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# Determination of the absorption length of $CO_2$, Nd:YAG and high power diode laser radiation for a selected grouting material

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**Abstract**

The laser beam absorption lengths of $CO_2$, Nd:YAG and a high power diode laser (HPDL) radiation for a newly developed $SiO_2/Al_2O_3$-based tile grout 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 the lasers. The absorption lengths for the $SiO_2/Al_2O_3$-based tile grout for $CO_2$, Nd:YAG and HPDL radiation were calculated as being 232±11 μm, 193±4 μm and 183±8 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, Grout

## 1. Introduction

The potential of the high power diode laser (HPDL) as a most effective, and in certain cases unique tool for a whole host of materials processing applications is being increasingly realised. Therefore,

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it is imperative that a variety of comparative studies between HPDL's and the other main industrial lasers are conducted. This paper essentially compares the effects of wavelength differences between a $CO_2$, an Nd:YAG and a HPDL and the effects thereof on the lasers' absorption lengths in a newly developed $SiO_2/Al_2O_3$-based tile grout. 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 ceramics [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 large quantity of published literature to date testifies to the fact that the laser surface treatment of ceramics is an active field of research. The treatment of both bulk ceramic materials [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 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 $CO_2$, Nd:YAG and HPDL radiation in a newly developed $SiO_2/Al_2O_3$-based tile grout through the application of Beer-Lambert's law. The material studied has been recently developed to provide a crack and porosity free seal in the void between adjoining vitrified ceramic tiles. Essentially the material is there to provide an alternative to using commercially available epoxy tile grout to seal ceramic tiles. 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.

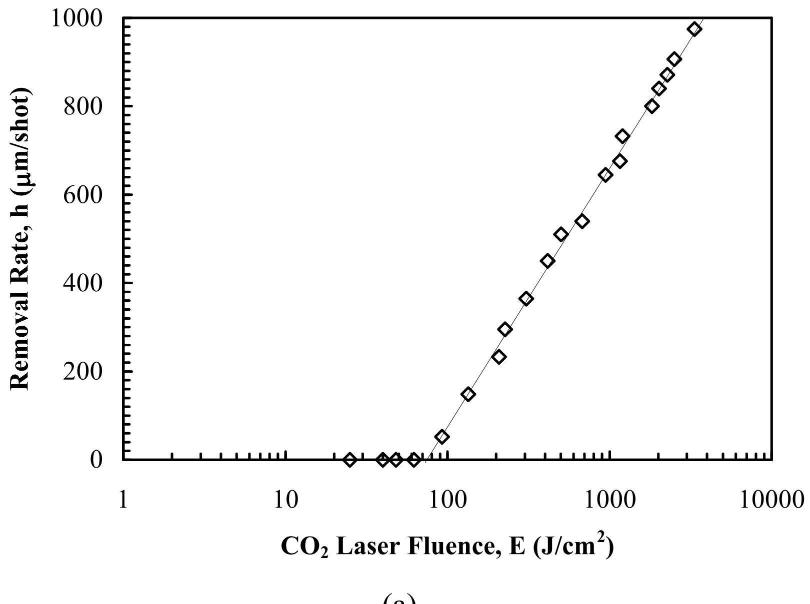
## 2. Experimental procedures

The composition by weight of the $SiO_2/Al_2O_3$-based tile grout is as follows: $SiO_2$ (72.0%), $TiO_2$ (1.6%), $Al_2O_3$ (20.5%), $Fe_2O_3$ (0.8%), CaO (1.0%), MgO (1.6%), $K_2O$ (2.0%), $Na_2O$ (0.5%). For the purpose of experimental convenience the $SiO_2/Al_2O_3$-based tile grout was sectioned into small cubes (20 x 20 x 10 $mm^3$) prior to laser treatment. The refractory was treated with lasers at room temperature and in normal atmospheric conditions.

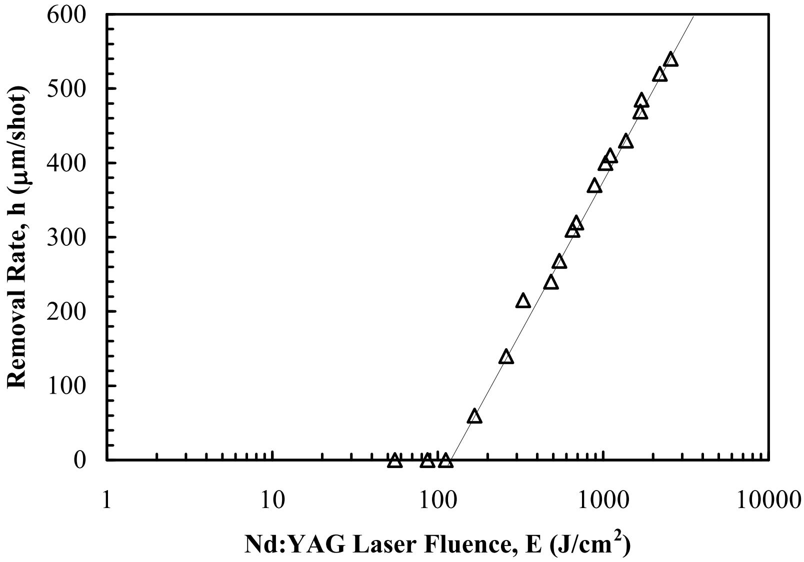
The work was carried out using a $CO_2$ laser (Rofin-Sinar GmBh) emitting at 10.6 μm with a maximum output power of 1 kW, an Nd:YAG (Lumonix Ltd.) emitting at 1.06 μm with a maximum output power of 400 W and a HPDL (Diomed Ltd.) emitting at 940 nm with a maximum output power of 120 W. The $CO_2$ laser beam was delivered to the work surface by focusing the beam through a 150 mm focal length ZnSe lens to give a stable diverging beam. The beam of the Nd:YAG laser was delivered to the work area by means of a 3 m long, 1 mm core diameter optical fibre. The beam was then focused on to the surface of the samples by means of a 120 mm focal length focusing lens assembly. Similarly, the HPDL beam was delivered to the work area by means of a 4 m long, 1 mm core diameter optical fibre, the end of which was connected to a 2:1 focusing lens assembly. In all instances the laser optics were protected by means of a coaxially blown Ar shield gas jet at a rate of 5 l/min. All three lasers produced a multi-mode beam. The laser fluences were set such that no melting occurred. An optical profiling system (ProScan) was employed to determine the various depth values. The absence of melting was verified by subjecting the irradiated areas to an X-ray diffraction (XRD) analysis to ensure the $SiO_2/Al_2O_3$-based tile grout retained its crystallinity.

**3. Results**

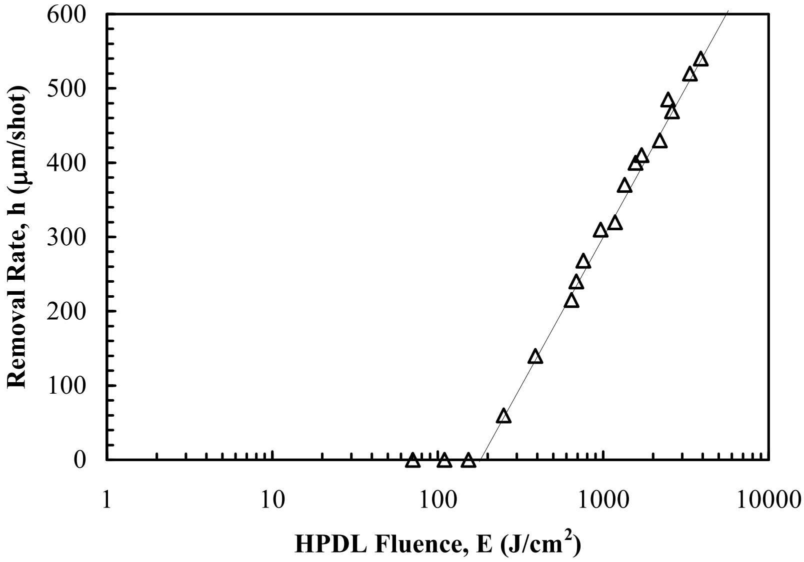
As one can see from Fig. 1, the depth rate per shot, *h*, for the surface of the $SiO_2/Al_2O_3$-based tile grout irradiated with both lasers was seen to exhibit a logarithmic dependence on the laser fluence, *E*. Using the optical profiling system, the values of *h* for the various values of *E*. It 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 74 J/cm$^2$ for the $CO_2$ laser, 135 J/cm$^2$ for the Nd:YAG laser and approximately 181 J/cm$^2$ for the HPDL.




(a)




(b)




(c)

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

## 4. Discussion

Although the approach described above has been adopted previously to examine pulsed lasers, namely excimer lasers, and has been shown to be a sound approach [16], the technique has also been used to investigate CW lasers [1, 17, 18]. Moreover, the distinct linearity of the data points shown in Fig. 1 further validates the use of this approach for the examination of CW lasers. It is important to note that this would assume a minimal conduction loss. But the $SiO_2/Al_2O_3$-based tile grout has a very low value of thermal conductivity (1.36 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:

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

where, $E_t$, is the threshold value of the fluence at which significant material removal occurs and can be estimated from [16]

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

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 Eqn. (1) takes no account of absorption of incident radiation by the plume of removed material and probable 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 Eqn. (1) in terms of the absorption length, $1/\alpha$, thus:

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

then it is possible to determine the absorption length of the $CO_2$, Nd:YAG and HPDL radiation into the surface of the $SiO_2/Al_2O_3$-based tile grout. By introducing the ablation depth rate per shot, *h*, and the corresponding value of laser fluence, *E*, for each data point into Eqn. (3), it was possible to calculate the average absorption length for each laser under the actual experimental conditions. These were found to be $1/\alpha=232\pm11$ µm for the $CO_2$ laser, $1/\alpha=193\pm4$ µm for the Nd:YAG laser and $1/\alpha=183\pm8$ 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 $SiO_2/Al_2O_3$-based tile grout. But, absorptivity measurements made at room temperature using a comparative technique detailed elsewhere [19] revealed that the surface of the $SiO_2/Al_2O_3$-based tile grout absorbed around 81% of $CO_2$ laser radiation, 70% of the Nd:YAG laser radiation and around 63% of the HPDL radiation.

**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 the $SiO_2/Al_2O_3$-based tile grout were determined. The absorption lengths for the $SiO_2/Al_2O_3$-based tile grout of $CO_2$, Nd:YAG and a HPDL radiation were 232±11 μm, 193±4 μm and 183±8 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 $SiO_2/Al_2O_3$-based tile grout. But, absorptivity measurements made at room temperature using a comparative revealed that the surface of the $SiO_2/Al_2O_3$-based tile grout absorbed around 81% of $CO_2$ laser radiation, around 70% of the Nd:YAG laser radiation and around 63% of the HPDL radiation.

**References**


1. M.J.J. Schmidt, L. Li, J.T. Spencer, Appl. Surf. Sci. 138/139 (1998) 378.
2. L. Bradley, L. Li, F.H. Stott, Appl. Surf. Sci. 138/139 (1998) 522.
3. J. Lawrence, L. Li, J. Phys. D 32 (1999) 1075.
4. J. Lawrence, L. Li, J.T. Spencer, Appl. Surf. Sci. 138/139 (1999) 388.
5. J. Lawrence, L. Li, J. Phys. D 32 (1999) 2311.
6. J. Lawrence, L. Li, Appl. Surf. Sci. 154/155 (2000) 664.
7. M. Quinglin, Z. Zengui, D. Xiangzhu, J. Northeast Inst. Tech. 36 (1983) 31.
8. F.S. Galasso, R. Veltri, Ceram. Bull. 62 (1983) 253.
9. M.F. Chen, Y.L. Ge, Z.Q. Hu, High Temp. Technol. 3 (1985) 29.
10. W. Maocai, J. Zhujing, W. Weito, Mater. Sci. Eng. 92 (1987) 145.
11. J.V. Armstrong, M. McLoughlin, J.G. Lunney, J.M.D. Coey, Supercond. Sci. Tech. 4 (1991) 89.
12. Z. Liu, W.M. Steen, W. O'Neill, in: T.S. Sudarshsn, D.G. Bhat, M. Jeaudin (Eds.), Surface Modifications Technologies IV, The Minerals, Metals and Materials Society, PA, USA, 1991.

13. R. Sivakumar, B.L. Mordike, Surf. Eng. 4 (1988) 127.

14. J. Pou, P. Gonzalez, E. Garcia, Appl. Surf. Sci. 79/80 (1994) 388.

15. S.Z. Lee, K.H. Zum Gahr, Mat.-Wiss. Und Werkstofftech 23 (1992) 117.

16. J.E. Andrew, P.E. Dyer, D. Forster, P.H. Key, Appl. Phys. Lett. 43 (1983) 717.

17. J. Lawrence, E.P. Johnston, L. Li, J. Phys. D 33 (2000) 745.

18. J. Lawrence, L. Li, Appl. Surf. Sci. 168 (2000) 72.

19. L. Li, J. Lawrence, J.T. Spencer, Proc. of SPIE: Europto'97 Lasers in Material Processing, Munich, Germany, 1997, 3097, 600