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Evaluation of Surface Cracks Following Processing of a ZrO_2 Advance Ceramic with CO_2 and Fibre Laser Radiation

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Abstract

This research examines the thermal shock know as cracking on a ZrO_2 advance ceramic (ZAC) during fibre and CO_2 laser surface engineering (LSE). A parameter window was designed and the effects of both the fibre and the CO_2 lasers were compared upon the specific ZrO_2 ceramic type used herein. Unlike previous studies, no pre-or-post heating techniques for the surface engineering process were adopted since such methods are a non-value adding feature to the laser surface treatment process. A threshold with minimal or no surface cracks was found for the ZAC during both the CO_2 and fibre laser surface engineering. The best laser processing parameter window for the type of ZAC used herein was presented for both the CO_2 and the fibre LSE. In addition, laser processing temperatures were measured to compare the heat distribution of both the CO_2 and the fibre laser to further justify the influence of the thermal shock induced thereof on the ZAC. The result from this study can be adopted to further improve laser based processes such as laser surface treatment and laser assisted sealing of hard to process materials such as advance ceramics.

Keywords

ZrO_2; Lasers; Surface Engineering; Cracking; Thermal Shock

Introduction

Ceramics have a low thermal conductivity and high resistance to withstand heat or thermal energy but there is still a limit or a threshold which it can resist before failure which occurs either by shattering *via* brittle fractures or sharp cracks. In general, failure of ceramics under thermal loading occur due to the introduction of the thermal shock know as cracking, particularly during exposure to intense energy beam such as a laser. This has been further justified in this paper but the most important aspect is to apply just enough energy into the ceramic so that it does not crack. For this to be successful, it is required that correct laser parameters are employed. Although, the literature review has provided some guidelines towards a range of parameters which are applicable for laser processing of various ceramics, but it is still unclear with respect to the threshold of the ceramics used in this research. This is because all ceramics are different due to their processing route, as the material composition (additives) and methods used to process the ceramics (used in this work) are somewhat different in comparison to that of the previous investigations. Therefore, a systematic method was used and presented in this paper which demonstrated the approach of changing one factor (parameter) at a time to obtain the optimum parameter window for the ZrO_2 advance ceramic (ZAC). A fibre and CO_2 laser were employed to conduct the experiments. Laser power, traverse speed, spot size and the appropriate power density were investigated since both ceramics have a different threshold for laser processing. In addition, processing parameters were established for both lasers to surface treat the ZAC used for this investigation and their effects were further compared. No post-and/or-pre-heating techniques were used unlike conventional laser/ceramic processing methods which was due to its costly affair and increments in the processing time in general. Also, attempts were made to generate the most desirable surface that contains minimal cracking, flaws, porosity and defects so further analysis can be conducted to elucidate the physical effects of laser-beam ceramic interaction. A fibre laser was used as there was minimal work done with engineering ceramics. On the other hand, the CO_2 laser was used to compare the effects as it has a higher wavelength than that of the fibre laser which will provide some guidelines on the suitability of wavelengths for these particular materials.

Laser surface engineering (LSE) conducted using a pulsed or continuous wave (CW) laser can bring about remarkable changes to the materials property. For the pulsed treatment, the laser beam can be focused to a small spot which may traverse over the material surface and create a tailored thermal shock wave as reported by Hackle, Wright and Hill. The CW beam traveled over the surface from start to finish without a stop respectively. This work focused on the use of a CW beam of both the CO_2 and the fibre laser to surface engineer a ZAC. The ZAC was chosen for the study due to its variety of application such as in the bio-medical sector for implants and dental parts, solid oxide fuel cell production within the power generation and in the electronic sectors. Through laser surface treatment there may-be possibilities of improving the mechanical, physical, microstructural and optical properties of the ceramic. However, the priority was to address a parameter window for the laser surface treatment process for this particular grade of ZAC. On account of this, the study herein attempts to address range of possibilities to establish various laser parameters during the surface treatment of the ZAC without using any pre-or-post heating techniques which is a feature in previous investigations by Murray as well as Triantafyllidis. Based on the study herein, future investigations could be focused on improving various possible applications for the ZAC based engineering and biomedical type ceramics.

Previous Research

Lawrence and Li conducted studies on the differences between laser beam interactions characteristics of SiO_2/Al_2O_3 ceramic by employing a CW CO_2, Nd:YAG, Excimer a high powered diode laser. Absorption, fluence threshold, thermal loading and the laser interaction at the melt-pool were examined also by Lawrence, Solomah, Lee, as well as Hao and Lawrence. Absorption length, thermal loading and melt-pool characteristics were determined by using the values from the experimental work presented by Lawrence and Li. The results showed that an evidence of re-solidification was found on the SiO_2/Al_2O_3 ceramics when applying the CO_2, Nd: YAG, and HPDL's. The ceramic has undergone some melting but insignificant influence of the excimer laser was found on the SiO_2/Al_2O_3. This was because of the lower wavelength (248 nm) of the excimer laser. The excimer laser was said to have no effect on the melting of the SiO_2/Al_2O_3 ceramic. Furthermore, Hao and Lawrence used ceramics for biomedical applications. These involved improvement of surface properties of ceramics by using industrial lasers on the Al_2O_3 and ZrO_2 ceramics. Other work by Lawrence and Li showed improvement in the surface properties of the same ceramics. A 60 W high powered diode laser was used to investigate the adhesion characteristics of Al_2O_3, SiO_2-TiO_2, clay tiles and other ceramic tiles. The findings showed improvement in the material roughness, and the contact angle which was reduced as the material exhibited better adhesion characteristics. In addition, oxidation was also found and formation of a glass element was observed. This indicated that the composition of the ceramic was changed. Hence, it resulted in the material composed of better adhesion characteristics. Sun *et al.* investigated the effects of CO_2 laser surface processing on the Si_3N_4 and eliminated imperfections within the ceramic by applying a CO_2 laser beam. Fracture behaviour was considerably affected by surface treating the Si_3N_4 using the CO_2 laser. Fracture origins from the machining process and bending strength were improved. Sun *et al.* used a CO_2 laser to minimise the detrimental effects caused by grinding as the heat from the sliding motion created friction. Laser surface treatment was done after sever grinding of the ceramic in order to remove the mechanically induced cracks. Both high and low power CW CO_2 lasers were used to treat the Si_3N_4. It was found that the condition of grinding has a big influence on the fracture strength of the Si_3N_4. Longitudinal direction grinding in comparison with transverse directional grinding demonstrated much more resistance to fracture as reported by Sun *et. al*. Results showed machine induced cracks and inherent flaws found from the material (porosity). This should, however, be the case with Si_3N_4 ceramics due to its characteristic and material structure.

Morita *et al*. worked with Si_3N_4 ceramics to produce a crack-free surface by using a Nd:YAG pulsed laser. The increase in peak output power caused the crack propagation and generation of a thick re-cast layer. The peak power was said to be kept low as possible and the pulse duration to be as short as possible for a crack-free processing of ceramics. This also allowed reduction in the thermal stress which justified the elimination of crack generation during the process. The strength of the laser treated samples was also compared with that strength of ground polished surface by a diamond wheel. The strength of the laser treated samples was reported by Morita *et al* to be 10% to 20% reduction in comparison with the diamond polished sample due to the residual compressive stress layer removed by the laser process.

Determination of laser parameters is an important aspect to study prior to any laser processing. This is because it allows one to understand the materials behaviour and the capacity of the material to withstand the thermal energy of the laser beam. This is specifically important for ceramics as they are prone to cracking when exposed to thermal shock generally introduced during the laser-ceramic interaction. To date, only limited investigations have been performed with respect to achieving a ideal surface treatment of various ceramics being crack-pore- and defect-free. Those are the work of Lingfi, Naeem, Kaur, Voisey, Cappelli, and Solomah. Murray *et al.* as well as Triantafyllidis *et. al.* performed several investigations by using the a CO_2 laser to cut ceramics which used a pre-heating method of the ceramic substrate to temperature up to 1500°C in a furnace and then the laser cutting process was performed. Ester *et al.* conducted an investigation on Al_2O_3 and ZrO_2 based oxide ceramics by employing a HPDL. Laser irradiated area of 50mm x 7mm was said to have a crack-free surface. This was performed by controlling the laser power, traverse speed, and the sample temperature by pre-heating the surface of the ceramic. Triantafyllidis *et al.* performed several investigations on laser surface treatment of mainly Al_2O_3 based refractory ceramics by employing the HPDL. Earlier work of Triantafyllidis *et al.* identified solidification cracking due to the generation of very large temperature gradients that occurred within the ceramics. Triantafyllidis *et al.* further showed that the refractory Al_2O_3 ceramic can be treated with a combination of laser source (HPDL beam trailed by a CO_2 laser or vice versa), to eliminate the crack propagation by temperature control. However, such methods were not always repeatable with ease and efficiency, since it required timely set-up and complex arrangement to take place. Further investigation showed that crack-free surfaces improved the properties of the ceramic surface. Those properties were corrosion resistance, contact characteristics and surface morphology, contact angle, wetting and water permeability. Another investigation by Triantafyllidis *et al.* stood out from the others as it used the HPDL to process refractory Al_2O_3 ceramic by using none of the post of pre-heating methods which are conventional ideas in processing ceramics with lasers. Triantafyllidis *et al.* reported that a crack-free surface treatment was possible with the parameter window speed being 0.4mm/sec and a power density of 6×102 W/cm^2 which led to a crack-free surface treatment for the Al_2O_3 refractory ceramics. However, these parameters are unique for the refractory Al_2O_3 only with the particular composition. Other ceramics such as the ZrO_2 and Si_3N_4 are somewhat different due to their chemical composition which also changes the mechanical and thermal properties and has an effect during laser processing.

Material Background and Experimentation

A cold isostatic pressed (CIP) ZrO_2 Advance ceramic with 95 wt% ZrO_2 and 5 wt% yttria (Tensky International Company, Ltd) was used for experimentation. Each of the samples was obtained in a bulk of 10 x 10 x 50mm^3 using the CIPing technique. This was because the dimensions previously mentioned were best suited for the laser processing experiments. The surface roughness was 1.57μm for the ZrO_2 as-received from the manufacturer. The experiments were conducted in ambient condition at a known atmospheric temperature (20 °C).

A fibre laser (SPI-200c-002; SPI, Ltd.) emitting a CW mode beam at a wavelength of 1.075μm and 200 W maximum power was used herein. The fibre laser had a Gaussian beam configuration of TEM_{00} with a beam quality factor of $M^2 = 1.2$. Experiments were conducted by varying one parameter at a time and by keeping the other parameters constant. Therefore, the laser power was varied from 25 to 200 W (max laser power) and simultaneously, the traverse speed was varied from 25 to 500 mm/min by keeping the focal position constant for the ZAC. From this, identification of the range of laser power density required to reach the material threshold was achieved and represented by graphical means. The processing gas used for this set of experiment was compressed air which was supplied at a flow rate of 25 litre/min. Programming of the laser was conducted by using an SPI software which integrated with the laser system. A 50mm line was programmed by using numerical control (NC) programming as a potential beam path which was transferred by a .dxf file.

A 1.5 kW, Everlase S47, Coherent, CO_2 laser was employed to conduct experiments on the ZAC. The CO_2 laser comprised a Gaussian beam configuration of TEM_{01} with a beam quality factor of $M^2 = 1.3$. One parameter was changed at any one time in order to determine the ultimate parameter window. The trials ranged from 50 to 200 W of laser power with a CW beam applied with a 10.6μm wavelength, while the beam spot size was kept constant at 3mm with a gas flow rate of 25 litre/min by using compressed air assist gas. The traverse speed ranged from 25 to 700 mm/min to determine the ultimate speed required to process the ZAC. Programming of the laser was conducted by using an independent software which integrated with the laser machine. A 50 mm line was programmed by using NC programming as a potential beam path transferred by a .dxf file. Stand-off distance between the nozzle and the work-piece was kept to 16 mm in order to obtain a focal spot size of 3 mm. Parameters used for the CO_2 laser surface treatment were not directly comparable to those of the fibre laser surface treatment. This was due to the difference in the wavelength and the nozzle shape and diameter as well as the high power laser not being able to execute stably when operating at lower laser powers.

A portable infra-red thermometer (Cyclops 100 B; Land instruments international Ltd, U.K) was used to measure surface temperature during both the CO_2 and the fibre LSE. The device was bolted on a tripod and positioned 1m away from the laser processing area to achieve the most accurate reading. The device comprised of a helium-neon (He-Ne) laser which assisted in aligning the work-piece. The laser beam was then switched on during the surface treatment and was switched off shortly just before the laser beam was switched off. This procedure was adopted for every measurement that was taken for the experiment. This allowed an average temperature reading to maintain closer to the real temperature of the processing area. The temperature measurement was conducted on five different areas of the surface of the ZAC. Each area was measured in one pass of the laser beam. An average reading of the temperature was taken from five passes on five different samples.

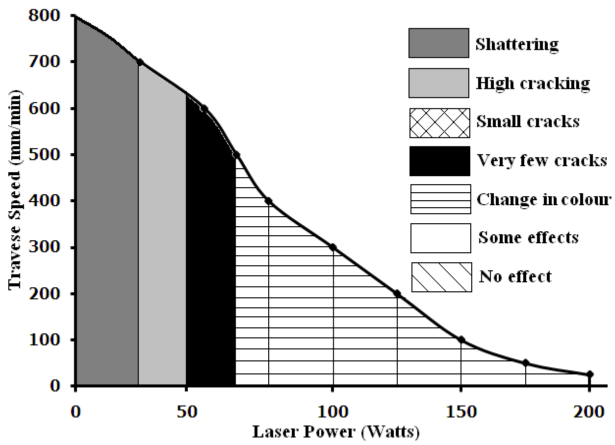

FIGURE 1 RELATIONSHIP BETWEEN LASER POWER & TRAVERSE SPEED SHOWING THE EFFECTS OF THE CO_2 LSE OF ZEC WITH RESPECT TO CRACKING.

Results and Discussion

CO_2 Laser Surface Engineering

Figure 1 illustrates the effects of the CO_2 laser on the ZAC as the laser power was changed along with the traverse speed. It can be seen that at 100 mm/min of constant power produced sufficient amount of cracking followed by shattering of the ZrO_2. This is when the laser power was applied from 25W to 200W. It was not clear from Figure 1 as to what parameters can be used until experiments were conducted with varying the traverse speed. Hence, the laser power was selected at 62.5W. This was in-between the area where there was no effect on the ZrO_2 (at 50 W), and where evidence of small cracking began to appear at 75W. Therefore, 62.5 W was selected with the traverse speed ranging from 25 to 700 mm/min (see Figure 2). The coded key is used to show the effects in the Figures 1 to Figure 5. Shattering was found until the traverse speed of 100 mm/min was applied at constant laser power of 62.5W and 1736 W/mm^2 power density by using a 3mm diameter CO_2 laser beam.

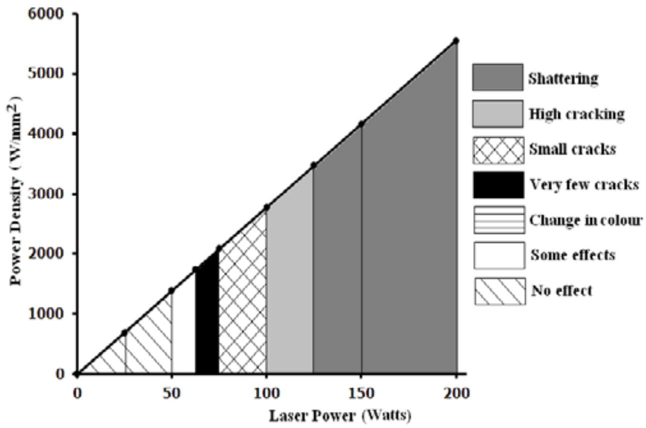

FIGURE 2 RELATIONSHIP BETWEEN LASER POWER & POWER DENSITY SHOWING THE EFFECTS OF THE CO_2 LSE WITH RESPECT TO CRACKING.

Figure 2 shows the relationship between the laser power and the power density during the CO_2 LSE of the ZAC. Up to 50W and 1379 W/mm^2 of power density at the speed of 600 mm/min, the ZAC showed very little affect but began to show some changes on the surface beyond 50 W and 1379 W/mm^2. Minimal cracking was found at 62.5 W with the power density of 1736 W/mm^2 which increased as the laser power and the power density were raised and resulted to high cracking and further shattering. This was different to the effects which the fibre laser had upon the ZAC as higher power density, laser power and low traverse speed were used to obtain the same result.

From 200 to 400 mm/min, high cracking was observed. This was reduced to small cracks as the traverse speed increased to 500 mm/min. At 600 mm/min, smallest cracks were to be seen. Beyond 600 W, there were no effects to be observed with traverse speed of up to 700 mm/min. The results at 600 mm/min with an applied laser power of 62.5 W and a gas flow rate of 25 l/min showed that the ZrO_2 had shattered or produced high cracking by using a spot size below 3mm. Between 3 to 3.5 mm, the CO_2 laser surface treated ZrO_2 composed of the lowest surface cracks. Beyond 3.5mm, colour change within the ZAC was to be seen. No significant effect was found with the spot diameter of up to 4.5 mm (see Figure 3). The colour change generally indicated the induction of the thermal energy in to the ZAC. With other ceramics such as a Si_3N_4, the colour change occurred when the material was oxidized but such is not the case with the ZrO_2 ceramic as it has been an oxide ceramic already, but the ZrO_2 generally turned yellow and then black with increase in the heat input which indicated that the ceramic has decomposed and such event could is to be avoided by processing only sufficient thermal energy.

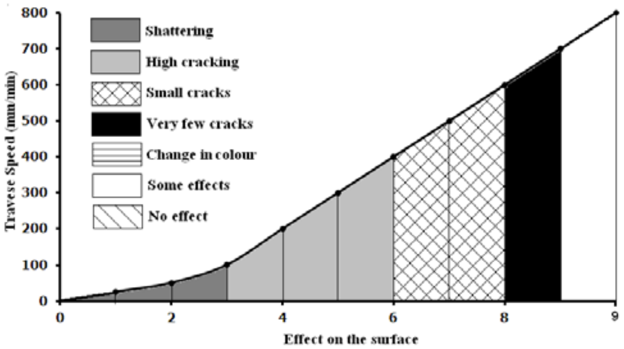

FIGURE 3 EFFECTS OF THE TRAVERSE SPEED ON THE ZAC WITH REESPECT TO CRACKING.

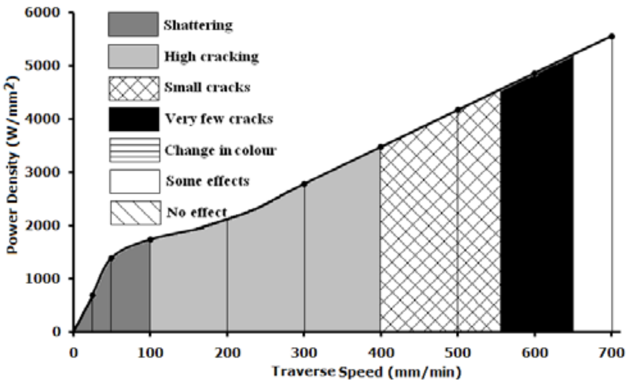

FIGURE 4 RELATIONSHIP BETWEEN TRAVERSE SPEED & POWER DENSITY OF THE CO_2 LASER ENGINEERED ZAC WITH RESPECT TO CRACKING.

The effects of the traverse speed as presented in Figure 3 showed shattering of the ZAC at low speed of up to 100 mm/min. High surface cracking was found beyond this and up to 350 mm/min. Thereafter, small cracks were evident until 600 mm/min. Beyond 600 mm/min very few surface cracks were found. The ZAC showed some evidence of laser-material interaction beyond the traverse speed of 650 mm/min. The comparison between the effects of laser power density and traverse speed showed that the traverse speed was more contributory in inducing the thermal energy into the ceramic because the ZrO_2 shattered at low power density but the speed was considerably low. With increasing power density and speed some reduction in the cracks was shown. However, considerable amount of cracking was prominent until 500 mm/min and was reduced to very small cracks until 650 mm/min (see Figure 4).

Figure 5 showed that the small spot size with increasing power density resulted in generating high cracking on the ZAC. The high cracks were found until 2 mm of spot diameter and then produced very few cracks at 3 mm. Beyond 3.5 mm spot size there was some change in colour on the ZAC. This continued to occur as the power density was raised despite the increasing spot size and large power distribution on the ZAC.

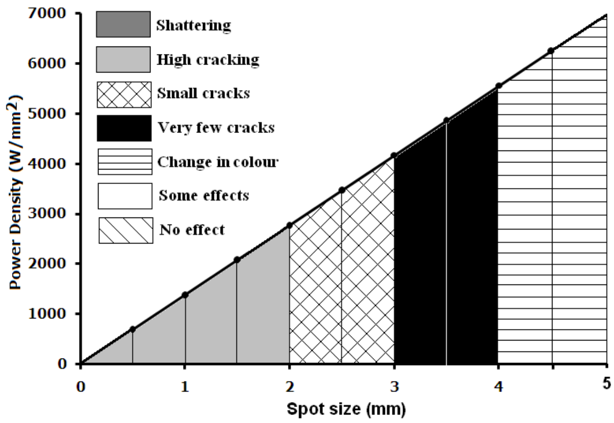

FIGURE 5 RELATIONSHIP BETWEEN POWER DENSITY & SPOT SIZE SHOWING OF THE CO_2 LASER ENGINEERED ZAC WITH RESPECT TO CRACKING.

Fibre Laser Surface Engineering

Preliminary experiments showed that it was fairly easy for heat to be transferred to the ZAC from the incident fibre laser radiation which intrinsically would produce higher thermal shock as well as surface cracking. The approach to find the threshold of the ZAC was the same as that previously used for the CO^2 LSE process. The power was varied from 25 to 200 W and the traverse speed was initially kept constant to 100 mm/min by using a constant spot size of 3 mm (see Figure 6). The fibre laser has began to affect the surface of the ZAC from changing its colour at 75 W to producing a very few to high cracks at various power intervals and eventually being cracked at 200 W of laser power.

It was established that the ideal laser power was 137.5 W in order to generate the lowest surface cracks so the traverse speed was investigated with its effects presented in Figure 6. This is where the laser power, focal spot size, power density and the gas flow rate were kept constant and the traverse speed was varied from 25 to 500 W. Thus it was confirmed that within 100 to 150 mm/min, the lowest cracks were produced and beyond the speed of 150 mm/min colour changes were up to 350 mm/min and had no further visual effects on the surface of the ZAC. Lower speeds of 50 to 70 mm/min generated high cracking and further shattered the ceramic when the traverse speed was reduced to 25 mm/min. This was obvious as the laser beam spent more time on the ZAC surface which increased the thermal energy input and generated the surface cracks. Figure 7 shows the effects of varying spot size on the ZAC as the spot size was varied from small beam to large. It was found that the ZAC has shattered below 2 mm spot diameter. Above 2mm of spot diameter, the laser beam produced high level of cracking and then generated the lowest cracks at a beam diameter of 3 to 3.5 mm. Fibre laser beam diameter larger than 3.5mm showed some influence on the ceramic. However, beyond 4.5mm has showed no visual effects. The coded key show the effects in Figure 6 to Figure 11.

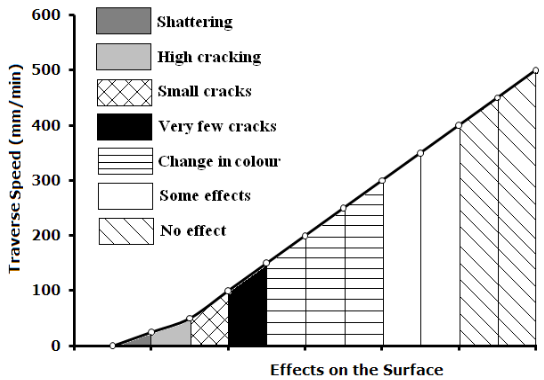

FIGURE 6 EFFECTS OF TRAVERSE SPEED ON THE SURFACE OF THE ZAC OF THE FIBRE LASER ENGINEERED ZAC WITH RESPECT TO CRACKING

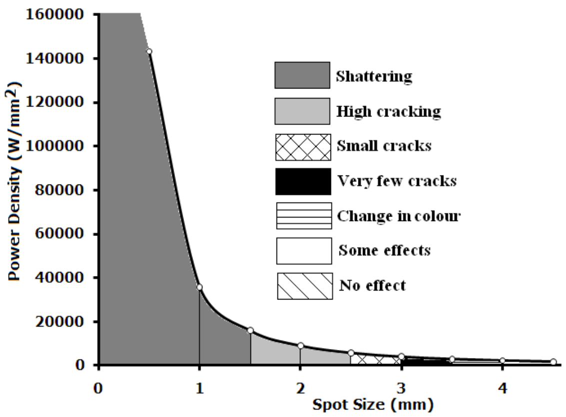

FIGURE 7 RELATIONSHIP BETWEEN POWER DENSITY & SPOT SIZE FOR THE FIBRE LASER ENGINEERED ZAC WITH RESPECT TO CRACKING

Figure 7 presents the effect of the spot size *versus* the power density and shows that the laser beam diameter at 3mm produced a power density of 3719 W/mm² at a constant traverse speed of 100 mm/min and laser power of 137.5 W. This generated the lowest cracking on the fibre laser irradiated layer. Increase in the spot size has resulted in no effect and decrease in the spot diameter has resulted in significant cracking and shattering of the engineering ceramic. As one can see that the smallest cracks only appeared at sufficient power density of 3719 W/mm² and a laser power of 137.5 W. Until then, the effects were minimal on the surface of the ZAC.

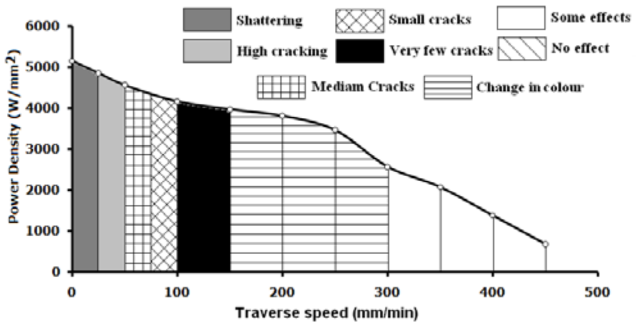

FIGURE 8 RELATIONSHIP BETWEEN POWER DENSITY & TRAVERSE SPEED OF THE FIBRE LASER ENGINEERED ZAC WITH RESPECT TO CRACKING.

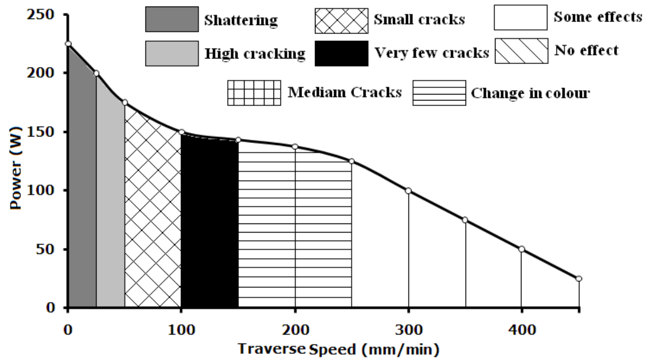

FIGURE 9 RELATIONSHIP BETWEEN LASER POWER & TRAVERSE SPEED OF THE FIBRE LASER ENGINEERED ZAC WITH RESPECT TO CRACKING.

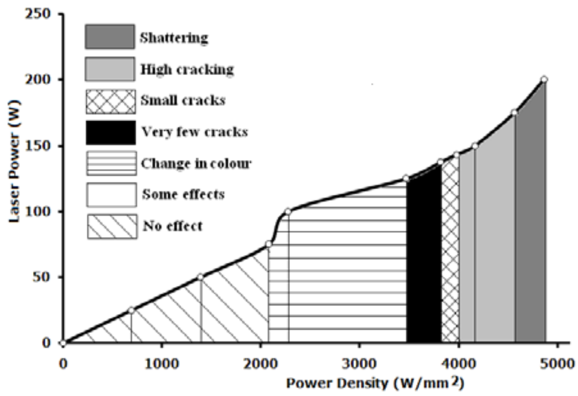

FIGURE 10 RELATIONSHIP BETWEEN LASER POWER & POWER DENSITY OF THE FIBRE LASER ENGINEERED ZAC WITH RESPECT TO CRACKING.

Figure 8 represents the appearance of the surface cracks with increasing laser power densities and traverse speed. As it can be observed from the graph that with high power density and low traverse speed, the ZAC has shattered. But as the power density decreased and the traverse speed increased, the cracking of the ceramic began to reduce until there was no significant effect on the material beyond 450 mm/min. The effects were also similar with the graph illustrating the relationship between the laser power and traverse speed (see Figure 9). Increase in the laser power at low traverse speed has produced shattering and high cracking within the ZAC. Further reduction in the crack propagation occurred with high traverse speed and lower laser power. This reduced the effect of the thermal shock on the surface of the ZAC.

Table 1 shows the ideal parameters found from conducting the laser surface treatments by using the CO_2 and the fibre lasers on the ZAC. This utilized a smaller beam diameter and a lower laser power. By comparing the results herein with those of the previous workers, it can be said that the difference is mainly in the terminology of crack definition as the crack-free surface described in their research is more realistically described in this research as surface comprising minimal or very few cracks.

TABLE 1 IDEAL PARAMETER WINDOW FOUND FOR BOTH THE CO_2 AND FIBRE LASER SURFACE ENGINEERING OF ZAC.

	Lasers	
	CO_2 Laser	Fibre Laser
Traverse Speed (mm/min)	600	100
Laser Power (W)	62.5	137.5
Power Density (W/mm^2)	1736	3719
Spot size (mm)	3	3
Gas flow rate (L/min)	25	25

Influence of Temperature on Cracking of the ZAC

Table 7 illustrates the temperatures found by the CO_2 and fibre laser surface treatment of the ZAC at the interaction zone. It can be seen that there is a considerable difference in the temperatures obtained by the two lasers. The CO_2 laser irradiated surface temperature was 1752°C and in comparison to the fibre laser was up to 42% lower since the average temperature after 5 passes was found to be 2472 °C for the fibre laser radiated surface ZrO_2.

It was clear that the temperature of the fibre laser surface treatment in comparison to that of the CO_2 laser was higher due to the influence of many factors resulting from the laser-ZAC interaction. Such factors are namely:

- The difference in the brightness (radiance) of the two lasers since the fibre laser exhibits a higher brightness value which consequently results in a bigger interaction zone as well as the increase in activity at the laser-ZrO_2 interaction zone as observed by Shukla. This in turn resulted in the fibre laser temperature being conciderably higher.

- The near infra-red wavelength of the fibre laser in comparison was more transparent to the oxide ceramic, so the energy of the fibre laser would be absorbed deeper. This caused low cracking at equivalent laser parameters compared to the CO_2 laser.

- On the other hand, the absorption of the CO_2 laser wavelength with the ZAC was somewhat lower in comparison to that of the fibre laser radiation. However, a previous study by Shukla and Lawrence showed that the CO_2 laser surface interaction with the ZAC was remarkably noticed from a topographical analysis, but the influence of the CO_2 laser was limited to the local surface and the sub-surface only. Another investigation by the same authors found that at the same time, the fibre laser in comparison to the CO_2 laser was absorbed to a sufficient level of depth. This also resulted to recording high processing temperatures.

One of the reasons why the ZAC has the tendency to fail was because it has undergone a thermal shock resulting from the ZrO_2 being hard and brittle making it become prone to cracking. In addition, low thermal conductivity, high thermal expansion, and low toughness of the ceramics lead to the cracks during exposure to high temperature. It was also the exposure to temperature change which in turn led to the cracking effect.

A thermal shock is produced when high temperature is introduced to the ceramic whilst the ceramic is in a state of ambience. It is also similar during laser surface treatment as the high power density from laser beam acting on a small diameter on the ZAC (20 to 25°C in ambiance). From the laser-ZrO_2 interaction temperature measured (see Table 7), it is know that the processing temperatures for both the laser processes are considerably high. Therefore, the increase in temperature within seconds from a state of ambiance of the ZAC to around 1700 °C for the CO_2 laser and 2400 °C for the fibre laser produced detrimental failure of the ZAC. Within a second the rapid increase in temperature causes a degree of instability within the ZAC. In addition, it is then rapidly cooled after the laser beam has passed to another surface area. But consistently, the instantaneous heating, rapid cooling would lead the ZAC expanding. The untreated area is considerably cooler whilst the heated region expands due to the inhibited heat so the untreated cooler part produced contraction within the ceramic, whereas the high thermal energy needs to escape as suggested by Shukla and Lawrence in two separate studies. This inherently, causes expansion in form of a tension. The tension acts as a force towards contraction which is in form of a compressions within the bulk from the cooler areas. In case that the tension is sufficient enough and induced to certain depth, then it will overcome the compression which, in turn, causes the ZAC to fail by cracking and often shattering to pieces.

Cracking can be avoided by reducing the resulting temperature difference by changing the temperature of the ceramic more slowly by means of pre-heating and post-heating the ceramic prior to and after the laser processing if needed be as adopted in the previous studies by Murray et.al and Triantafyllidis *et al.*. This avoids the rapid change in temperature and the clash of hot and cold areas within the bulk and the surface of the ceramic. Pre-heating or post heating can be performed as an additional process and could compliment the laser surface treatment process.

Alternatively, the dual laser beam technique can also be adopted to pre-or-post heating the ceramics. However, looking at a broader picture, both the dual laser beam processing technique and the pre-and post-heating techniques are additional processes and are non-value adding that would increase the process time, cost of tooling and labour. Also, more energy is required for pre-and post-heating technique to take place. Moreover, if two lasers are used as a leading and a trailing heat source then the cost would almost double. Therefore, it is rather economic and less time consuming to use single beam laser source for such applications.

Conclusions

A parameter window of the ZAC was determined during CO_2 and the fibre laser surface engineering without the use of any pre-or-post heating techniques. The best surface with very few cracks on the ZAC was produced by applying 137.5W at a traverse speed of 100 mm/min when the fibre laser surface treatment is employed. A traverse speed of 600 mm/min at 62.5 W has produced the best results using the CO_2 laser respectively. Both LSE processes utilized a spot diameter of 3 mm and a gas flow rate of 25 l/min. The fibre laser surface of the ZAC was somewhat different to that of the CO_2 laser in terms of the wavelength and the beam delivery system because the fibre laser was delivered from a fibre cable and the CO_2 laser delivered by mirrors and galvano-meters. And therefore, both the lasers produced different results on the surface of the two ceramics. It was found that the low power and high traverse speed was required for the CO_2 laser when surface engineering the ZAC in comparison to the fibre laser as when the effects of the two lasers were compared. This was because the ZAC shattered when identical parameters to those that of the fibre laser were applied. The shattering resulted from a thermal shock and as the mid infra-red wavelength of the CO_2 laser was only absorbed into the top surface layer of the ceramic, whereas the near infra-red laser beam of the fibre laser penetrated more deepely. The result herein can be used as a guide to further improve surface engineering technique of zirconia advance ceramics using different wavelengths from the electromagnetic spectrum.

REFERENCES

Cappelli, E., Orlando, S., Mattel, G., Montozzi, M., Pinzari, F., and Seith, D. Surface Modification of Carbide Ceramics Induced by Pulsed Laser Treatment, *Applied Physics A* 1999 69S, S515-S519.

Ester, F.J., Merino, R. I., Pastor, J. Y., Martin, A., and Llorca, J. Surface Modification of Al_2O_3-ZrO_2(Y_2O_3) eutectic oxides by laser melting: Processing and wear resistance. *Journal of the American Ceramic Society* 2007 91(11), 2552-3559.

Hackle, L. Shaping the future-laser peening technology has come of age. *Metal Improvement Company. TSP.* 2005 19(3), n.pp.

Hao, L., and Lawrence, J. Effects of Nd:YAG laser treatment on the wettability characteristics of a zirconia-based bio-ceramic. *Optics and Lasers in Engineering* 2006 44, 703- 714.

Hao, L., and Lawrence, J. Numerical modelling of the laser surface processing of magnesia partially stabilized zirconia by the means of three-dimensional transient finite element analysis. *Proceedings of the Royal Society A* 2006 462 (2065), 43-57.

Hill, M. R., De Wald, A. T., and Demma A. G. *Laser Peening Technology.* City: ASM International publications 2003 161(7) or www.asminternational.org/AMP.

Hoe, L., Lawrence, J., and Chian, K. S. Osteoblast cell adhesion on a laser modified zirconia based bio-ceramic.

Journal of Material Science: Materials in Medicine 2005 16, 719– 726.

Kaur, A.S., Doloi, B., and Bhattacharyya, B. Experimental investigations on Nd:YAG laser cutting of silicon nitride', *International Journal of Manufacturing Technology and Management*, 2005 7 (No. 2/3/4), 171 – 191.

Lawrence, J. An analysis of the bonding mechanism active in a high powered diode laser generated two stage ceramic tile grout. *Lasers in Engineering* 2002 12(4), 279 – 309.

Lawrence, J. *The characterization and feasibility of a two-stage ceramic tile grout sealing process using a high power diode laser*, PhD thesis, Institute of Science and technology: University of Manchester 1999.

Lawrence, J., and Li, L. Augmentation of the mechanical and chemical resistance characteristics of an Al_2O_3-based refractory by means of high power diode laser surface treatment. *Journal of Materials Processing Technology* 2003 142, 461 – 465.

Lawrence, J., and Li, L. On the difference between the beam interactions characteristics of CO_2, Nd: YAG Excimer and high powered diode lasers with a SiO_2/Al_2O_3 ceramic. *Lasers in Engineering* 2002 12 (2), 71 – 93.

Lee, Y.C., and Kuo, S.H. Miniature Conical Transducer Realized by Excimer Laser Micro- Machining Technique'. *Sensors & Actuators* 2001 93, 57 – 62.

Lingfi, J., and Yan, Y. Crack free cutting of thick and dense ceramics with CO_2 laser by single – pass process. *Optics and Lasers in Engineering* 2007 46, 775 – 790.

Morita, N., Watanabe, T., and Yoshida, Y. Crack Free Processing of Hot – Pressed Silicon Nitride Ceramics using Pulsed YAG Laser. *JSME International Journal Series III*, 1991 34 (1), 149 – 153.

Murray, A.J., and Tyrer, J.R (1997) 'Pulsed CO_2 and Nd: YAG laser drilling of PSTZ – A study into the wavelength, effects on Recast layer micro-cracking'. *Lasers in Engineering* **9**, 23 -37.

Murray, A.J., and Tyrer, J.R (1997) Nd:YAG Laser cutting and drilling of PSTZ- influence of substrate heating temperature on recast layer microcracking'. *Journal of Laser Applications* **11 (3)**, 127-135.

Naeem, M., Preston, M. E., and Tyrer, J.R. Processing of Engineering Ceramics with High Powered CO_2 Lasers, *Material & Design* 1979 10, 271- 375.

Shukla, P. *Characterization and Viability of the laser surface treatment of Engineering ceramics*, A doctoral Thesis, Loughborough University 2011.

Shukla, P.P., and Lawrence, J. A Comparative Study on the Processing Parameters during Fibre and CO_2 laser Surface Treatments of Silicon Nitride Engineering Ceramic. *International Journal of Advanced Manufacturing Technology* 56, (1-4), 143 – 155.

Shukla, P.P., Lawrence, J. (2011) 'Characterization and compositional study of a zirconia engineering ceramic irradiated with a fibre laser beam'. *Optics & Laser Technology* 43, 1292-1300.

Shukla, P.P., Lawrence, J. (2011) 'Examination of temperature distribution on silicon nitride engineering ceramics during fibre laser surface treatment'. *Optics and Lasers in Engineering* 49 (7), 998 – 1011.

Solomah, A.G., Mannik, L., and Brown, S.K. Laser Machining of Silicon Nitride Ceramics, Proceedings of the international conference on machining of advanced materials, Gaithersburg: USA 1993 747, 543-547.

Solomah, A.G., Mannik, L., and Brown, S.K. Laser Machining of Silicon Nitride Ceramics. *Proceedings of the international conference on machining of advanced materials.* 1993.

Sun, L., Malshe, A.P., Jiang, W., and Mccluskey, P.H. Effect of CO_2 Laser Surface Processing on Fracture Behaviour of silicon Nitride Ceramic. *Journal of Engineering Materials and Technology* 2006 127, 460 – 467.

Sun, L., Malshe, A.P., Wen Ping, J., and Mccluskey, P.H. Experimental Investigation of Laser Surface Processing of Flexure Silicon Nitride Ceramics. *Transaction of Nonferrous Metals Society of China* 2006 16, 557 – 65.

Triantafyllidis D., Li L., and Stott F. H. (2006) 'Crack-free densification of ceramics by laser surface treatment'. *Surface and Coating Technology* **210**, 3163 – 3173.

Triantafyllidis D., Li, L. and Stott F. H. (2002) 'Surface treatment of alumina-based ceramics using combined laser sources'. *Applied Surface Science* **176**, 140–144.

Triantafyllidis, D., Bernstein, J. R., and Stott, F.H. (2003) 'Dual Laser beam modification of high alumina ceramics'. *Journal of Laser Applications* **15(1)**, 49-54.

Voisey, K. Laser Processing of Ceramics. *Industrial Laser User* 2003 33, 23 -25.

Wright, C. Shot Peening Applications Ninth Edition. *Metal Improvement Company: a subsidiary of Curtis-Write Corporation* 2005 1-60 (www.metalimprovement.com).

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