Contrasting the beam interaction characteristics of selected lasers with a partially stabilised zirconia (PSZ) bio-ceramic

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Abstract

Differences in the beam interaction characteristics of a CO_2 laser, a Nd:YAG laser, a high power diode laser (HPDL) and an excimer laser with a partially stabilised zirconia (PSZ) bio-ceramic have been studied. A derivative of Beer-Lambert's law was applied and the laser beam absorption lengths of the four lasers were calculated as 33.55 x 10^{-3} cm for the CO_2 laser, 18.22 x 10^{-3} cm for the Nd:YAG laser, 17.17 x 10^{-3} cm for the HPDL and 8.41 x 10^{-6} cm for the excimer laser. It was determined graphically that the fluence threshold values at which significant material removal was effected by the CO_2 laser, the Nd:YAG laser, the HPDL and the excimer laser were 52 J/cm^2, 97 J/cm^2, 115 J/cm^2 and 0.48 J/cm^2 respectively. The thermal loading value for the CO_2 laser, the Nd:YAG laser, the HPDL and the excimer laser were calculated as being 1.55 kJ/cm^3, 5.32 kJ/cm^3, 6.69 kJ/cm^3 and 57.04 kJ/cm^3 respectively.

Keywords: Laser; Partially stabilised zirconia (PSZ); Bio-ceramic; Interaction characteristics; Threshold fluence; Thermal loading

1. Introduction

There is undoubtedly much global interest in advancing medical science and technology in the area of biomaterials. Consequently, work to this end is often at the forefront of research in many disciplines, with laser materials processing being no exception. Yet despite this, to date only an extremely limited amount of work pertaining to the use of lasers for treating and processing biomaterials has been published. To improve the corrosion characteristics of NiTi shape memory alloys (SMAs) in physiological solutions, Villermaux *et al* [1] examined the possibility of treating the surface of the SMAs with excimer laser radiation. The study concluded that the corrosion resistance of the material was increased due to homogenisation of the surface as a result of melting, surface hardening and the thickening of the surface oxide layer. Work by Guzzardella *et al* [2] found that low power diode laser (LPDL) treatment of implanted prosthetic bone devices fabricated from hydroxyapatite (HA) brought about considerable enhancement in the bone-HA implant interface. Using CO_2, Nd:YAG excimer and high power diode laser (HPDL) radiation Lawrence and Li found that it was possible to effect changes in the wettability characteristics of the bio-polymers polymethyl methacrylate (PMMA) [3] and polyethylene (PE) [4].

But, if the laser is to open up entirely new technologies and unique application areas within the biomaterials field then the fundamental differences in the beam absorption characteristics by materials that exist between different lasers must be investigated. This is particularly true for the relatively contemporary HPDL. Such studies are necessary as the outcomes of many laser processing procedures are inextricably influenced by this parameter. For direct surgical applications this implication has been realised and consequently, many studies have been carried out to examine the effects of laser wavelength variation [5-11]. These studies have revealed clear differences in the performance and effectiveness of many different lasers when interacting with various body parts. In contrast, comparative investigations of the differences in the beam interaction characteristics of the predominant materials processing lasers, the CO_2, the Nd:YAG and the excimer laser, are few in number [12-15]. Even fewer in number are practical comparisons between the established materials processing lasers and the recently arrived HPDL. Previously Schmidt *et al* [16] compared the performance of CO_2, excimer and HPDLs in the removal of chlorinated rubber coatings from concrete surfaces and remarked on wavelength dependant differences in the process performance. Also, Bradley *et al* [17] compared the CO_2 and HPDL for the treatment of Al_2O_3-based refractory materials in terms of microstructure and observed wavelength dependant microstructural characteristics unique to each laser. In more comprehensive investigations, Lawrence and Li compared the effects of CO_2, Nd:YAG, excimer and HPDL radiation on the wettability characteristics of ceramic [18], metallic [19, 20] and polymeric [3, 4] materials, noting that changes in the wettability characteristics of the material varied depending upon the laser type. Furthermore, Lawrence *et al* carried out a comparative study of the characteristic of the glazes generated on the surface of concrete with CO_2 and HPDL's [21, 22], as well determining the absorption depths of CO_2 and HPDL beams in ordinary Portland cement [23, 24] and an Al_2O_3-based refractory [25].

By using a CO_2, Nd:YAG, excimer and a HPDL this paper aims to provide comparative information on the absorption characteristics (in terms of laser wavelength variations) of a partially stabilised zirconia (PSZ) bio-ceramic through such attributes as absorption length and thermal loading. PSZ is a ceramic that has found wide usage in medical and dental surgery. Within medicine it is commonly used to fabricate hip ball joints, whilst in dentistry it is used to manufacture dental implants, dental posts, brackets and inlays. Consequently, it is believed that this work will provide valuable insight into some of the performance characteristics of the HPDL in comparison with the other more traditional materials processing lasers for the treatment of biomaterials, in particular PSZ.

2. Experimental procedures

Four industrial lasers were used in this work: a CO_2 laser (Rofin-Sinar, RS-3000), a Nd:YAG laser (Lumonix, JK704) a KrF excimer laser (Lambda Physik, 200mc) and a GaAlAs HPDL (Rofin-Sinar, DL 015). The general operating characteristics of the lasers used in the study are detailed in Table1. The CO_2 laser beam was delivered to the surface of the PSZ bio-ceramic samples by focusing the beam through a 150 mm focal length ZnSe lens to give a stable diverging beam with beam diameters of 0.6-1.8 mm. The HPDL beam used ranged in size from 1.6- 2.1 mm in diameter and was delivered to the surface of the PSZ bio-ceramic samples by means of a 5 m long, 1.5 mm core diameter optical fibre, the end of which was connected to a 42 mm focal length lens assembly. The beams produced by both the CO_2 laser and the HPDL were multi-mode. For the Nd:YAG laser, the beam was delivered to the surface of the PSZ bio-ceramic samples by means of a 4 m long, 1 mm core diameter optical fibre. The beam, which was of a Gaussian profile, was then focused on to the surface of the PSZ bio-ceramic samples by means of a 120 mm focal length focusing lens assembly with diameters of 1.2-2.2 mm. In the case of the Nd:YAG and HPDLs the focussing optics assembly units were attached to the z-axis of a 3-axis computerised numerical control (CNC) gantry table, whilst the PSZ bio-ceramic samples were placed on the x-axis. In the CO_2 laser arrangement the focussing optics were fixed and the PSZ bio-ceramic samples were placed on the x-axis of a CNC x-y table. In all three instances the laser optics were protected by means of a coaxially blown Ar shield gas jet a rate of 5 l/min. The excimer laser radiation was firstly passed directly through a circular aperture and then a beam homogenizer. The beam was then focussed on the surface of the PSZ bio-ceramic samples to a spot size of 0.5 x 0.5 mm^2 to 3.5 x 3.5 mm^2. Here the PSZ bio-ceramic samples were attached using double-sided tape to the x-axis of a CNC x-y table. The whole arrangement was tipped vertically so as to be perpendicular the incident excimer laser beam. The excimer laser beam had a square top hat profile and the processing took place in an air atmosphere.

For the purpose of experimental convenience the PSZ bio-ceramic was fabricated into blocks (25 x 25 x 5 mm) prior to laser treatment. The PSZ bio-ceramic was treated with all four lasers at room temperature and in normal atmospheric conditions. Experiments were carried out in order to determine the minimum threshold fluence, the absorption length and to examine the thermal loading characteristics of the PSZ bio-ceramic. Here it was necessary that the fluences of all four lasers were set such that no melting occurred. The absence of melting and vitrification was verified by subjecting the irradiated areas to an X-ray diffraction (XRD) analysis to ensure the PSZ bio-ceramic retained its crystallinity.

3. Results and discussion

The depth of material removed per pulse or shot, h, for organic polymer, inorganic insulating and semi-conducting materials has been frequently described by a logarithmic law which follows, heuristically, from Beer-Lambert's law [26]

$$h = \frac{1}{\alpha} \ln\left(\frac{F}{F_t}\right) \tag{1}$$

where α is the optical absorption coefficient, F is the laser fluence and F_t is the threshold value of the fluence at which significant material removal occurs. Moreover, this expression has been shown to be completely applicable to other composite and ceramic materials [23-25]. It is important to realise that the validity of (1) rests on the assumption that the plume species resulting from material removal absorb the laser beams in a similar manner to the solid. Also, probable changes in the absorption level of the material as removal progresses are not taken in account by (1). Nonetheless, as the work of

Andrew *et al* [27], Schmidt *et al* [16] and Lawrence *et al* [23-25] demonstrated, this simple form of the expression is quite adequate as a first approximation. Also, according to Bäuerle [26] the expression is applicable to ablation processes which are either photophysical or photochemical in nature. It is therefore acceptable to use the expression in instances such as this, where laser wavelengths, and consequently interaction mechanisms, vary considerably (from UV to IR).

The relationship between h and F for the four laser beams incident with the PSZ bio-ceramic are given in Figs. 1, 2, 3 and 4. As one can see from these plots, h for the PSZ bio-ceramic irradiated with all four lasers was seen to display a logarithmic dependence on F. Further, by using an optical profiling system (ProScan, Nanofinder) to determine the values of h for the various values of F, the minimum required threshold fluence for discernible material removal, F_t, was determined for each laser (see Figs. 1, 2, 3 and 4) and is given in Table 2. Although this approach has hitherto been employed to examine pulsed lasers (excimer) and shown to be sound [27], the technique has also been used to investigate continuous wave (CW) lasers [16, 23-25]. What is more, the distinct linearity of the data points for the CO_2 and HPDLs in Figs. 1 3 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 PSZ bio-ceramic has relatively low thermal conductivity of only 1.8 W/mK [28], thus it is reasonable to assume that the laser power densities used were high enough and that the shots were short enough to minimise the thermal conduction loss.

Now, the term $1/\alpha$ is the absorption length, so by rearranging (1) thus:

$$\frac{1}{\alpha} = \frac{h}{\ln\left(\frac{F}{F_t}\right)} \tag{2}$$

then it is possible to determine the length to which the beams of all four lasers are absorbed by the PSZ bio-ceramic. By introducing h and the corresponding value of F for each data point into (2) it was possible to calculate the average absorption length for each laser under the actual experimental conditions (see Table 2). From a comparison of these absorption length values with the wavelengths at which each of the four laser emits given in Table 1, one can see that the absorption length appears to decrease with decreasing laser wavelength. It is worth remarking, however, that this decease is disproportionate to actual laser wavelength.

It is interesting at this point to consider the actual absorptivity value of the surface of PSZ bio-ceramic. Absorptivity measurements made at room temperature using a comparative technique detailed elsewhere [29] revealed that the surface of the PSZ bio-ceramic absorbed around 68% of CO_2 laser radiation, around 63% of the Nd:YAG laser radiation, around 59% of the HPDL radiation and around 53% of the excimer laser radiation. Now, for thick materials the sum of the absorptivity, A, and the reflectivity, R, is one. Accordingly A is related to R, which in turn depends upon the (complex) refractive index. These present results suggest that the real part of the index is dominant. So, since these figures are of a similar order, it can be said that correlation between the actual absorptivity of the PSZ bio-ceramic and the absorption length for each of the four lasers is not evident. Thus it is reasonable to assume that absorption length, rather than actual absorptivity, plays a greater role in material coupling.

Work Dyer *et al* [30, 31] has revealed that the surface energy density or thermal loading, γ, of a material increases in an almost linear manner until F_t is attained. Beyond this point γ becomes almost constant due to the rapid ablation of products which carry away excess energy and consequently limit the maximum temperature rise. The value of γ necessary to bring about removal is given by [31]

$$\gamma = F_t \alpha \tag{3}$$

From a rearrangement of (2) it is possible to calculate the value of the absorption coefficient, α, for each of the four lasers. So, by introducing the values of F_t for each of the four lasers deduced earlier from Figs. 1, 2, 3 and 4, along with the values of α for each laser into (3), then γ for the CO_2 laser, the Nd:YAG laser, the HPDL and the excimer laser were calculated (see Table 2).

4. Conclusions

Through the utilisation of a derivative of Beer-Lambert's law, the laser beam absorption lengths of CO_2 laser, Nd:YAG laser, HPDL and excimer laser radiation for a PSZ bio-ceramic were determined. The absorption lengths, $1/\alpha$, were calculated as 33.55×10^{-3} cm for the CO_2 laser, 18.22×10^{-3} cm for the Nd:YAG laser, 17.17×10^{-3} cm for the HPDL and 8.41×10^{-6} cm for the excimer laser. The fluence threshold values at which significant material removal occurs, F_t, for the CO_2 laser, Nd:YAG laser, HPDL and excimer laser were found to be 52 J/cm^2, 97 J/cm^2, 115 J/cm^2 and 0.48 J/cm^2 respectively. The thermal loading, γ, value for the CO_2 laser, the Nd:YAG laser, the HPDL and the excimer laser were determined as 1.55 kJ/cm^3, 5.32 kJ/cm^3, 6.69 kJ/cm^3 and 57.04 kJ/cm^3 respectively. Correlation between the actual absorptivity of the PSZ bio-ceramic and the absorption length for each of the four lasers was not evident. Thus it is reasonable to assume that absorption length, rather than actual absorptivity, plays a greater role in material coupling.

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List of Figs.

Fig. 1. Removal rate per shot, *h*, as a function of CO_2 laser fluence, *F*.

Fig. 2. Removal rate per shot, *h*, as a function of Nd:YAG laser fluence, *F*.

Fig. 3. Removal rate per shot, *h*, as a function of HPDL fluence, *F*.

Fig. 4. Removal rate per shot, *h*, as a function of excimer laser fluence, *F*.

Fig. 1

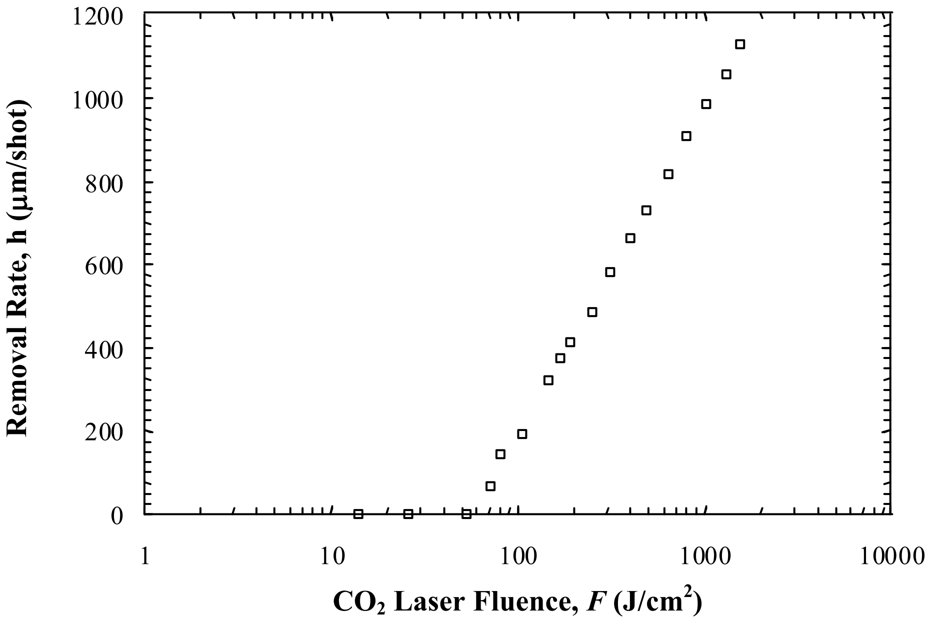
1200
1000
800
600
400
200
0
Removal Rate, h (µm/shot)
1
10
100
1000
10000
CO₂ Laser Fluence, F (J/cm²)

Fig. 2

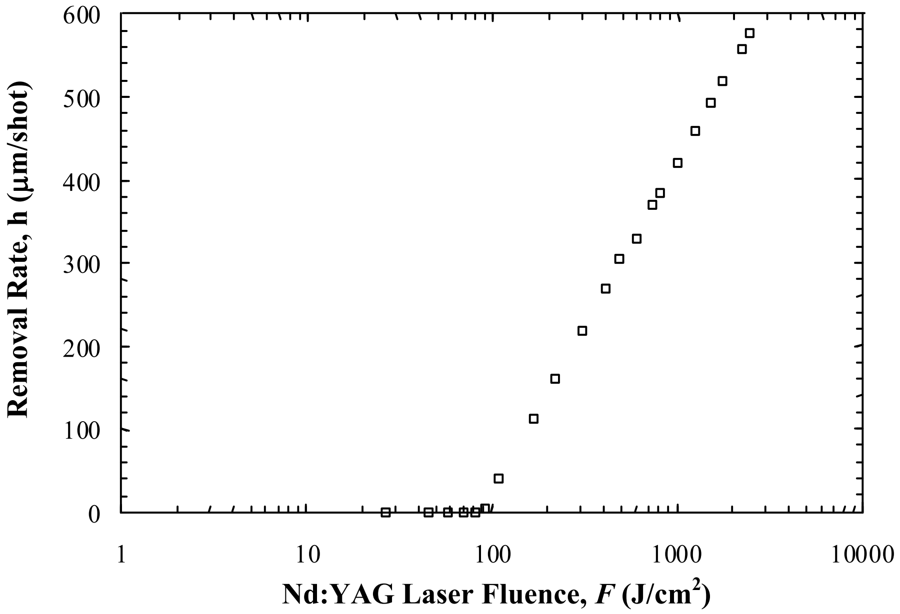
600
500
400
300
200
100
0
Removal Rate, h (μm/shot)
1
10
100
1000
10000
Nd:YAG Laser Fluence, F (J/cm²)

Fig. 3

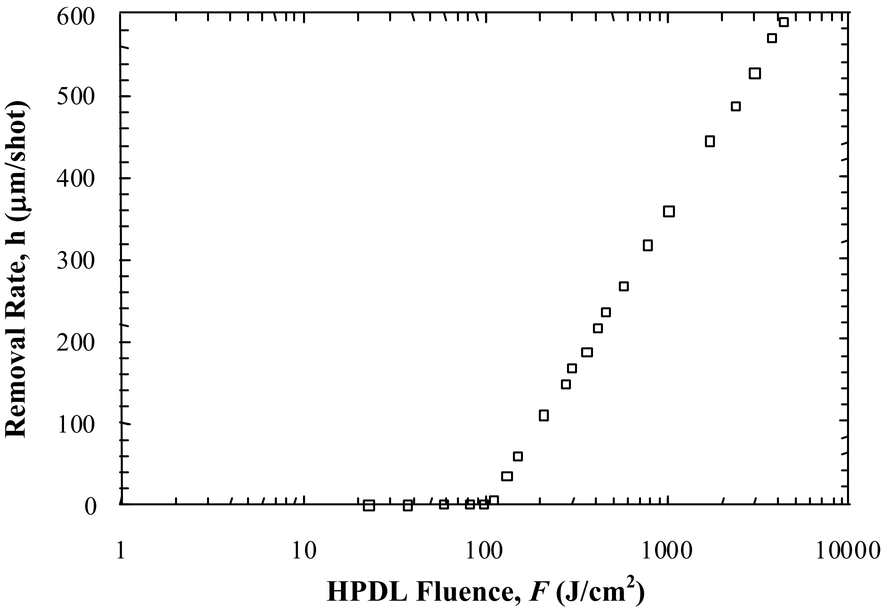
600
500
400
300
200
100
0
Removal Rate, h (µm/shot)
1
10
100
1000
10000
HPDL Fluence, F (J/cm²)

Fig. 4

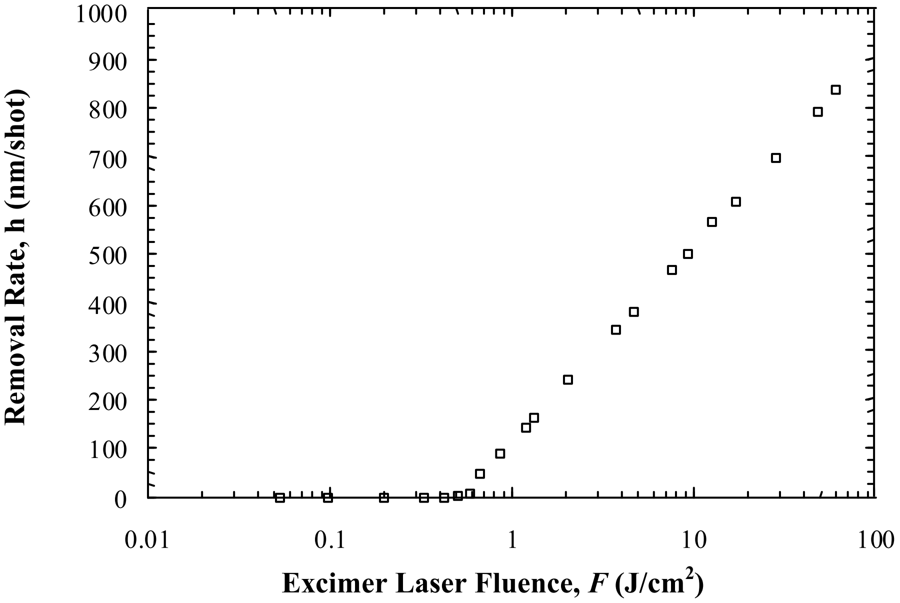
1000
900
800
700
600
500
400
300
200
100
0
0.01
0.1
1
10
100
Removal Rate, h (nm/shot)
Excimer Laser Fluence, F (J/cm2)

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Table 1

Operating Characteristic	**Laser Type** **CO_2**	**Nd:YAG**	**HPDL**	**Excimer**
Lasant	CO_2 gas	Nd:YAG crystal	GaAlAs	KrF gas
Wavelength	10.6µm	1.06µm	940 ±10nm	248nm
Maximum average output	3 kW	400 W	1.5 kW	5 W
Maximum pulse energy	~	55 J	~	35 J
Pulse width	~	0.3 - 20 ms	~	20 ns
Repetition rate	~	0.2 - 500 Hz	~	1-55 Hz
Fibre core diameter	~	1 mm	1 mm	~
Mode of operation	CW	Pulsed (rapid)	CW	Pulsed (multiple)

Table 2

Value	Laser Type			
	CO_2	**Nd:YAG**	**HPDL**	**Excimer**
Threshold fluence, F_t	52 J/cm^2	97 J/cm^2	115 J/cm^2	0.48 J/cm^2
Absorption length, $1/\alpha$	33.55 x 10^{-3} cm	18.22 x 10^{-3} cm	17.17 x 10^{-3} cm	8.41 x 10^{-6} cm
Absorption coefficient, α	29.81 cm^{-1}	54.88 cm^{-1}	58.22 cm^{-1}	118825.21 cm^{-1}
Absorptivity, A	68%	63%	59%	53%
Thermal loading, γ	1.55 kJ/cm^3	5.32 kJ/cm^3	6.69 kJ/cm^3	57.04 kJ/cm^3