Laser Shock Peening of Si_3N_4 Ceramics: Experimental Set-up and General Effects

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Introduction

Laser shock peening (LSP) or laser peening has been an established technique for over two decades for the surface treatment of metals and alloys due to the known benefits offered by the process, in particular: increased compressive residual stress, reduction in friction and wear, surface topography changes and increase in hardness [1]. With that said, laser shock peening of advance ceramics is unreported and requires much development. This is because of obvious reasons such as the physical characteristics that prevent ceramics from behaving in the same way as metals when exposed to short pulses of laser energy. Thus, mechanical yielding and plastics deformation within ceramics is difficult to introduce. Therefore, the same benefits found with metals/and alloys are not common with hard brittle materials such as ceramics. As such, it is of a great interest to investigate LSP of ceramics to understand the short pulse laser-material interaction, and the surface and bulk property modification, if any. One of the reasons why this type of research with difficult to process materials draws an interest is because a successful technique to surface engineer advanced ceramics would first open new avenues for their use in demanding applications. For instance, LSP of ceramic armor plating and in conditions where high level of mechanical and thermal stress and corrosive environment is present. Typical ceramic products in engineering, namely; as high performance cutting tools; knives, and machine tools could also benefit from LSP. Much work has been conducted in the area of of metallic parts [2-3]. With that said, the only previous investigation that closely relates to the work in this study is that of Koichi *et.al*. [4]. The work in their investigation involved the use of a Nd:YAG laser (532nm wavelength) to peen a Si_3N_4 ceramics. Having said that, the research herein is very important because the wavelength used by Koichi *et.al*. was different. They also presented contradictory results and did not consider the surface effects or any potential microstructural modifications. Our work is a first-step towards developing a laser peening technique of ceramics with a broader view to first understand the science behind the technique, particularly for ceramics by analyzing mechanical, physical, and internal aspect of the material. Upon success, our goal is to implement the technique to engineer (strengthen) components from range of industrial sectors. Thus, we present firstly an experimental set-up of our research with general effects that the EPSRC funded ultra-high power (10J) Nd:YAG laser, (NSL4) system.

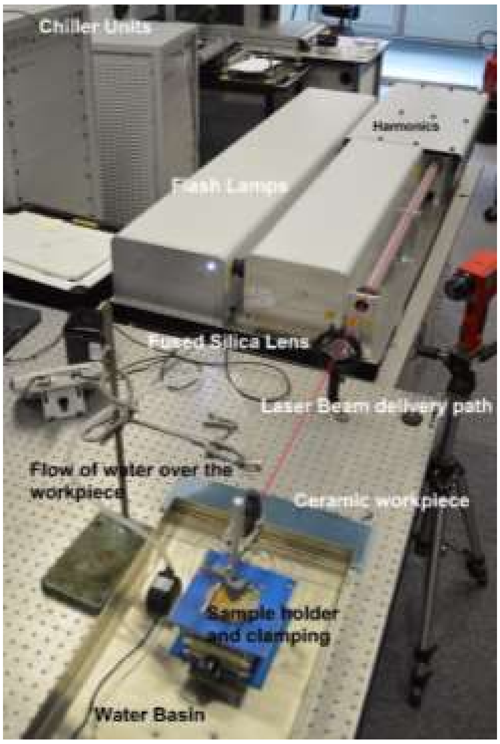
Material Details

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 (b) and (c). The advanced Si_3N_4 ceramic comprised of 90.5wt% Si_3N_4, and 6 wt% yttria, and 4 wt% unspecified content. The Si_3N_4 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 prior to all experimentation. 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$^{1/2}$.

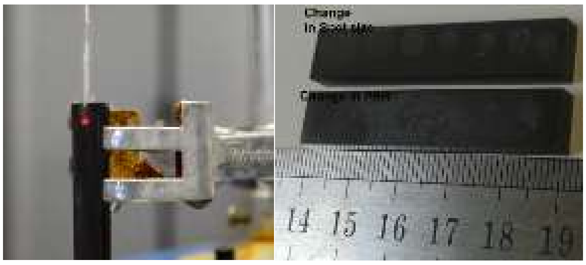
Laser Experimental Set-up

The laser used in this investigation was a 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 laser was set-up to operate at 1064nm wavelength, whilst spot size was changed from 1.5mm to 10.25mm, pulse repetition rate from 1Hz – 10 Hz and the Q-switch delays from 80µs – 700µs was changed (one-at-time) using a single shot to explore the effects and the best suitable parameter to surface engineer the Si_3N_4 advanced ceramic by LSP. No assist gas was used for the laser peening.

Our experiments showed that the use of absorptive layer did not affect the material and rather require higher energy to penetrate into the material, thus, the absorptive layer was not used. However, de-ironized water was used to flow over the top of the sample with a continuous circular feed (see Figure 1(a)). The water layer interacts with the laser and increases the generation of plasma which then absorbs into the ceramic creating a shockwave that generally places the material under compression *via* plastic deformation. Five samples were used for the experiments in order to evaluate the effect of LSP on the Si_3N_4.



(a)



(b) (c)

Figure 1 Experimental set-up of LSP experiments in (a); the flow of water over the Si_3N_4 in (b); and (c) the single pulse LSPned samples.

Material Characterization Prior/Post Laser Peening

Surface finish and topography was examined using a chromatic confocal imaging device (3-D Surface Profiler; Micromeasure 2; Polytec Ltd; Hertfordshire; England). All crack lengths were observed using an optical microscopy (Leica-LEICA DM2700M; Wetzlar, Germany). Fracture toughness parameter K_{Ic} was determined based on the methodology in our previous publication [5].

Surface Effects Post Laser Shock Peening

Despite using an optical microscopy, a first-step investigation of the LSPned surface showed no sign of cracking. This is generally the case with laser pulse processing of hard, brittle materials such as ceramics. Firstly, the pre-existing striations from machining marks on the un-peened region were removed as evident from Figure 2. Secondly, an indication of the change in microstructure was also seen at a spot size of 4.8 mm, 215µs Q-switch delay, with a PRR of 5 Hz at 1.70J of laser energy. This proved to be sufficient to bring about a possible phase change that is postulated to be a transformation from α-phase to β-phase formation in region indicated in Figure 2. Further study of a possible phase transformation will be conducted in our future investigations.

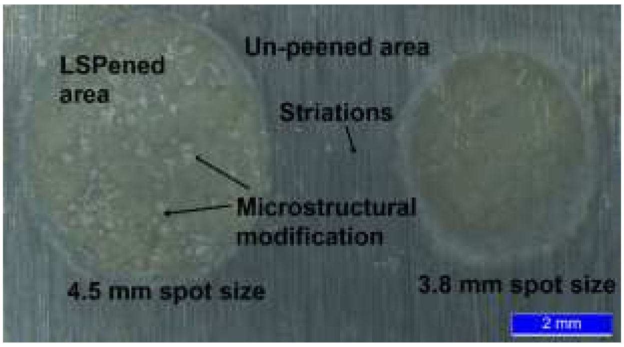


Figure 2 Optical image of two different LSPned regions and an indication of a microstructural modification.

Initial observations of the surface topography measured over 5 samples elucidated that the modified the surface finish when compared to the as-received surface (see Figure 3). Both the Ra and Sa values were modified for the ned surface. For instance the surface roughness for the ned surface was Ra = 1.73µm whilst the as-received surface was Ra = 4.79µm ned surface was measured to Ra = 1.73µm. This was a significant increase for the samples measured. The surface roughness parameters are directly influenced by the laser parameters, thus, it will be of interest to investigate this aspects in future studies.

(a)

(b)

Figure 3 As-received surface in (a); and LSPned surface in (b) of the Si_3N_4 advanced ceramic.

Conclusions

This work shows a first-step study on LSP of Si_3N_4 advanced ceramic using the EPSRC funded NSL4 ultra-high powered laser system. Key finding from this work firstly elucidated an appropriate and simplistic set-up in order to conduct a feasibility study using continuous flow of liquid media which can be easily changed and filtered. Various parameters were explored to LSPeen Si_3N_4 advanced ceramic in order to produce surfaces without any cracks. A study of the low resolution microstructure indicated a possible phase change within the Si_3N_4 employed herein. The principle investigator of this grant is currently investigating the phase transformation, microstructural evolution at high resolution, surface property modifications, namely: wear, friction, hardness and fracture toughness of not only Si_3N_4 but wide range of advanced ceramics from different industry sectors.

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