Laser Shock Peening and Mechanical Shot Peening Processes Applicable for the Surface Treatment of Technical Grade Ceramics - A Review

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Abstract

Laser Shock Peening and conventional method of mechanical Shot Peening are both comparable processes generally applicable to surface treat various metals and alloys. Commercial advantages offered by the laser systems such as flexibility; deep penetration of shocks with precise control of the thermal energy; shorter process times; high speeds; accuracy and aesthetics are attractive in comparison with the mechanical shot peening technique. Laser shock peening in the recent years has proved to be successful with steels, aluminium and titanium surfaces and metallic alloys in general. Nevertheless, minimal research has been conducted on laser shock peening and mechanical shot peening of technical grade ceramics. This paper presents an update of the theory and to-date, relevant literature within the two subject areas, as well as a comparison and contrast between the mechanical and laser shock peening techniques. In addition, various gaps in knowledge are identified to propose further research to develop both the techniques applicable for the surface treatment of technical grade ceramics.

Keywords: Shot; Shock; Peening; Lasers; Technical; Ceramics

1. Introduction

Pre-stressing of materials by mechanical means has dated back to the time of the crusades (1100-1400 A.D). Records show objects found near the ancient shoreline of the Persian Gulf, dating back to 2700 B.C consisting of properties of cold work hardening by controlled hammering. The technique was used on metals such as copper, iron, bronze and steels when manufacturing weapons and tools [1]. Previously, a ball pein hammer was used to work harden the material as it improved the material's resistance to wear and lengthened the life of the treated product. The word "peen", as it is known to us today, originates from the term "pein" [2, 3]. The term shot peening began from the principle of firing steel shots at the material surface. During early 19th century, the process was considered as unpredictable, with its effects being somewhat unknown. The process then developed over time and continuous research was conducted from 1920's onwards [2 - 4]. From being a remedial process to treat engineering components in the 1980's [5], shot peening has been introduced into product design specifications for advancing industrial applications for number of years. Common materials treated by shot peening are carbon steels, alloy steels, stainless steel, aluminium and titanium alloys.

Shot Peening is a type of surface treatment used to enhance the service life of engineering components. It is a cold working process that fires balls (shot) of steel, ceramics or glass beads at the work-piece (metals in particular) to mechanically pre-stress the material beyond its yielding point [6 - 9]. The localised plastic deformation induces residual stresses into the surface layer of the material. The surface residual stresses are compressive. The induced compressive residual stresses inhibit crack growth under cyclic loading, increasing the material hardness, fatigue life and resistance to stress corrosion cracking (SCC).

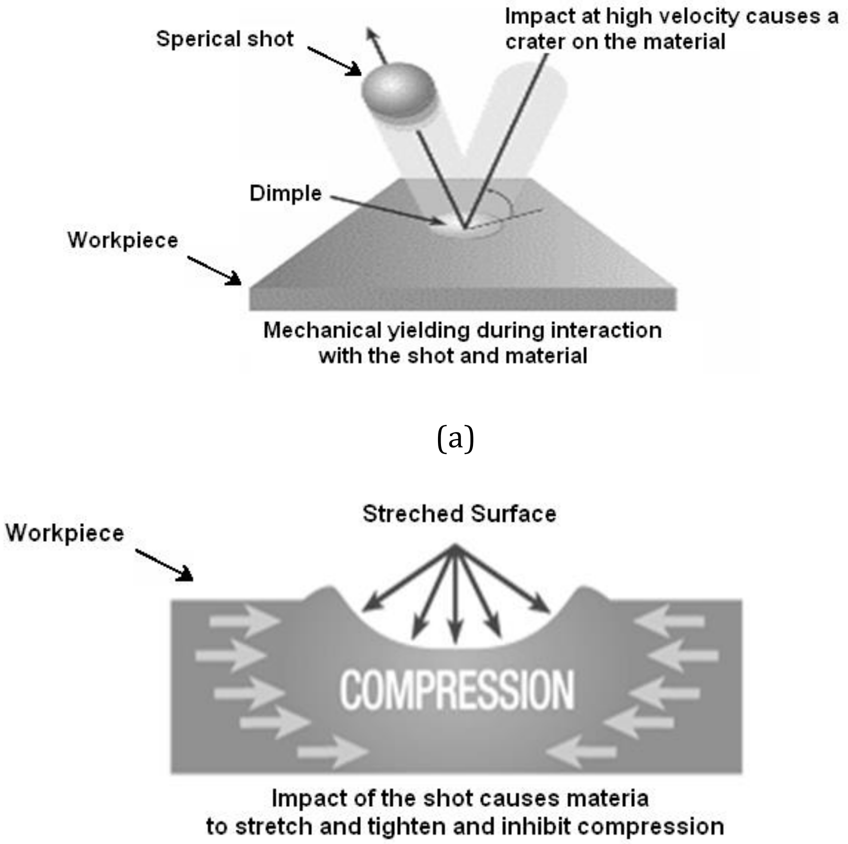
Having said this, one alternative which surpasses the benefits and advantages offered by the conventional shot peening technique is laser shock processing or laser shock peening [10 - 12]. Commercial advantages and economic benefits have made the laser systems popular. The benefits offered are high processing speeds, accuracy, shorter process times, deep penetrating treatment applied with precise control of the thermal input and aesthetics, which are far too attractive to be ignored. Laser peening in the recent years has developed and proven its success with steels, aluminium, titanium and magnesium alloyed surfaces [13 - 16]. Having said this, minimal research has been conducted on laser surface treatment of advanced, technical grade, engineering type ceramics. Applications of ceramics have been limited due to their crack sensitivity and low fracture toughness (K_{1c}). However, the use of ceramics has advanced over the years [17 -25]. They are now considered as the new type of material used to manufacture components for the aerospace, automotive, military sectors, biomedical, power generation as well as electronic sectors. Engineering ceramics offer exceptional mechanical properties, which allows them to replace the more conventional materials currently used for high demanding applications [26 - 32].

A survey of current literature in the field of laser shock peening, showed that sufficient research have been carried out by various workers around the world and considerable improvement has been made from the laboratory environment to the manufacturing set-up. Presently, the process has many industrial applications particularly in the automotive and the aerospace industry to surface treat metal/alloys. Nonetheless, the effects are not yet fully understood when the process is applied to technical grade ceramic materials. In addition, this area of research could be useful also because limited research has demonstrated in the laser shock peening of technical grade ceramics and the laser-material interaction from the view point of topographical, mechanical, thermal and microstructural aspects.

2. The theory

2.1 Shot Peening - The Mechanical Process

The main objective of shot peening is to plastically deform the top surface layer of a material or the component being treated by the impact of steel shot (balls) fired at high velocity. The steel shot fulfilling the purpose of the pein hammer to plastically deform the surface of the component part being treated. During this impact, a portion of the kinetic energy carried by the shot impacts to the material surface generating localised plastic deformation. This results in a small increase in the temperature at the point of impact. The residual kinetic energy carried by the shot enables it to deflect from the surface of the component [5 - 9].



(a)

(b)

Figure 1 Schematic of the mechanical shot peening principle in (a) and (b) a schematic of the work-piece under plastics deformation after being compressed by a shot.

The level of plastic deformation is dependent on the hardness and the thickness of the material. Therefore, more shot kinetic energy is required for thicker and harder surfaces. This can be obtained by increasing the size or the weight of the shot and its velocity. The type of shot material used also varies the rate of deformation. The denser steel shot has high deformation energy which would impact the material in comparison with ceramic or glass particles [5 - 9]. However, for shot peening ceramics, it is necessary to employ a ceramic based material shot to avoid deformation of the shot material and enable the shots to be re used with maximum effect.

The shot cause plastic deformation as they are fired onto the surface, which locally expands. The plastic deformation of the stretched surface is resisted by the underlying (elastic) bulk material, which pushes the surface into compression. Hence the core is left at a low level of tension. The system is balanced with respect to forces (stress area) where high surface residual compression exists in the surface region and low bulk residual tension in core. The component part or the material being treated is also reduced in size. This is due to the top layer of the material being compressed. The deformation is dependent on the shot size and velocity.

To understand the effect of shot peening; it is important to analyse the structure under three point bending. When a beam is placed under three-point bending the distribution of compressive stress is acting diagonally across its cross section. The top part of the beam is in tension as the material is being bent. Hence, the bottom part of the beam is in compression where the forces are acting in the -ve direction. The point in the centre of the beam is therefore under equilibrium where the forces are balanced. This is presented in Figure 2. If the particular bent surface is shot peened, the distributed stress area is modified to avoid the beam to fracture from tensile stresses, where the tensile and compressive stresses are equally distributed over the structure. This distribution is called the resultant stress (the sum of the material under three point bending and the peened structure put into three point bending). The material is compressed during the impact and allows the top layer to stretch and tighten, causing the surface beneath to compress. The compressive layer introduces stresses into the material which are deemed negative as illustrated in Figure 2 by line 1. Surface tensile stresses deemed positive (line 2 in Figure 2), would aid the propagation of surface cracks, where resultant tensile stress pre-exist in the core of the material (line 3 in Figure 2). If a crack is to propagate on the material surface, then the applied tensile stress must first overcome and increase the residual compressive stress induced by shot peening before a crack is generated. A crack will only propagate if applied tension exceeds the induced compression. The tensile stress in the middle of the material induces a surface compressive stress for mechanical equilibrium. The surface compressive stress inhibits crack propagation. The tensile forces must overcome the compressive forces in order to propagate a crack on the surface. For example if shot peening induces a compressive force of $-200\ \mathrm{N/mm^2}$, the acting tensile stress must be over $+200\ \mathrm{N/mm^2}$ for the material to generate a crack.

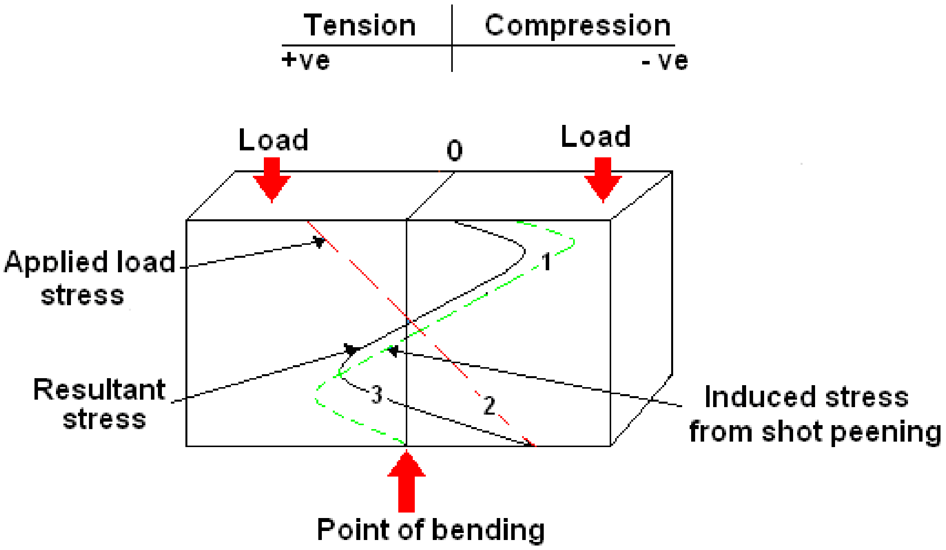
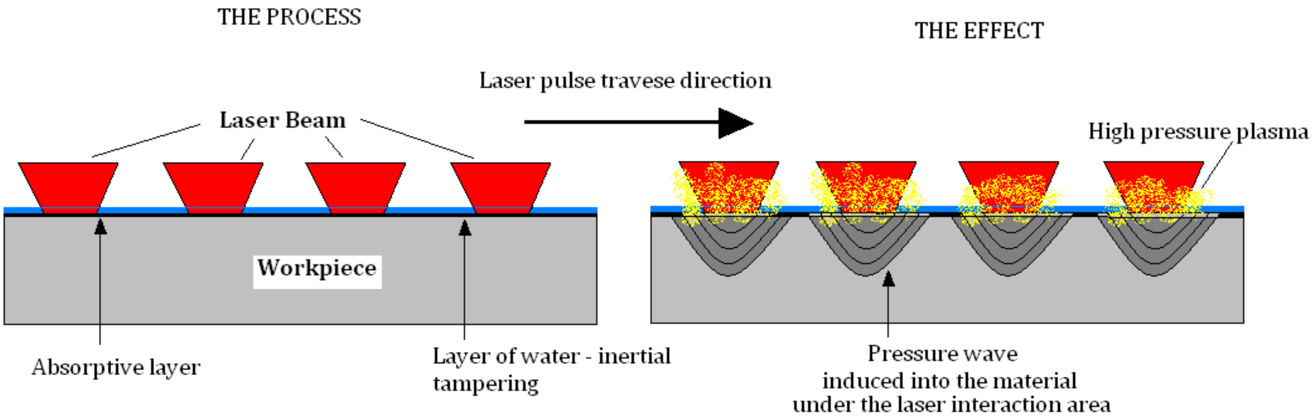


Figure 2 Applied residual stress on the material and distribution of shot peening stresses.

2.2 Laser Shock Peening – The contact-less Process

Laser shock peening relies on an intense pulse generating a plasma ball which totally absorbs the incoming radiation and so creates an intense pressure (measured in 100s of atmospheres) [32 - 42]. This photon bundle behaves like a steel ball and actually leaves a rounded indentation in the surface. If the process is not done correctly, the power is not delivered as a very short and very strong pulse, then the laser would start to drill a hole.

Typically a shorter wavelength laser in the range of 1µm tends to be used to generate a pulsed beam to impact a material which then produces a shock-wave (thermal expansion) through the bulk of the surface as illustrated in Figure 3. Recent advances have employed laser pulses in the range of picosecond and femtosecond [42 43] compared to the conventionally used nanosecond and microsecond pulses [39, 40]. The compressive residual stress is induced through a shock wave induced into the cross section of the material (see Figure 3). This in turn creates plastics deformation, allowing the material to tighten and generate compression. A layer of black absorptive tape is placed with flowing water is which allows a generation of plasma which consequently helps to absorb the thermal energy and generate the shock wave passing through the material, deep into the cross section. The laser pulse can be fired on the work-piece several times to induce compressive residual stress depending on the required depth of the stress. The input of the compressive residual stress is as much as four times larger than of the conventional mechanical shot peening technique [32, 33, 37]. The deep residual stresses induced into the material help to combat fatigue and corrosion failures. Component life and hardness of the material is enhanced in the same way as it would with that of the conventional shot peening technique.



(a) **(b)**

Figure 3 A set-up showing series of laser shocks on a material in (a), and (b) the residual stress induced by the high pressure plasma.

3. Benefits of Plastic Deformation and Pre-stressing of Materials

3.1 Avoids or Prevents Stress Corrosion Cracking

Static stresses can be left in materials through manufacturing processes such as welding or fixation of components with mechanical fasteners or bolts flanges. Stress corrosion cracking develops when the material experiences the tensile stress, susceptible material, and a corrosive environment. Tensile stress is removed through shot peening by inducing compressive stress in the opposite direction [44]. Therefore, one necessary condition from the above three is eliminated which causes SCC, and so, the propagation of surface cracks and SCC can be avoided.

3.2 Increased Hardness

Localised surface impact causes the material to stretch and tighten by inducing residual compressive stresses into the surface layer of a material. Hence, the surface hardness increases due to work hardening of the surface layer during the shot peening process. Work hardening of the material allows plastic deformation and produces mechanical yielding.

Moreover, the main advantage of the laser as compared to shot peening is the size of the impact zone. This is why the laser shot peening process creates a deeper hardened zone. Another advantage is that the laser can harden into corners which a finite size ball could not reach - and also where fatigue properties are most needed.

3.3 Improvement in Fatigue Life

Shot peening allows the material to become much harder and wear resistant. The wear resistance prevents failure at the early stage and elongates the life span. This is especially applicable to components under frictional and shear stresses. The functional life of the engineering components is predicted by either fracture mechanics methods or statistical S/N fatigue test data [45]. Previous study showed shot peened components with fatigue failure predicted at 60 % of its life span.

3.4 Increase in Load Capacity and Bending Strength

During bending, tension exists on the top part of the structure and compression would therefore occur on the bottom part as shown in Figure 4. The forces acting on the top layer are pulling the structure apart, meaning that the material under bending has the potential to fracture if the tensile stress reaches the materials UTS (ultimate tensile strength). The bottom part of the structure is under compression which forces the material to compress into its own area. This creates equilibrium in the centre part of the structure under the bending moment. shot peening or laser shock peening could induce additional compressive stress on the top layer where the tensile stress is acting (see Figure 4). This would reverse the positive tensile stress into negative compressive stress and prevent the structure from fracturing or being pulled into two parts. It would also enhance the materials resistivity to fracture at higher bending load capacity. Since the material is under compression, the required force to initiate yielding at the top surface (layer) will also increase.

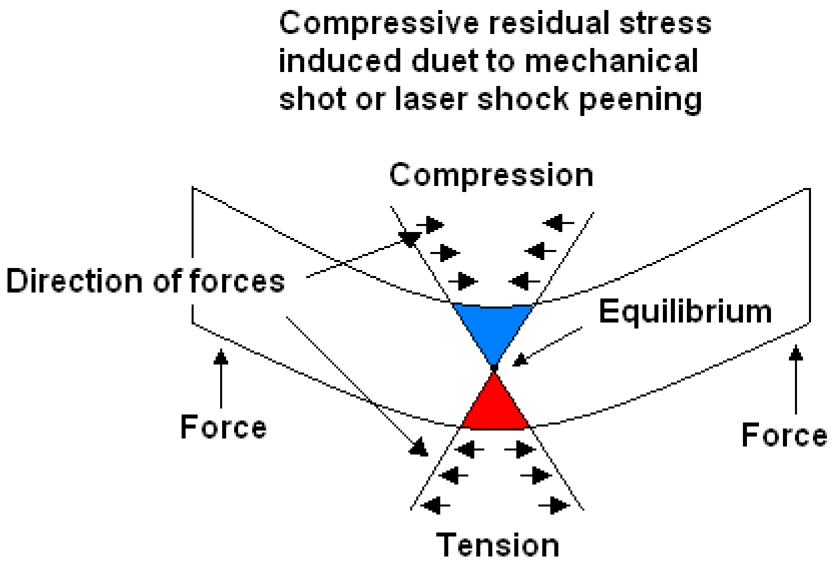


Figure 4 Enhancement in the bending strength due to compressive stress induced by shot peening

Due to applying the aforementioned surface treatment process such as shot peening or laser shock peening, the compressive stress acting on the top layer will mean that the tensile stress produced during the bending moment is required to overcome the compression. This shows that the bending strength of the material is enhanced by introducing a layer of compressive stress, allowing the material to comprise of higher bending strengths in comparison with the untreated material under the same bending conditions.

4. Applications of Mechanical Shot Peening and Laser Shock Peening

Both laser peening and shot peening are now widely applied in various industrial sectors. In the recent times, due to advanced capabilities for automating the laser system and rapid processing speeds as well as the ability to peen complex geometries and shapes has led the laser peening techniques to be readily used for such applications in various industrial sectors [44]. Nevertheless, the application of shot peening is more traditionally applied to mainly the automotive and the aerospace sectors. Table 1 shows the typical applications of both the mechanical shot peening and laser shock peening processes in various industrials sectors.

Table 1 Specific applications of both mechanical shot peening and laser shock peening technique in various industrial sectors.

Surface Treatment	Applications in Various Sectors				
	Medical	Aerospace	Other	Automotive	Motorsports
Shot Peening	Surgical tooling and devices; Medical needle free applicators; Scissors; Clamps; Stents; Biomedical implants; Guide wires; Cardiac assist devices; Electrosurgical tools; Mandrels and moulds; Catheters; Elastomeric seals; Needles and epidural probes; Medical Electronics; Prothesis; Stent	Turbine blades; Rocker arms Link rods - Master rods and caps/ Crankshafts; Propeller shafts; Miscellaneous shafts; Compressor blades (roots only); Turbine shafts; Landing gear [46]	General industrial uses; specialized military applications; Low contamination equipment; Lifting and mobility equipment; storage tanks; tubing; welded structures.	Gears; crankshafts; pistons Drive shafts; Compression springs;	Springs; gears; drive pinions; steering knuckle; crankshaft [47].
Laser Shock Peening	Spinal implant rod and fixation devices; Orthopaedic implants; knee replacements joints; [48].	Turbine blades; turbine air foils; fan blades; engine compressor; Components of helicopter [49]	Land based power generation [49]; Geology [50]	Gears; Pistons; crankshafts; axel; rotating engine parts; impellers;	Connecting rods; Pistons; Crankshafts, Valves, Springs; High loading engine components.

5. State-of-the-Art in Mechanical Shot Peening and Laser Shock Peening

5.1 Mechanical Shot Peening

Conventional shot peening by means of blasting balls of hard material to surface treat another equally or less hardened materials has been around since decades [6 - 9]. Even so, published literature in the field of mechanical shot peening of engineering and technical grade ceramics is still scarce. This is because the enhancement in strength, increase in resistance and compression which could be inhibited into the metallic materials does not generally occur with hard brittle ceramics. Thus, when shot peened, the hard brittle ceramics on the other hand tend to fracture and fail, hence, the use of shot peening rather resulted to undesirable and adverse effects on the so called hard brittle ceramics. Nonetheless, Frey and Pfeiffer [51], and Pfeiffer and Frey [52] conducted investigations on the feasibility of shot peening ceramics. Firsts of which demonstrated the strengthening of a Si_3N_4 and Al_2O_3 ceramic with increased load capacity, residual stress as well as roughness [51]. Ceramics treated by other surface strengthening techniques such as traditional metal working (pein hammering) or sand blasting tends to develop fractures whereas shot peening of ceramics was more successful due to its process controllability and precise setting of shot peening parameters. And the preliminary study by the researchers showed this to be possible [51, 52, 54]. With shot peening the level of shot size and velocity can be controlled. Reported results showed that by using shot peening, high compressive residual stresses can be introduced into the top surface of the Si_3N_4 and consequently, improvement of load capacity under 4 point bending conditions can be obtained [52]. The examined results revealed that high compressive stresses (in the range of GPa) were present in the Si_3N_4 accounting for increase in the load capacity (4 point bending) by a factor of 9 [52]. The shot peened samples showed compressive stresses up to 1.25 GPa. These compressive surface stresses enabled the load to increase from 3 kN to 9 kN which is over 200 % increase. The shot peening of the surface of Si_3N_4 and Al_2O_3 increased the roughness up to 0.09 µm (Ra) for Si_3N_4 sample and 0.14 µm (Ra) for the Al_2O_3. This was because Si_3N_4 is a much harder material than Al_2O_3. This could also be compared with the laser peening processes since the surface topography was believed to contain minimum damage due to the fact that there is no physical contact of the laser beam energy on the materials surface, hence the surface should be much smoother in comparison with the conventionally shot peened surface. Pfeiffer and Wenzel [52] proved that conventional shot peening was feasible to induce residual stresses into the ceramics in order to gain some of the benefits that were obtainable with shot peening of metallic materials. Another investigation by the same authors reported that the dislocation of the shot peened surface was affected by two phenomena; localised microscopic surface deformation and appearance of dislocations in the surface crystals [53]. Dislocation multiplication and local surface deformation serve to increase the compressive residual surface stresses and creating a strengthened material surface [53]. In addition, K_{1c}, the fracture toughness parameter was also improved when compared to the surfaces of the ceramics which were not treated [53]. Pfeiffer and Wenzel [54] later showed similar improvements in the near surface layer of brittle materials namely: cemented carbides and hard chromium platings [54]. The technique to shot peen engineering ceramics has taken birth and is now in the process of being automated for production environment which could be capable of covering large surface areas, and healing/strengthening of distorted ceramics components [55].

Despite the benefits, the conventional, mechanical shot peening technique has several constraints, those are:

- Changes in the Surface topography as result of the shots impacting on the surface which would create circular indents on the surface of the substrate and intrinsically, affect the surface finish – making the material much courser.

- Whilst the shots impact the surface, the surface not only has the tendency to deform but more importantly, the shots blasted at high velocity impacting a harder surface would in turn, deform to a more “egg shaped” profile. This means that with every cycle of the treatment, the shots are required to be replaced by newer fully circular shape.

- Thus, change of shot size causes additional cost and requires timely machine set-up which consequently increases the lead-time and decreases the production rate and operator cost, making the product much costly to manufacture.

- Shot diameter is only suitable for a specific type of nozzle so in the case that a larger shot size is required (dependent on the surface condition and intensity of the treatment), would mean that a larger or smaller nozzle is needed to accommodate the shots passing through the nozzle. As such, this also requires a timely set-up, adding extra cost to treat the surface.

- Having treated a surface using the shot peening technique, it is then required that the shots are recollected for the next cycle for the shot peening process to begin. This requires recollection of shots which were used for the previous cycle. Some shots are deformed and others are still within the tolerance and could be used again. However, quality checks have to be performed so deformed shots can be separated from those that comply with the tolerance which in its own was is also a non value adding process [3].

- During shot peening correct control of parameters, shot intensity (velocity) and shot diameter is required. If this is not set-up correctly then it is possible that the treatment may result to producing material failure. This is certainly important for the ceramics as such material are prone to cracking and fracture.

- In case that the material being shot peened has a considerably low thickness then it is possible that distortion of material being treated may occur particularly if the shot intensity and size are not correct [6, 56].

Laser shock peening on the other hand has feasibility issues when surface treating technical grade ceramics which are later discussed in this paper, although, there are several obvious advantages which enable laser shock peening to be a much superior process in comparison to the mechanical shot peening technique:

- Penetrating depth of residual stress induced into the material is known to be much greater than that induced by the shot peening surface treatment. This means the failure rate of the component being treated is much lower than the components treated by the mechanical shot peening technique.

- Laser shock peening also offers improvement with surface roughness unlike the mechanical shot peening technique which places dimples on to the materials surface making it much courser.

- Mechanical shot peening requires tools change whereas no tool change is required for laser shock peening. This eliminates the unnecessary set-up times and in turn increases production rate and throughput within a production line since the process allows shorter lead-time to undergo the surface treatment.

- No recollection of the fired shot is required as the laser shock peening is a contact-less process which offers a infinite tool (laser) exhibited at constant and repetitive set parameters to conduct the surface treatment offering minimal maintenance and high quality standards.

- All laser systems now operate with superior motion system and freedom of movement that aids programming of complex shapes and geometries which allow easy programming from a 2D to 3D CAD pattern (tool path or beam path) and this inherently allows movement in 6 axis of motion which is not on offer unless specified by the mechanical shot peening technology.

- In addition, laser shock peening also offers a precise quality control where parameters of the laser can be monitored in real-time which upon an error can be immediately corrected. This would leads to a better control of the process and its effects thereon the material.

5.2 Laser Shock Peening

Having considered the constraints associated with the mechanical shot peening technique and justifying the rationale for the implementation of laser shock peening it is yet a question if the same effects can be achieved with laser shock peening of technical grade ceramics to those obtained by the previous researchers on the mechanical shot peening of the few ceramics that were investigated? This is an issue to be considered, understanding the fact that if mechanical deformation could occur on the surfaces, and sub-surfaces of the technical grade ceramics, then a laser beam may also have a potential to cause the same effect, however, with a different principle. The contact-less laser beam offers the treatment to be conducted in a superior fashion by inducing heat and a shock wave into the material. Furthermore, the science and the wider effects of laser shock peening of technical grade ceramics is still unclear with respect to its capability to generate dislocation boundaries and achieve plastic deformation.

Research in the field of laser shock peening of metals has been proven to be successful and has been implemented in production environment for over a decade [5-9, 35, 44, 46, 57-59]. Earlier research in the year 2000 by Qureshi *et. al.* investigated the feasibility and the potential of the process as an industrial solution and compared it with the conventional shot peening technique. Basic comparisons for both of the processes were presented by taking in account of the residual stresses induced from each process and the depth of penetration through copper, aluminium, zinc, brass, tin and other alloys which all showed promise for future research work [35]. Altenburger [60] demonstrated the laser peening process performance in comparison with the conventional methods and stated that laser peening as an industrial solution could have a great future as an alternative technique. The research findings then transformed from the laboratory to larger scale applications in 2001 [60]. Altenberger in his later work [61] established that laser shock peening was a superior technique in comparison with deep rolling, conventional shot peening, and water peening. Metal/alloy materials were used for the study to show that laser shock peening resulted to longer life cycles at higher stress amplitudes, deeper residual stress and also proved to be cost effective than other processes as lead-time was minimized due to the superior motion systems and produced fast throughput to consequently deliver products at a faster pace to the customers.

Research by Prevey *et. al.* [57] in 2000 described the application of laser shock peening to minimize fatigue, stress corrosion cracking, enhancement in the materials hardness and improved the microstructural properties of metallic materials. Such improvements were said to maximize the use of the materials for their applications. Further work by Prevey *et. al.* [61] showed that high powered lasers achieve better surface finish, aesthetics, minimize the process time as well as induce deep shock waves into the material surface aided by the pulse beam, resulting in deeper penetration. This makes laser shock peening a superior process and more useful towards an industrial application. Qureshi *et. al.* also gives an example of the aerospace manufacturing sector where laser shock peening is slowly taking over the more classical method of surface treatment using shot peening [35].

Specht and Harris [63] introduced the laser shock peening process in greater detail explaining technical issues such as the type of lasers used, process parameters, and the beam quality aspects. Experiments were conducted using the Almen strip which was also used for conventional shot peening technique to monitor and control the process. The authors state that their research can help OEM's (Original Equipment Manufacturers) to successfully use the laser peening process in a production environment and classified the process as complimentary to the conventional industrial shot peening technique [63]. Since then, Metal Improvement Company Ltd. have developed the process that is more applicable at industrial scale namely: for shock peening automotive gears; shafts, springs; valves and many rubbing components that require high hardness; improvement in fatigue and longer functional life [63].

Laser Shock peening, however, is utilised frequently within the aerospace industry to surface treat turbine engine components (turbine blades, rotors and aerofoils specifically) [38, 46, 56]. The shock peening process is conducted during finishing stage of the turbine blades. The turbine blades are shock peened to increase fatigue and improve life cycles which enhances the components functional life. The laser shock peening technique is also used as a remedial process to cure damaged turbine blades [46]. The laser shock peened spot is precisely of 0.67 mm diameter and is fired 3 times on the same surface area and the treatment is conducted on both the leading (L/E) and trailing edge (T/E) of the blade. The fan blades are simultaneously shocked peened on both sides also for equal distribution of the induced residual compressive stress [38]. The authors compared three types of processes such as gravity peening, low plastic burnishing, shot peening, and laser shock peening that were conducted on turbines engine components (Inconel - IN718) supper alloy. It was also reported that laser shock peening in comparison with the other processes shows better relaxation of the components during their operation at elevated temperatures [38].

Laser peening technology offers a greater degree of process control, allowing much deeper level of compressive stress as well as maintaining the appropriate quality of the surface finish on metals [36, 64]. An intense laser beam focused to a small spot is used to create a tailored thermal shock wave. This thermal shock wave travels deep into the metal and induces residual stresses which can be controlled to the requirement and only on selected areas of the surface of the component. The local region being treated does not introduce any detrimental levels of heat into the bulk material. Enhancement in fatigue resistance could be generated by laser peening compared to the allowable stress amplitude vs. the number of cycles for as machined, shot peened and laser peened aluminium alloy [64].

Hackel *et. al.* stated that a pulsed beam of 25 J for 25 ns was produced by an Nd: YLF (yttrium lithium fluoride) [36]. The beam was focused onto the work-piece and the desired area to be peened was covered with material (black coloured adhesive tape) which acts as an ablative and thermal insulating layer. Water was made to flow over this to absorb the laser pulse energy and thermal shocks. Ionization and vaporization are created due to the absorption which formed a plasma on the treated material would act as a further absorbing mechanism for the remainder of the laser pulse. Gathering of plasma within the water produces pressure that creates the shock waves and immediately penetrate into the surface of the metal, plastically straining the surface. The plastic strain then induces compressive residual stresses into the metal at depth of 1mm to 8mm depending on the power density of the focused beam and other system parameters [36]. This is a very interesting concept and could prove to be beneficial upon the feasibility of supplying water during the laser shock peening process.

The benefit of laser peening has only showed with metal alloys. It was feasible to induce deep residual stresses into the surface. The same effect has not been proven at greater depth with ceramics to date. This is due to ceramics being brittle: by firing a pulse of laser at the material could be equivalent to throwing a sharp hot rod at the material. This increases the potential for the material to crack since it is already brittle and has a porous structure. Metals in comparison are much more ductile and comprise of higher fracture strength (ductility), hence, the energy of the laser shock is absorbed well into the material.

Laser peening of ceramics has not been performed due to lack of industrial demand. If there was a demand for such applications requiring laser peening then it would be considered for further research. However, many applications not only in the aerospace and automotive sectors but also in the motorsports sectors make use of high performance technical grade ceramics which would benefit from undergoing the laser shock peening process. In particular, it would be highly beneficial if the movement of dislocations be increased within the technical ceramics so that plastic deformation could occur which in turn could enhance the strength of the ceramics. Moreover, if the hardness is improved then it is possible that the ceramic components within a system operating in the aforementioned industrial sectors would enable them to operate at higher cyclic stresses, undergo lower wear rate and operate for a longer time period compared to their counterparts. Alternatively, shock peened ceramics could also operate under much harsher loads and in high demand applications. What is more, it is possible to also improve the K_{1c} of engineering ceramics if the hardness is improved since hardness tends to be a function of the K_{1c} calculations. And improving the K_{1c} of a ceramic material could potentially allow more opportunities for ceramics to be used within industrial sectors where demand for better performance and durability is highly required.

An investigation by Husson and Proust [66] employed both the CO_2 laser with an on and off sequence for 1 min and a pulsed Nd:YAG laser with a 7 ns pulse duration. The material used was a 99.9 % yttrium sesquioxide ceramics (Y_2O_3). Although a like-by-like comparative study was undertaken for the two lasers, the effects of the two laser wavelengths at various pulse durations can be seen. The results showed that a molten zone was formed without ablation around the impact point. A micrographic investigation showed solidified molten zone with granulometry in the surface with grains about 100 um in diameter and hexagonal or pentagonal shape resulting from the effect of the CO_2 laser pulsed processing. After several hundred shots of the Nd:YAG laser showed the ceramic was ablated with the formation of a crater about 1 mm in diameter where a solidified molten zone appeared. Further, it was also reported that the non laser affected regions comprised of the original C (cubic) phase, however, a Y-O bonds slightly different of those of the C phase were present.

Akita et. al. [67] employed a laser peening technique to surface treat a Si_3N_4 technical grade ceramics which was reported to be for the first time. The results reported evidence of plastic strain leading to inhibiting compressive residual stress. In addition, as the peak power density increased, the compression also increased with the surface of the ceramic becoming much courser and an increase in Weibull modulus was found.

A letter to the editor [68] based publication introduced a process called laser peened texturing which created micro dimple cavities on a 2024 aluminium alloy, OFHC copper and SUS304 stainless steel with a thickness ranging from 1.9 mm to 2.55 mm. This investigation however, was limited to metals only, it was still valuable since the approach of this study could be used to analyse ceramics after being treated with laser shock peening. The investigations comprised of influences of laser power density, laser spot diameter and repeated shock number on the morphology, micro hardness and metallography of micro dimples. Reported results showed that the diameter, depth and aspect ratio of the micro dimples increased with power density. With the increase of the laser spot diameter, the depth, aspect ratio of the micro dimple and the diameter, showed variation. Another study, investigation also showed improvement in hardness which also had a close effect on the relationship with the depth of the micro dimples. In addition, no other change in the micro dimples was reported by the authors [68].

Melookaran *et. al.* [69] studied multiple laser shock processing of polycrystalline cubic boron nitride (PcBN). Changes in the hardness, microstructure and phase transformation were reported. Moreover, it showed that laser shock processing is a viable technique for increasing the hardness up to 15% and 12 % for PcBN and laser sintered of nanodiamond on PcBN. Baerga, and Molian [70] investigated the mechanical (non-thermal) sintering behaviour of nanopowder green compacts of zirconia based ceramic (YSZ). The laser used was a Nd:YAG pulsed in the range of ns. Findings showed that around 15% improvement in density was found and 44% increase in hardness whilst a single shock of the Nd:YAG laser was used. Further analysis showed that with a peak shock pressure of 4.34 GPa - plastic strain of 0.02 on the surface layer, and shockwave penetration depth of 0.25 mm was found. So therefore, it is feasible to generate multiple shocks improve the mechanical and thermal properties of ZrO_2 based ceramics.

Zhang *et. al.* [71] investigated the laser shocking to the Al_2O_3 ceramics and studied the fracture morphology that formed from the strong laser shock processing. It was found that brittle fractures occurred at laser pulse energy of 42J. When the laser energy reduced to 25J, the brittle fracture of ceramics appears to comprise of plastic deformation. Further reduction in the energy (15J), the Al_2O_3 ceramics did not fracture and micro-hardness increased. Also, micro-plastic deformation was somewhat at that particular energy level. This goes to show that the crack-free laser processing would be done better up to 15J of laser energy. Zhang *et. al.* [72] later investigated the effect of ZrO_2 ceramics by Nd:YAG laser shock processing and analyzed its failure characteristic and the brittleness. Zhang et.al reported that the fracture morphology showed that the failure of ceramics is primarily caused by delamination as typical brittle features and grains are pulled out on the fractured surface. The delamination layer does not expand along the single surface plane, but occurs in stages where the fracture is caused by reflected tensile wave. In addition, the generation of compression within the material surface layer was also reported where no layer delamination occurred. An increase in the fracture toughness was reported for the ZrO_2 ceramic. However, no real justification was given to the theoretical mechanism for the change in hardness and the toughness. Zhang *et.al.* [73] also studied the phase transformation of TZP ceramics applying laser shock wave and reported that tensile stress was caused on back surface of TZP ceramics by the laser shock wave, and further phase transformation was generated under tensile stress. About 48% tetragonal phrases t-ZrO_2 transformed into monoclinic phrases m-ZrO_2. This expanded the volume of the ceramic and gave rise to micro-cracks which impeded the expansion of major cracks and realized the need of phase transformation toughening.

Chen *et.al.* [74] performed a laser shock processing study of ZnO varistor ceramics using a Nd-YAG laser. The results showed that ZnO varistor ceramics to have improved dielectric constant, X-ray Diffraction (XRD) readings showed that phase transition of Bi_2O_3 took place, and generatedδ-Bi_2O_3 which increased the density of interface and donor concentration, caused changes in electrical properties, especially the nonlinear coefficient is significantly increased. Internal stress occurred due to Bi_2O_3 phase transition that caused the increase of dielectric constant.

6. Discussion

6.1 Further Research

Table 2 represents the typical parameters used by previous workers to laser peen technical grade ceramics. From collecting the data, several technical details can be gathered which enables one to realize the type of lasers, wavelength, power density, as well as pulse parameters employed to laser shock peen the limited technical grade ceramics that the process has been applied to. From the work of these authors, firstly, a laser system most appropriate for the shock peening process is predominantly Nd:YAG laser with a wavelength in the range of 1 µm. Although, the work of Melookaran et. al. [69] uses 532 nm and 10.06 um by Husson and Proust *et. al.* [65]. Despite this, it is first necessary to understand the laser-beam material interaction so that a correct wavelength is employed. From the results of other investigation on continuous wave laser processing [75 - 77], and a close observation of the physical effects of the laser-material interaction of a fibre and a CO_2 laser - it was found that a fibre laser with a wavelength just over 1 µm but with much better beam quality and was ideal to bring about a considerable modification to the surface of both the ZrO_2 and Si_3N_4 engineering ceramics. With this in mind, it can be further suggested that a fibre laser be employed to conduct future studies but it is also known that the absorption of ceramics becomes higher with decreasing wavelengths [75], and so, it would prove to be ideal if a wavelength in the range of UV is employed which could have a potential to be absorbed further into the ceramics and penetrate much further, which in turn would prove to be a much beneficial since dislocation movement could be increased at further depth into the ceramic. This inherently could have more plastic deformation into the ceramics surface and sub-surface of the ceramics. The use of wavelength in the range of far infra-red region would not be ideal for a laser shock peening application since firstly the absorption is not significant enough. Secondly, although operating a source such as a CO_2 laser on pulse mode has become common, but is still not very stable. From the previous research, it is also evident that limited ceramics have been explored as one can see from Table 2. The effects of laser-material interaction during laser shock peening with other technical grade ceramics such as boron carbide (BC); silicon carbide (SiC); boron nitride (BN); zirconium dioxide ($ZrCO_2$), silicon dioxide ($SiCO_2$), alumina nitride (Al_2N_4); magnesia stabilized zirconia (MSZ); other mixtures namely: zirconia toughened alumina, and mixture of ceramics and metals (cermets) such as tungsten carbide are still not investigated. In any case, it would therefore, be useful to carry out independent studies focused on the effects of these materials under shock processing. Consequently, upon success of inhibiting plastic deformation and compressive residual stress could lead enhanced performance in various industrial sectors where ceramics and cermets are highly desirable. From Table 2 the possible parameters which can be adopted to undergo a laser shock peening treatment on the ceramics used already and also the ones which have not been experimented with can be gathered. Having said this, a proper investigation justifying the possibilities occurring as result of applying wide range of pulse parameters and its effects in details from physical, microstructural, mechanical and thermal aspect is still required on various range of ceramics from the family tree to further understand the laser-ceramic interaction and develop the laser shock peening technique to an industrial scale.

Table 2 Typical parameters used for laser shock peening of technical grade ceramics.

Ceramic Type	Lasers Types	Wavelength	Spot Size	Laser Power density	Ave Power	Peak Power density	Pulse Duration	Repetition rate	Gas Pressure
Polycrystalline cibic Boron Nitride (PcBN) [69]	Nd:YAG – Q switched	1.064 µm	1mm defocused	2.55 GW/cm2	2 W	1–5 GW/cm2	10 ns	10 Hz	N/A
Yttria-stabilized Zirconia (YSZ) [70]	Nd:YAG laser	532 nm	0.76 mm	Work this out	0.16 W	2.20 GW/cm2	5 ns	3 Hz	N/A
Silicon Nitride (Si_3N_4) [67]	Nd:YAG laser	1.06 µm	1 mm – 3 mm	1 – 4 GW/cm2	1.5 – 3 W	2 GW/cm2	10ns	5 Hz	N/A
yttrium sesquioxide ceramics (Yz03) [66]	YAG laser	532 nm	2 and 5 mm	Work out	20 and 70 mJ	1.4 and 8.6~10' W.cm-2	7 ns	?? doesn't say	10 -9m bar
yttrium sesquioxide ceramics (Yz03) [66]	CO2 (CW)	10.06 µm	3 mm	400 W/cm-2	N/A	N/A	N/A	N/A	N/A
ZnO varistor ceramics[73]	Nd:YAG	1.06 µm	1 mm – 3mm	2.5 GW/cm2	2W	2 GW/cm2	10 ns	10 Hz	N/A
Al2O3[71]	Nd:YAG	1.06 µm	1.5 mm	3 GW/cm2	2 W	2,5 GW/Cm2	10ns	5 Hz	N/A

From reviewing the previous work conducted on the mechanical shot peening of technical grade ceramics, it is clearly evident that limited research has been conducted on this area. From the work of Pfeiffer [53], Frey and Pffeir [51, 52] and Pffeir and Wenzel [54] focused on mainly the shot peening effects of Si3N4 ceramics - no other investigation presents the possibility of shot peening technical grade ceramics particularly for ZrO_2, Al_2O_3, SiC, BC, BN and the family of engineering ceramics employed within the engineering and bio-medical sectors. Although, mechanical shot peening may be a less superior technique in comparison to the laser shock peening, there is much knowledge still to be filled in this area. If the effect can be achieved by the work of previous authors on all nitrides, carbides, and oxide ceramic, then much interest can be gained for their applications in the aforementioned industrial sectors would again be a lot of interest generated from various industrial sectors.

6.2 Cost Comparison

It is generally difficult to determine the cost of shot peening or laser peening so that a comparison can be made, because the dependency of cost is upon many factors such as the size, shape, material type, required depth of treatment, area of coverage as well as the required surface quality of the components needed such a surface treatment, although, cost becomes cheaper with high quantity and coverage of large areas.

The cost of shot peening system is somewhat lower than the laser peening system. Nonetheless, laser peening is classified as a superior process with controllable parameters offering shorter process times. A small size, brand new shot peening machine could cost up to €35000. In comparison, an average Nd: YAG, Nd:YLF, Nd: Glass, or a fibre laser would cost in the range of € 58K to € 98.5K if purchased brand new. However, the mechanical shot peening machinery at the higher end of the market in the recent times have advanced and comprises of robotic motion system which provides movement in various axis. The cost of a robotic system starts from approximately € 200K, a machine with a 2-axis gantry system which would cost approximately €150K which includes an acceptance test at a manufacturer's facility, shipping, installation to the customer's premises, commissioning, final acceptance and training. A medium sized laser system associated with a robotic motion system may cost 75 to 100 K cheaper than that quoted for a shot peening machinery.

Laser peening system is expensive to purchase but the running cost of a newer laser system is much cheaper than those of shot peening as minimal maintenance cost is required to replace parts whereas this is necessary for a shot peening system. Notwithstanding this, small, medium size manufacturers do not invest on laser peening systems for carrying out such a surface treatments. Naturally, manufacturers tend to turn to job shops and sub-contractors that specialise in laser peening applications for first-time surface treatment or as a remedial process for enhancing performance and elongating the functional life of components.

The charges made by the job shops and sub-contractors are primarily dependant on the component size, shape, geometry, weight quantity, ablative layer, area of peening (number of laser spots required) and the customer specification. Estimation of cost for laser peening applications is not specific since the above factors mentioned play a big part in varying the cost. However, they also state that it is more expensive than the conventional shot peening process and is only performed according to the customer demand and required specification of the component.

A typical hourly rate charged by a laser job shop for laser peening a welded heat exchanger part would cost around 85 (GBP) per hour. This included labour, machine set-up and variable costs such as electricity wear and tear of the system used. The number of hours spent on one particular job is again purely dependant on the features of the component. In comparison with laser shock peening rates, the typical charge for the mechanical shot peening process cost around 80 (GBP) per hour. The reason for the cost of laser shock peening being higher than that of the mechanical shot peening is due to the machine programming skills required by the operator. Depending on the complexity of a shot peening machine – a machine set-up is rather needed than programming.

7. Conclusions

This paper presents a review of both the mechanical shot peening and laser shock peening techniques for the surface treatment of technical grade ceramics in particular. Firstly, the mechanical shot peening as a process consists of several constraints and with benefit offered by the laser shock peening process, new avenues would open for research in the field. However, it is vital that the particular ceramic under investigation would yield mechanically or plastically so that compression can be induced into the technical grade ceramics in order to gain benefits from the effects of either one of these processes.

Surface treatment techniques such as laser such as laser peening have proved to be successful for metals by generating benefits to the materials performance compared to the more conventional mechanical shot peening technique. Constraints within the conventional mechanical shot peening technique could be eliminated on the basis that laser peening is classified as a superior process. Nevertheless, the cost of the laser systems is much higher in comparison with the mechanical shot peening system. But, laser peening is much superior to the conventional shot peening due to the depth of the compressive residual stress obtainable. Other reasons as previously discussed such as faster processing time, flexibility with treating components of complex geometry and overcoming the constraints existing by mechanical shot peening will attract large manufacturing companies to implement such a system. However, SME's (Small Medium size Enterprises) will most likely revert to sub-contract the process to job shops and sub-contractors for their laser peening applications.

Laser peening at the moment is only performed according to the customer demand and component specifications, typically when the product demands deep induced residual stress (automotive gears) for example. The designers and the engineers have to make a choice between processing cost and quality of treatment when choosing either laser peening or the conventional mechanical shot peening process.

In any case, this paper presents a contrast between the two systems for a potential application of surface treating engineering ceramics which demand further research in either using both the processes. Upon success could bring about the same benefits which we know of today obtained with metals/alloys to technical grade ceramics.

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