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Role of Laser Beam Radiance in Different Ceramic Processing: A two Wavelengths Comparison

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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 on 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 to 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.

Keywords: Lasers; Radiance; 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 (radiative flux) acting on a surface. The units for radiance are ($W. mm^2. Sr^{-1}$), whereas the units of irradiance are W/m^3. 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, 10 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 much complicated and involves timely set-ups, hence, theoretical approach is more desirable and an accurate means for prediction.

This paper emphasizes that by 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. It is also a means to characterize the laser beam. 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 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 of 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 emmiting high radiance have been used in the recent years by several workers [19, 20]. But it is the term brightness which is comonly 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 was 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 940nm wavelength was used by Li *et al.* [15], to investigated the reliability and efficiency. The results demosntrated that maximum power conversion efficiency of 60% was acheived with a good beam quality factor and 72W laser power. A semiducnudctor 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. By 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 showed 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 was 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 effect 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 ralation 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 indentical process parameters, employed on the Si_3N_4 and ZrO_2 advanced ceramics to demostrate the importance of radiance during laser-material processing. Moreover, a comparison is made to 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 ceramic were purchased from Tensky International Company, Ltd.. Each test piece was obtained in a bulk of 10 x 10 x 50 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 manufacture. All experiments were conducted in atmosheric condition in room temperature of 25°C.

2.2 Laser Processing Method

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

2.2 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 Equation 1 [12 - 17], where B is the brightness (radiance), P is the input laser power, M^2 is the beam quality factor (taking in account of the solid angle of divergence being inversely proportional to the beam quality factor), and λ^2 being the wavelength.

$$B = \frac{P}{M^2 \lambda^2} \quad (1)$$

When the values of the previously mentioned beam parameters were placed into Equation 1, would then allow the determination of the laser beam radiance for a particular laser. Using Equation 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 of radiance as one can see from the difference in radiance in Table 1. But this will deferentiate a like-by-like experimental condition. Thus, it will certainly affect the comparative study, since one laser is radiant or simply brighter than the other. Having said this, the parameter which has caused the change in the radiance was M^2. This is not a readily changeable parameter when using single mode laser processing systems which was the case for this study. Therefore, the focus of this work was to maintain identical parameters (which are changeable by the operator) and employ them into Equation 1, along with the individual laser beam characteristics (M^2 value, solid angle of beam divergence and Gaussian beam mode) to determine the laser beam radiance.

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)	Pout (W/mm^2)	M^2	M^4	λ (µm)	λ^2 (µm)	M^4x λ^2	Radiance (W/mm^2/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

2.3. Microstructural and Optical Analysis

The as-received and the laser engineered samples were mounted in epoxy resin (Epofix, Struers Ltd.) and were finely polished by using a semi-automatic polishing machine (TegraPol-25, Struers Ltd.), aided by a successively finer diamond polishing discs. The final polishing of the adavanced ceramics were conducted by using a 0.04μm colloidal silica suspension (OP-S; Struers Ltd.). The samples were then removed from the epoxy resin. Thereafter, the samples were etched by using a thermal etching technique in order to expose the grains, to determine the grain size and to investigate the microstructure. Temperature of 1300˚C was applied in a furnace to samples of the as-received, fibre and Nd^{3+}:YAG laser engineered Si_3N_4 and ZrO_2 advanced ceramics. The samples were held at 1300˚C for 5min with a heating/cooling rate of 10˚C /min.

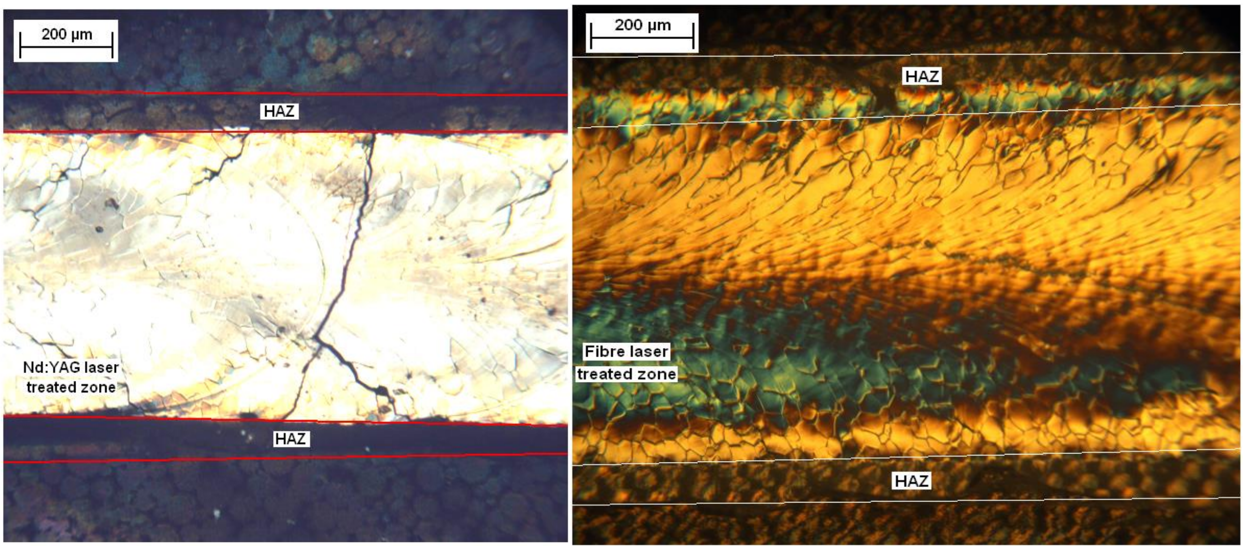
Optical microspcy was used to observe the Vickers indentations prior to and after the laser surface engineering. In addition, the as-received, fibre laser and the Nd^{3+}:YAG laser treated zones were all observed by employing the optical microscopy (Optishot; Nikon Ltd.). Moreover, the microstructure of the advanced ceramics was then observed by FEGSEM (Ultra-high-resolution, 1530VP; Leo Ltd.).

3. Results

3.1 Effect of Laser beam radiance on the Dimensional Size

3.1.1 ZrO_2 Advanced Ceramics

From the optical images of both the Nd^{3+}:YAG and fibre laser iduced foot-prints, it can be reported that around 32% difference was seen between the width of the surface tracks created by the two lasers. Table 2 shows the dimentions as result of the surface engineering undertaken by the two lasers for the ZrO_2 advanced ceramic. The average width of the Nd^{3+}:YAG laser engineered track in comparison to the track width of the fibre laser was much smaller and proved to have a 24% difference in size. The average dimention of the heat affected zone (HAZ) being stretched out for the Nd^{3+}:YAG laser engineered surface of the ZrO_2 was 91μm, whereas the fibre laser in comparison was somewhat smaller (85μm). The reason for the HAZ being smaller for the fibre laser despite having a bigger track was due to the beam quality and sharpness resulting to a clean track possibly penetrating deep into the surface compared to the beam quality of the Nd^{3+}:YAG laser which was considerably low. This in turn resulted to a larger HAZ and smaller track width.



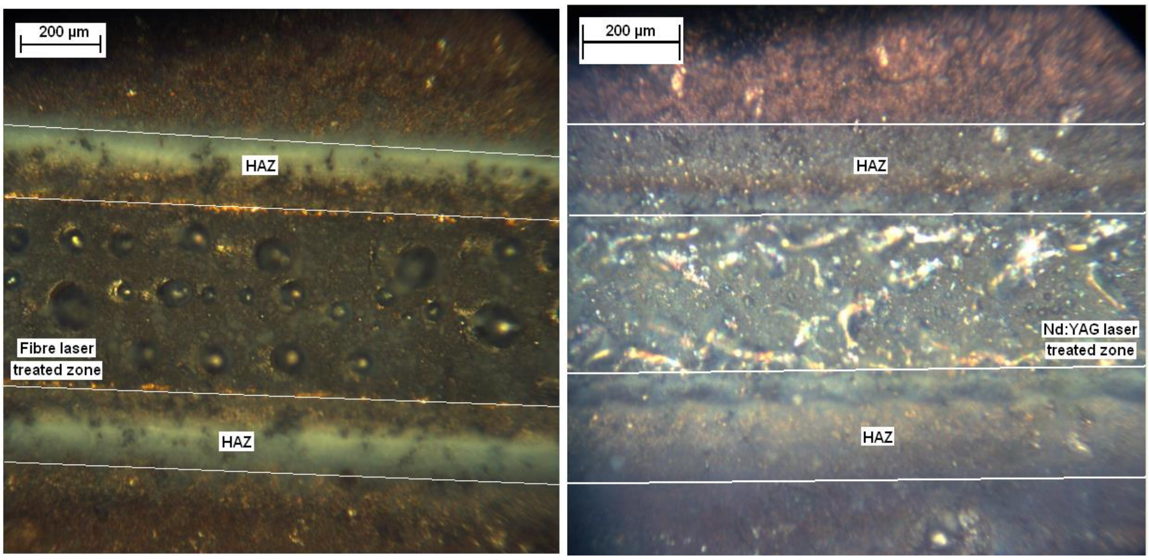
(a) **(b)**

Figure 1 Optical images of (a) the width of the Nd^{3+}:YAG laser engineered track and (b) the width of the fibre laser engineered track of the ZrO_2 advanced ceramic.

3.1.2 Si_3N_4 Advanced Ceramic

The optical images presented in Figure 2 showed the fibre laser engineered track of the Si_3N_4 which was over 9% higher than that of the Nd^{3+}:YAG laser. The dimentions of the fibre laser created surface track was 419μm, whereas the Nd^{3+}:YAG laser was 383μm. The size of the HAZ was 155 μm for the fibre laser engineered area, whereas the Nd^{3+}:YAG laser engineered area was 220μm. This goes to show that the same effect previously seen with the ZrO_2 advanced ceramics was also seen with the Si_3N_4. This was due to a better beam quality factor being exhibited by the fibre laser as previously explained.

Having applied identical laser parameters to surface treat both the advanced ceramics, the fibre laser surface treated zone was much bigger. This indicated that higher radiance produced by the fibre laser resulted to high power per unit area in a tight angle of divergence. This characteristically produced a larger interaction zone in comparison to the one produced by the Nd^{3+}:YAG laser. Although, the higher radiance laser resulted to a bigger interaction zone of the ceramic surfaces, but at the same time the HAZ for the fibre laser engineered surfaces were considerably smaller. This also implied that the difference in the laser beam quality factor M^2 between the two lasers would have much contribution. The beam quality factor M^2 was better for the fibre laser (M^2 = 1.1) than the one for the Nd^{3+}:YAG (M^2 = 6.7), which is a remarkebly large difference in the beam quality. In any case, the better beam quality for the fibre laser attributed a sharper beam profile in comparison to the Nd^{3+}:YAG laser, indicating that a highly radiant beam resulted to larger power per unit area per steradian but the beam quality is much better with a clean sharp beam that penetrated deeper and generated sharper tracks on the surface which were cleaner and with minimal spread of energy. This consequently attributed to the HAZ's of the ceramic being smaller for the fibre laser engineering surfaces.



(a) **(b)**

Figure 2 optical images of (a) the fibre laser engineered surface and (b) the Nd^{3+}:YAG laser engineered surface of the Si_3N_4 advanced ceramic.

Table 2 average track width of the fibre and the Nd^{3+}:YAG laser engineered surfaces.

	Fibre Laser		**Nd^{3+}:YAG**	
	Laser Engineered Track	**HAZ**	**Laser Engineered Track**	**HAZ**
ZrO_2	**837 µm**	**85 µm**	**632 µm**	**91 µm**
Si_3N_4	**419 µm**	**155 µm**	**383 µm**	**220 µm**

3.2 Effect of Laser beam Radiance on the Microstructure

3.2.1 Si_3N_4 Advanced Ceramics

The micrograph in Figure 3 illustrate the fibre laser engineered surface of the Si_3N_4 advanced ceramic. On account of observing the micrograph shown in Figure 3, it could be confirmed that the measurements presented in Figure 2 (a) and (b) of the track created by the fibre laser was somewhat larger than that of the Nd^{3+}:YAG laser engineered sample. The SEM image in Figure 3 showed that there is certainly an evidence of larger activity and bigger interaction zone in comparison to the image in Figure 6(b) of the Nd^{3+}:YAG laser. This indicated that the depth of penetration of the fibre laser engineered surface would also be higher. Having said that, a cross-sectional investigation to confrm this effect could be undertaken for further understanding.

Owing to the higher radiance exhibited by the fibre laser, Figure 6(a) shows an evidence of melting, oxidation, and entrapment of gas bubbles, which in comparison to the Nd^{3+}:YAG laser treated surface (exhibiting a low radiance) generated low temperature. Hence, a smaller interaction zone, surface melting and oxidation was created. The Si_3N_4 advanced ceramic generally decomposes at 1900 ˚C [27]. Therefore, it can also be ascribed that the higher radiance of the fibre laser caused the Si_3N_4 to partially melt and decompose somewhat above the decomposition temperature to about 2400 ˚C [27]. In comparison, for the Nd^{3+}:YAG laser engineered surface, the induced heat would be much below the decomposition temperature of the Si_3N_4. On this more, it is also suggested that an experimental investigation comparing the radiance temperature is carried-out to demonstrate the differences of heat generated between each laser source during laser-material interaction.

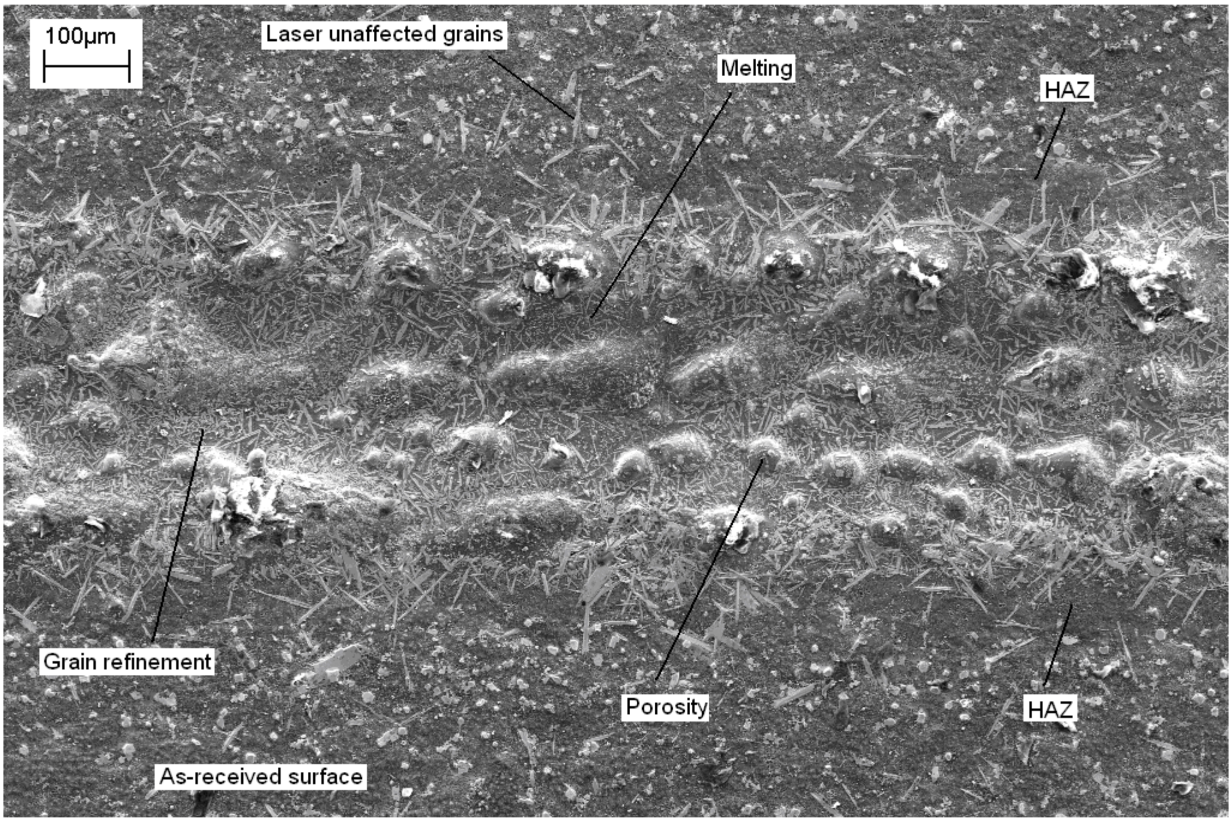


Figure 3 A micrographic image of the fibre laser engineered surface of the Si_3N_4 advanced ceramic.

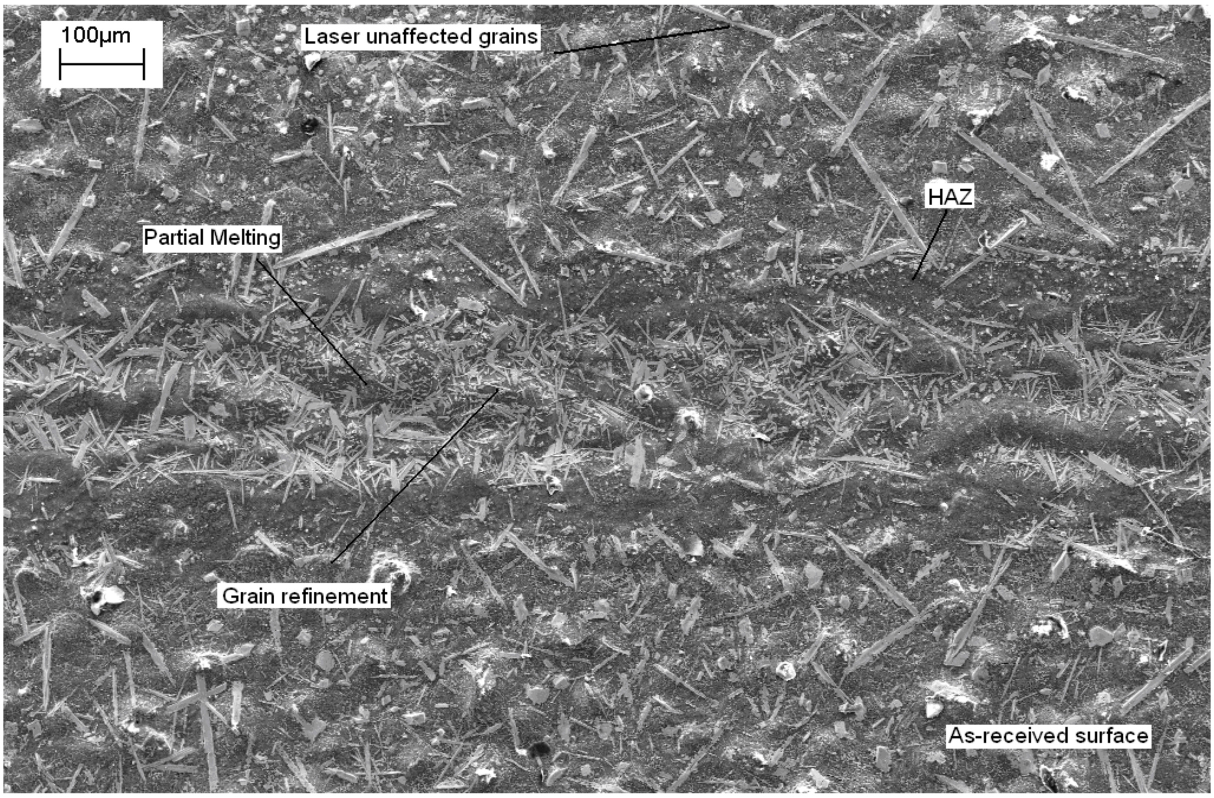
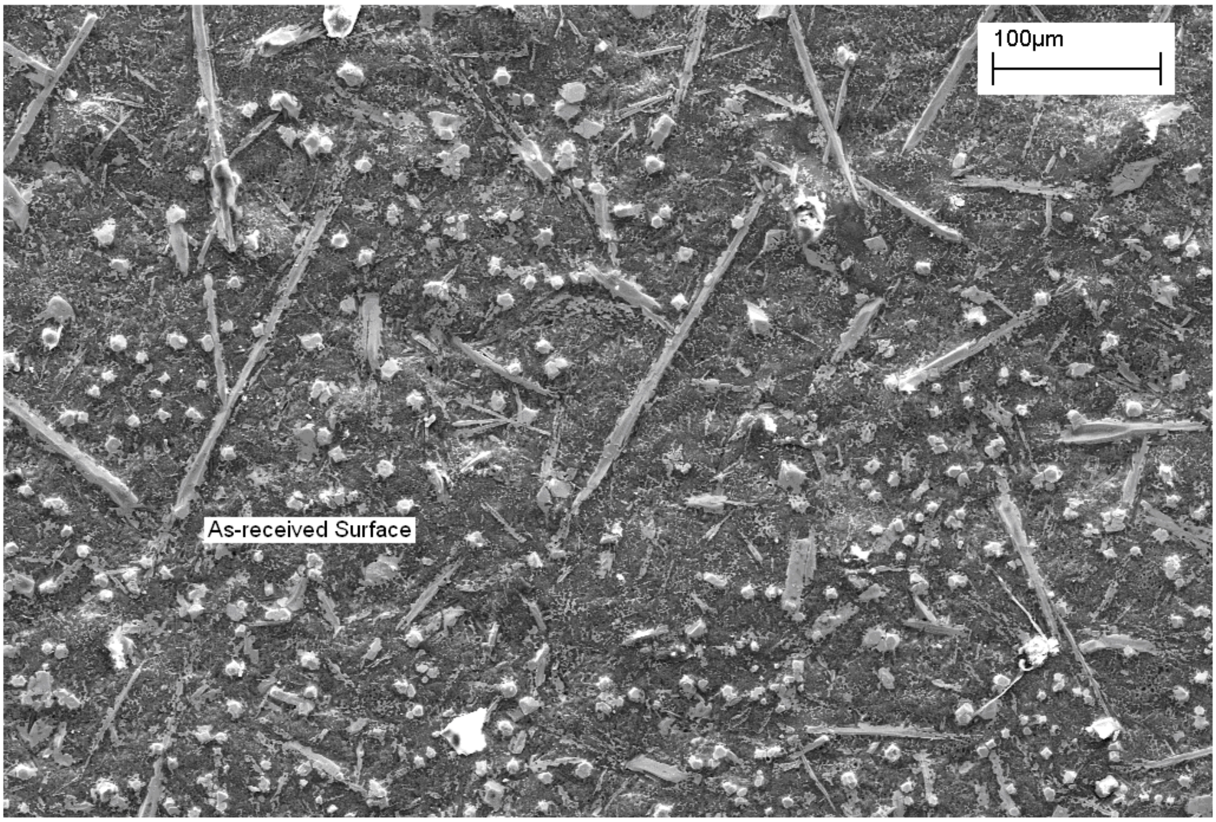
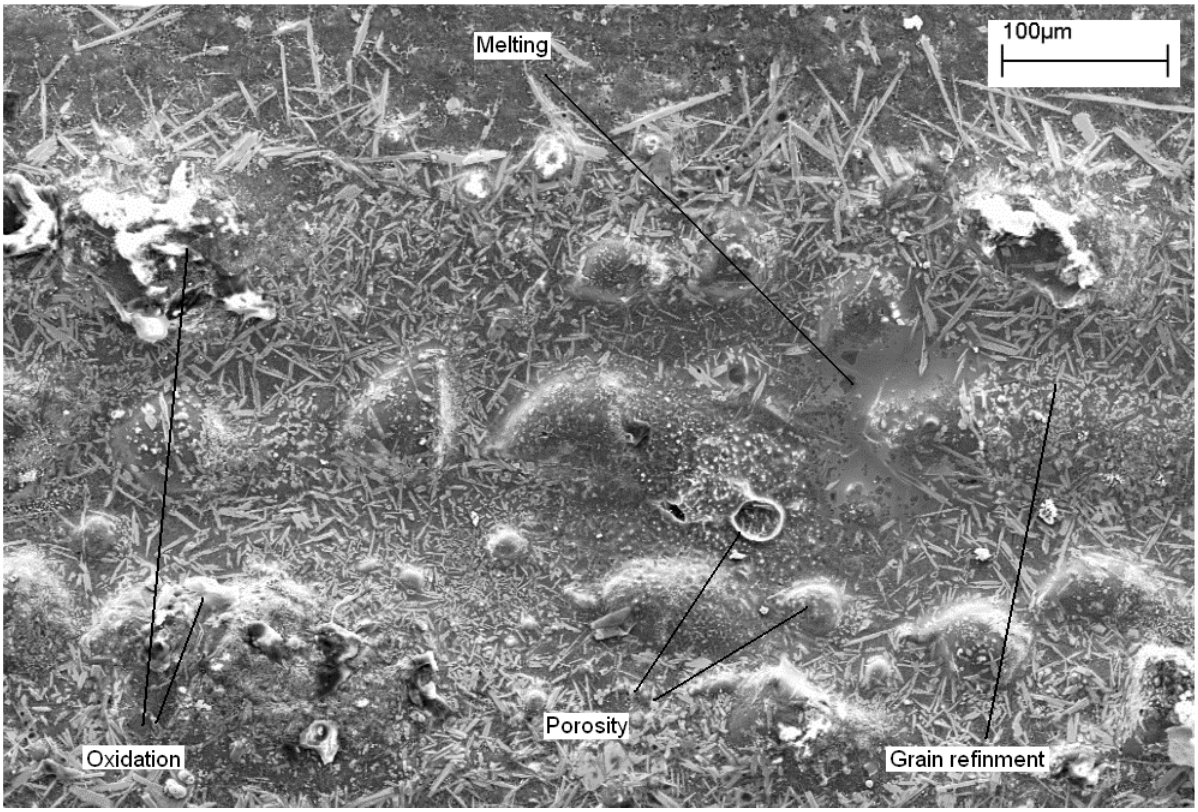


Figure 4 A micrographic image of the Nd^{3+}:YAG laser engineered surface of the Si_3N_4 advanced ceramic.

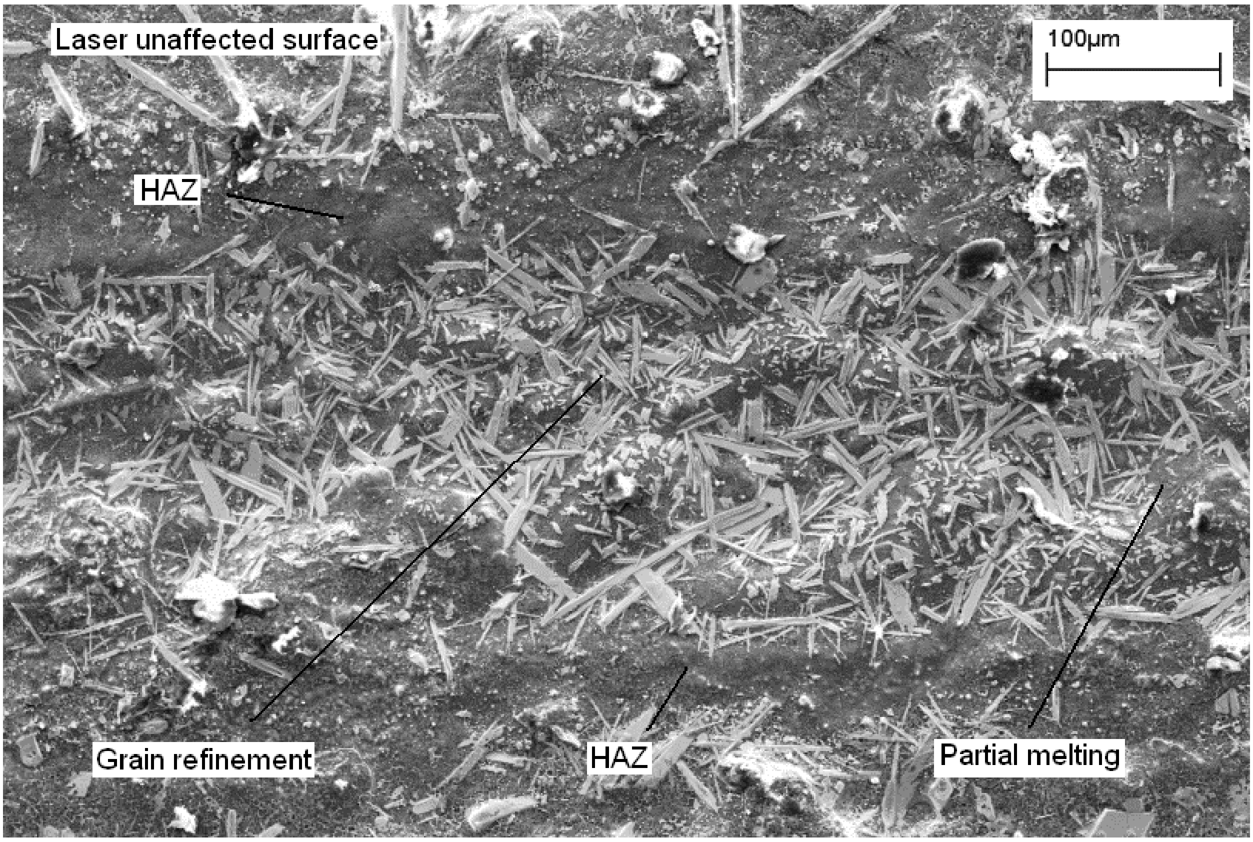
From observing the micrograph of the untreated surface of the Si_3N_4 in Figure 5 (a); it can be observed that sharp rods like features are present but are not equaly shaped along with the presence of square shaped blocks. During the laser-Si_3N_4 interaction it is possible that upon re-melting of the near surface layer affected the dimensional sizes of the elongated sharp rods to reduce in size. Having said this, the effect is more evident with the sample surface engineered by the fibre laser (see Figure 5(b)) as the rods are much finer and became smaller in size compared to the Nd^{3+}:YAG laser engineered surfaces presented in Figure 5 (c). The change in the microstructure produced by the two lasers would have occurred due to the higher melting and vaporization as well as a possible tranformation of phases as comfirmed by previous investigation on the fibre laser irradiation of Si_3N_4 engineering ceramics [27, 28], where an alpha (α) to beta (β) transformation occurred whilst the surface was strengthened.



(a)



(b)

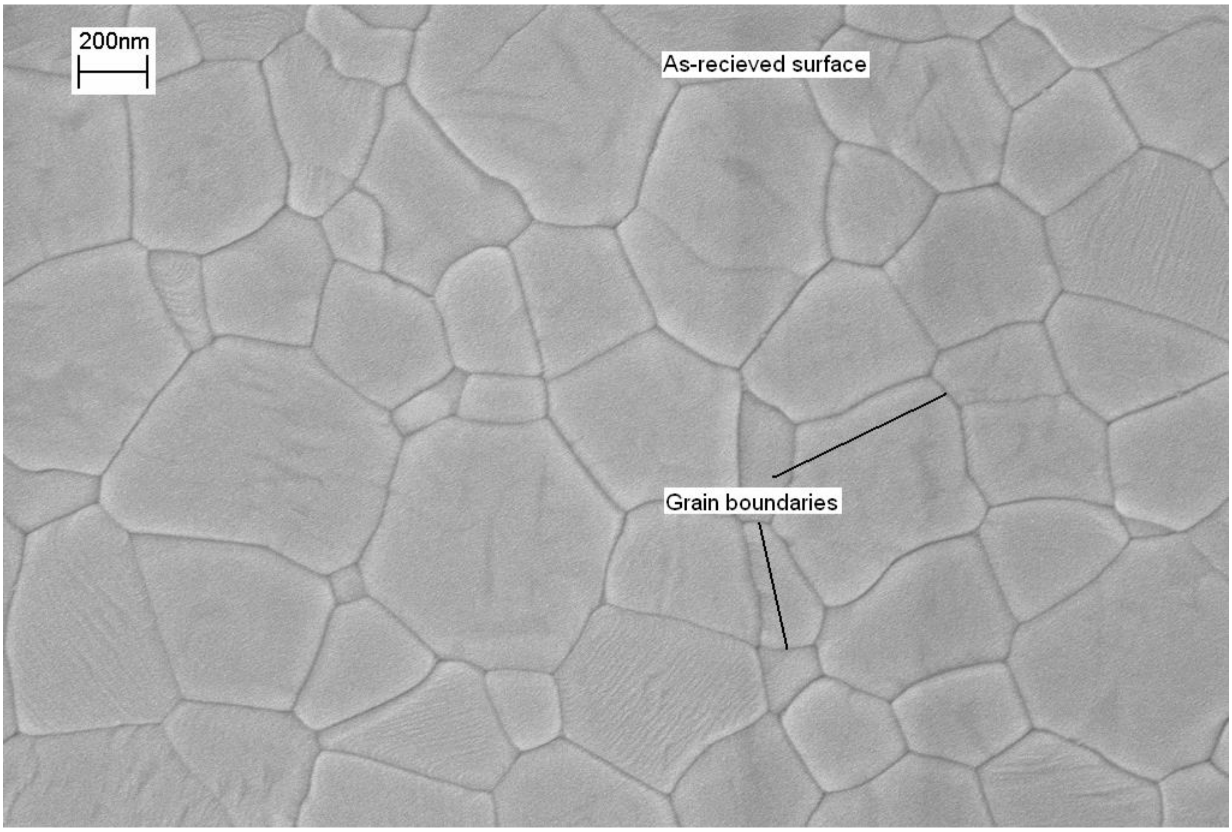


(c)

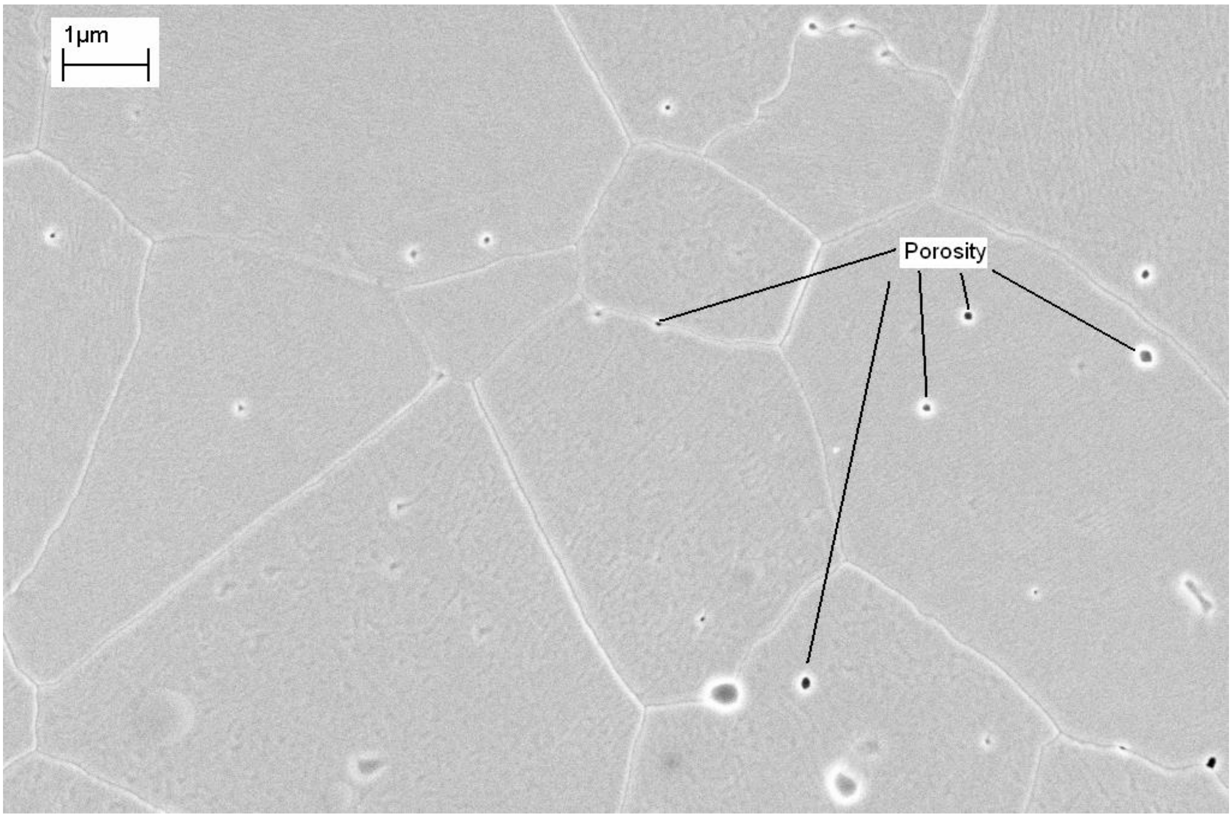
Figure 5 Micrographs of the as-received surface in (a) the fibre laser engineered surface in (b), and (c) the Nd^{3+}:YAG laser engineered surface of the Si_3N_4 advanced ceramic.

3.2.2 ZrO_2 Advanced Ceramics

The grain boundaries of the fibre laser engineered surface of the ZrO_2 advanced ceramic shown in Figure 6(a) have enlarged and elongated in comparison to the ground and polished untreated surface in Figure 6(b). Nevertheless, an increase in surface flaws and porosity has occurred after the fibre laser surface engineering have taken place when compared to the as-received ground and polished surface. This is believed to have resulted from escaped gas during the fibre laser-ZrO_2 interaction. In addition, the grain sizes tend to vary from 3μm to 10μm from the near-surface layer and through the sub-surface, and the bulk of the ZrO_2. This was due to the laser-ZrO_2 processing temperature at the near surface layer being somewhat higher than the sub-surface and the bulk of the ceramic. This could also be confirmed from a previous investigations [26, 27]. As shown in Figure 6(c) of the cross-section of the microstructure, the grain size increases from the bulk of the ZrO_2 to the sub-surface and the top surface layer of the fibre laser engineered zone. The microstructure at the near surface layer is somewhat different as significant grain growth has occurred due to the high temperature gradient existing at the laser-ZrO_2 interaction.



(a)



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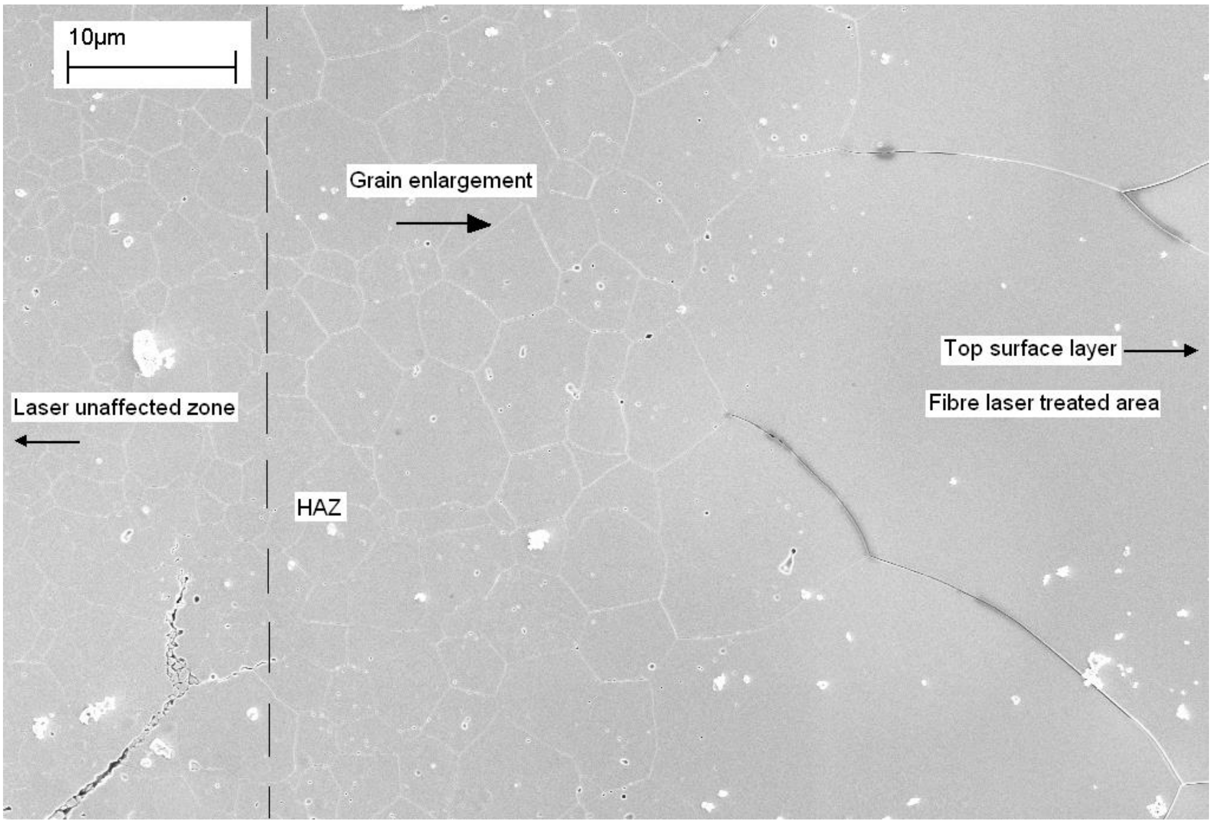
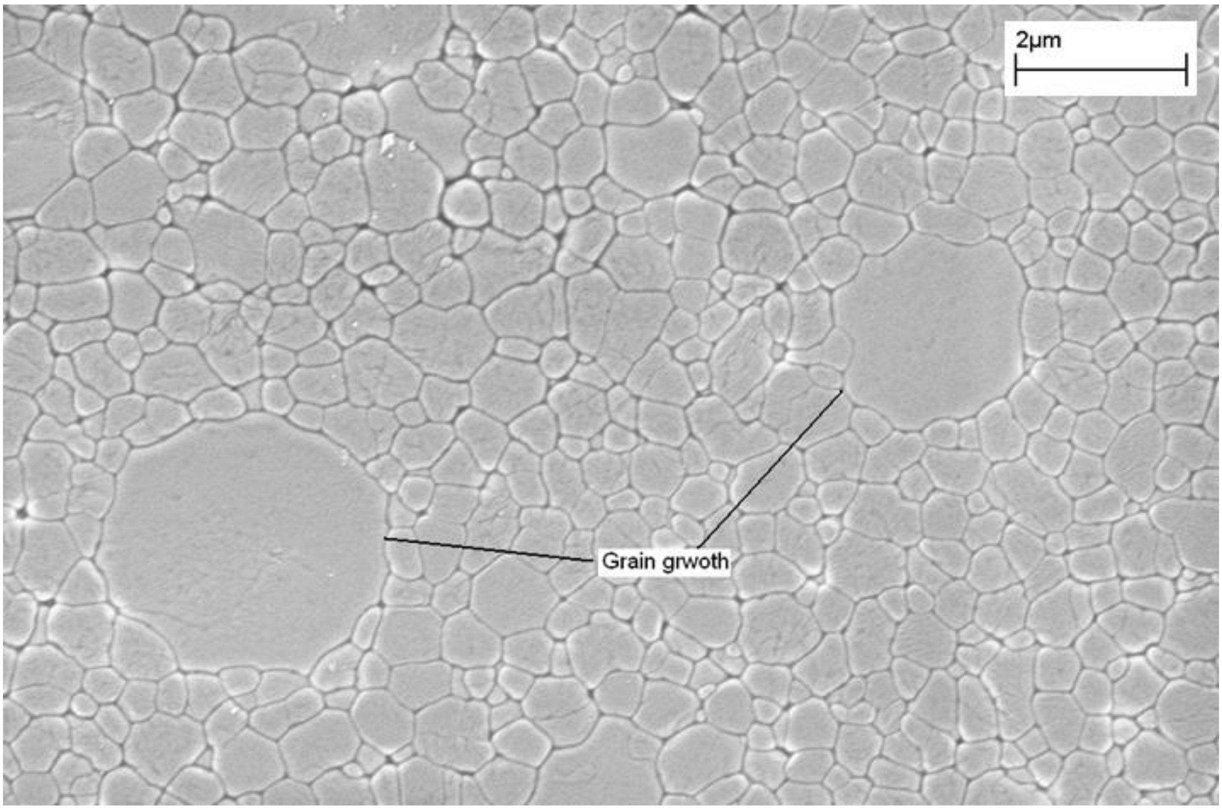


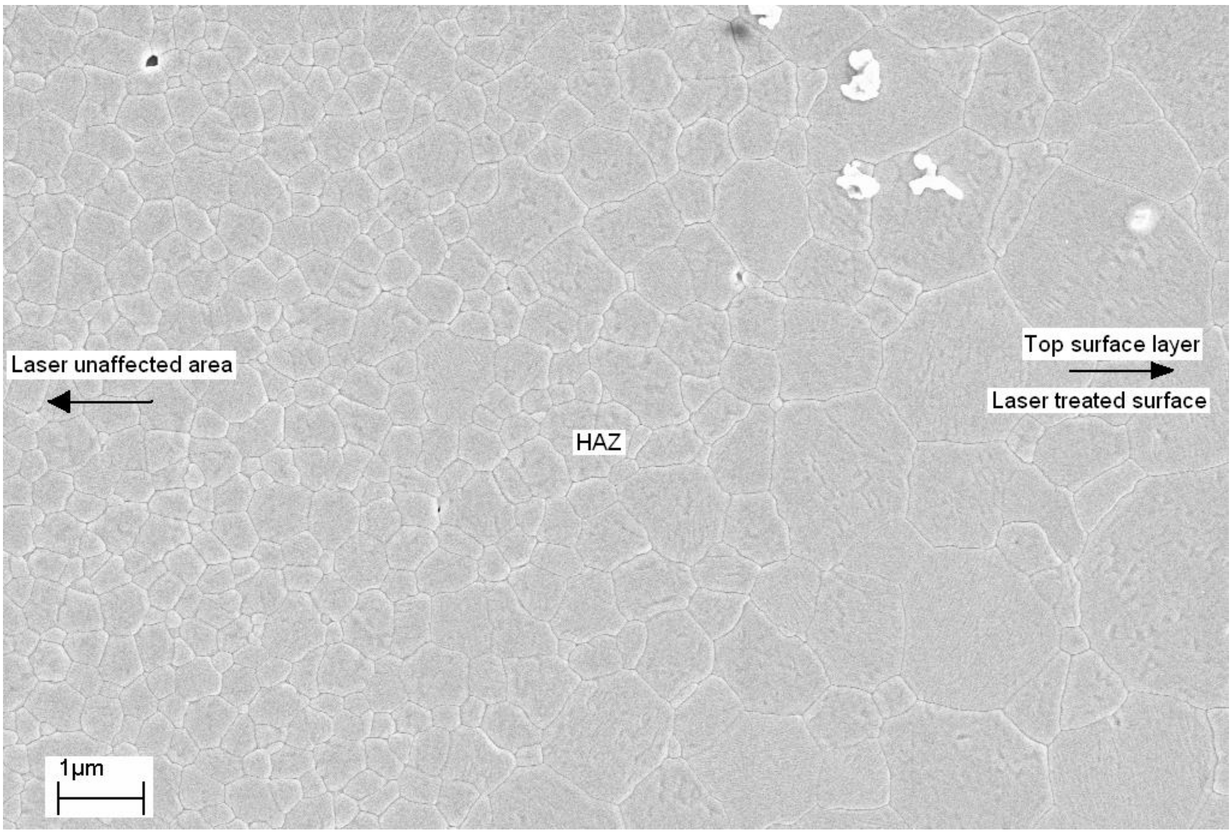
(c)

Figure 6 Micrograph of the cross-section of the sub-surface layer of the the as-received ground and polished surface in (a), and (b) the fibre laser surface and its cross-section in (c) of the ZrO_2 advanced ceramic.

The microstructure of the Nd^{3+}:YAG laser engineered surface in comparison to the as-received surface was reasonably modified (see Figure 7 (a) and (b)). The grain sizes herein range from about 3.5μm to 7μm and an average grain size was of about 5μm. This in comparison to the untreated surface was considerably large. When the results of the Nd^{3+}:YAG laser were compared to the fibre laser engineered surfaces, the grain boundaries were somewhat smaller as evident in Figure 7(b) and (c)). Similar effects also occurred with the ZrO_2 samples engineered by both the lasers, though the results of the Nd^{3+}:YAG laser were less significant. The image seen in Figure 7(a) within the cross-section comprised of larger grains at the near surface layer of the ZrO_2. This further reduced as it was observed at the sub-surface and the bulk of the ZrO_2 advanced ceramic (see Figure 7(a)). Nonetheless, the particular grian growth seen in Figure 7(a) appears to be somewhat abnormal as grain elongation only in random sections of the laser treated zone has appeared. Figure 7(b) shows the very near surface layer of the ZrO_2 advanced ceramic surface engineered by the Nd^{3+}:YAG laser. The microstructure in this image was reasonably modified in comparison to the microstructure where the laser-ZrO_2 interaction did not occur.


2μm
Grain grwoth

(a)


Laser unaffected area
Top surface layer
Laser treated surface
HAZ
1μm

(b)

Figure 7 Micrograph of the Nd^{3+}:YAG laser engineered sample in (a) showing an abnormal grain growth in various regions of the sub-surface and (b) the elongation of grains when moving closer to the surface region of the ZrO_2 advanced ceramic within the sub-surface region.

Figure 8 shows a melted glassy amorphous zone produced by the Nd^{3+}:YAG laser - was a mixture of $ZrCO_2$. This could be postulated from a previous investigation using the fibre laser to surface engineered ZrO_2 that demonstrated similar findings [29]. Evidance of surface melting can be seen with the Nd^{3+}:YAG laser engineered surface, although, it was not as remarkable as the fibre laser treated surface of the ZrO_2 since large proportion of the cross-section was found to be of the amorphous glass layer. This in turn confirmed that the formation of the considerable melt-zones found at the fibre laser surface interaface would have occurred from a higher laser-material interaction temperature, whereas the Nd^{3+}:YAG laser surface temparatures would have been somewhat lower to have only comprised of the pratial melting. This difference occurred despite using identical laser processing parameters between the two lasers used. Moreover, the fibre laser with a higher radiance value had created much higher temperature which characteristically melted the surface and generated a larger melt-pool. On the other hand, the Nd^{3+}:YAG laser-material interaction temperature was lower due to the low radiance value. This would generate low power per unit area in steradian. In addition, to complement this statement – considerable amount of surface cracking was also found with the fibre laser engineered sample in comparison to the Nd^{3+}:YAG laser which suggested that the temperature gradient as well as the cooling rate by each laser would have varried leading to the observed differences.

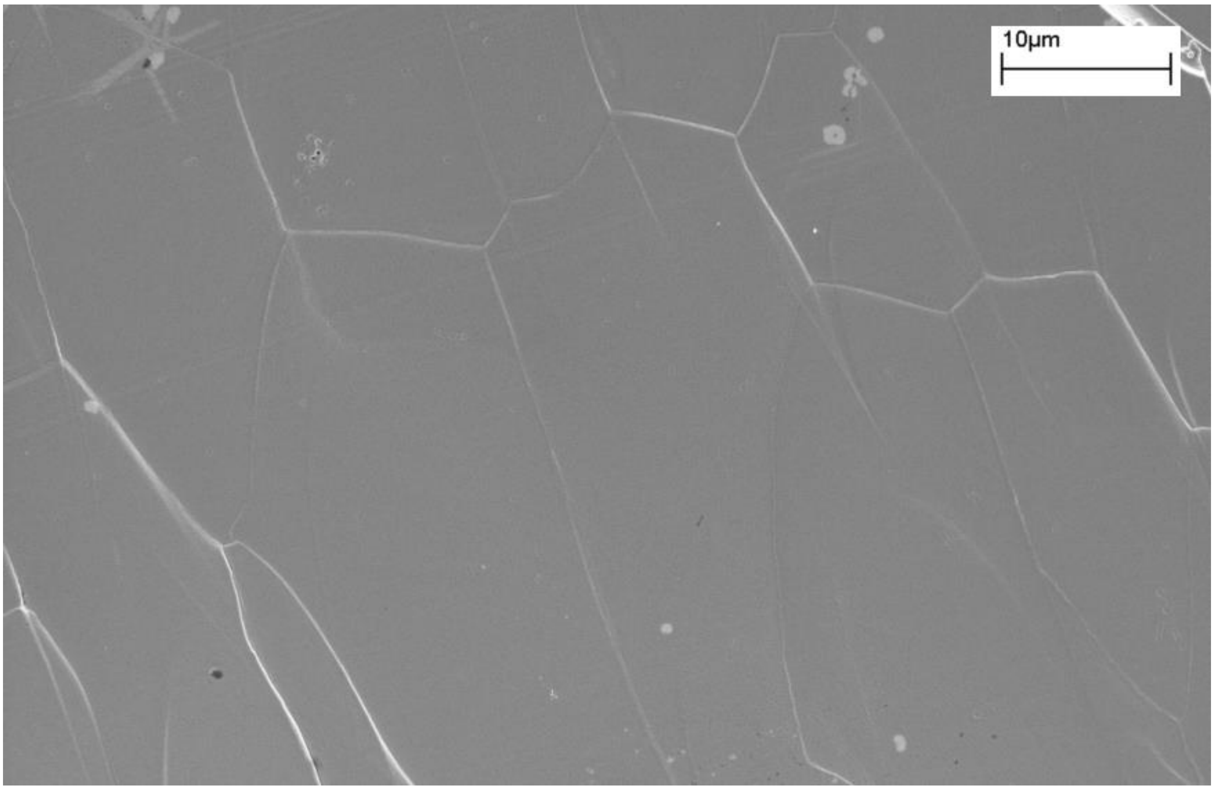


Figure 8 Micrograph of the cross-section of the Nd^{3+}:YAG laser engineered surface of the ZrO_2 advanced ceramic showing the surface layer with partial melt zones.

4. Discussion

4.1 Contribution of Laser Beam Paramaters to Effect Radiance

Due to the theory behind the calculation of laser beam radiance [12 - 17], it is indicative that several laser beam ralated parameters effect the calculation and contribute in someway or another. These aforementioned parameters are namely:

- the output laser power;
- spot size;
- power density;
- the beam quality factor - M^2;
- transverse mode;
- beam divergence.

However, the amount of contribution each parameters has thereon the end radiance value is yet unclear and further analysis is currently being undertaken by the leading author of this study to show the contribution of each parameter to effect the laser beam radiance. Thus, it can be attributed that a high quality laser beam leads to higher radiance value which instrinsically generates high power per unit area and causes considerable difference as seen from the study herein. On this more, the difference in the beam divergence and the quality factor M^2 between the two lasers led to a change in brightness as the fibre laser divergence was much smaller than the Nd^{3+}:YAG laser which emitted a brighter beam.

Furthermore, a highly radiant laser beam generally penetrates deeper into the surface as high brightness beams produce deeper penetration [27], longer depth of focus, larger impact or the track width, and microstructural changes, despite using identical parameters to a laser beam of lower radiance as seen from the study herein. This allows the high radiance laser to operate at lower power levels to produce the same surafce treatment to that of a low radiance laser. This characteristically reduces with a reduction in cost. Further work is also being undertaken by the leading author of this study to determine the cost difference between high and low radiance lasers.

4.2 Comparison of the Effects of Laser Beam Radiance theron the Advanced Ceramics

Up on comparing the results found with the effects of the laser beam radiance on both the Si_3N_4 and ZrO_2 advanced ceramics it can be observed that the effects of high laser beam radiance exists with both the nitride and oxide ceramics as larger surface tracks were seen and microstructural changes were also much significant using the high radiance laser. Thus, it is important to mention at this point the difference in the temperature exhibited between the two lasers at the laser material interaction zone. The fibre laser comprising of a much radiant and brighter beam and emitted higher peak temperature in comparison to the Nd^{+3}:YAG laser [27]. This leads to difference in heating rate and then the cooing of the two ceramics. The fibre laser would generally heat up the material faster and allow a slower cooling rate to take place. This consequently would allow not only a change in the microstructure as seen in the results herein, but would also enable the heat to spread in a larger surface area and would attribute to creating larger track widths.

Moreover, it can be reported that thicker track width was seen using both lasers for the ZrO_2 (oxide ceramic) when compared to the Si_3N_4 (nitride ceramic) when employing the high radiance fibre laser. This indicated that comparison of the effects of laser beam radiance would be more predominent and obvious if two ceramics were compared from the same branch of the ceramics family tree. Examples are namely: comparison of Si_3N_4 to boron nitride (BN) or ZrO_2 to alumina oxide (Al_2O_3) and likewise, SiC to boron carbide (BC). This will enable one to understand the specific difference the radiance of a laser has up on the particular branch of materials in future investigations.

Previous result have shown that high brightness lasers exhibit high processing temperatures during laser-ceramic interaction [27]. This is particularly so for the fibre laser and significant difference in the solidification rate would occur, which thereby, re-creates a different microstructure as can be seen with the results obtained herein for the fibre laser engineered Si_3N_4 and the ZrO_2 advanced ceramics in comparison to that of the Nd^{+3}:YAG laser. The high processing temperature by the fibre laser has yielded refined grain structure with the Si_3N_4 and evidence of significant melting and possibly what appears to be a glassy layer with the ZrO_2. The modified microstructure in turn results to difference in the surface properties of the ceramics such as a change in the hardness, fracture toughness parameter K_{1c}, and depending on the peak processing temperature; there could be a probable phase change for the two ceramics, whereby the Si_3N_4 could have transformed from alpha-phase to beta-phase and the ZrO_2 from a monoclinic phase to tetragonal, or from a tetragonal to a cubic phase. In any case, further investigation would be required to confirm such modifications using the same experimental conditions and the two ceramics used in this study.

3. Conclusions

A comparative study regards to the effects of laser beam radiance, commonly known as brightness was investigated during surface treatment of a Si_3N_4 and ZrO_2 advanced ceramics by employing a fibre laser and a Nd^{3+}:YAG laser. Like-by-like laser parameters were used to investigate the change in the microstructure and the laser induced foot-prints. The results showed that the effects of the fibre laser surface engineering on both the advanced ceramics differed from the effects of the Nd^{3+}:YAG laser as larger track width (foot-print), porosity, oxidation, surface melting and decomposition took place. Moreover, considerable changes in the microstructure were evident and sharp rods-like features were much reduced in size due to high laser beam radiance of the fibre laser, creating high temperature during laser-ceramic interaction for the Si_3N_4 advanced ceramic. This consequently caused higher melting of the ceramic. For the ZrO_2 advanced ceramic the microstructural changes also showed that the fibre laser engineered surface was producing large grains in comparison to the Nd^{3+}:YAG laser engineering surface by over 20% difference in size which also attributes to the higher temperature characteristically generating a high melt zone to occur.

The dimentional and the microstructural effects on the two advanced ceramics differed for the two lasers treatments despite using like-bylike parameters. Owing to this, the laser beam radiance is taken into account since higher power per unit area in a solid angle in steradian would have generated high interaction temperatures, causing larger thermal gradient to produced a bigger melt zone. As result, the difference in the dimentional size of the laser induced foot-prints and the differnce in the microstructure were found for the two ceramics.

On account of the findings herein, it is concluded that laser beam radiance during laser surface engineering and other processes should be considered as its not only a sum of the laser power density but it also takes in account of other important parameters of the laser beam. High radiance lasers have the potential to also generate effective and possibly efficient surface engineering process which could enable the use of lower wattage for the same treatment. This inherently leads to cost reduction for the process. Further investigation into the effects of radiance on other material types; comparison of cost between high and low radiance lasers; temperature difference between various lasers with different randiances and the contribution of each laser beam parameter to the end value of radiance is currently being investigated by the authors of this study.

4. Vitae

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Dr. Pratik Shukla is a research fellow at the University of Lincoln (Laser and Photonics Engineering Group), actively conducting research in the field of laser surface engineering of technical grade ceramics, improving functional properties of engineering and bio-medical ceramics by means of ultra-short pulse lasers, wider effects of the laser beam brightness in laser processing and laser assisted joining of zirconia based fuel cells. He was previously a research engineer in the laser-material processing industry and a manufacturing engineer in aerospace/industrial turbine blade manufacturing. Dr. Shukla also worked as a lecturer at Tongji University, China and at Sharda University, Delhi (India).

4.2 Professor Jonathan Lawrence - Professor of Laser Materials Processing

Professor Lawrence is currently Director of Laser and Photonics Engineering Group in the University of Lincoln, Editor-in-Chief of the international journal Lasers in Engineering and a Member of the Engineering Professors' Council. His main contribution has been in the field laser radiation on the wettability characteristics of materials; improving the biocompatibility of materials using laser radiation; as well as studying the feasibility of using lasers for the forming of sheet metal and developing a technique for laser ignition in gas turbines. He has presented and published widely in these areas, including five patents, seven books and over 120 journal papers.

5. Acknowledgements

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Role of Laser Beam Radiance in Different Ceramic Processing: A two Wavelengths Comparison

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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 on 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 to 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.

Keywords: Lasers; Radiance; Ceramics

4. 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 (radiative flux) acting on a surface. The units for radiance are (W. mm^2. Sr^{-1}), whereas the units of irradiance are W/m^3. 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, 10 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 much complicated and involves timely set-ups, hence, theoretical approach is more desirable and an accurate means for prediction.

This paper emphasizes that by 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. It is also a means to characterize the laser beam. 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 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 of 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 emmiting high radiance have been used in the recent years by several workers [19, 20]. But it is the term brightness which is comonly 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 was 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 940nm wavelength was used by Li *et al.* [15], to investigated the reliability and efficiency. The results demosntrated that maximum power conversion efficiency of 60% was acheived with a good beam quality factor and 72W laser power. A semiducnudctor 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. By 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 showed 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 was 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 effect 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 ralation 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 indentical process parameters, employed on the Si_3N_4 and ZrO_2 advanced ceramics to demostrate the importance of radiance during laser-material processing. Moreover, a comparison is made to the effect of laser beam radiance from the materials aspect.

5. 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 ceramic were purchased from Tensky International Company, Ltd.. Each test piece was obtained in a bulk of 10 x 10 x 50 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 manufacture. All experiments were conducted in atmosheric condition in room temperature of 25°C.

2.2 Laser Processing Method

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

2.2 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 Equation 1 [12 - 17], where B is the brightness (radiance), P is the input laser power, M^2 is the beam quality factor (taking in account of the solid angle of divergence being inversely proportional to the beam quality factor), and λ^2 being the wavelength.

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

When the values of the previously mentioned beam parameters were placed into Equation 1, would then allow the determination of the laser beam radiance for a particular laser. Using Equation 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 of radiance as one can see from the difference in radiance in Table 1. But this will deferentiate a like-by-like experimental condition. Thus, it will certainly affect the comparative study, since one laser is radiant or simply brighter than the other. Having said this, the parameter which has caused the change in the radiance was M^2. This is not a readily changeable parameter when using single mode laser processing systems which was the case for this study. Therefore, the focus of this work was to maintain identical parameters (which are changeable by the operator) and employ them into Equation 1, along with the individual laser beam characteristics (M^2 value, solid angle of beam divergence and Gaussian beam mode) to determine the laser beam radiance.

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)	Pout (W/mm^2)	M^2	M^4	λ (μm)	λ^2 (μm)	M^4x λ^2	Radiance (W/mm^2/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**

2.3. Microstructural and Optical Analysis

The as-received and the laser engineered samples were mounted in epoxy resin (Epofix, Struers Ltd.) and were finely polished by using a semi-automatic polishing machine (TegraPol-25, Struers Ltd.), aided by a successively finer diamond polishing discs. The final polishing of the adavanced ceramics were conducted by using a 0.04μm colloidal silica suspension (OP-S; Struers Ltd.). The samples were then removed from the epoxy resin. Thereafter, the samples were etched by using a thermal etching technique in order to expose the grains, to determine the grain size and to investigate the microstructure. Temperature of 1300˚C was applied in a furnace to samples of the as-received, fibre and Nd^{3+}:YAG laser engineered Si_3N_4 and ZrO_2 advanced ceramics. The samples were held at 1300˚C for 5min with a heating/cooling rate of 10˚C /min.

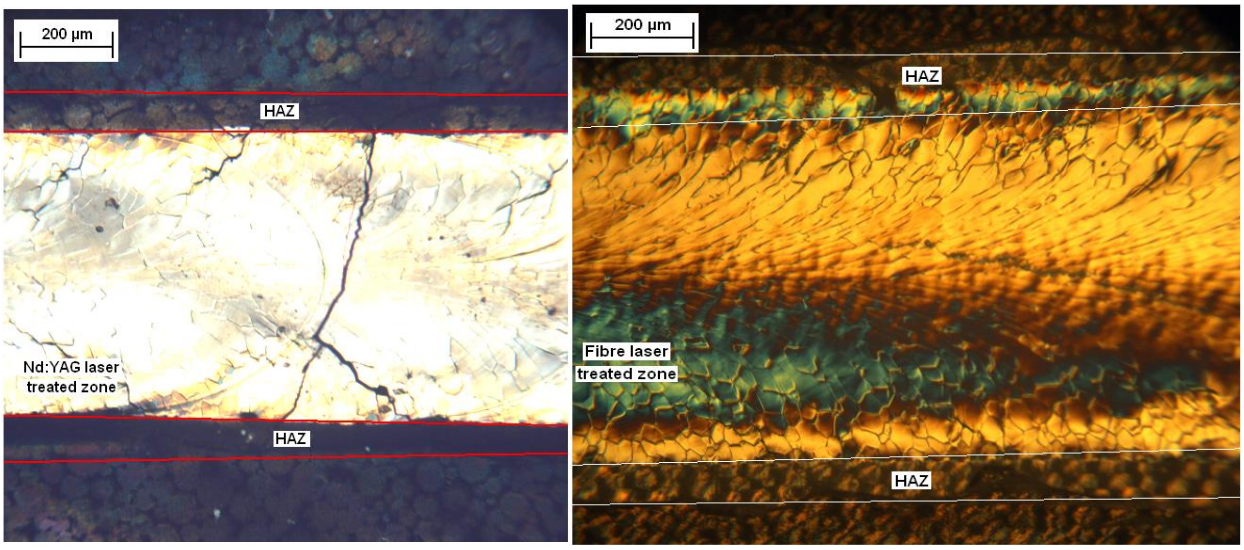
Optical microspcy was used to observe the Vickers indentations prior to and after the laser surface engineering. In addition, the as-received, fibre laser and the Nd^{3+}:YAG laser treated zones were all observed by employing the optical microscopy (Optishot; Nikon Ltd.). Moreover, the microstructure of the advanced ceramics was then observed by FEGSEM (Ultra-high-resolution, 1530VP; Leo Ltd.).

3. Results

3.1 Effect of Laser beam radiance on the Dimensional Size

3.1.1 ZrO_2 Advanced Ceramics

From the optical images of both the Nd^{3+}:YAG and fibre laser iduced foot-prints, it can be reported that around 32% difference was seen between the width of the surface tracks created by the two lasers. Table 2 shows the dimentions as result of the surface engineering undertaken by the two lasers for the ZrO_2 advanced ceramic. The average width of the Nd^{3+}:YAG laser engineered track in comparison to the track width of the fibre laser was much smaller and proved to have a 24% difference in size. The average dimention of the heat affected zone (HAZ) being stretched out for the Nd^{3+}:YAG laser engineered surface of the ZrO_2 was 91μm, whereas the fibre laser in comparison was somewhat smaller (85μm). The reason for the HAZ being smaller for the fibre laser despite having a bigger track was due to the beam quality and sharpness resulting to a clean track possibly penetrating deep into the surface compared to the beam quality of the Nd^{3+}:YAG laser which was considerably low. This in turn resulted to a larger HAZ and smaller track width.



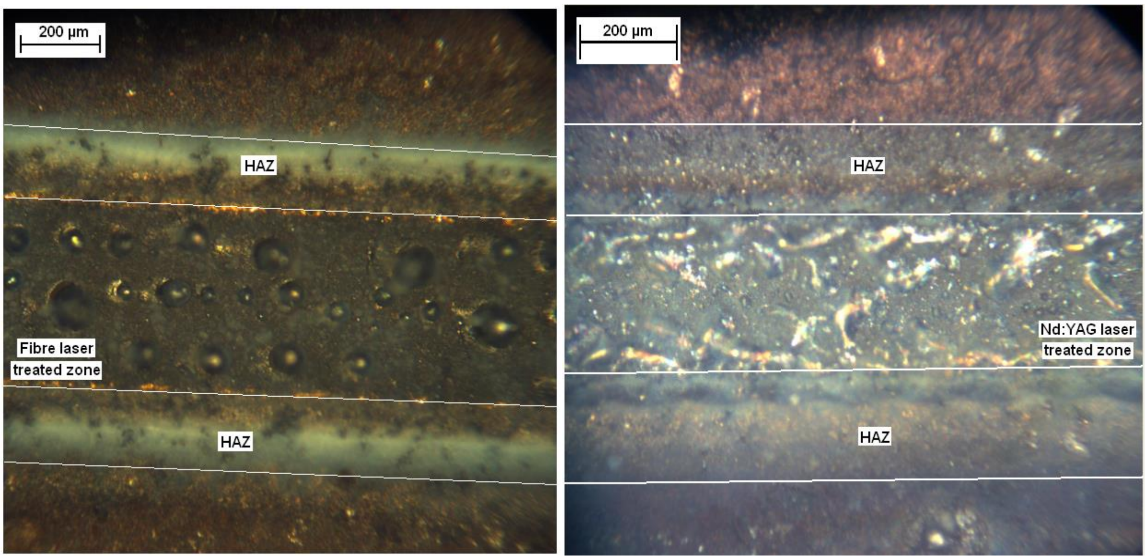
(a) **(b)**

Figure 1 Optical images of (a) the width of the Nd^{3+}:YAG laser engineered track and (b) the width of the fibre laser engineered track of the ZrO_2 advanced ceramic.

3.1.2 Si_3N_4 Advanced Ceramic

The optical images presented in Figure 2 showed the fibre laser engineered track of the Si_3N_4 which was over 9% higher than that of the Nd^{3+}:YAG laser. The dimentions of the fibre laser created surface track was 419µm, whereas the Nd^{3+}:YAG laser was 383µm. The size of the HAZ was 155 µm for the fibre laser engineered area, whereas the Nd^{3+}:YAG laser engineered area was 220µm. This goes to show that the same effect previously seen with the ZrO_2 advanced ceramics was also seen with the Si_3N_4. This was due to a better beam quality factor being exhibited by the fibre laser as previously explained.

Having applied identical laser parameters to surface treat both the advanced ceramics, the fibre laser surface treated zone was much bigger. This indicated that higher radiance produced by the fibre laser resulted to high power per unit area in a tight angle of divergence. This characteristically produced a larger interaction zone in comparison to the one produced by the Nd^{3+}:YAG laser. Although, the higher radiance laser resulted to a bigger interaction zone of the ceramic surfaces, but at the same time the HAZ for the fibre laser engineered surfaces were considerably smaller. This also implied that the difference in the laser beam quality factor M^2 between the two lasers would have much contribution. The beam quality factor M^2 was better for the fibre laser (M^2 = 1.1) than the one for the Nd^{3+}:YAG (M^2 = 6.7), which is a remarkebly large difference in the beam quality. In any case, the better beam quality for the fibre laser attributed a sharper beam profile in comparison to the Nd^{3+}:YAG laser, indicating that a highly radiant beam resulted to larger power per unit area per steradian but the beam quality is much better with a clean sharp beam that penetrated deeper and generated sharper tracks on the surface which were cleaner and with minimal spread of energy. This consequently attributed to the HAZ's of the ceramic being smaller for the fibre laser engineering surfaces.



(a) **(b)**

Figure 2 optical images of (a) the fibre laser engineered surface and (b) the Nd^{3+}:YAG **laser engineered surface of the Si_3N_4 advanced ceramic.**

Table 2 average track width of the fibre and the Nd^{3+}:YAG **laser engineered surfaces.**

	Fibre Laser		Nd^{3+}:YAG	
	Laser Engineered Track	**HAZ**	**Laser Engineered Track**	**HAZ**
ZrO_2	**837 µm**	**85 µm**	**632 µm**	**91 µm**
Si_3N_4	**419 µm**	**155 µm**	**383 µm**	**220 µm**

3.2 Effect of Laser beam Radiance on the Microstructure

3.2.1 Si_3N_4 Advanced Ceramics

The micrograph in Figure 3 illustrate the fibre laser engineered surface of the Si_3N_4 advanced ceramic. On account of observing the micrograph shown in Figure 3, it could be confirmed that the measurements presented in Figure 2 (a) and (b) of the track created by the fibre laser was somewhat larger than that of the Nd^{3+}:YAG laser engineered sample. The SEM image in Figure 3 showed that there is certainly an evidence of larger activity and bigger interaction zone in comparison to the image in Figure 6(b) of the Nd^{3+}:YAG laser. This indicated that the depth of penetration of the fibre laser engineered surface would also be higher. Having said that, a cross-sectional investigation to confrm this effect could be undertaken for further understanding.

Owing to the higher radiance exhibited by the fibre laser, Figure 6(a) shows an evidence of melting, oxidation, and entrapment of gas bubbles, which in comparison to the Nd^{3+}:YAG laser treated surface (exhibiting a low radiance) generated low temperature. Hence, a smaller interaction zone, surface melting and oxidation was created. The Si_3N_4 advanced ceramic generally decomposes at 1900 °C [27]. Therefore, it can also be ascribed that the higher radiance of the fibre laser caused the Si_3N_4 to partially melt and decompose somewhat above the decomposition temperature to about 2400 °C [27]. In comparison, for the Nd^{3+}:YAG laser engineered surface, the induced heat would be much below the decomposition temperature of the Si_3N_4. On this more, it is also suggested that an experimental investigation comparing the radiance temperature is carried-out to demonstrate the differences of heat generated between each laser source during laser-material interaction.

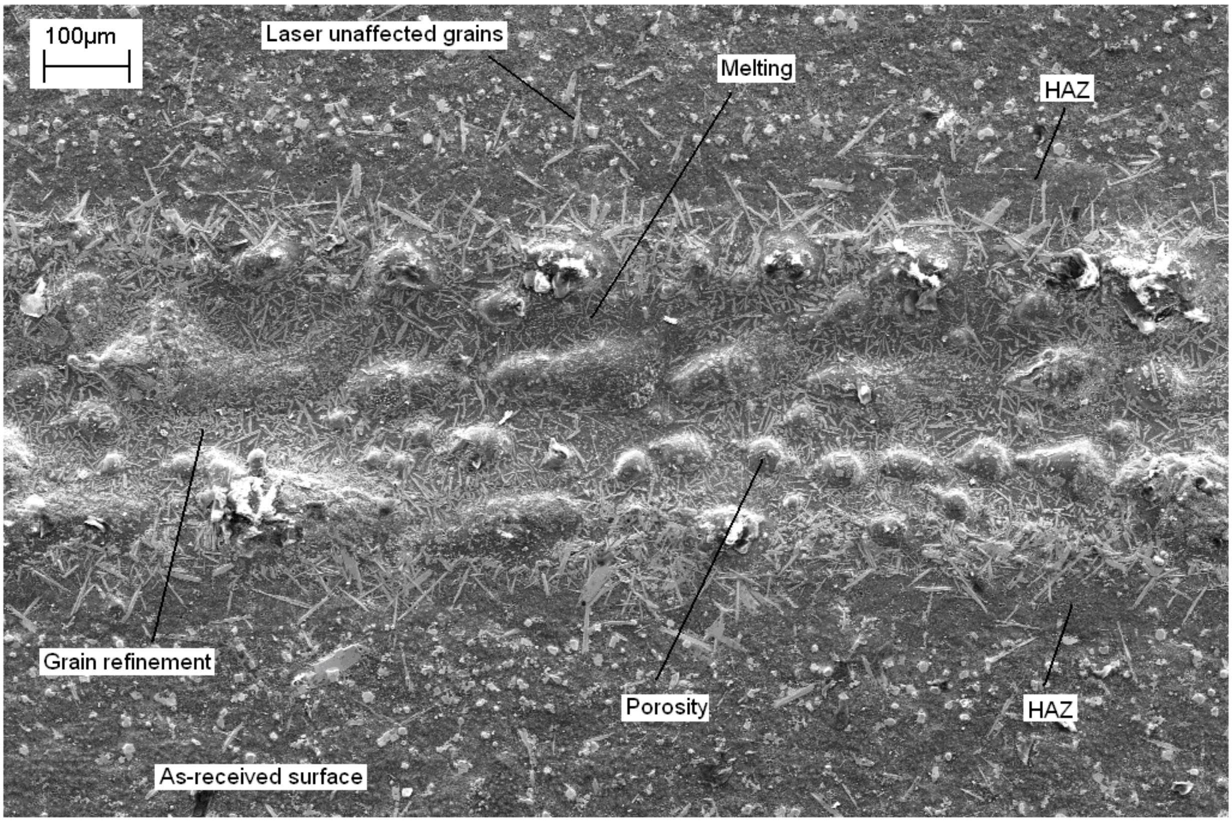


Figure 3 A micrographic image of the fibre laser engineered surface of the Si_3N_4 advanced ceramic.

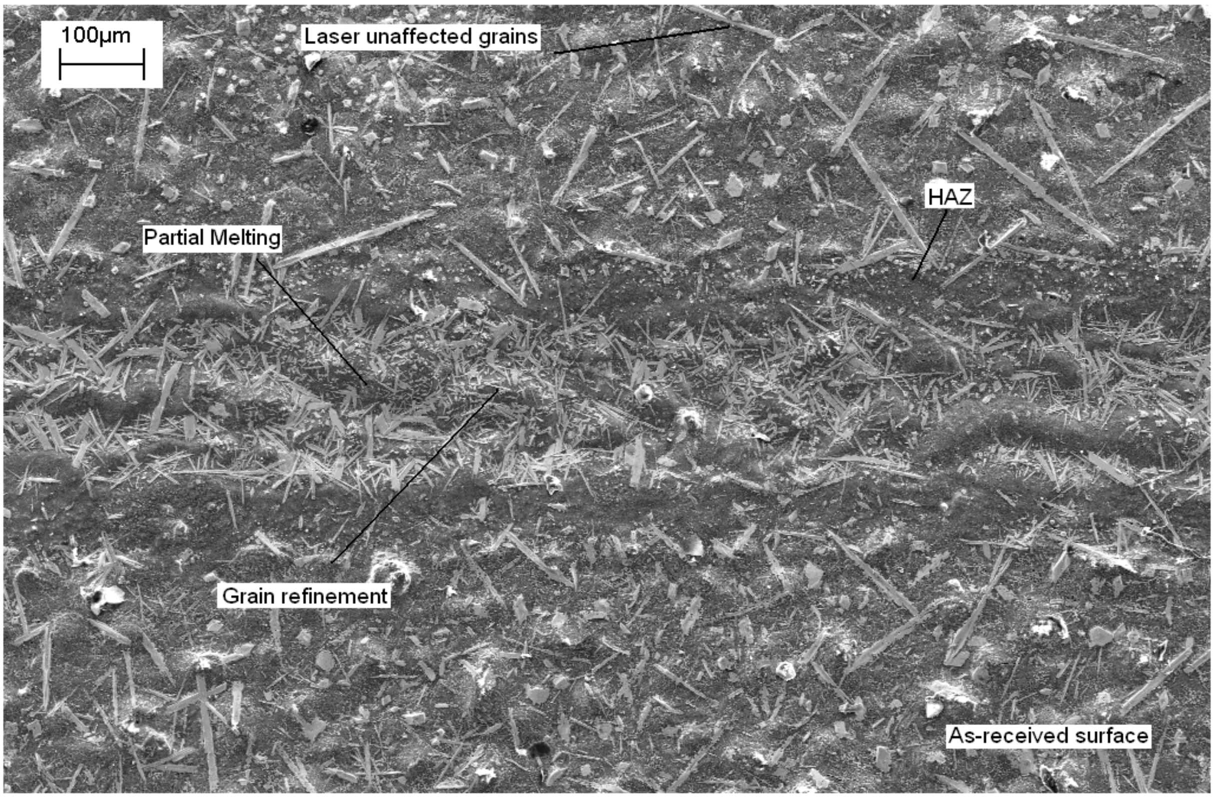
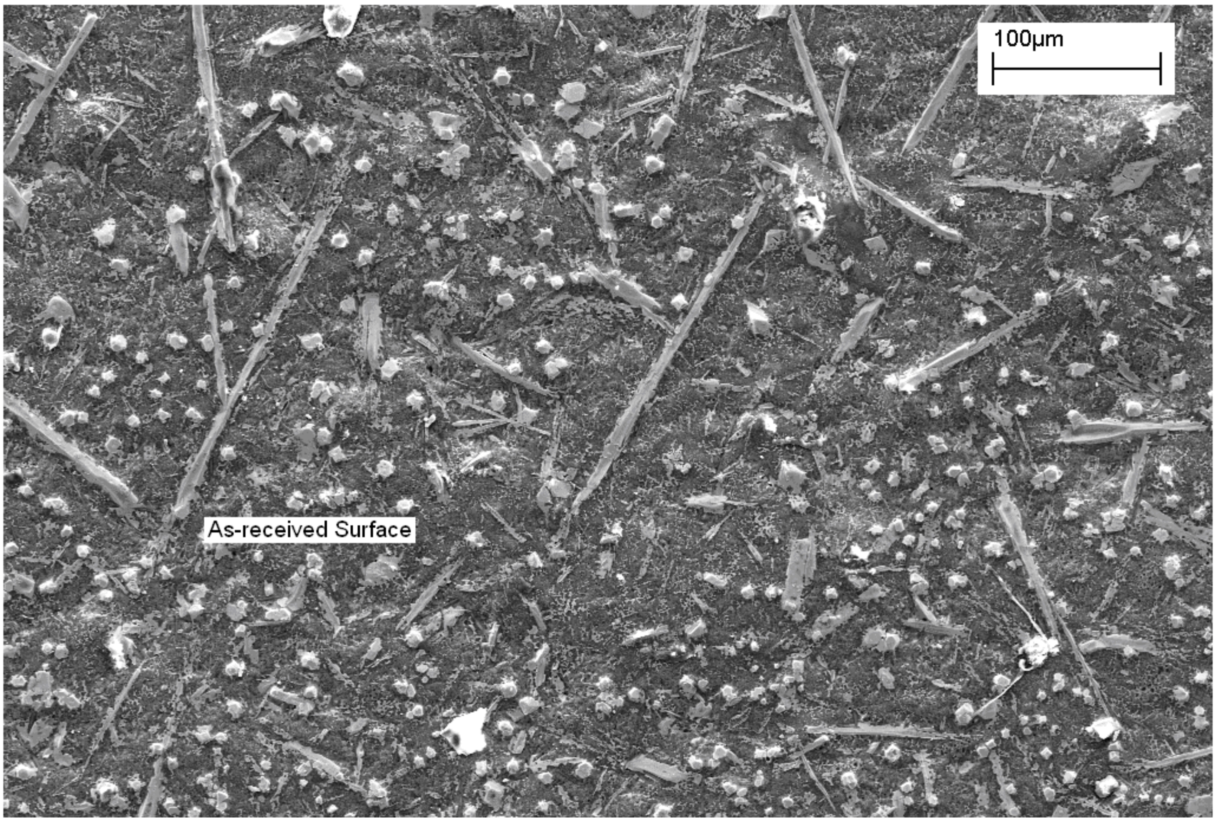
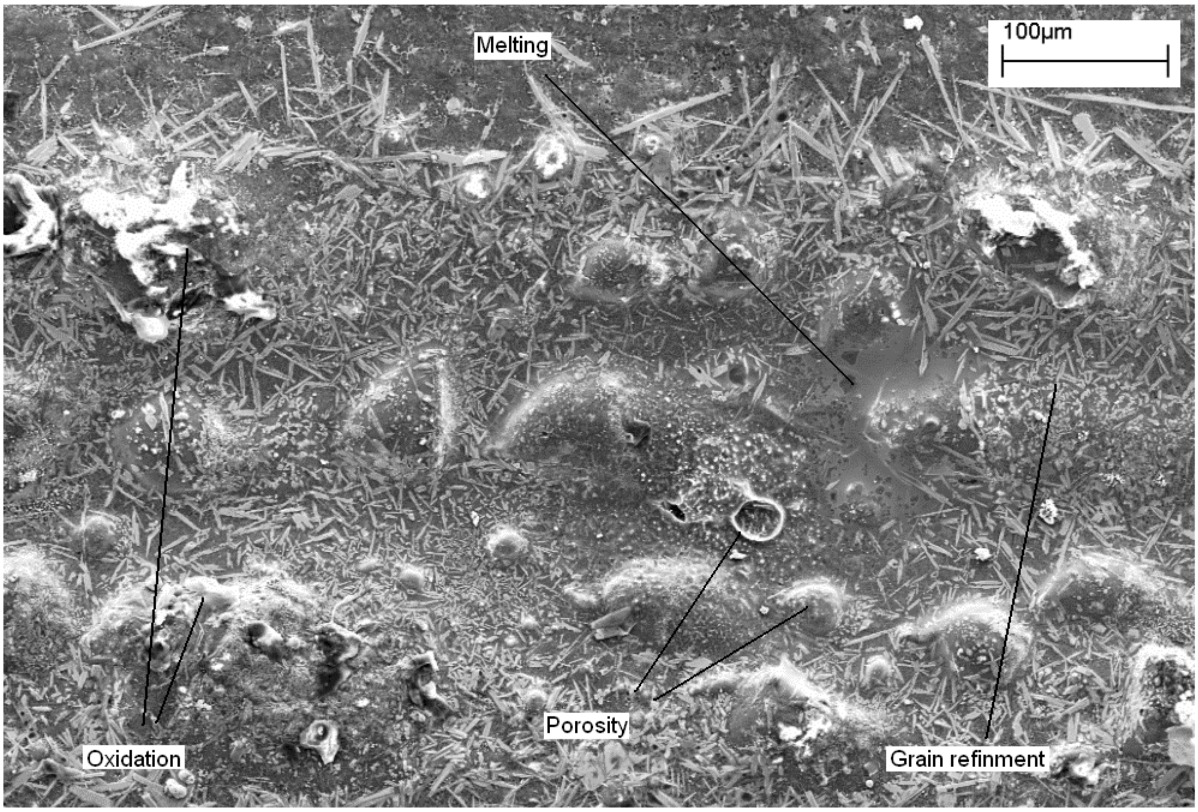


Figure 4 A micrographic image of the Nd^{3+}:YAG **laser engineered surface of the Si_3N_4 advanced ceramic.**

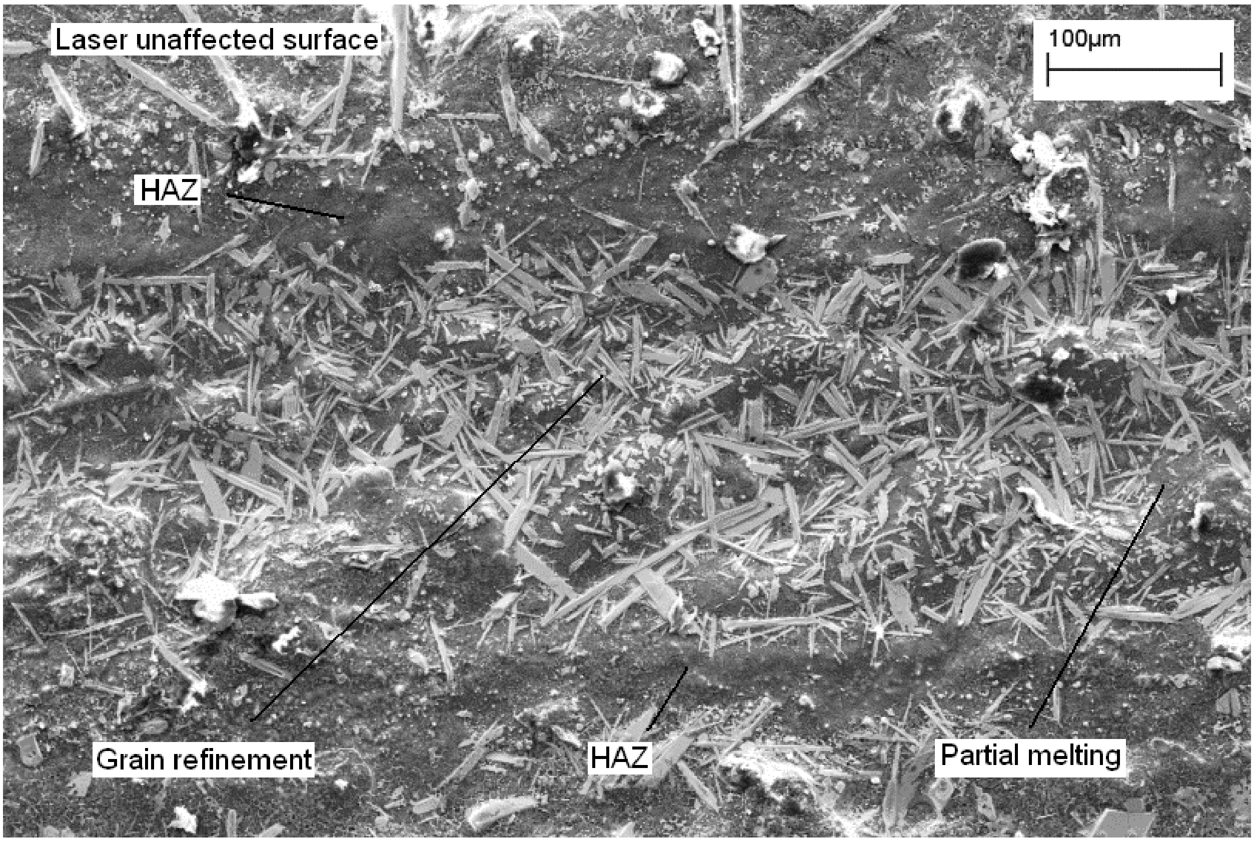
From observing the micrograph of the untreated surface of the Si_3N_4 in Figure 5 (a); it can be observed that sharp rods like features are present but are not equaly shaped along with the presence of square shaped blocks. During the laser-Si_3N_4 interaction it is possible that upon re-melting of the near surface layer affected the dimensional sizes of the elongated sharp rods to reduce in size. Having said this, the effect is more evident with the sample surface engineered by the fibre laser (see Figure 5(b)) as the rods are much finer and became smaller in size compared to the Nd^{3+}:YAG laser engineered surfaces presented in Figure 5 (c). The change in the microstructure produced by the two lasers would have occurred due to the higher melting and vaporization as well as a possible tranformation of phases as comfirmed by previous investigation on the fibre laser irradiation of Si_3N_4 engineering ceramics [27, 28], where an alpha (α) to beta (β) transformation occurred whilst the surface was strengthened.



(a)



(b)

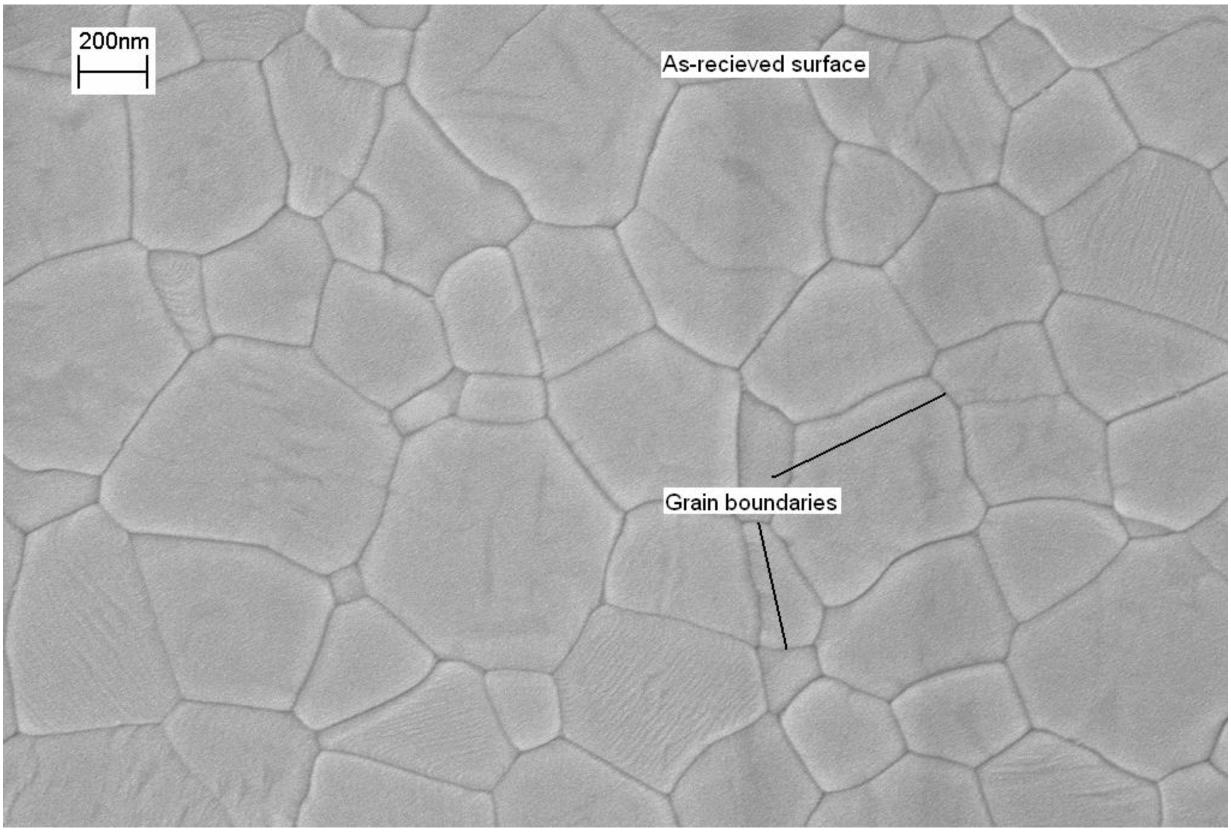


(c)

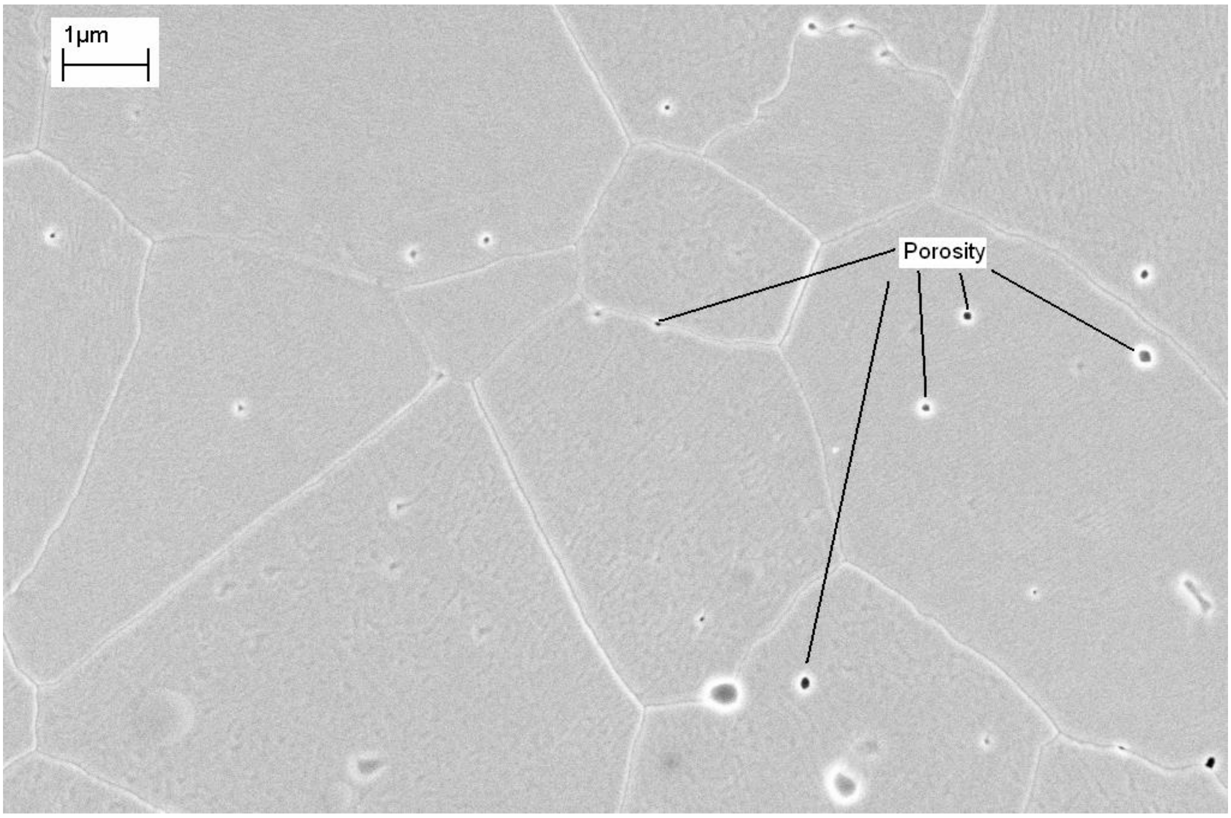
Figure 5 Micrographs of the as-received surface in (a) the fibre laser engineered surface in (b), and (c) the Nd^{3+}:YAG **laser engineered surface of the** Si_3N_4 **advanced ceramic.**

3.2.2 ZrO_2 Advanced Ceramics

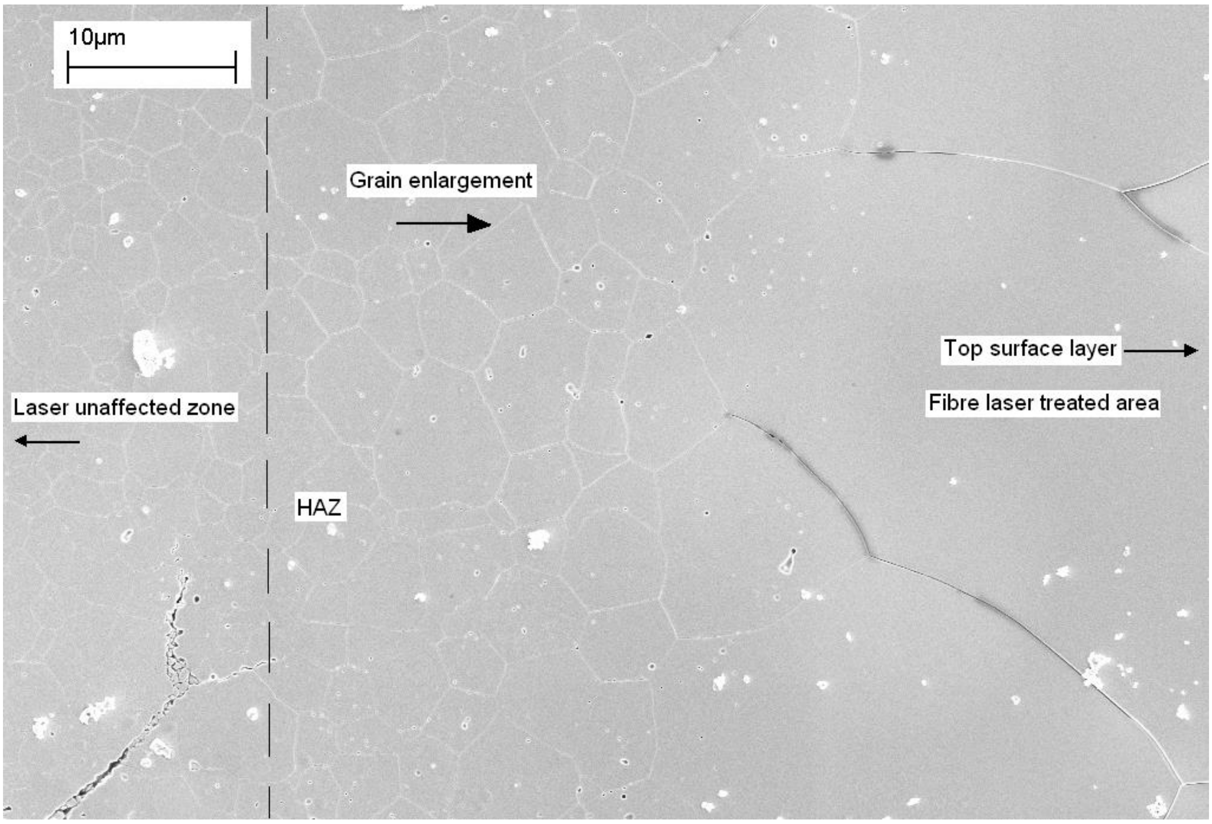
The grain boundaries of the fibre laser engineered surface of the ZrO_2 advanced ceramic shown in Figure 6(a) have enlarged and elongated in comparison to the ground and polished untreated surface in Figure 6(b). Nevertheless, an increase in surface flaws and porosity has occurred after the fibre laser surface engineering have taken place when compared to the as-received ground and polished surface. This is believed to have resulted from escaped gas during the fibre laser-ZrO_2 interaction. In addition, the grain sizes tend to vary from 3μm to 10μm from the near-surface layer and through the sub-surface, and the bulk of the ZrO_2. This was due to the laser-ZrO_2 processing temperature at the near surface layer being somewhat higher than the sub-surface and the bulk of the ceramic. This could also be confirmed from a previous investigations [26, 27]. As shown in Figure 6(c) of the cross-section of the microstructure, the grain size increases from the bulk of the ZrO_2 to the sub-surface and the top surface layer of the fibre laser engineered zone. The microstructure at the near surface layer is somewhat different as significant grain growth has occurred due to the high temperature gradient existing at the laser-ZrO_2 interaction.



(a)



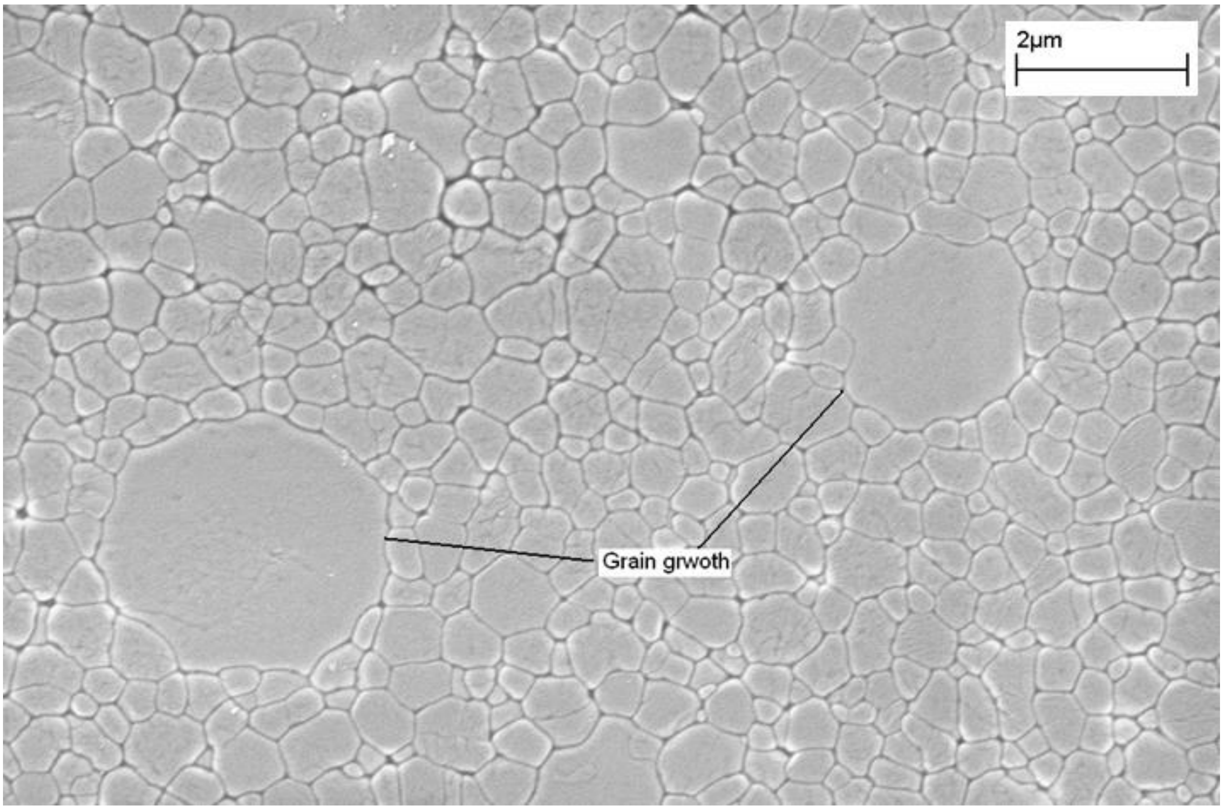
(b)



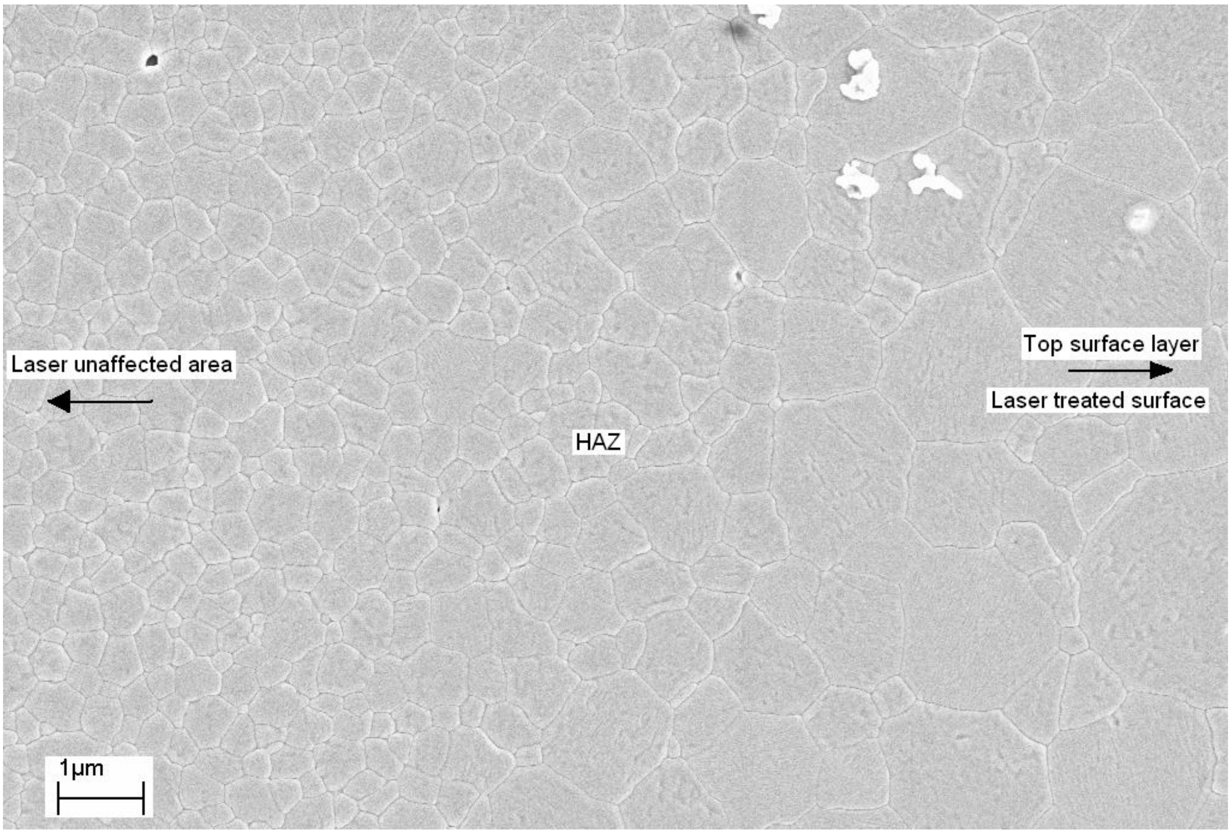
(c)

Figure 6 Micrograph of the cross-section of the sub-surface layer of the the as-received ground and polished surface in (a), and (b) the fibre laser surface and its cross-section in (c) of the ZrO_2 advanced ceramic.

The microstructure of the Nd^{3+}:YAG laser engineered surface in comparison to the as-received surface was reasonably modified (see Figure 7 (a) and (b)). The grain sizes herein range from about 3.5μm to 7μm and an average grain size was of about 5μm. This in comparison to the untreated surface was considerably large. When the results of the Nd^{3+}:YAG laser were compared to the fibre laser engineered surfaces, the grain boundaries were somewhat smaller as evident in Figure 7(b) and (c)). Similar effects also occurred with the ZrO_2 samples engineered by both the lasers, though the results of the Nd^{3+}:YAG laser were less significant. The image seen in Figure 7(a) within the cross-section comprised of larger grains at the near surface layer of the ZrO_2. This further reduced as it was observed at the sub-surface and the bulk of the ZrO_2 advanced ceramic (see Figure 7(a)). Nonetheless, the particular grian growth seen in Figure 7(a) appears to be somewhat abnormal as grain elongation only in random sections of the laser treated zone has appeared. Figure 7(b) shows the very near surface layer of the ZrO_2 advanced ceramic surface engineered by the Nd^{3+}:YAG laser. The microstructure in this image was reasonably modified in comparison to the microstructure where the laser-ZrO_2 interaction did not occur.


2µm
Grain grwoth

(a)


Laser unaffected area
HAZ
Top surface layer
Laser treated surface
1µm

(b)

Figure 7 Micrograph of the Nd^{3+}:YAG **laser engineered sample in (a) showing an abnormal grain growth in various regions of the sub-surface and (b) the elongation of grains when moving closer to the surface region of the ZrO_2 advanced ceramic within the sub-surface region.**

Figure 8 shows a melted glassy amorphous zone produced by the Nd^{3+}:YAG laser - was a mixture of $ZrCO_2$. This could be postulated from a previous investigation using the fibre laser to surface engineered ZrO_2 that demonstrated similar findings [29]. Evidance of surface melting can be seen with the Nd^{3+}:YAG laser engineered surface, although, it was not as remarkable as the fibre laser treated surface of the ZrO_2 since large proportion of the cross-section was found to be of the amorphous glass layer. This in turn confirmed that the formation of the considerable melt-zones found at the fibre laser surface interaface would have occurred from a higher laser-material interaction temperature, whereas the Nd^{3+}:YAG laser surface temparatures would have been somewhat lower to have only comprised of the pratial melting. This difference occurred despite using identical laser processing parameters between the two lasers used. Moreover, the fibre laser with a higher radiance value had created much higher temperature which characteristically melted the surface and generated a larger melt-pool. On the other hand, the Nd^{3+}:YAG laser-material interaction temperature was lower due to the low radiance value. This would generate low power per unit area in steradian. In addition, to complement this statement – considerable amount of surface cracking was also found with the fibre laser engineered sample in comparison to the Nd^{3+}:YAG laser which suggested that the temperature gradient as well as the cooling rate by each laser would have varried leading to the observed differences.

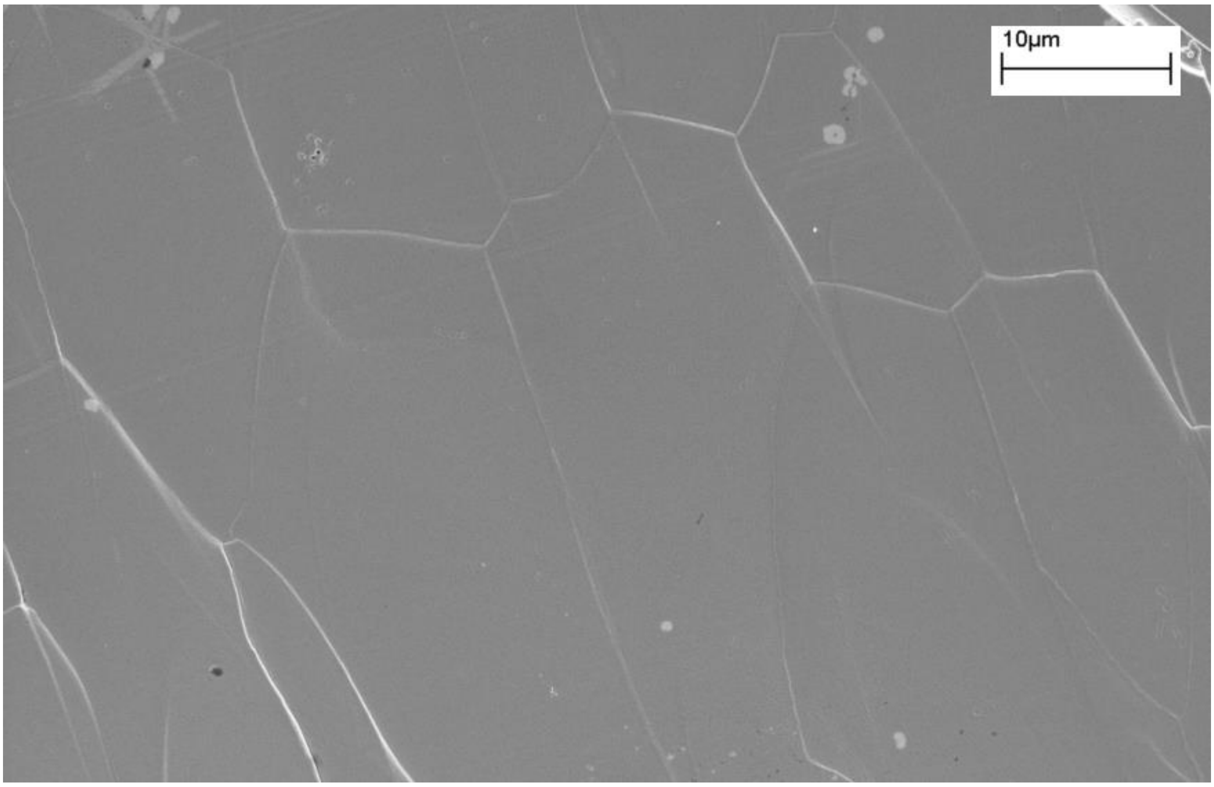


Figure 8 Micrograph of the cross-section of the Nd^{3+}:YAG **laser engineered surface of the ZrO_2 advanced ceramic showing the surface layer with partial melt zones.**

4. Discussion

4.1 Contribution of Laser Beam Paramaters to Effect Radiance

Due to the theory behind the calculation of laser beam radiance [12 - 17], it is indicative that several laser beam ralated parameters effect the calculation and contribute in someway or another. These aforementioned parameters are namely:

- the output laser power;
- spot size;
- power density;
- the beam quality factor - M^2;
- transverse mode;
- beam divergence.

However, the amount of contribution each parameters has thereon the end radiance value is yet unclear and further analysis is currently being undertaken by the leading author of this study to show the contribution of each parameter to effect the laser beam radiance. Thus, it can be attributed that a high quality laser beam leads to higher radiance value which instrinsically generates high power per unit area and causes considerable difference as seen from the study herein. On this more, the difference in the beam divergence and the quality factor M^2 between the two lasers led to a change in brightness as the fibre laser divergence was much smaller than the Nd^{3+}:YAG laser which emitted a brighter beam.

Furthermore, a highly radiant laser beam generally penetrates deeper into the surface as high brightness beams produce deeper penetration [27], longer depth of focus, larger impact or the track width, and microstructural changes, despite using identical parameters to a laser beam of lower radiance as seen from the study herein. This allows the high radiance laser to operate at lower power levels to produce the same surafce treatment to that of a low radiance laser. This characteristically reduces with a reduction in cost. Further work is also being undertaken by the leading author of this study to determine the cost difference between high and low radiance lasers.

4.2 Comparison of the Effects of Laser Beam Radiance theron the Advanced Ceramics

Up on comparing the results found with the effects of the laser beam radiance on both the Si_3N_4 and ZrO_2 advanced ceramics it can be observed that the effects of high laser beam radiance exists with both the nitride and oxide ceramics as larger surface tracks were seen and microstructural changes were also much significant using the high radiance laser. Thus, it is important to mention at this point the difference in the temperature exhibited between the two lasers at the laser material interaction zone. The fibre laser comprising of a much radiant and brighter beam and emitted higher peak temperature in comparison to the Nd^{+3}:YAG laser [27]. This leads to difference in heating rate and then the cooing of the two ceramics. The fibre laser would generally heat up the material faster and allow a slower cooling rate to take place. This consequently would allow not only a change in the microstructure as seen in the results herein, but would also enable the heat to spread in a larger surface area and would attribute to creating larger track widths.

Moreover, it can be reported that thicker track width was seen using both lasers for the ZrO_2 (oxide ceramic) when compared to the Si_3N_4 (nitride ceramic) when employing the high radiance fibre laser. This indicated that comparison of the effects of laser beam radiance would be more predominent and obvious if two ceramics were compared from the same branch of the ceramics family tree. Examples are namely: comparison of Si_3N_4 to boron nitride (BN) or ZrO_2 to alumina oxide (Al_2O_3) and likewise, SiC to boron carbide (BC). This will enable one to understand the specific difference the radiance of a laser has up on the particular branch of materials in future investigations.

Previous result have shown that high brightness lasers exhibit high processing temperatures during laser-ceramic interaction [27]. This is particularly so for the fibre laser and significant difference in the solidification rate would occur, which thereby, re-creates a different microstructure as can be seen with the results obtained herein for the fibre laser engineered Si_3N_4 and the ZrO_2 advanced ceramics in comparison to that of the Nd^{+3}:YAG laser. The high processing temperature by the fibre laser has yielded refined grain structure with the Si_3N_4 and evidence of significant melting and possibly what appears to be a glassy layer with the ZrO_2. The modified microstructure in turn results to difference in the surface properties of the ceramics such as a change in the hardness, fracture toughness parameter K_{1c}, and depending on the peak processing temperature; there could be a probable phase change for the two ceramics, whereby the Si_3N_4 could have transformed from alpha-phase to beta-phase and the ZrO_2 from a monoclinic phase to tetragonal, or from a tetragonal to a cubic phase. In any case, further investigation would be required to confirm such modifications using the same experimental conditions and the two ceramics used in this study.

6. Conclusions

A comparative study regards to the effects of laser beam radiance, commonly known as brightness was investigated during surface treatment of a Si_3N_4 and ZrO_2 advanced ceramics by employing a fibre laser and a Nd^{3+}:YAG laser. Like-by-like laser parameters were used to investigate the change in the microstructure and the laser induced foot-prints. The results showed that the effects of the fibre laser surface engineering on both the advanced ceramics differed from the effects of the Nd^{3+}:YAG laser as larger track width (foot-print), porosity, oxidation, surface melting and decomposition took place. Moreover, considerable changes in the microstructure were evident and sharp rods-like features were much reduced in size due to high laser beam radiance of the fibre laser, creating high temperature during laser-ceramic interaction for the Si_3N_4 advanced ceramic. This consequently caused higher melting of the ceramic. For the ZrO_2 advanced ceramic the microstructural changes also showed that the fibre laser engineered surface was producing large grains in comparison to the Nd^{3+}:YAG laser engineering surface by over 20% difference in size which also attributes to the higher temperature characteristically generating a high melt zone to occur.

The dimentional and the microstructural effects on the two advanced ceramics differed for the two lasers treatments despite using like-bylike parameters. Owing to this, the laser beam radiance is taken into account since higher power per unit area in a solid angle in steradian would have generated high interaction temperatures, causing larger thermal gradient to produced a bigger melt zone. As result, the difference in the dimentional size of the laser induced foot-prints and the differnce in the microstructure were found for the two ceramics.

On account of the findings herein, it is concluded that laser beam radiance during laser surface engineering and other processes should be considered as its not only a sum of the laser power density but it also takes in account of other important parameters of the laser beam. High radiance lasers have the potential to also generate effective and possibly efficient surface engineering process which could enable the use of lower wattage for the same treatment. This inherently leads to cost reduction for the process. Further investigation into the effects of radiance on other material types; comparison of cost between high and low radiance lasers; temperature difference between various lasers with different randiances and the contribution of each laser beam parameter to the end value of radiance is currently being investigated by the authors of this study.

4. Vitae

4.1 First Author - Dr. Pratik P. Shukla

Dr. Pratik Shukla is a research fellow at the University of Lincoln (Laser and Photonics Engineering Group), actively conducting research in the field of laser surface engineering of technical grade ceramics, improving functional properties of engineering and bio-medical ceramics by means of ultra-short pulse lasers, wider effects of the laser beam brightness in laser processing and laser assisted joining of zirconia based fuel cells. He was previously a research engineer in the laser-material processing industry and a manufacturing engineer in aerospace/industrial turbine blade manufacturing. Dr. Shukla also worked as a lecturer at Tongji University, China and at Sharda University, Delhi (India).

4.2 Professor Jonathan Lawrence - Professor of Laser Materials Processing

Professor Lawrence is currently Director of Laser and Photonics Engineering Group in the University of Lincoln, Editor-in-Chief of the international journal Lasers in Engineering and a Member of the Engineering Professors' Council. His main contribution has been in the field laser radiation on the wettability characteristics of materials; improving the biocompatibility of materials using laser radiation; as well as studying the feasibility of using lasers for the forming of sheet metal and developing a technique for laser ignition in gas turbines. He has presented and published widely in these areas, including five patents, seven books and over 120 journal papers.

5. Acknowledgements

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