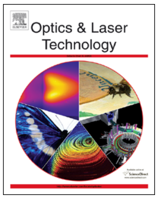
Optics & Laser Technology 54 (2013) 380–388

Contents lists available at SciVerse ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec



# Role of laser beam radiance in different ceramic processing: A two wavelengths comparison

Pratik Shukla*, Jonathan Lawrence

*Lasers and Photonics Group, Lincoln School of Engineering, University of Lincoln, Brayford Pool, Lincoln LN6 7TS, United Kingdom*

## ARTICLE INFO

*Article history:*
Received 12 March 2013
Received in revised form
21 May 2013
Accepted 11 June 2013
Available online 19 July 2013

*Keywords:*
Lasers
Radiance
Ceramics

## ABSTRACT

Effects of laser beam radiance (brightness) of the fibre and the $Nd^{3+}$:YAG laser were investigated during surface engineering of the $ZrO_2$ and $Si_3N_4$ advanced ceramics with respect to dimensional size and microstructure of both of the advanced ceramics. Using identical process parameters, the effects of radiance of both the $Nd^{3+}$:YAG laser and a fibre laser were compared thereon the two selected advanced ceramics. Both the lasers showed differences in each of the ceramics employed in relation to the microstructure and grain size as well as the dimensional size of the laser engineered tracks—notwithstanding the use of identical process parameters namely spot size; laser power; traverse speed; Gaussian beam modes; gas flow rate and gas composition as well the wavelengths. From this it was evident that the difference in the laser beam radiance between the two lasers would have had much to do with this effect. The high radiance fibre laser produced larger power per unit area in steradian when compared to the lower radiance of the $Nd^{3+}$:YAG laser. This characteristically produced larger surface tracks through higher interaction temperature at the laser–ceramic interface. This in turn generated bigger melt-zones and different cooling rates which then led to the change in the microstructure of both the $Si_3N_4$ and $ZrO_2$ advance ceramics. Owing to this, it was indicative that lasers with high radiance would result in much cheaper and cost effective laser assisted surface engineering processes, since lower laser power, faster traverse speeds, larger spot sizes could be used in comparison to lasers with lower radiance which require much slower traverse speed, higher power levels and finer spot sizes to induce the same effect thereon materials such as the advanced ceramics.

## 1. Introduction

### 1.1. *Background of laser beam radiance*

Brightness of a light source could be quantified as radiance or luminescence [1,2]. However, when dealing with lasers it is important to define which quantity is more related, since luminescence is the measure of a light source in relation to the sensitivity of a human eye, whereas radiance is related to the measure of that quantity of light at a practical level in relation to the energy exhibited per unit area, generally measured in wattage [3–4]. Having said that, laser beam brightness could be defined as radiance (power per unit area in a solid angle of divergence measured in steradian) for practicality and for the comparison of two light sources (which is the case in this paper) and for simplification [5,6]. Radiance is often confused with irradiance which is the power per unit area (radioactive flux) acting on a surface. The units for radiance are ($W\,mm^2\,Sr^{-1}$), whereas the units of irradiance are $W/m^2$. In simplest terms, radiance is the power from the source per area into a certain solid angle as diverted, whereas irradiance is the power onto a surface per area.

Due to monochromatic, coherent and unidirectional properties of the laser beam, its focus in a small surface area enables the laser light to produce highly radiant beams in comparison to other light sources [7,8]. The radiance is generally not affected by any changes to the parameters by the end use [9–11]. Laser beam parameters, namely solid angle of divergence, wavelength, beam quality factor ($M^2$), spot size and laser power are major contributors to the laser beam radiance and are used to calculate [12–17], or to measure [18–20], the radiance value for laser beams. However, practical measurement of the laser beam radiance is very complicated and involves timely set-ups; hence, theoretical approach is more desirable and an accurate means for prediction.

This paper emphasizes that taking laser beam radiance into consideration during design of process parameters would allow one to characterize the laser beam since it is a measure of many parameters combined. The reason for the emphasis of this paper is due to the simple understanding of laser beam radiance being a parameter that involves the laser power, spot size (power density) beam mode, $M^2$, and the wavelength. The laser beam radiance as a

---

* Corresponding author. Tel.: +44 7739461805.
*E-mail address:* pratik.shukla@talk21.com (P. Shukla).

0030-3992/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.optlastec.2013.06.011

whole is then classified as the input power per unit area per solid angle [19–20] as stated before. On account of this, it is proposed that laser beam radiance is an important parameter in laser-material processing and should be used when designing parameters since, laser material processing by using high radiance laser such as a fibre laser, characteristically, gives fine spot sizes and generates longer focusing distance. This in turn enhances the flexibility of laser processing since large areas can be covered.

### *1.2. Previous research in the field of high radiance lasers and material processing*

Lasers emitting high radiance have been used in the recent years by several workers [19,20]. But it is the term brightness which is commonly used rather than radiance in previous literature. Lower operating costs were reported with the use of bright and highly radiant laser sources by Wallace [9]. Increase in reliability and efficiency was reported by Wenzel et al. [10]. Cutting and drilling of aerospace alloys were reported by Brown and Frye [11] with the use of a $Nd^{3+}$:YAG laser. This achieved good cut quality and shallow hole angles. A high radiant laser of 940 nm wavelength was used by Li et al. [15], to investigate the reliability and efficiency. The results demonstrated that maximum power conversion efficiency of 60% was achieved with a good beam quality factor and 72 W laser power. A semiconductor laser was modified by Treusch et al. [21] using collimated lenses which increased the radiance by two folds to affect material processing. Leibreich and Treusch [22] conducted an investigation to enhance the brightness of a semiconductor diode laser. The investigation involved the use of laser beams of different wavelengths. Doing so enhanced the output power as well as the visual brightness of the laser beam. In addition, alteration in the transverse mode was made to enhance the laser beam radiance as shown by Hanna [23,24]. Val et al. [25] followed an investigation which reported the effects of radiance during laser cladding of stainless steel and co-based super-alloy powder as a coating material by employing a $Nd^{3+}$:YAG laser and a Yb:YAG laser. Enlarged clad tracks and deeper penetration were also reported on metals and alloys. This effect would have taken place due to the better beam quality and high radiance of the fibre laser [25].

### *1.3. Research rationale*

Various investigations have shown methods to improve the laser beam radiance [9,10,19,20]. Some studies have also shown the effect of a high brightness or radiant laser to affect metals and alloys [11,15,21,25]. However, to date, no work has been conducted hitherto by employing the fibre and $Nd^{3+}$:YAG laser to surface treat advanced ceramics in relation to the laser beam radiance, except the work of the authors herein. The work in this paper follows the finding obtained by previous studies [16,17] to compare the effects of laser beam radiance, thereon, two like-by-like laser sources, with identical process parameters, employed on the $Si_3N_4$ and $ZrO_2$ advanced ceramics to demonstrate the importance of radiance during laser-material processing. Moreover, a comparison is made on the effect of laser beam radiance from the materials aspect.

## 2. Materials and methods

### *2.1. Details of the advanced ceramics*

The first ceramic used for the experiments was a $Si_3N_4$ cold isostatically pressed (CIPed) with 90% $Si_3N_4$, 4% Yttria, 4% $Al_2O_3$ and 2% other content. The second advanced ceramic used was a cold isostatic pressed (CIP) $ZrO_2$ with 95 wt% $ZrO_2$ and 5 wt% yttria. Both ceramics were purchased from Tensky International Company, Ltd. Each test piece was obtained in a bulk of $10 \times 10 \times 50\ \text{mm}^3$ with a surface roughness of 1.58 μm for the $ZrO_2$ and 1.56 μm for $Si_3N_4$, as-received from the manufacturer. All experiments were conducted in atmospheric condition at a room temperature of 25 °C.

### *2.2. Laser processing method*

A $Nd^{3+}$:YAG laser (HK, SL902; Hahn & Kolb Ltd.) with 65 W capacity (CW mode) operating at 1.064 μm wavelength was first employed. The second laser for the comparative study was a 200 W fibre laser (SPI-200c-002; SPI, Ltd.) emitting a CW mode beam with a 1.075 μm wavelength. Both lasers were set to obtain a 2.2 mm spot size at a known laser power of 65 W. The processing gas used for both laser surface engineering on the advanced ceramics was $N_2$ flowing at 25 l/min. CAD software was used to programme a 50 mm beam path to engineer the surfaces. A traverse speed ranging from 4 and 100 mm/s was used. From these trials it was found that 10 mm/s at 65 W was the ideal laser parameter to use in terms of achieving a sufficient foot-print on the material to conduct further analysis.

### *2.3. Laser beam related analysis and the determination of radiance*

For the experiments to be valid, it was important to ensure a like-by-like investigation was undertaken. Accordingly, identical laser power and spot size (power density), similar wavelength and traverse speeds were used as mentioned in the laser processing section. Nevertheless, the beam characteristics were not like-by-like as this aspect is internal of the laser system and cannot be changed or modified by the operator. So, laser beam parameters namely laser power, spot size, wavelength, laser beam quality factor ($M^2$) were all employed to calculate the laser beam radiance using Eq. (1) [12–17], where $B$ is the brightness (radiance), $P$ is the input laser power, $M^2$ is the beam quality factor (taking into account the solid angle of divergence being inversely proportional to the beam quality factor), and $\lambda^2$ is the wavelength.

$$B = \frac{P}{M^2 \lambda^2} \tag{1}$$

When the values of the previously mentioned beam parameters were placed into Eq. (1), it would then allow the determination of the laser beam radiance for a particular laser. Using Eq. (1), the determined values for radiances of the fibre and the $Nd^{+3}$:YAG lasers are shown in Table 1. The calculation was conducted using the new version of Microsoft Excel 2013.

Experiments were conducted using identical input parameters as previously mentioned. However, the beam quality factor –$M^2$, was different for both the lasers which have affected the end value

**Table 1**
Calculated values of laser beam radiance for both the $Nd^{3+}$:YAG and fibre laser.

| Lasers | Power (W) | Spot size (mm) | $D^2$ (mm) | $P$out (W/mm²) | $M^2$ | $M^4$ | $\lambda$ (μm) | $\lambda^2$ (μm) | $M^4 \times \lambda^2$ | Radiance (W mm² Sr⁻¹) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Fibre** | **65** | **2.2** | **4.84** | **3357.43** | **6.7** | **44.89** | **1.064** | **1.13** | **50.81** | **6.60** |
| **$Nd^{3+}$:YAG** | **65** | **2.2** | **4.84** | **3357.43** | **1.2** | **1.44** | **1.075** | **1.15** | **1.66** | **201.75** |