPC surface of concrete using a high power diode laser (HPDL) has been shown to occasion a glaze that does not suffer from spallation or display excessive cracking and porosity formation [11, 12]. It is believed that the absorption length of the laser radiation for the OPC surface of the concrete has a significant influence on these observed differences in performance.

2. Experimental procedures

In this work a CO_2 laser (Rofin-Sinar) emitting at 10.6μm with a maximum output power of 1 kW and a HPDL (Diomed) emitting at 810±20nm with a maximum output power of 60 W were employed. 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 OPC retained its crystallinity. In order to obtain results of a practical and useful nature the cement used in the experiments was the common 'as cast' OPC surface of concrete. In this case the OPC surface of the concrete had a thickness of 2.5 mm. For the purpose of experimental convenience the as-received concrete blocks were sectioned into squares (120 x 120 x 20 mm) prior to laser treatment. The cement was treated with both lasers at room temperature and in normal atmospheric conditions.

3. Determination of absorption length

As one can see from figure 1 and figure 2, the ablation depth rate per shot, h, for the OPC surface of the concrete 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 figure 1 and figure 2 that a threshold for discernible material removal exists, with the minimum required fluence being approximately 68 J cm^{-2} for the CO_2 laser and approximately 135 J cm^{-2} for the HPDL. Although this approach has been adopted previously to examine pulsed lasers (excimer) and shown to be sound [13], the technique has also been used to investigate continuous wave (CW) lasers [14]. 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, concrete has relatively low thermal conductivity, 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:

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

where, E_t, is the threshold value of the fluence at which significant material removal occurs and is defined as [13]

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

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 (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. [13] and Schmidt et al. [14] demonstrated this simple form of the expression is quite adequate as a first approximation. By rearranging (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 OPC surface of the concrete. By introducing the ablation depth rate per shot, h, and the corresponding value of laser fluence, E, for each data point into (3) it was possible to calculate the average absorption length for each laser under the actual experimental conditions. These were found to be $1/\alpha=470\pm22$ µm for the CO_2 laser and $1/\alpha=177\pm15$ µm for the HPDL.

4. The effects of differing absorption lengths on the depth of melting

The practical implications of the significant differences in the absorption length of the CO_2 laser and the HPDL can be seen in figure 3. Here the incident beams of both lasers on the OPC surface of the concrete were traversed across the surface thus generating a single melt track. In both instances the power density was fixed at 780 W cm^{-2} (power 55 W and spot diameter 3 mm) whilst the traverse speed was set at 540 mm min^{-1}. As one can see clearly from figure 3, the maximum depth of melting achieved when employing the CO_2 laser was 600 µm compared with around 300µm when using the HPDL. This is perhaps surprising when one considers the thermal diffusion length, z_t, which is given by

$$z_t=2\sqrt{at} \tag{4}$$

where, a, is the thermal diffusivity of the material and, t, is the beam material interaction time. Clearly, according to (4), the thermal diffusion length, and hence melting, is a function of the material. Therefore some other factor must come into play in order to cause the differences in the melt depth experienced by the OPC surface of the concrete when exposed to CO_2 and HPDL radiation.

The two most prominent factors that may influence the melt depth differences are arguably the absorption length, $1/\alpha$, and the actual absorptivity of the OPC surface of the concrete. Absorptivity measurements made at room temperature revealed that the OPC surface of the concrete absorbed around 75% of CO_2 laser radiation and around 69% of HPDL radiation. Since these figures are similar, it is perhaps reasonable to assume that absorption length is the primary influence on the melt depth.

5. Conclusions

By employing Beer-Lambert's law, the laser beam absorption lengths of CO_2 and a high power diode laser (HPDL) radiation for concrete were determined. The absorption lengths for concrete of CO_2 and a HPDL radiation were 470±22 μm and 177±15 μm respectively. Further, this difference in absorption length was apparent from a cross-sectional analysis of the melt region produced by both lasers, which revealed melting occurred to a greater depth when the CO_2 laser was used.

The primary factors that may influence the melt depth differences are arguably the absorption length and the actual absorptivity of the OPC surface of the concrete. But, absorptivity measurements made at room temperature revealed that the OPC surface of the concrete absorbed around 75% of CO_2 laser radiation and around 69% 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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Figure 1

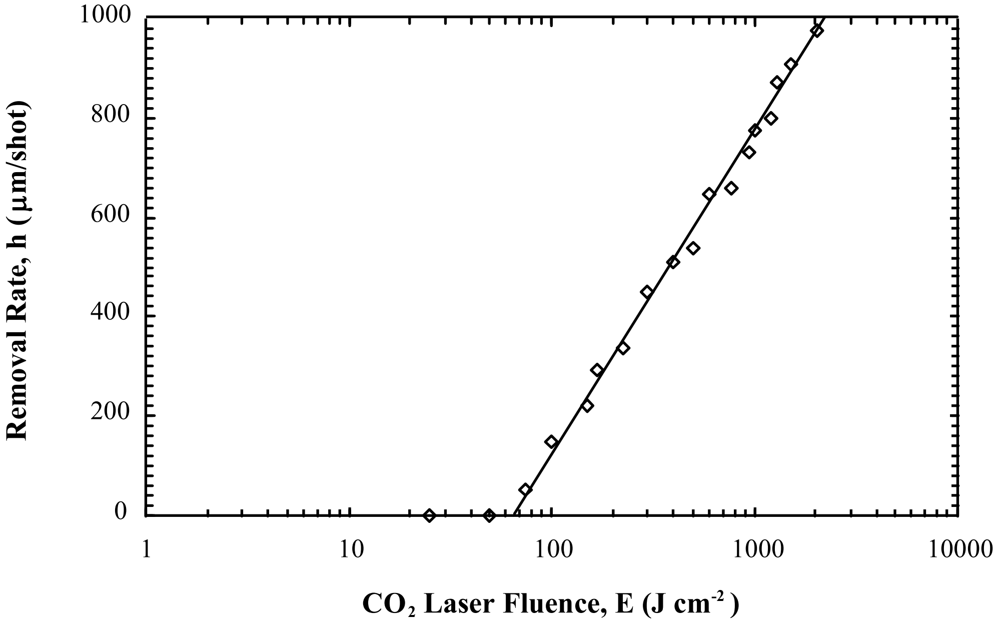
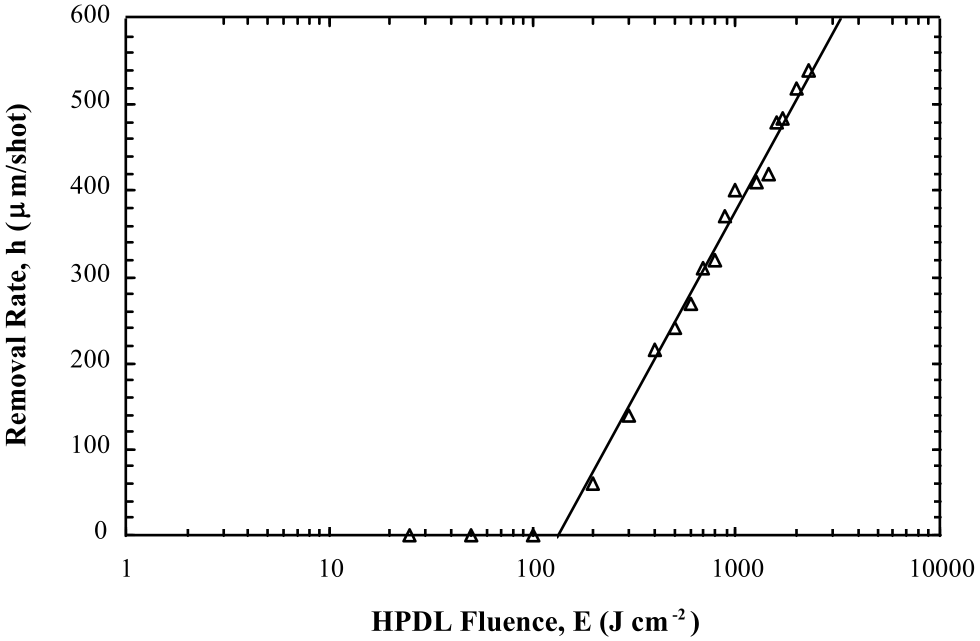
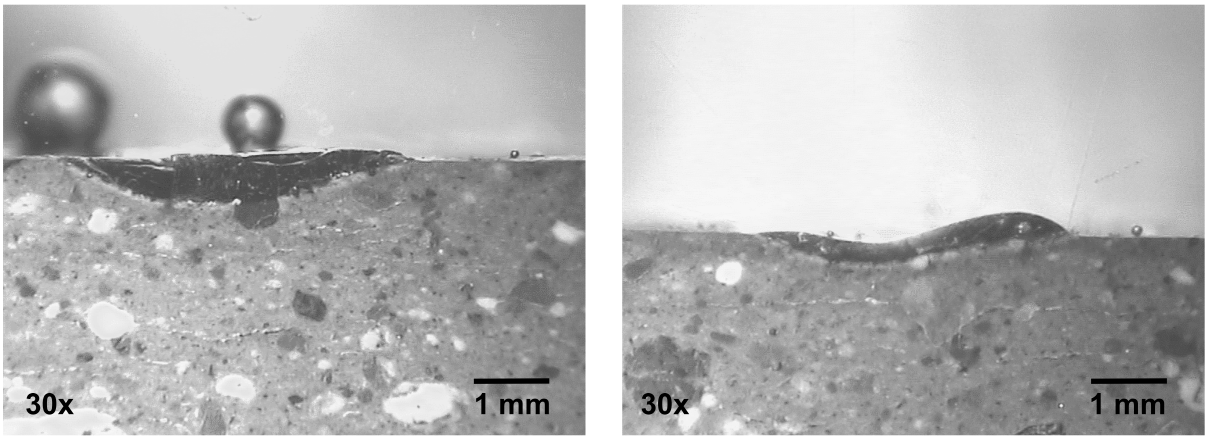

Removal Rate, h (μm/shot)
1000
800
600
400
200
0
1
10
100
1000
10000
CO2 Laser Fluence, E (J cm-2)

Figure 2



Removal Rate, h (μm/shot)
600
500
400
300
200
100
0
1
10
100
1000
10000
HPDL Fluence, E (J cm^{-2})

Figure 3



(a)

(b)