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The influence of Brightness during Laser Surface Treatment of Si_3N_4 Engineering Ceramics

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Highlights

This paper is a first-step study of the effects and the influence of the laser-beam brightness thereof on a Si_3N_4 engineering ceramic. It addresses the physical and microstructural changes which the brightness as a parameter has upon the ceramic material after the laser surface treatment. In order to address the effects, a fibre and an Nd:YAG laser is used for the comparison by applying identical processing parameters. To date, the brightness of a laser beam is somewhat an idle feature and is not readily thought of during laser aided material processing (process design) but in theory it is the power per unit area in steradian should be considered during a laser process design. The work in this paper has now shown that at a practical level, the statement is correct and the laser-beam brightness being the power per unit area in steradian has a considerable influence on the ceramic and possibly other materials when two identical laser sources are employed and compared.

Abstract

A comparative study between the fibre and an Nd:YAG laser during the surface treatment of a Si_3N_4 engineering ceramic was conducted to investigate the contribution of the laser-beam brightness. A fibre and an Nd:YAG laser with identical process parameters were employed. The effects of the laser-beam brightness were investigated with respect to the change in the dimensional size of the laser irradiated zones and the microstructure of the Si_3N_4 engineering ceramic. The results showed a change in the dimensional size and the microstructure of the surface treated by the two lasers despite using identical laser processing parameters. This was due to the difference between the laser-beam brightness of the two lasers as the fibre laser produced larger power per unit area in steradian in comparison to the Nd:YAG laser. Owing to this, high interaction temperature, larger fibre laser-ceramic interaction zone and melt-pool at the laser-Si_3N_4 interface were found which further led to changes in the physical attributes of the Si_3N_4. This goes to show that laser surface treatment using high brightness would be cost effective as the brighter laser utilizes lower power for the same surface treatment in comparison to that of a low brightness laser. Therefore, it could very ideal and economical to process engineering ceramics and other materials by employing high brightness lasers.

Keywords: Lasers, Brightness, Si_3N_4

1. Introduction

Current application of the fibre lasers in particular are expanding in the industrial scene with processing metals, plastics and some ceramics. Nevertheless, from a laser material interaction view point, the effects of the fibre laser interaction on engineering ceramics are not fully discovered and understood as fibre lasers are still new in the market. This research is focused on a comparison of the physical effects during the interaction of a fibre and an Nd:YAG laser whilst the surface treatment of a silicon nitride (Si_3N_4) engineering ceramic.

High brightness laser sources such as a fibre laser or a disc laser produce high temperature during material interaction [1-5]. A fibre laser also offers a longer depth of field (long focal length), small spot sizes and beam quality as well as stability during its execution. The brightness of a laser is more effective in comparison to the laser power intensity. This is because by achieving a high brightness would generate high processing temperatures [5]. This is particularly important for processing engineering ceramics such as a Si_3N_4 to achieve surface melting, infilling the surface cracks and to achieve localized modification as well as phase transformations within the ceramic.

Despite many studies published in the area of improving the laser-beam brightness, there is still very little work published for the use of a high brightness fibre laser to surface treat materials such as ceramics in particular. To date, no work has been reported hitherto with regards to the influences of the high brightness fibre lasers and its contributions during the laser surface treatment of engineering ceramics such as a Si_3N_4. Laser-beam brightness (radiance) is generally classified as the power per unit area in steradian. The brightness parameter of lasers should be considered rather than the laser power during laser processing of materials. In addition, laser-beam brightness is an important parameter of laser material processing rather than the input laser energy (power). The laser-beam brightness tends to influence the material being processed rather than the laser power intensity. Having said that, laser-beam brightness as a parameter is generally not taken into consideration in the laser material processing sector. This work is a first step introduction to demonstrate the physical effects, namely: the microstructural and dimensional changes during the surface treatment of a Si_3N_4 engineering ceramic and attempts to compare the contribution and the effects of the fairly novel fibre laser-beam brightness to that of the conventional Nd:YAG laser.

2. Previous Research on High Brightness Laser Processing

Several workers in the recent time have worked with high brightness lasers for processing materials. Wallace [6] used the high brightness diode lasers to produced high efficiencies and lower operating costs. Wenzel *et al.* [7] used a high brightness semiconductor laser to show that high reliability and efficiency can be achieved with a low beam quality factor. Brown and Frye [8] worked with high brightness cutting and drilling process for aerospace materials with the aid of a Nd:YAG laser. The results showed improved cutting and achieved shallow angle holes. Li *et al.* [9] worked on the reliability and efficiency of high brightness lasers by using the 940 nm wavelength to show the maximum power conversion efficiency of 60% at an output power of 72 W with very good beam quality. Treusch *et al.* [10] applied a high-brightness semiconductor laser and found that collimation lenses can be used to increase the brightness of the laser by a factor of two. In addition, the wavelength and polarization coupling also contributed to the increase in laser-beam brightness. Leibreich and Treusch [11] conducted a similar investigation on improving the brightness of a semiconductor diode laser using laser beams of various wavelengths to increase the output power and the brightness. The results showed that the laser-beam brightness can be doubled without any changes to the beam quality factor (M^2). This in general could be a new prospective within the laser materials processing industry. Furthermore, increase in the brightness was found by altering the transverse mode found by Hanna [12, 13]. Also, Hanna suggested that by varying the transverse mode would lead to a change in the beam divergence and also alters the brightness of the laser source [13]. However, altering the brightness involves careful measurement of the laser beam which is considerably difficult to measure for an industrial laser as it requires complex set-up and a time consuming procedure. British standards [14 – 16], demonstrate a detailed technique for this measurement.

Investigation conducted by Del Val *et al.* [17] showed the effects of laser cladding of stainless steel plates and co-based super-alloy (powder coating material) using a Nd:YAG laser and a Yb: YAG fibre laser. The findings revealed that fibre laser in comparison to that of the Nd:YAG showed versatile parameter window and enlarged clad track and deeper penetration, but similar hardness was obtained from applying both laser types. Val *et al.* then reported that this effect had occurred because of the higher beam quality as well as the high brightness produced by the fibre laser. This is ideal for creating thinner clad tracks but a Nd:YAG laser is ideal for producing wider clad tracks. Val *et al.*'s work closely relates to the work in this investigation since the effects of brightness between the Nd:YAG laser and the fibre laser are studied. But, this research investigates the Si_3N_4 engineering ceramic for the first time by rather employing the surface treatment method in terms of laser processing with a high brightness laser beam.

3. Background, Theory and Preliminary Analysis of the Laser-Beam Brightness Parameter

Brightness is defined as a light is transmitted to a surface per unit of area measured in steradian and is a significantly important parameter of a light source [18-19]. Brightness is expressed when a visual quality of a light source related to contrast and glare is discussed but brightness also relates to a light source such as a lamp or a candle and it is found through reflection and transmission. As an example, high reflections are produced by bright surface and low reflections are produced by a dull surface [20]. The term brightness is used also when comparing two light sources which may or may not differ when judged by a human eye, as it varies in intensity on the surface of the retina [20]. Other definition of brightness is classified as candles per square meter of light which is emitted on a surface. This is classified as radiance or luminescence depending on its application [19, 21]. Usually, the term luminescence is applied for a photometric quantity and the term radiance is used for a radiometric quantity [19]. The term luminescence is defined as the direction of light emitted which means that the brightness of a light source depends on the direction or the angle from which it is seen [21]. In addition, luminescence is also the intensity of light that is passed from the surface. The opposite of luminescence is the illuminescence which is the intensity of light that is directed or received on the surface. The radiometric term of a light is more commonly used in the literatures for simplicity. This is particularly so when expressing the laser-beam brightness. Laser-beam brightness is the power per unit area per solid angle of divergence which is measured in steradian [22-23].

Industrial laser beams exhibit high brightness when compared to other light sources. This is because a laser light exhibits very high power levels in a small diameter [24, 25]. Thus, the allowable spot diameter of the laser beam is a significant factor [26]. Laser-beam brightness cannot be changed meaning that the focusing or defocusing the laser beam will not alter the laser-beam brightness parameter [27]. Brightness is inversely proportional to the solid angle. This means that a Gaussian laser beam will not change. The solid angle of the laser beam is proportional to the square of the divergence angle θ. Therefore, the brightness is dependant on the beam divergence - the smaller the divergence, the higher the brightness. Moreover, laser beams with high brightness tends to have the most ideal beam profile and a high M^2 value.

Laser-beam brightness parameter and the power intensity parameter both are closely related. This is because the laser power is input power per spot size which is multiplied by the Gaussian beam configuration value whereas the brightness is the input power per unit area per solid angle [28-29]. This investigation suggests that laser-beam brightness is a parameter in laser aided material processing and is significant. This is due to the intensity obtained within a focusing area within a lens is proportional to the brightness of the beam. Laser processing using high brightness lasers allows fine spot size of the beam and allows longer focusing distance. This brings about more flexibility to the process since more distance is covered during the laser process. In the case for this research, it is particularly offered when laser processing the Si_3N_4 engineering ceramic by fairly novel fibre laser.

Laser beam brightness can be calculated theoretically by using Equation 1 [30-33]:

$$Br = P_{out} / A\Omega \qquad (1)$$

Where P_{out} is the power, A is surface area and Ω is the solid angle of divergence of the beam. Brightness is inversely equal to the solid angle of divergence. The solid angle of divergence created by a laser beam is equal to the square of the divergence angle θ as shown in Figure 1. The solid angle of a Gaussian beam equals to Equation 2 and is inversely proportional to ($\pi w^2{}_0$).

$$\Omega = \pi \theta^2 = \lambda^2 / \pi w^2{}_0 \qquad (2)$$

The solid angle of divergence is usually small for laser beams in comparison to other light sources. This is because of their high directionality which in turn generates high brightness laser beams. Equation 3 represents a propagation ration for a circular Gaussian laser beam, where $M^2{}_y$ and $M^2{}_x$ represent the ration of beam propagation in the x-and the y-direction. Consequently, the laser brightness can be derived in Equation 4 which consists of feature in Equation 1 to 3:

$$M^4 = M^2{}_y \,.\, M^2{}_x \qquad (3)$$

$$Br = \frac{P_{out}}{M^4 \text{ x } \lambda^2} \qquad (4)$$

The solid angle of beam divergence is presented in Figure 1. The solid angle of beam divergence is a unique dimension for all laser beams with different beam profile and Gaussian configuration. The solid angle of divergence is the spread of the beam after being focused from the focusing lens. As a comparison, the characteristics and properties as well as the solid angle of beam divergence for the two lasers used in this research are presented in Table 1. The values in Table 1 were calculated using Equation 4 (according to the individual features by each of the fibre and the Nd:YAG laser employed for the experimentation for this study).

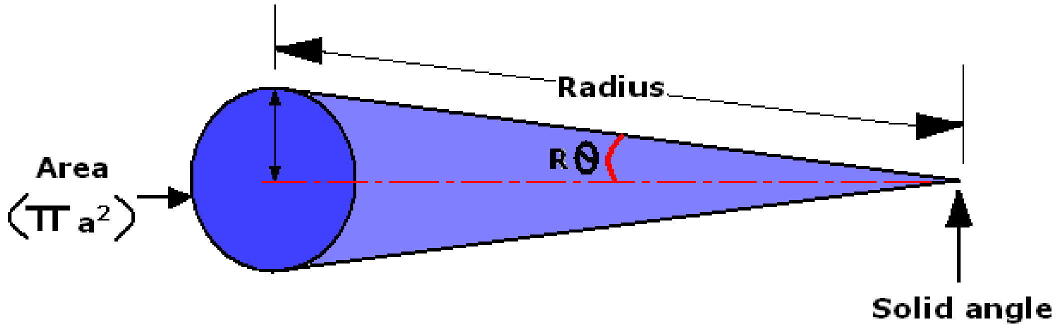
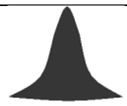
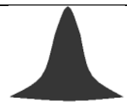


Figure 1 A schematic illustration of the solid angle of divergence of a laser beam.

Table 1 Properties of the Nd:YAG and the fibre laser as used for the investigation in this study.

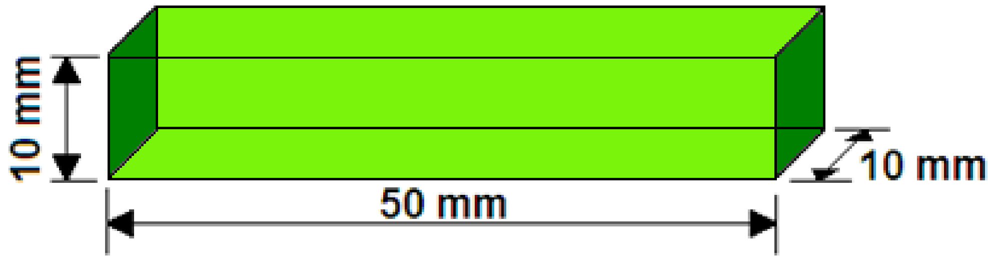
Type of Laser		**Nd:YAG Laser**	**Fibre Laser**
Beam divergence (m/rad)		5.5	0.2
Brightness (W. $sr^{-1}.m^2$)		609.50	1855.37
Beam quality factor (M^2)		6.8	1.1
Gaussian beam shape	**Cross-sectional view**		
	Plan view		
Gaussian mode		TEM_{00}	TEM_{00}

Note: The fibre and the Nd:YAG laser-beam brightness values were calculated using the features of each laser systems as the input parameters within Equation 4.

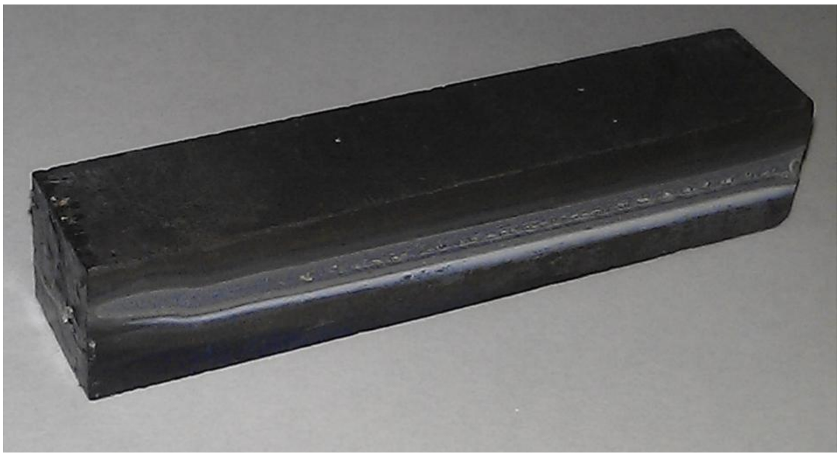
4. Experimental Method

4.1. Background of Si_3N_4 Engineering Ceramic

The Si_3N_4 engineering ceramic used for this research was a cold isostatically pressed (CIPed) Si_3N_4 with 90% Si_3N_4, 4% Yttria, 4% Al_2O_3 and 2% other content as specified by the manufacturer (Tensky International Company, Ltd. Taiwan). The bulk dimensions of the Si_3N_4 were 10 x 10 x 50 mm^3 (see Figure 2(a and b)) with a surface roughness of 1.56 µm were obtained for the experiments. The experiments were conducted in ambient condition at a known atmospheric temperature (20°C).



(a)



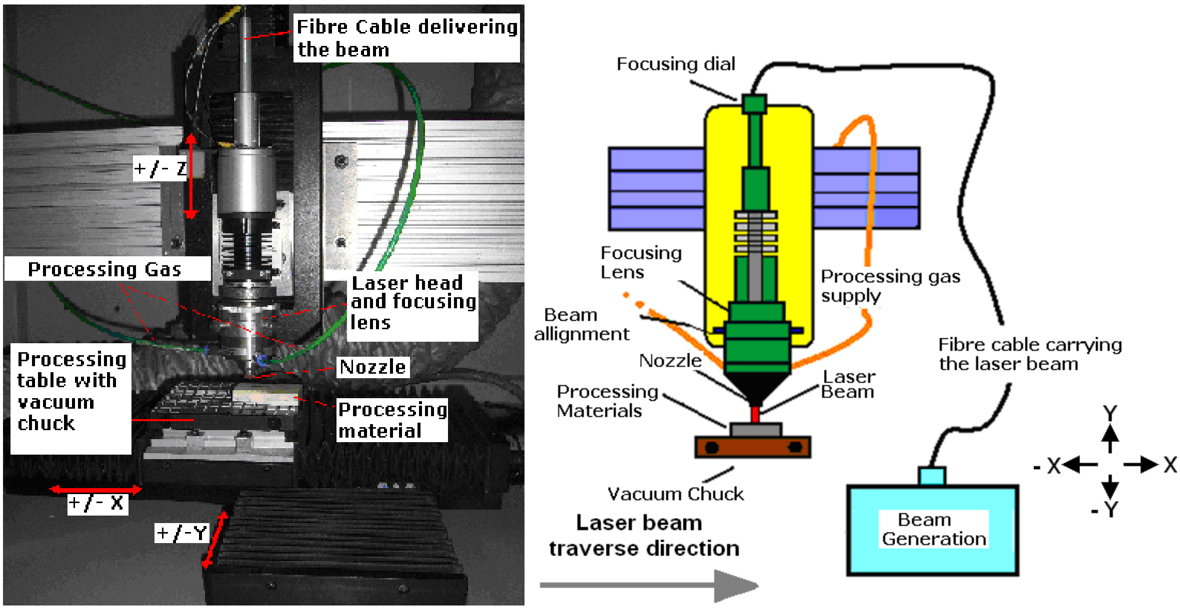
(b)

Figure 2 A schematic diagram of the experimental sample in (a) and the photographic image in (b) for the Si_3N_4 engineering ceramic.

3.1 Laser Surface Treatment

A continuous wave (CW) fibre laser (200 W) from SPI-200c-002; SPI, Ltd. Southampton, U.K. was employed for the first laser surface treatment trials (see Figure 3 (a and b). The wavelength of the laser was 1.075 μm. The focal position was kept to 20 mm above the work-piece to obtain a 2.2mm spot size. The processing gases used were N_2 and ambient air (no gas) supplied at a flow rate of 25 l/min. An SPI software was used to programme the laser. A 50 mm line was programmed using numerical control (NC) as a potential beam path which was transferred by a .dxf file. To obtain an operating window, trials were conducted at the fixed spot size of 2.2mm

65W and at a traverse speed between 10 mm/sec so that an equal comparative study of the effects of the Nd:YAG laser and the fibre laser could be conducted.



(a) **(b)**

Figure 3 An image of the experimental set-up of the fibre laser surface treatment of the Si_3N_4 engineering ceramic in (a) and a schematic diagram in (b).

A continuous wave Nd:YAG laser (65W) from Hahn & Kolb Ltd. U.S.A. (HK, SL902) was the second laser used for this work. The wavelength of the laser was 1.064 µm. To obtain a 2.2mm spot size, a focal length of 210mm above the work-piece was used. The processing gas employed was N_2 at a flow rate of 25 l/min. Programming of the laser was conducted using a Hahn & Kolb, U3 computer aided design (CAD) software. A 50 mm line was programmed using NC as a potential beam path. To obtain an operating window, trials were conducted at the fixed spot size of 2.2mm and 65W by varying the speed between 4 and 100mm/sec. From these trials it was found that 10mm/sec at 65W were the ideal laser parameter to use in terms of achieving a sufficient footprint on the Si_3N_4 to conduct further analysis. Figure 4 illustrates a schematic diagram of the experimental set-up.

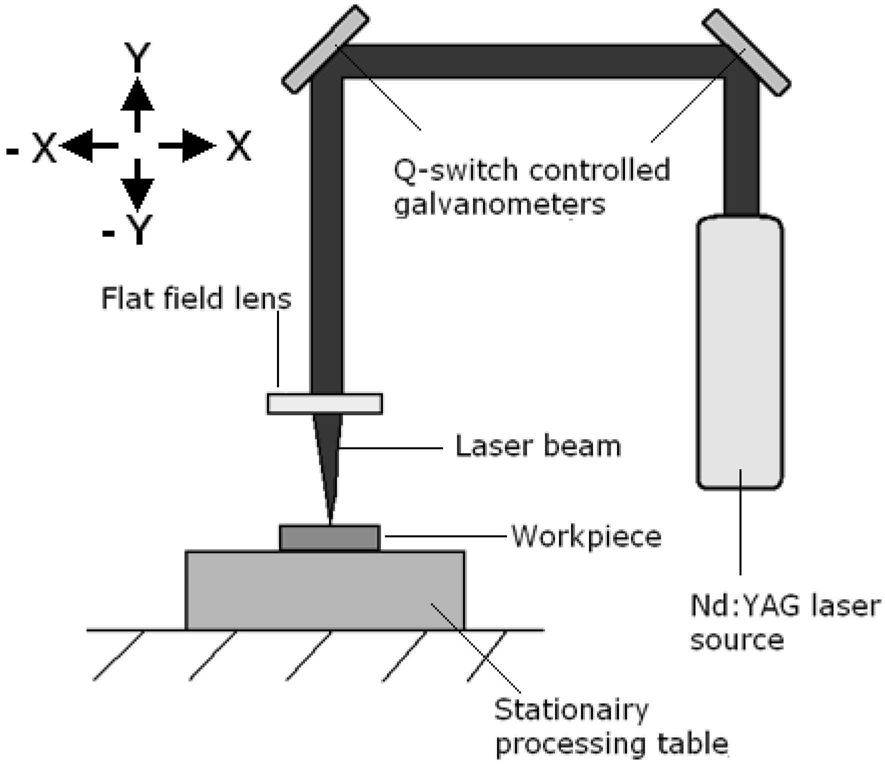


Figure 4 A schematic showing the experimental set-up of the Nd:YAG surface treatment of Si_3N_4 engineering ceramic.

5. Results

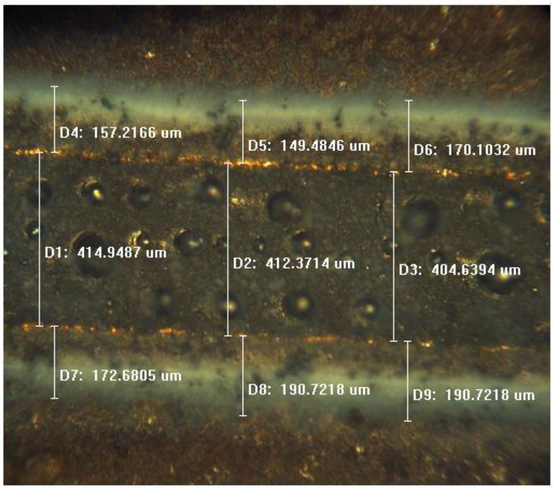
5.1. Dimensional Aspects

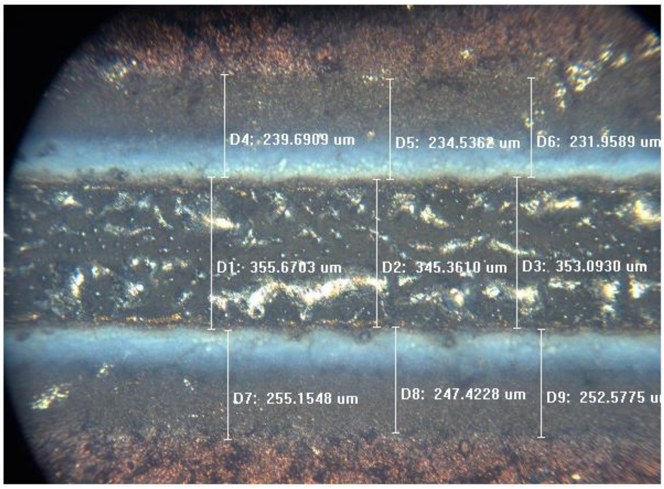
Except the laser-beam brightness being higher for the fibre laser, all other parameters were identical during both the fibre and the Nd:YAG laser surface treatment of the Si_3N_4 engineering ceramic. Despite applying identical laser parameters to surface treat the Si_3N_4, the fibre laser irradiated track of the Si_3N_4 was over 9% higher than that of the Nd:YAG laser (see Table 2 and Figure 5). On account of this, it can be suggested that due to higher brightness exhibited by the fibre laser resulted to high power per unit area on the ceramic. The high power per unit area applied to the Si_3N_4 produced a larger impact zone and bigger interaction in comparison to the interaction and the impact zone produced by the Nd:YAG laser.

Table 2 average track width of the fibre and the Nd:YAG laser treated surface

	Dimensions (µm)	
	Fibre Laser	**Nd:YAG**
Laser irradiated track	**419 µm**	**383 µm**
Heat affected zone (HAZ)	**155 µm**	**220 µm**

Notwithstanding this, the HAZ of the fibre laser irradiated surface of the Si_3N_4 was somewhat different to that of the Nd:YAG laser as the average HAZ was 42% smaller. Naturally, as previously stated that higher brightness of the fibre laser has resulted to a bigger interaction zone of the Si_3N_4 surface but at the same time the HAZ for the fibre laser irradiated surface was considerably smaller. As one can see from Table 1 that the despite the transverse electro magnetic mode (TEM) being TEM_{00} for both the lasers, the beam quality factor M^2 was better for the fibre laser (M^2 = 1.1) than the one for the Nd:YAG (M^2 = 6.8). On account of this, it can be gauged that the difference between the beam quality factor was remarkably large. On this more, the better beam quality for the fibre laser indicated a sharper beam front in comparison to the Nd:YAG laser indicating that the impact or the footprint is bigger but the energy induced into the surface was focused on a narrow area and was localized rather than being spread outwards which was the case with the HAZ of the Si_3N_4 surface irradiated by the Nd:YAG laser.



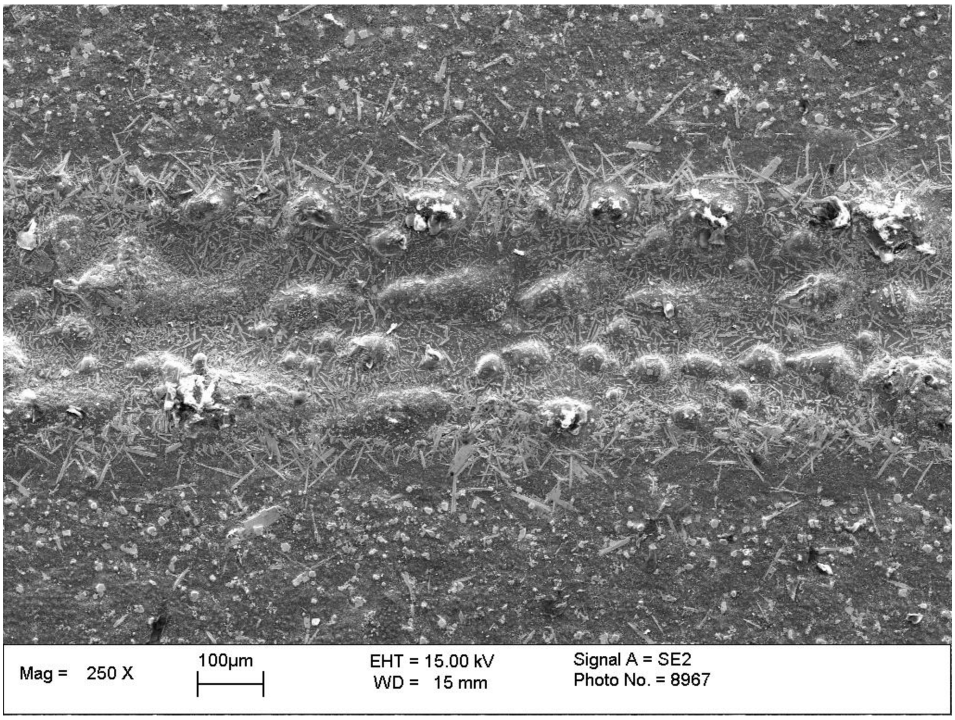


(a) **(b)**

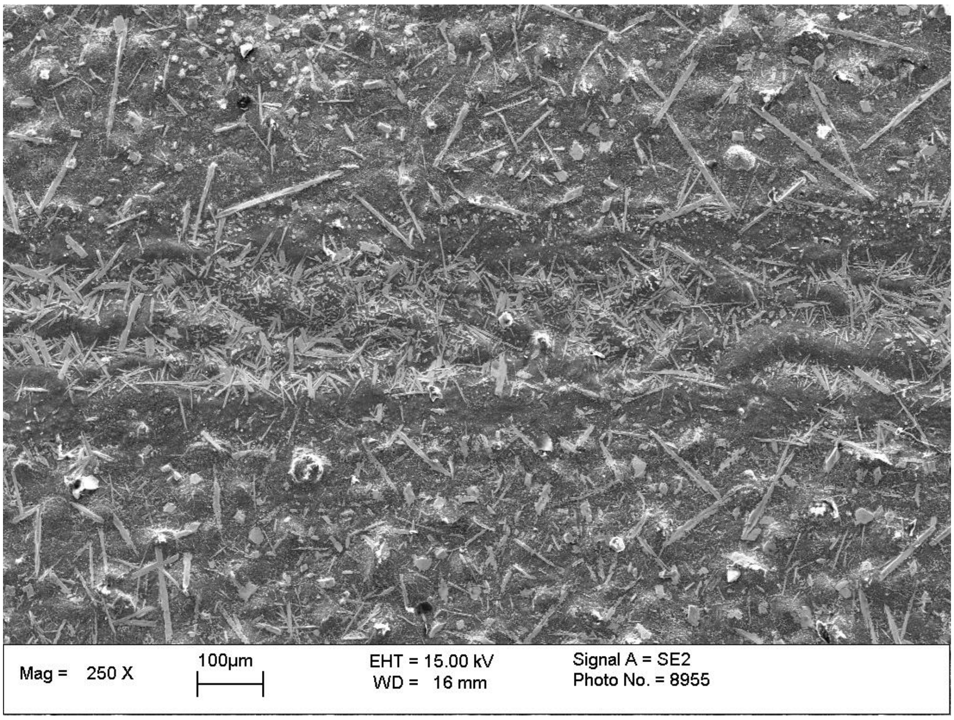
Figure 5 optical images of (a) the fibre laser irradiated surface compared to the Nd:YAG laser irradiated surface in (b) of the Si_3N_4 engineering ceramic.

5.2 Microstructural Aspects

Figure 6(a) shows the SEM image of the fibre laser irradiated surface and (b) the Nd:YAG laser irradiated surface of the Si_3N_4 engineering ceramic. From observing both the images, it is confirmed that the measurements presented in the optical microscopy where the track created by the fibre laser is somewhat larger than that of the Nd:YAG. The SEM image in Figure 6(a) 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:YAG laser. This indicated that the depth of penetration of the fibre laser irradiated surface would also be higher, although, further study is currently being conducted to confirm this effect. Furthermore, due to the higher brightness exhibited by the fibre laser, there is evidence of melting, oxidation, and entrapment of gas bubbles which as illustrated in Figure 6(a). Such features do not appear on the Nd:YAG irradiated surface due to its lower brightness which induced low temperature and produces a smaller interaction zone, surface melting and oxidation. The Si_3N_4 engineering ceramic generally decomposes at 1900 °C [2, 3, 34]. On account of this, it also confirms that the higher brightness of the fibre laser has caused the Si_3N_4 to partially melt and decompose much above the decomposition temperature to about 2400 °C [2, 3]. As for the case of the Nd:YAG laser irradiated surface, the heat induced should be much below the decomposition temperature of the Si_3N_4.



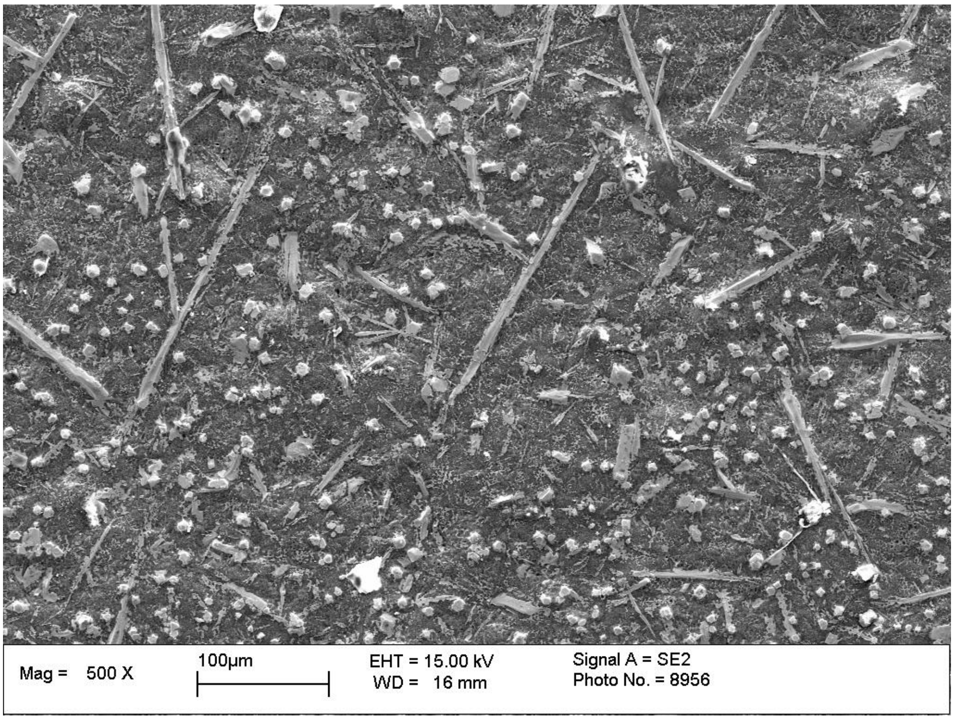
(a)



(b)

Figure 6 An SEM image of the fibre laser irradiated surface in (a) and (b) the Nd:YAG laser irradiated surface of the of the Si_3N_4 engineering ceramic.

From observing the SEM images of the untreated surface of the Si_3N_4 at x 500 magnification in Figure 7(a); it can be manifested that the sharp rods and irregularly squared shaped blocks are present. When those are heated by the two incident laser beams, the dimensional sizes of the elongated sharp rods were reduced to smaller size. However, this effect is much significant with the surface irradiated by the fibre laser as the rods are much finer and reduced in size (see Figure 7(b)) and the Nd:YAG laser irradiated surface (see Figure 7(c)). This is due to the higher melting and vaporization which would have caused the change in the microstructure. Nevertheless, further study on the microstructure with regards to changes in the grain size and phase transformation is suggested.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100µm
EHT = 15.00 kV
WD = 16 mm
Signal A = SE2
Photo No. = 8956

(a)

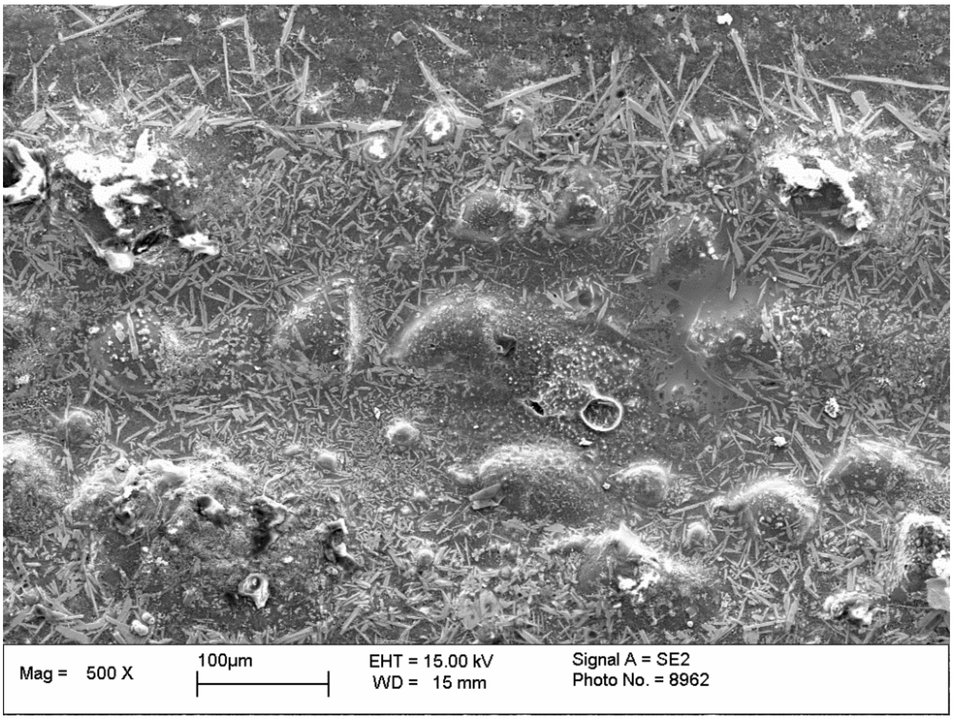
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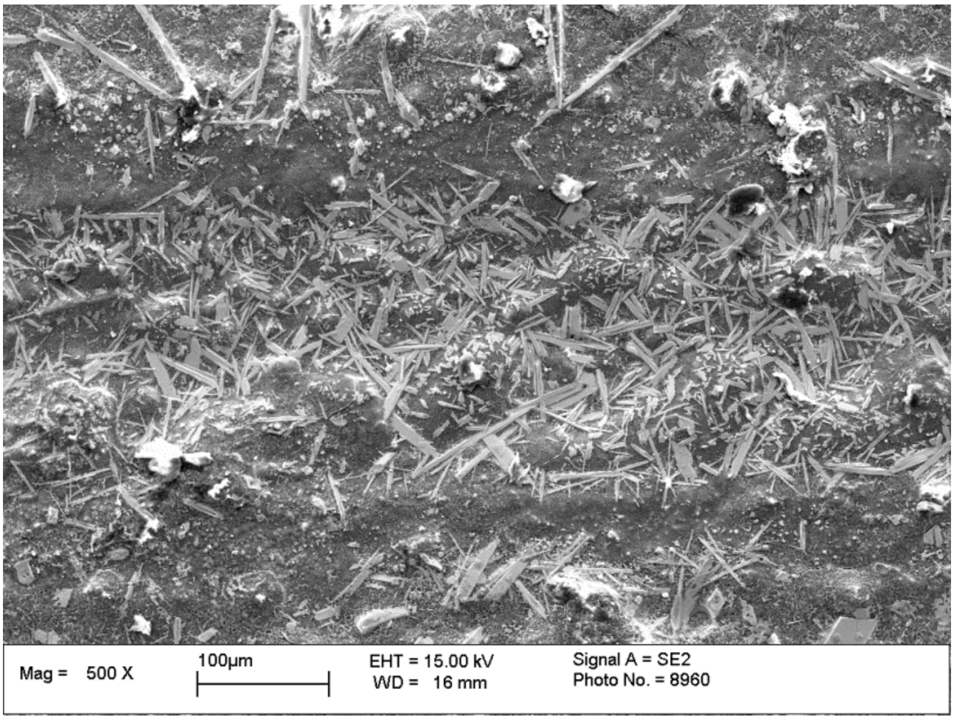
Photo No. = 8962

(b)



(c)

Figure 7 An SEM image of the untreated surface in (a); fibre laser irradiated surface in (b) and (c) the Nd:YAG laser irradiated surface of the Si_3N_4 engineering ceramic at x 500 resolution.

6. Discussion

Laser-beam brightness is dependant on the output of the laser, the beam quality factor M^2, transverse mode as well as the angle of divergence. However, the predominant parameter of laser- beam brightness is the transverse mode and the M^2 factor. High quality laser beam leads to higher brightness which is the case for the fibre laser used in this study (see Table 1). 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:YAG which emitted a brighter beam.

A relationship between the amount of laser-beam brightness needed and the resulting effects which it may have on a material can be established. However, it would require considerable amount of experimental work with employing various laser sources and processing materials since each material has a unique absorption limit, physical, mechanical and optical properties. In addition, high brightness beams produce deeper penetration [1, 3], longer depth of focus, larger footprint or the tack width and microstructural changes despite using identical parameters to a laser beam of a lower brightness as seen from the study herein. This allows the higher brightness laser to operate at lower power levels to produce the same treatment to that of a low brightness laser. This could consequently allow the laser process to be cost effective in the long run [1, 3] as the laser processing could often be conducted on a low cost per wattage basis but affects just as much as the low brightness laser operating at higher cost per wattage to produce the same result.

7. Conclusions

The effects of laser-beam brightness were studied for the fibre and the Nd:YAG laser during surface treatment of a Si_3N_4 engineering ceramic by maintaining identical processing parameters namely: power; spot size; traverse speed; wavelength; gas flow rate and Gaussian beam mode during the surface treatment. Despite using the same parameters, it was found that the effects of the fibre laser surface treatment of the Si_3N_4 engineering ceramic differed from that of the Nd:YAG laser as larger track width (footprint), porosity, oxidation, surface melting and decomposition was occurred. In addition, significant microstructural modifications were also found where sharp rods like features were much reduced in size due to high laser-beam brightness of the fibre laser creating high temperature during laser-ceramic interaction. This in turn, caused large melt zones to be present.

Furthermore, the high laser-beam brightness in general produces bigger temperature gradient during laser-material interaction and further leads to a remarkable activity and interaction when compared to a low brightness laser-beam. Based on this, and the lack of attention given to the laser-beam brightness during laser assisted material processing, it is suggested that the laser-beam brightness should be taken account of during the design of laser process parameter window. This is because it has proven to be a fundamental parameter from the first-step study herein. In addition, it is suggested that the laser beam brightness is not only measured theoretically but it should also be measured by experimental means for verification. Further studies involving high laser-beam brightness and its interaction with materials are being investigated by the authors of this paper.

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Figures

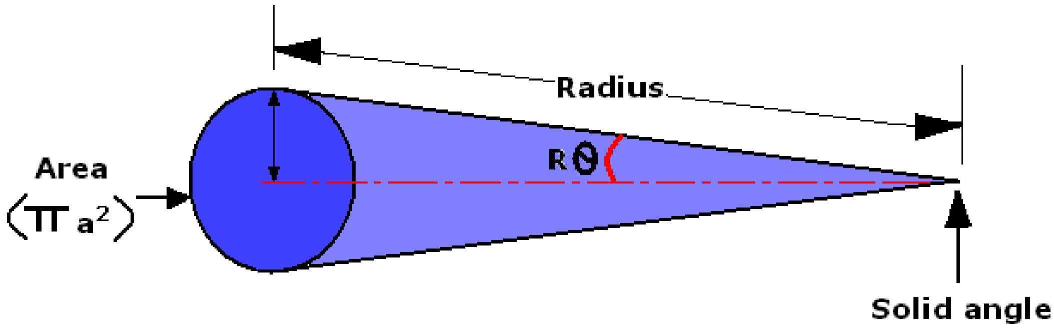
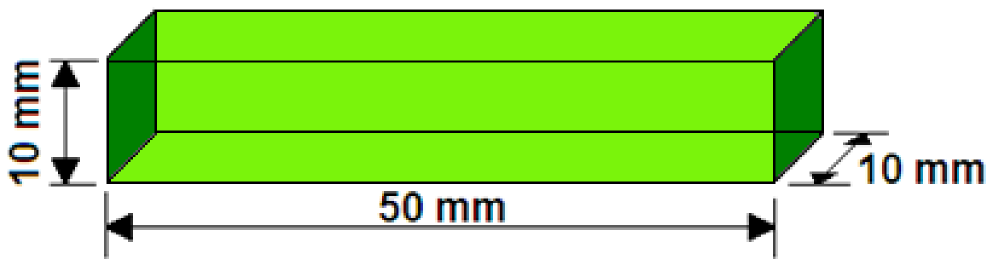
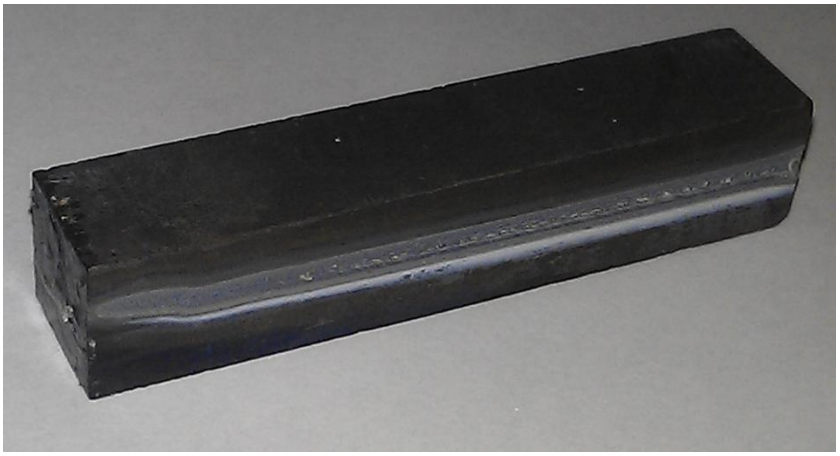


Figure 1 A schematic illustration of the solid angle of divergence of a laser beam.

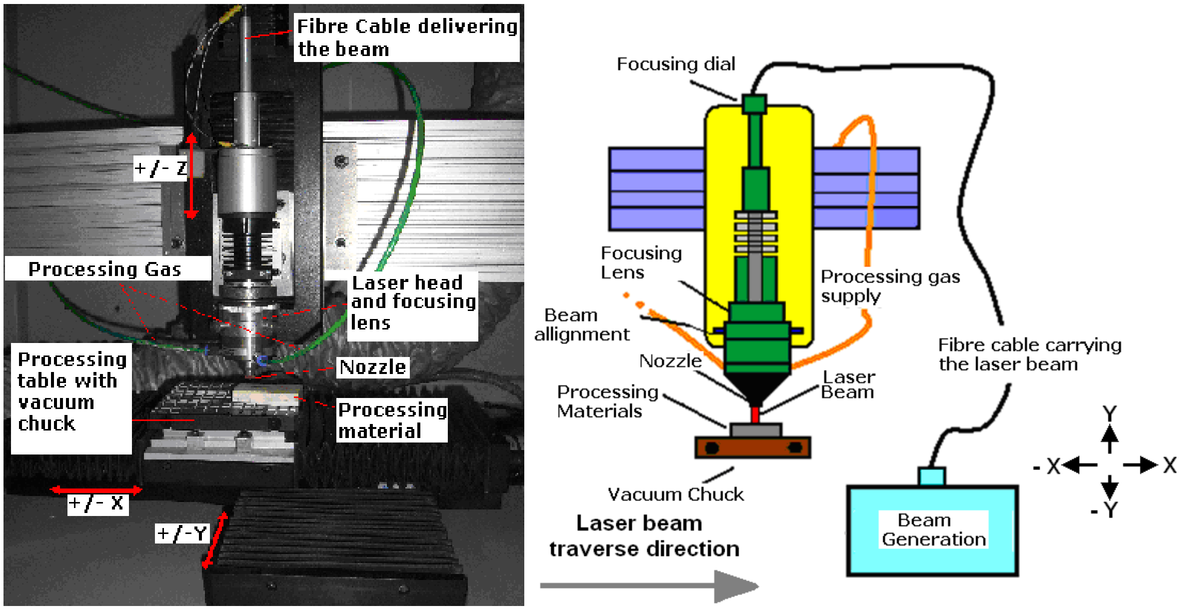


(a)



(b)

Figure 2 A schematic diagram of the experimental sample in (a) and the photographic image in (b) for the Si_3N_4 engineering ceramic.



(a) (b)

Figure 3 An image of the experimental set-up of the fibre laser surface treatment of the Si_3N_4 engineering ceramic in (a) and a schematic diagram in (b).

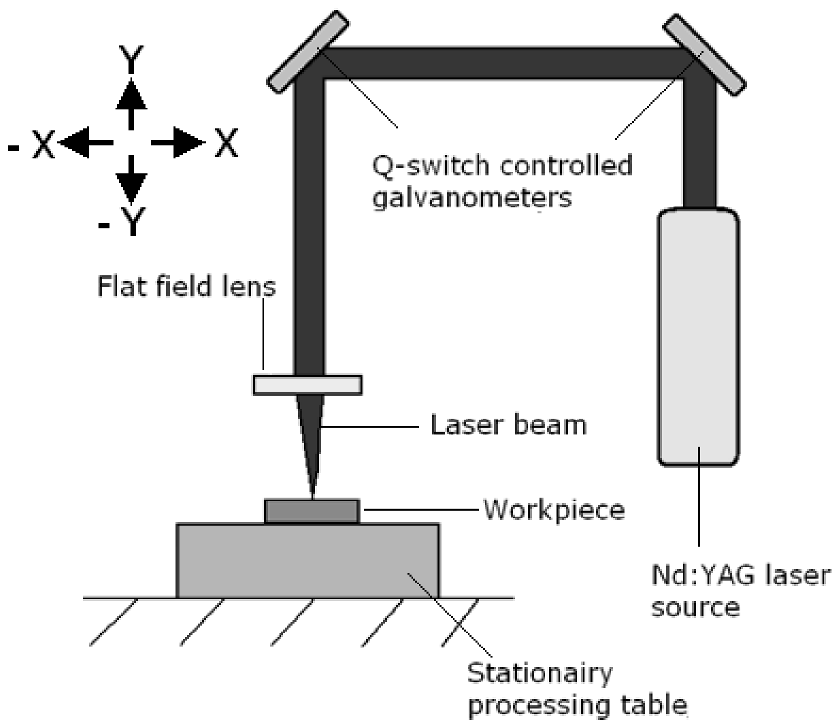
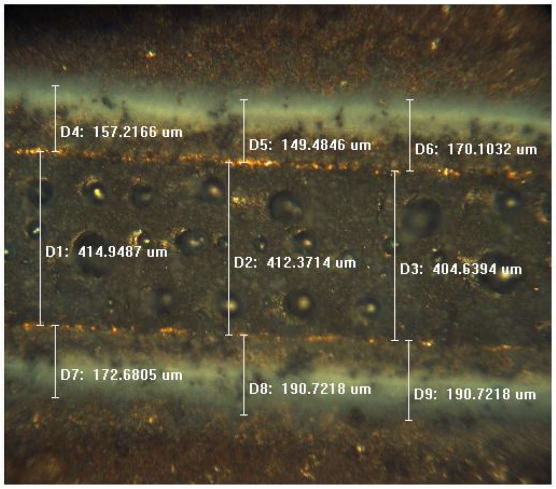
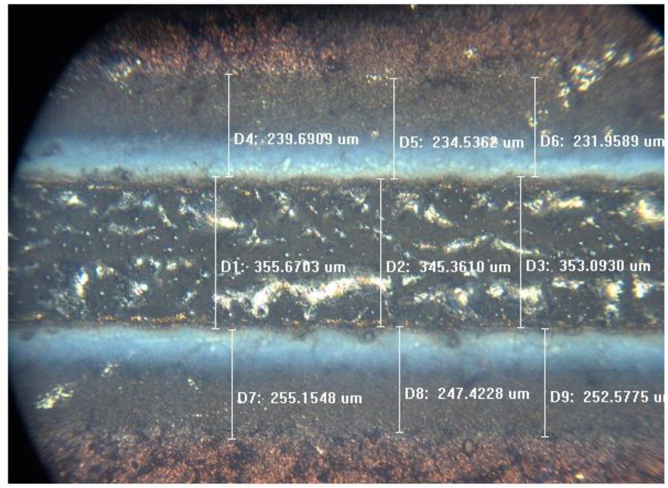


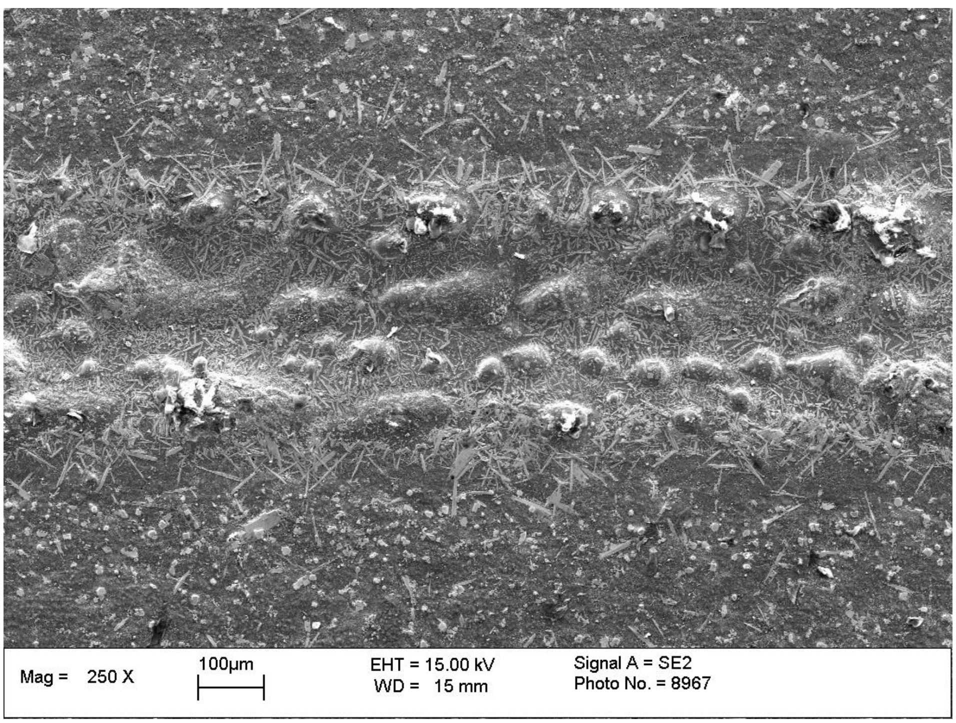
Figure 4 A schematic showing the experimental set-up of the Nd:YAG surface treatment of Si_3N_4 engineering ceramic.



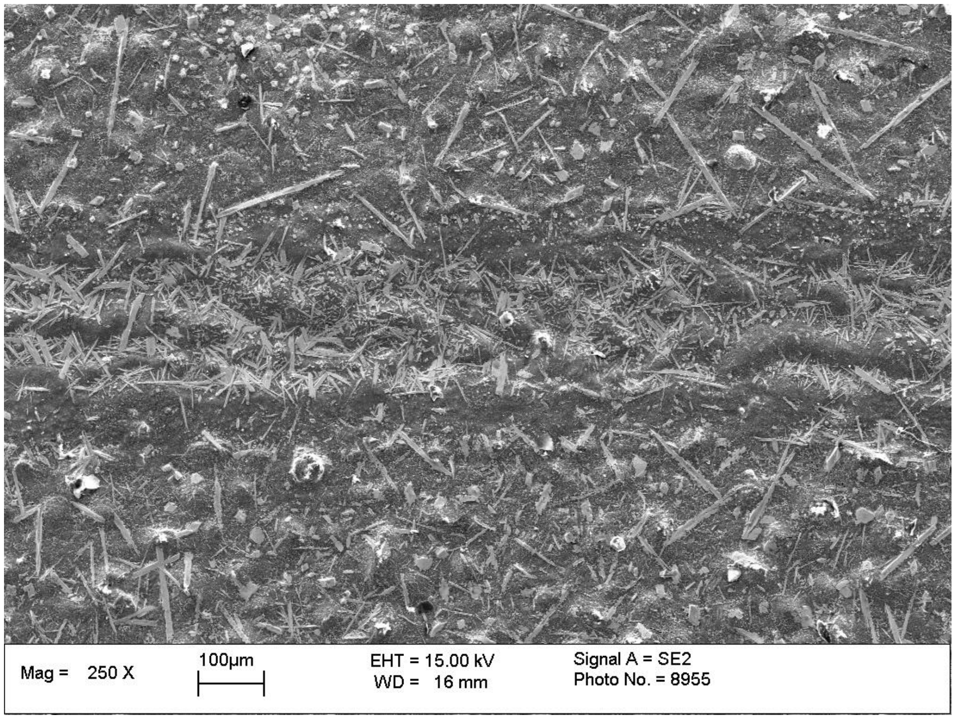


(a) **(b)**

Figure 5 optical images of (a) the fibre laser irradiated surface compared to the Nd:YAG laser irradiated surface in (b) of the Si_3N_4 engineering ceramic.

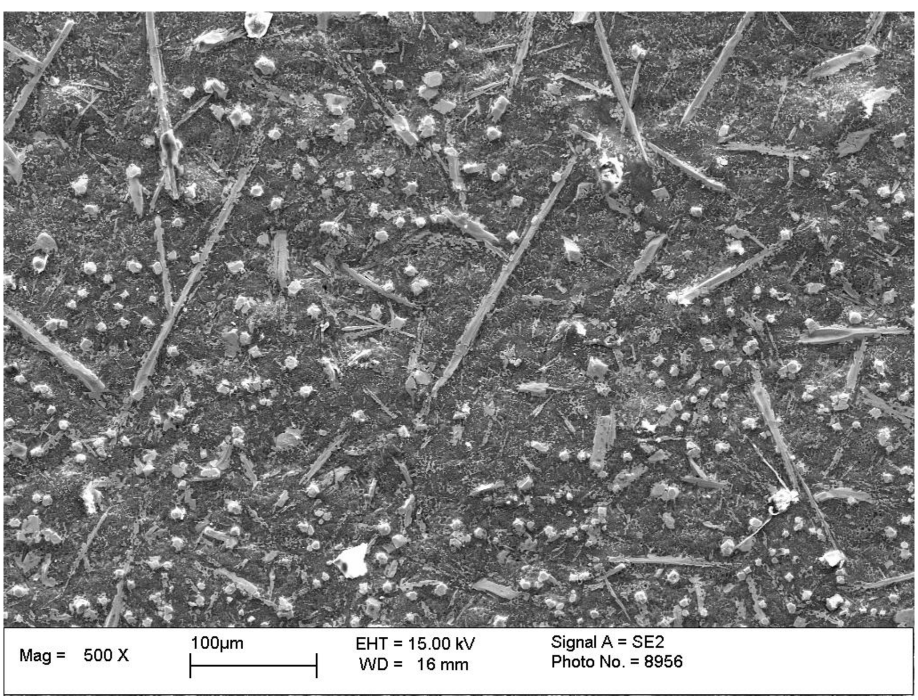


(a)

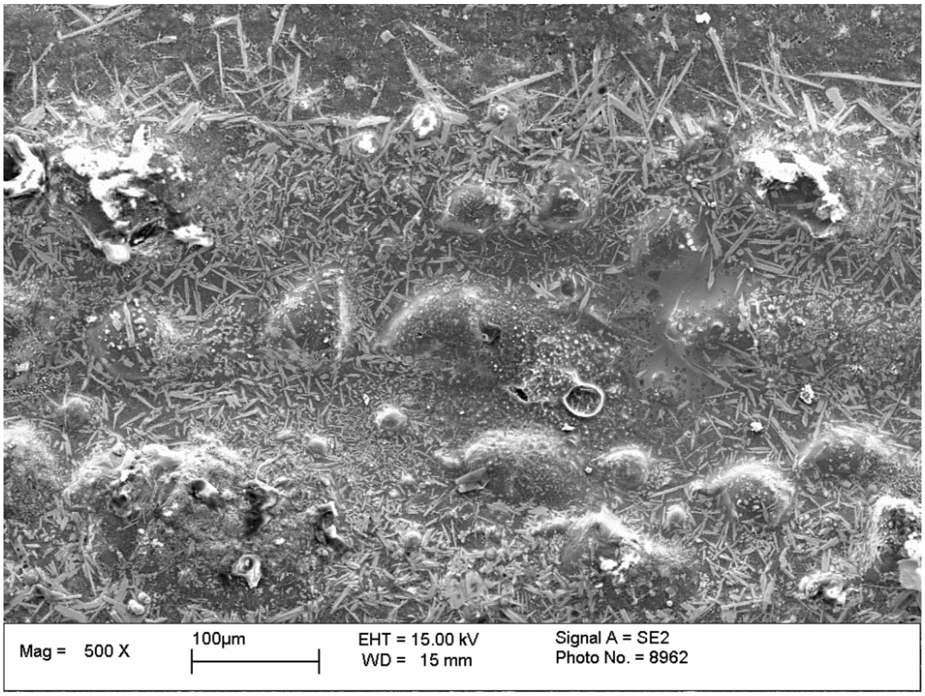


(b)

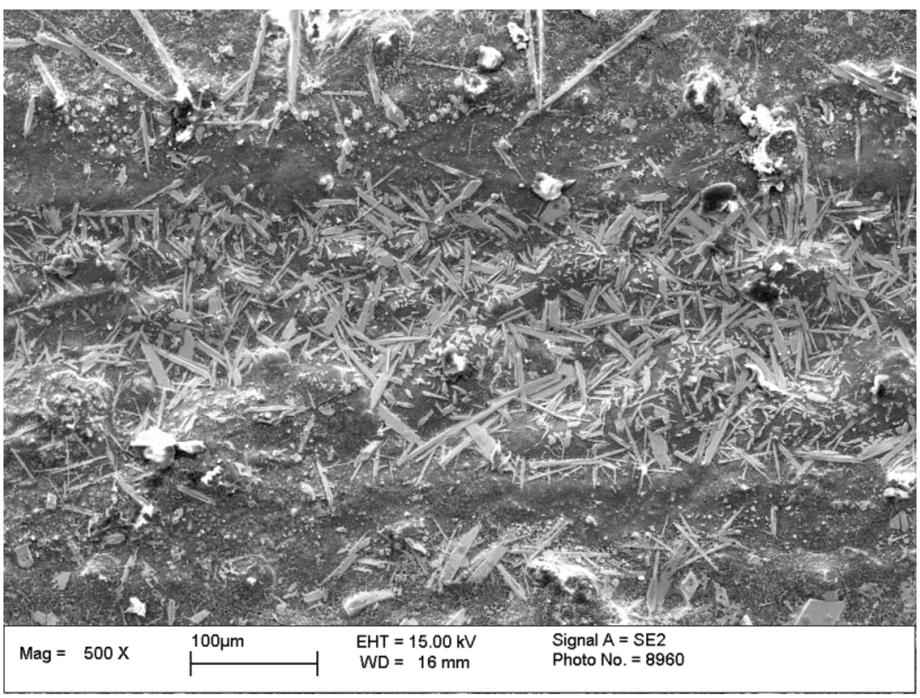
Figure 6 An SEM image of the fibre laser irradiated surface in (a) and (b) the Nd:YAG laser irradiated surface of the of the Si_3N_4 engineering ceramic.



(a)



(b)

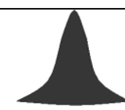


(c)

Figure 7 An SEM image of the untreated surface in (a); fibre laser irradiated surface in (b) and (c) the Nd:YAG laser irradiated surface of the Si_3N_4 engineering ceramic at x 500 resolution.

Tables

Table 1 Properties of the Nd:YAG and the fibre laser as used for the investigation in this study.

Type of Laser		Nd:YAG Laser	Fibre Laser
Beam divergence (m/rad)		5.5	0.2
Brightness ($W. sr^{-1}.m^2$)		609.50	1855.37
Beam quality factor (M^2)		6.8	1.1
Gaussian beam shape	Cross-sectional view		
	Plan view		
Gaussian mode		TEM_{00}	TEM_{00}

Note: The fibre and the Nd:YAG laser-beam brightness values were calculated using the features of each laser systems as the input parameters within Equation 4.

Table 2 average track width of the fibre and the Nd:YAG laser treated surface

	Dimensions (µm)	
	Fibre Laser	Nd:YAG
Laser irradiated track	419 µm	383 µm
Heat affected zone (HAZ)	155 µm	220 µm