Alteration of Fracture toughness (K_{Ic}) of Si_3N_4 Advanced Ceramics by Laser Shock Peening

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Introduction

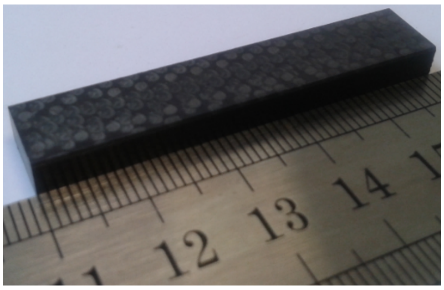
A Si_3N_4 advanced ceramic is one of the most applicable ceramic material in industry from the family of advanced ceramics. Compared to other ceramics, a Si_3N_4 has nominal hardness which is not too hard and yet not too brittle. At the same time, its Young's modules is in the mid-range when compared to a ZrO_2 or a SiC advanced ceramics. Si_3N_4 is also dense and light weight, has good corrosive properties but has relatively low fracture toughness (K_{Ic}). Some of the industrial application of Si_3N_4 are namely: valves; pistons; exhaust manifold; seals; turbo chargers; bearings; turbine blades; rocket nozzles and rotors [1]. For such applications, fracture toughness parameter - K_{Ic} is an essential property since low fracture toughness in comparison to metals and alloys is one of the disadvantages of the ceramics in general and Si_3N_4 in particular. Crack sensitivity and low K_{Ic} can limit the use of Si_3N_4, particularly for high demand applications. Nevertheless, the applications of Si_3N_4 have gradually increased on account of the desirable physical properties and longer functional life which often gives the Si_3N_4 a commercial advantage over the conventional materials in use. With that said, an increase in the K_{Ic} would therefore, lead to an enhancement in the ceramic components functional life and improve performance. Ultimately, this leads to reduction in the maintenance time and cost of the component/part. Conventional metals and alloys especially can be replaced by advanced ceramics such as Si_3N_4 due to its exceptional mechanical and thermal properties offered. Lasers are known to influence the surface properties of ceramics materials in general. This study is a continuation of our work in laser shock peening (LSP) of Si_3N_4 to study the effects on the surface hardness and K_{Ic}. LSP has been an established technique for over number of years for the surface treatment of metals in particular [2 -5]. However, LSP of advance ceramics is still an under-developed process for a number of reasons [2]. It is therefore interesting to study the effects of laser LSP of the advanced ceramics to understand the short pulse laser-material interaction and the change in physical and internal properties. Previous work by Koichi *et.al.* [6] employed a 532nm Nd:YAG laser to peen a Si_3N_4 ceramic, but did not consider a possible change in the K_{Ic} or microstructural modifications to any depth. This work is a first-step towards developing the LSP process of ceramics in general. It does not only fill the gap in knowledge, but also provides a first step towards the understanding of the science behind the unique process. We therefore, present our preliminary study using the awarded high power Nd:YAG laser (NSL4) system.

Material Details

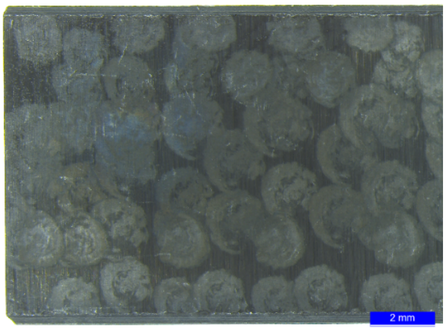
A cold issotatically pressed (CIPed) Si_3N_4 advanced ceramic was used as an experimental material from Shanghai Unite Technology (Shanghai, China) with the dimension 50mm x 10mm x 5mm bar as shown in Figure 1 (a) and (b). The Si_3N_4 advanced ceramic comprised of 90.5wt% Si_3N_4, and 6 wt% yttria, and 4 wt% unspecified content. It was CIPed at 455 bar pressure from all of its orientations and sintered at 1200℃ for 5 hours (as specified by the manufacturer). The ceramic was mechanically and microstructurally characterized before to all experiments. The average as-received surface finish (from 5 samples) was Ra 1.50µm. The surface hardness was measured to be 1467HV using 10kg indentation load, and a plane strain fracture toughness (K_{Ic}) was measured to be 2.91 $MPa.m^{1/2}$.

Experimental Set-up

The laser used in this investigation was the EPSRC funded loan-pool laser (Litron; LPY10J, ultra-high energy pulsed Nd:YAG Laser; Rugby; UK). The laser exerted an average maximum power of 10J, delivered at 5Hz in 8ns. The laser beam comprised of a flat-top profile and a divergence angle of 0.5mrad. The LSP process used a 1.5mm spot size with an over-lap of 50% at 80% coverage. The laser was set-up to operate at 1064nm wavelength, with a pulse repetition rate (PRR) of 1Hz and Q-switch delays of 457µs to surface engineer the Si_3N_4 advanced ceramic. No assist gas was used for the laser peening. The initial experiments demonstrated that the use of absorptive layer with laser peening did not affect the material and rather require higher energy to penetrate into the material. So the use of absorptive layer was not adopted. Although, de-ironized water was used to flow over the top of the sample with a continuous circular feed (see Figure 1(c)). The water layer interacts with the laser and increases the generation of plasma. The plasma then absorbs into the ceramic creating a shock-wave that puts metallic materials under compression *via* plastic deformation. Identical experiments conducted on five in order to evaluate the effect of LSP on the Si_3N_4.



(a)



(b)

(c)

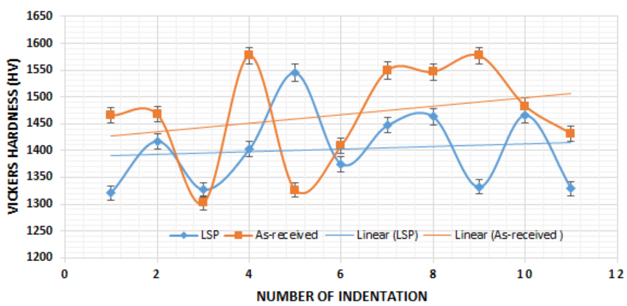
Figure 1 Set-up of the LSP technique in (a); and (b and c) showing the optical images of the LSP of Si_3N_4 at 80% coverage and 50% overlap.

Material Characterization Prior/Post Laser Peening

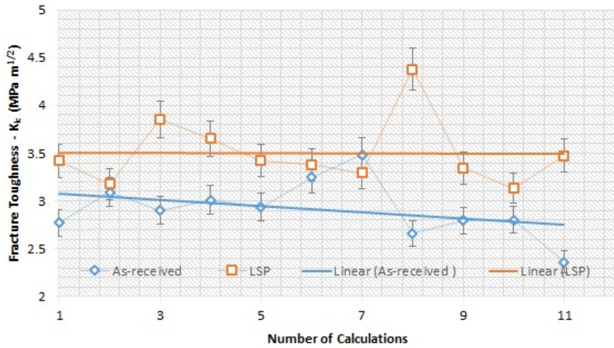
Hardness of the ceramic was measured using a conventional Vickers indentation tests. The applied load was 10kg. The indentation machine was: VHTM 2000; Vickers Ltd. Engineering Group; Sheffield; England. All crack lengths were observed using an optical microscopy (Leica-LEICA DM2700M; Wetzlar, Germany). Fracture toughness K_{Ic} data was tabulated on Microsoft Excel 2013 was determined based on the methodology in our previous publication [7].

Hardness, Fracture Toughness and Crack Propagation

Comparison of the hardness of the as-received Si_3N_4 with that of the LSPned Si_3N_4 showed a slight change in the surface hardness. The LSPned surface comprised 4.5% lower hardness (see Figure 3(a)). Upon taking into consideration a ±10% error in measurement, 4.5% change in hardness would be neglected. However, when observing the footprints of the Vickers indentations, and the associated crack geometry, it was found that the exerted crack lengths over 11 tests had reduced by about 8% for the LSPned Si_3N_4. This was an evidence of Si_3N_4 surface exhibiting ductility so the Si_3N_4 surface deemed a better response under a mechanical impact of around 98N. On account of the reduction in hardness and brittleness, and crack-response, the LSPned surface improved the K_{Ic} by about 16.5% (see Figure 2(b)). A full microstructural study backed by further phase modification data will confirm the change in the surface properties found herein. Although, an improvement in such an important property of ceramics such as a K_{Ic} could open avenues for its use ceramics in general, particularly where metals and alloys generally fail.



(a)



(b)

Figure 2 Surface hardness in (a); and the K_{Ic} in (b) of the LSPned Si_3N_4 advanced ceramic.

Conclusions

The findings herein present our results of a first-step study of laser shock peening advanced Si_3N_4 ceramics. We explore the change in the near surface property such as K_{Ic}. Our results showed a 4.5% reduction in the surface hardness after LSP which indicate that the LSPned surface became less brittle. Although such a small difference is negligible, it was still found that the crack lengths generated by the Vickers diamond impact were reduced by 8% after LSP and thus, improved the K_{Ic} of the Si_3N_4 by about 16.5%. This goes to show that for demanding and high mechanical impact applications LSP of Si_3N_4 could become useful.

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