Overview of Laser Shock Processing Development in South Africa: Industrial Applications

D. Glaser[1,2], M. Newby[2], C. Polese[3], R. Scheepers[4]

1 Council for Scientific and Industrial Research (CSIR), Photonics Centre, Meiring Naudé Road Brummeria, Pretoria, South Africa
2 Nelson Mandela University, Mechanical Engineering, University Way, Summerstrand, Gqeberha, South Africa
3 University of the Witwatersrand, School of Mechanical, Industrial and Aeronautical Engineering & DSI-NRF Centre of Excellence in Strong Materials, Jan Smuts Avenue, Braamfontein, Johannesburg, South Africa
4 Eskom Holdings SOC Ltd, Johannesburg, South Africa

Keywords: Laser Shock Peening, Low Pressure Steam Turbine Blade, Raised Bore Drilling, Distortion Correction

Abstract

The Laser Shock Peening (LSP) process can be utilised to enhance the life of critical metal components or to provide precision engineered distortions for forming applications. In South Africa, the CSIR, in collaboration with industry and academia, is developing LSP technology to address local requirements. In the power generation industry, Low Pressure (LP) steam turbine blades are typically susceptible to stress corrosion cracking and fatigue. The resulting LSP performance on FV566 material shows deeper levels of beneficial compressive residual stress with minimal surface roughness compared to the mechanical Shot Peening process already implemented. In the mining sector, large steel components may require refurbishment and life extension solutions due to their harsh operating environment. The physical size of these components has pushed for the development of a mobile LSP capability. Three-point bending fatigue testing on AISI4330V reveals over 20x lifetime enhancement compared to the base material. In the aerospace sector, distortion correction of a machined AA7050-T7451 component has successfully been demonstrated.

Introduction

Laser Shock Peening (LSP), also referred to as Laser Shock Processing, is a residual stress engineering technology specifically used to introduce beneficial compressive residual stresses into critical components to enhance fatigue and/or stress corrosion cracking (SCC) resistance [1]. The precise introduction of surface strains can also be implemented for distortion engineering applications.

The schematic in Figure 1 below illustrates the mechanism of LSP technology. A laser pulse with a short duration (typically 5-25 ns) is used to produce laser intensities in the order of GW/cm^2. The high intensity irradiation results in the near instantaneous vaporization of the target into a plasma. The surface of the target region is covered by a medium that is transparent to the laser wavelength to achieve inertial confinement of the plasma generated [2]. A photograph in Figure 1 illustrates the thin water layer after a subsequent laser shot. The plasma reaches a few thousand degrees Celsius within nano-seconds, and expands at a rapid rate. The confined plasma generates peak pressures with a magnitude in the range of Gigapascals acting over a short timeframe, which results in the formation of a shockwave within the target material. The shock wave propagates with sufficient strength to exceed the material's dynamic yield strength, and therefore introduces plastic strains within the surface region. The peening action is generated by the elastic response of the surrounding material to form beneficial compressive residual stresses through the target surface. Due to the unique shock-wave mechanism, the LSP process can achieve deep levels of compressive residual stress (typically >1 mm), with minimal surface deterioration, therefore enabling the achievement of significant performance enhancements.

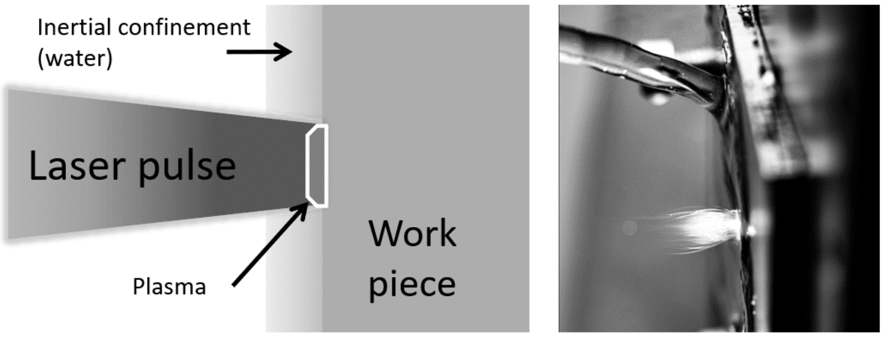

Figure 1: A schematic of the LSP process mechanism (left), and a photograph after the LSP process (right)

The LSP process was successfully commercialized in the late 1990's in the USA and Japan. In the USA, LSP was initially used to enhance the life of critical aircraft engine fan blades that were susceptible to Foreign Object Damage (FOD). The process developed in the USA typically includes a sacrificial ablative overlay to prevent thermal effects at the surface due to laser irradiation, as well has high energy levels (>10 J) [3]. In Japan, the initial commercial applications were developed to mitigate Stress Corrosion Cracking (SCC) on nuclear reactor components, where the process involves direct irradiation of the target with specifically tuned parameters to address direct laser-material interaction effects (typically low energy levels of < 0.2 J) [4].

Although LSP technology has matured significantly since early adoption with many innovative applications, the technology is still regarded as fairly niche, and is only applied industrially in a limited number of countries globally. In South Africa, LSP R&D activities initially commenced via academic studies with local Higher Education Institutions (HEIs). Due to the significant value offering of LSP as an advanced engineering solution, a technology pull has resulted in the effort to develop the LSP process for industrial applications in South Africa. The current paper provides a brief overview of some of the key local applications under development for sectors such as power generation, mining, and aerospace.

In the power generation industry, Low Pressure (LP) steam turbine blades are typically susceptible to stress corrosion cracking and fatigue. The photograph in Figure 2 illustrates typical LP blades in a turbine assembly, where blade lengths may approach or exceed 1 m. Conventional mechanical Shot Peening (SP) is already applied to the highly stressed blade attachment regions at service intervals as a mitigation measure to failure phenomena [5]. The potentially deeper levels of compressive residual stress possible with a lower surface roughness presents scope for superior performance offered by LSP.

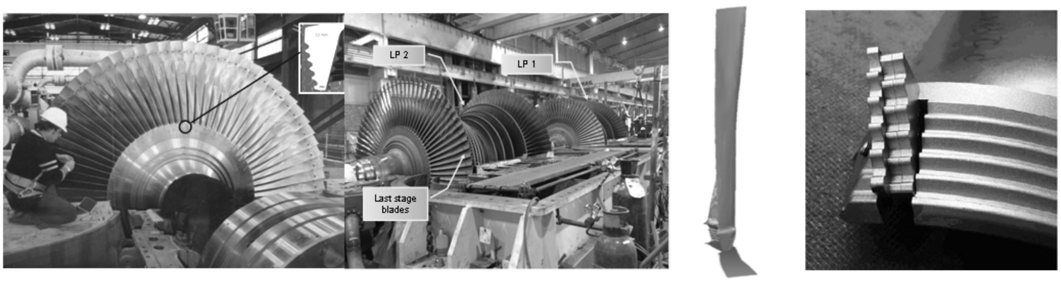

Figure 2: Photographs of LP steam turbine blades (left), a CAD model of a single blade (centre), and a close up of a fir attachment region after coupon removal (right) [5]

In the mining sector, large machines may require refurbishment and life extension solutions for critical metal components. An example of current applications investigated includes life enhancement for Raise Bore Drilling (RBD) components which experience significant alternating loads within a harsh operating environment and are therefore susceptible to both fatigue and stress corrosion cracking. A schematic of a generic RBD operation is depicted in Figure 3 (A). The RBD process involves first drilling a pilot hole from the drill rig at the surface to an underground tunnel. A large reamer head with cutters is attached to the drill string which applies tension and torsion causing cutting of the rock from the tunnel to the surface. The cuttings fall into the tunnel which are then removed by loading machinery. The entire load chain is exposed to significant loads which may vary, depending on rock conditions.

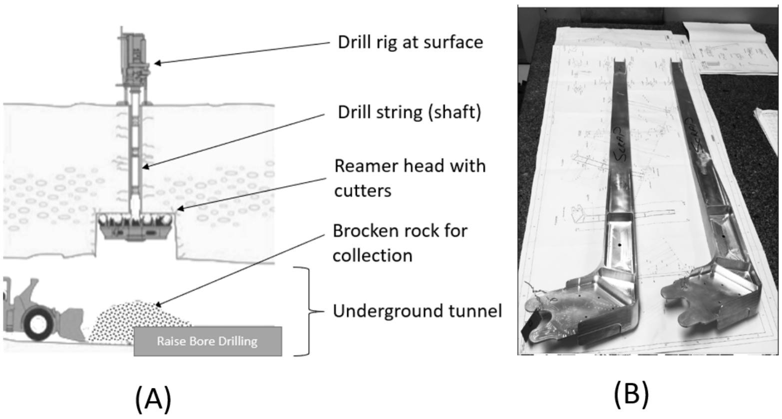

Figure 3: A schematic of the Raise Bore Drilling (RBD) process (A) [6], and of machined aerospace components that are scrapped due to distortion (B)

In the local aerospace sector, South African companies manufacture several precision aluminum components for both domestic and international markets. Manufacturing of precision thin-walled aluminum components often encounters distortion challenges, due to pre-existing residual stresses within the billet as well as machining induced residual stresses. Since LSP can apply precision residual strains to a surface, the laser process may potentially be applied as a distortion correction technology. The current project identified a typical component that has historically presented a number of challenges with distortions, resulting in undesirable scrapping of components. The identified component is depicted in Figure 3 (B), where the current project aimed to demonstrate the technology capability on a previously scrapped component. The challenge for this project is that the resulting distortion of each component is different, therefore the capability to precisely tailor the resulting engineered strain is required.

Experimental Methods

There are currently two LSP work-cells based at the Council for Scientific and Industrial Research (CSIR) in South Africa. A system operating at a wavelength of 1064 nm is used for Proof-of-Concept (POC) work in collaboration with local academia, and a 532 nm system is being devised for industrial applications. Due to the nature of the application in the mining sector, there is also a need for a mobile system for refurbishment applications where components are too large and heavy to handle at the current LSP processing facility. The LSP process in SA is applied in what is considered a “mid-range” energy level (compared to the initial high energy systems in the USA, or low energy systems in Japan). The LSP process is typically performed in the direct ablation mode [4], also referred to as Laser Peening without Coating (LPwC), which therefore requires refined process parameters to achieve suitable performance.

The material for the LP steam turbine blades is a 12% chromium martensitic stainless steel (FV566), which has been extracted from ex-service turbine blades. Process development reported here is on samples of 20x20x15 mm where results for residual stress are obtained by Synchrotron X-Ray Diffraction (SXRD) conducted at the ESRF facility (Grenoble, France), detailed further in a prior description by the authors for experiments [7]. Scale slices with a thickness of 15 mm have also been extracted from ex-service blades (as depicted in Figure 4), and processing has been implemented by motion of the target using a 4 degree of freedom precision motion system.

The material for the mining application for RBD is a AISI 4330V material with a microhardness in the range of 355-361 HV_{20}, which is typically employed due to its material property combination of high strength and impact toughness. The results presented are with respect to three-point bending fatigue testing conducted on samples with dimensions of 150x20x15 mm (R ratio of 0.1). The purpose of the current batch of fatigue samples was to first validate selected process parameters for the “mid-range” LSP approach. Processing has been performed at a laser power intensity of 10 GW/cm^2 and a wavelength of 1064 nm.

The component for the aerospace application reported is from an AA7050-T7451. The component was previously scrapped due to excessive allowable distortion. Process development occurred on off-cut material from the aluminium billets (80 mm thickness) used to machine new components. Mechanical testing for static and dynamic properties was required to demonstrate that the LSP process does not adversely affect material performance. An Almen strip approach adapted for the LSP process was devised to identify suitable parameter combinations that would allow for the required deformation to be generated [8]. Distortion results are also presented for an AA6082-T651 application for a non-aerospace application for components used in a precision machine.

Experimental Results and Discussion

The results from the LSP process applied to the steam turbine blade material are shown in Figure 4. Synchrotron XRD profiles reveal the current conventional shot peening process achieves a depth of Compressive Residual Stress (CRS) of around 0.25 mm, while LSP reveals a depth of CRS beyond 1 mm. The resulting surface roughness reveals a lower Ra of 1 µm for LSP compared to 3.2 µm for conventional mechanical SP. The LSP process has therefore been shown to produce deeper levels of compressive residual stresses combined with a lower surface roughness compared to mechanical SP. For the fir tree root configuration of LP blade attachments, the geometry is somewhat restricting to obtain line of sight at a near normal angle of incidence. For the conventional SP process, the effectiveness of the shot impact is reduced as the angle of incidence from the surface normal is reduced. However, for the LSP process, the plasma exerts a hydrodynamic pressure which always acts normal to the surface. The application of the LSP process to complex fir tree root sections is therefore a highly attractive technology option for LP blades that require further life extension solutions.

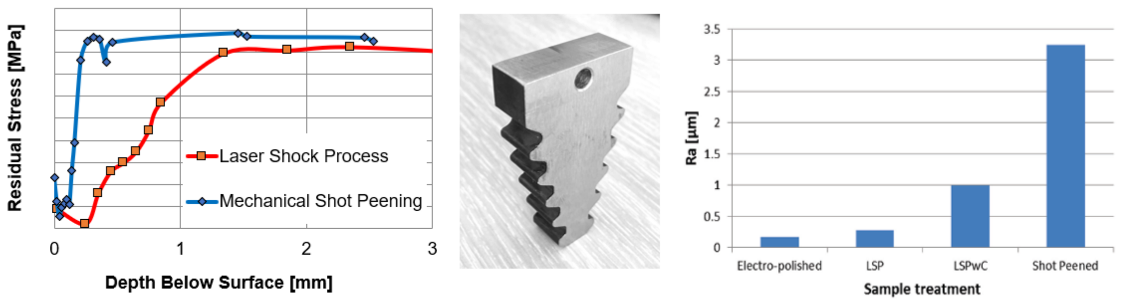

Figure 4: Synchrotron XRD results (left), A scale fir tree root section processed (centre), and resulting surface roughness (right) [7]

Three-point bending fatigue testing on the AISI 4330V material for the mining application reveal the effect of high magnitude and deep levels of compressive residual stress with minimal surface roughness. Figure 5 illustrates the fatigue results obtained at three different maximum stress levels from 1100 to 1186 MPa. The three base samples all failed in the range of 96 022 and 241 685 cycles, where all LSP samples achieved run-out defined at 5 million cycles (which reveals at least 20x life enhancement). This promising result illustrates the feasibility of “mid-range” energy LSP processing, where further testing will focus on technology validation to represent the component specific geometry and in-service loading conditions.

The components of interest for the RBD application have dimensions on the order of several meters, with a mass in the range of tons. Such large and heavy components cannot currently be accommodated at the CSIR LSP processing facility. To effectively cater to the needs for mining applications, a mobile LSP capability is currently under development. The photograph in Figure 5 below illustrates the mobile laser module after transportation testing from the CSIR (in Pretoria) to a customer site in Johannesburg (≈50 km). The mobile module ensures that the sensitive laser can be transported safely and operated effectively at a customer site. During transport, the sensitive laser system is protected from shock loading using passive isolation. The laser unit is housed within a sealed system to protect sensitive optical components from any possible contamination by dust. The module also provides active vibration isolation for the sensitive laser system to cater for possible workshop machinery in operation. The unit also includes a number of system diagnostics of the laser to ensure that all systems are within the required operational envelope.

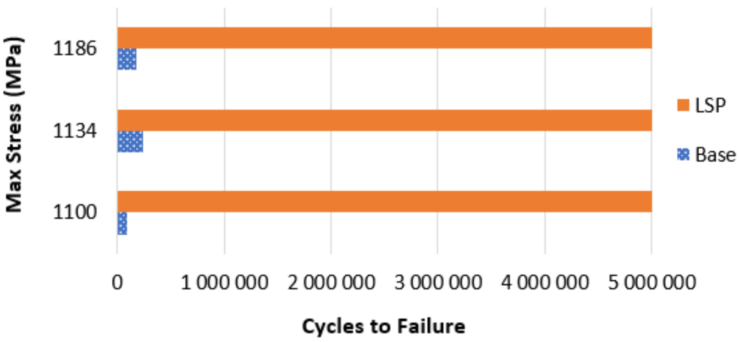

Figure 5: Three-point bending fatigue test results for the AISI 4330V material (left), and a photograph of the mobile laser unit under development during on-site testing (right)

The measured distortion of the aerospace component before and after application of the LSP process is shown in Figure 6 (A). Different parameter strategies of applying either a large single patch, or multiple smaller LSP stripes were explored. Both approaches were found to effectively achieve the required result, however the stripe approach enabled finer control of the process. The LSP process has several process parameters that can be varied to control the resulting effects. Typical parameters include power intensity, spot size, and spot coverage. This application however required proof that the LSP process does not adversely affect the material properties, and component structural integrity. The approach adopted was to therefore keep all LSP process parameters constant, and only vary the size of the LSP region to control resulting distortion.

The results in Figure 6 (B) illustrate the effectiveness of LSP to correct for the distortion on AA6082-T651 components which a local engineering company required for a precision machine. Four components were provided, each with a different level of distortion. The approach devised for the aerospace application was applied to four components to successfully correct for the varying levels of distortion. The AA6082-T6 components are the first LSP components to be processed locally to serve in an industrial application, which represents an important milestone for LSP technology development in South Africa.

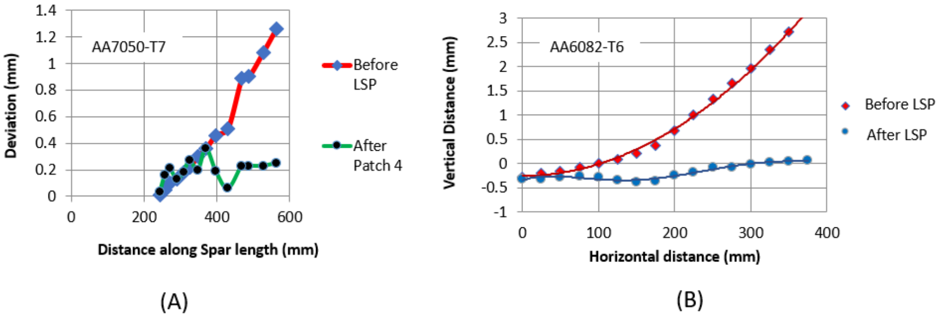

Figure 6: Distortion correction results before and after LSP for the AA7050-T7451 (A) and AA6082 material (B).

Conclusions

LSP technology may offer numerous benefits, however the technology is still highly niche with only a limited number of groups globally able to provide industrial and commercial services. While LSP activities in South Africa were initially academically orientated, local industry has demonstrated specific technological needs for the process. Local industrial development of LSP applications in SA is currently focused primarily on applications in the power generation sector, mining sector, and aerospace sector. The application for LP turbine blades and RBD components offers significant life extension for components susceptible to stress corrosion cracking and fatigue due to deep levels of compressive residual stress obtained with low surface roughness. The aerospace application developed for an AA7050-T7451 component distortion correction has subsequently successfully been implemented for AA6082-T651 components, which represents the first in-service LSP components locally. Work is on-going to enable industrial uptake of LSP in partnership with local stakeholders. Due to the large and heavy nature of components in the local mining industry, a mobile LSP capability is under development to enable on-site applications.

References

[1] L. Petan, J. Grum, J.A. Porro, J.L. Ocaña, R. Šturm, *Fatigue Properties of Maraging Steel after Laser Peening,* Metals *9.12 (2019): 1271.*
[2] R. Fabbro, P. Peyre, L. Berthe, and X. Scherpereel*, Physics and applications of laser-shock processing*, Journal of laser applications, (1998) 10(6), pp 265-279.
[3] A.H. Clauer, Laser shock peening, the path to production, Metals (2019) Vol. 9.6, pp 626
[4] Y. Sano, *Quarter century development of laser peening without coating*, Metals (2020) Vol. 10.1, pp. 152.
[5] M.N. James, M. Newby, D.G. Hattingh, and A. Steuwer, *Shot-peening of steam turbine blades: Residual stresses and their modification by fatigue cycling*. Procedia Engineering, (2010), Vol. 2(1), pp. 441-451.
[6] A. Lashgari, M. Majid Fouladgar, A. Yazdani-Chamzini and M. J. Skibniewski, Using an integrated model for shaft sinking method selection, Journal of Civil Engineering and Management, (2011), Vol. 17(4)
[7] M. Newby, A. Steuwer, D. Glaser, C. Polese, D. G. Hattingh, and C. Gorny, *Synchrotron XRD evaluation of residual stresses introduced by laser shock peening for steam turbine blade applications*, Mechanical Stress Evaluation by Neutron and Synchrotron Radiation 4 (2018), pp. 97-102.
[8] D. Glaser, C. Polese, A. M. Venter, D. Marais, and J. R. Plaisier, *Evaluation of laser shock peening process parameters incorporating Almen strip deflections*, Surface and Coatings Technology, (2022) Vol. 434, pp. 128158