

PAPER • OPEN ACCESS

Coupled explicit-damping simulation of laser shock peening on x12Cr steam turbine blades

To cite this article: Festus Fameso *et al* 2021 *J. Phys.: Conf. Ser.* **1780** 012002

View the [article online](#) for updates and enhancements.

You may also like

- [Status of black-hole-binary simulations for gravitational-wave detection](#)
Mark Hannam
- [X-Ray Emissions from Accreting White Dwarfs: A Review](#)
K. Mukai
- [Black holes, gravitational waves and fundamental physics: a roadmap](#)
Abbas Askar, Chris Belczynski, Gianfranco Bertone *et al.*



The Electrochemical Society
Advancing solid state & electrochemical science & technology

241st ECS Meeting

Vancouver, BC, Canada. May 29 – June 2, 2022

ECS Plenary Lecture featuring
Prof. Jeff Dahn,
Dalhousie University

Register now!

The banner features the ECS logo, a 'Register now!' button with a checkmark, and a photograph of Prof. Jeff Dahn pointing at a whiteboard. The background of the banner shows the Science World geodesic dome in Vancouver, BC, Canada, with mountains in the distance and water in the foreground.

Coupled explicit-damping simulation of laser shock peening on x12Cr steam turbine blades

Festus Fameso^{1,*}, Dawood Desai¹, Schalk Kok², Mark Newby³ and Daniel Glaser⁴

¹Department of Mechanical and Automation Engineering, Tshwane University of Technology, Pretoria., South Africa

²Department of Mechanical and Aeronautical Engineering, University of Pretoria, South Africa

³Eskom Holdings SOC Ltd, Johannesburg, South Africa

⁴National Laser Centre, Council for Scientific and Industrial Research, Brummeria, Pretoria, South Africa

*E-mail: festus.fameso@gmail.com

Abstract. Timely prevention of, and recovery from, downtimes due to in-service failure of crucial power plant components, like turbine blades, portends huge consequences in the form of operational and financial viability concerns. Intensive research and development in manufacturing, re-manufacturing and condition-based maintenance of these components have birthed a novel technique, which deploys high intensity lasers to induce compressive residual stresses to the surface of the blades. This paper presents the application of an alternate computational modelling technique in simulating this surface treatment technique on X12Cr steel, an exotic steam turbine blades material, while also investigating the economic parameters of the induced residual stresses. A numerical model is developed in this work using the commercial finite elements software ABAQUS®. The results show this computational modelling technique as being time efficient. The parametric outcomes of the simulation agreed with experimental results, lending credence to its validity. Induced compressive stresses as high as 700 MPa and depths close to 1 mm from the surface of the blade were obtained. This by indication can prospectively quell crack initiation, growth and unplanned failure of the blade while in service, with the introduced simulation technique offering a solution for timely, non-destructive mechanical integrity enhancement of engineered components.

1. Introduction

A cursory look at the global population-economy-energy demand interaction reveals the power/energy generation industry as one of the more affected sectors, with ever increasing global populations needing a regular supply of energy. As revealed by the international energy agency [1] global average energy demand continues to rise by over 2% annually, requiring a continual upscale in generation of over 3.1% to at least level-up, leaving the industry very little margins for error in terms of operations, in order to deliver to a growing population. Downtimes from in-service failure of power plant hardware portends dire consequences in the form of outages, economic losses and sometimes safety concerns [2]. Recurring downtimes are not unconnected with the overstretching-induced breakdown of such hardware, which are much more susceptible to failure while in service than other components. Low pressure (LP) steam turbine blades are even generally more at risk with almost 50% of their



failures being related to any of, or a combination of fatigue, stress corrosion cracking, and corrosion fatigue [3]. It has therefore become a major imperative to provide fast-paced solutions to operational concerns arising from incessant downtimes of failing power generation utilities. Through intensive research and development, the use of lasers to alter the mechanical properties of materials for specific applications, has evolved from being an idea of random academic curiosity to an industrially attainable process.

In a technique known as Laser Shock Peening (LSP), high intensity lasers are now being progressively employed to improve the surface properties of machinery parts such as blades, to mitigate detrimental structural defects such as crack initiation or growth, mechanical deformations and possible catastrophic damages and mechanical failures while in service. LSP is performed by firing beams of high intensity laser onto a target material in an opaque confining medium, forcing plasma formation from the ablation of an applied ablative layer, which drives shock waves into the underlying target. Consequently, compressive residual stresses (CRS) remain in the target material, improving its damage tolerance, fatigue strength and ultimately, its useful life. For far reaching effects, it is common in practice to laser-peen the part at different spots and/or at intervals as it is moved around, repeating the sequence at each of these spots [4]. This technique has been proven to induce CRS up to ten times deeper than other peening methods.

2. Methodology

2.1. Constitutive and material properties

Typical LSP strain rates are in the region of 10^6s^{-1} , in which the laser-plasma imparts shock waves resulting in plastic deformation and microstructural transformations of the target material [5]. Hence, an appropriate constitutive material model such as the mechanical threshold stress (MTS) model, a fully physics based constitutive model suited for nanoscale high speed shock simulation and stress saturation was implemented to account for the effects of deposition and distribution of residual stresses in the material. The MTS constitutive model which describes the flow stress (σ_y) as a function of the microstructural evolution and response of the material, based on the yield and strain hardening characterization with respect to temperature and strain rate sensitivities is given in equation 1 and 2 [6] as;

$$\sigma_{y(\epsilon_p, \dot{\epsilon}_p, T)} = \sigma_a + (S_i \sigma_i + S_e \sigma_e)^{\mu(P,T)} / \mu_0 \quad (1)$$

where; σ_y flow stress, σ_a representing the athermal yield stress component of the model. ϵ_p and $\dot{\epsilon}_p$ are the plastic strain and strain rates respectively and σ_i is the intrinsic component of flow strain due to barriers to thermally activated dislocation motion. σ_e is the strain hardening component of the flow stress, s_i, s_e, μ , and μ_0 are strain rate temperature dependent scaling factors, Shear modulus and Shear modulus at 0 Kelvin respectively. The scaling factor s is obtained from;

$$s = (1 - ((kT / g_0 \mu b^3 \ln \dot{\epsilon}_0 / \dot{\epsilon}))^{1/q})^{1/p} \quad (2)$$

where T is the reference temperature, k is Boltzmann's constant, b represents Burgers vector and p, q are empirical constants. The MTS properties for X12Cr are listed in table 1.

Table 1. MTS material properties for X12Cr steel. [7]

Density (kg/m ³)	Youngs Modulus (GPa)	Poisson's Ratio	Yield Stress (GPa)	Shear Modulus at 0 K (GPa)	Intrinsic Stress Component (GPa)	Saturation Threshold Stress at 0 K (GPa)	Athermal Yield Stress (GPa)	Nominal Shear Modulus (GPa)
7700	204	0.30	0.87	71.0	2.19	1.77	0	8.64

2.2. Simulation methodology

With the development of high-end computational machines with robust analytical and numerical capabilities, modelling the complex physics of collisions, elasto-plastic deformations and wave propagation associated with LSP was made possible. For this study, numerical integral algorithms were used to model and solve the set of nonlinear equations that describe the impinging high-pressure laser pulses on each crystal of the material. The ABAQUS © explicit solver was used to solve the dynamic processes of the plasma pressure impaction, as well as the damping of the propagated stress waves to saturation point in a single finite element analysis. Conventional methods according to [8–11] employed the explicit-implicit method in which two finite element codes, the Explicit and Standard solvers coalesce to model the dynamic evolution of the shock pressure waves generated by super-fast ablation on the surface of the target and the quasi-static relaxation of propagated stress waves during the subsequent dissipation of plastic energy respectively.

However, this study employs the ABAQUS explicit solver, a fully explicit integral algorithm, using a novel state variable integration method which renders the analysis time step size independent for high strain rate simulations, coupled with viscous and time stepped damping in a Coupled Explicit-Damping (CED) method, described summarily by the pictorial outline in figure 1. This essentially comprises sequences of two-stepped loading and unloading integral analyses where loading is applied in the first step and the second step is a no-load step, with viscous damping applied in the no-load step to provide quicker energy dissipation and attainment of stability in the system in fewer analysis increments, before the next succession of loading and unloading.

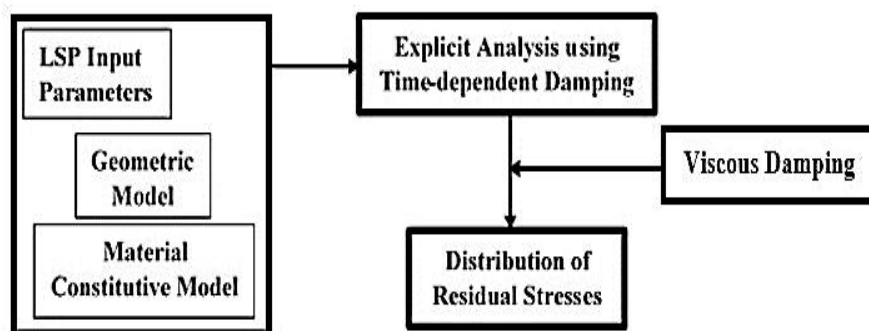


Figure 1. The CED analyses procedure.

An extended final step a few orders of magnitude greater than the loading step is introduced to allow for transmission of stress waves, dissipation of kinetic energy and distribution of the stress residues within the system, bringing it as close as possible to equilibrium, where its total kinetic energy has been damped to as low as 1% of the maximum achieved during the dynamic shock evolution phases. The extended final explicit damping step period thus de-excites the discrete lattice of the system to quasi-static equilibrium. The CED method summarily therefore incorporates both the dynamic processes as well as the damping of the propagated stress waves to saturation point in a single finite element analysis, thus eliminating the need to invoke implicit algorithm to obtain the final residual stress profiles in static equilibrium, there by addressing the constraints of computational cost and time. Other elements of the simulation model are graphically highlighted in figure 2.

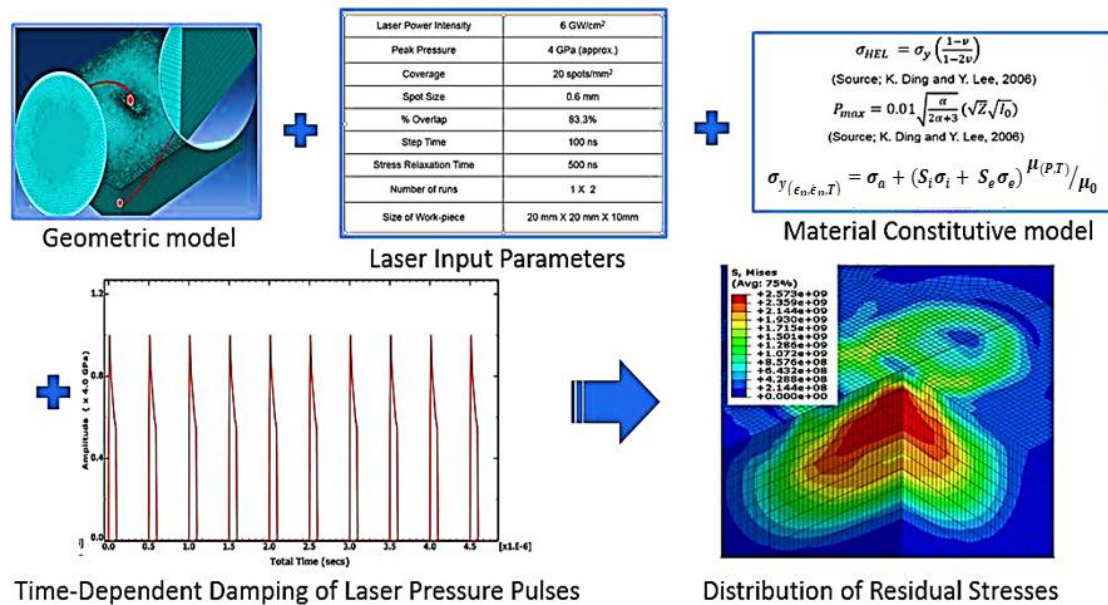


Figure 2. The CED simulation procedure on ABAQUS/CAE.

2.3. Experimental benchmark

As in experiments conducted by [12], a series of 20×20×10 (all in mm) X12Cr block samples were translated in the lateral and horizontal directions by a CNC controlled clamp table and peened through a layer of decarbonized water by a commercial Nd:YAG laser peening apparatus operating at a wavelength of 1064 nm. The samples were clamped on the base edges, providing a zero displacement and degree of freedom in any direction. A raster-travel peening pattern was implemented with beam shots of 0.6 mm diameter at 6 GW/cm² intensity, overlapping at 83% coverage of the immediate shot coverage area. In line with the methodology highlighted by [13] in their study, a combination of electro-polishing and x-ray diffraction techniques were employed in measuring the induced residual stresses in the peened block on completion of the laser shock peening process. The sample blocks were pre-treated by heating in a furnace at temperatures of up to 800 °C for up to 3 hrs to remove pre-existing internal stresses before being subjected to laser shock peening. This guarantees the LSP process contribution to the residual stresses measured.

3. Results

Essentially, the simulations implemented in this study were executed on a 32 GB RAM, 3.2 GHz dual Xeon Pentium Workstation operating on a 64-bit Windows 10 version of Microsoft windows operating system. figure 3 presents the results of the LSP simulation, using the CED method in comparison with experiments with the same input parameters and specifications. The economic parameters such as the residual stresses at zero depth, the attained maximum induced CRS (MCRS), the depth of MCRS and the maximum plastically affected depth, obtained from the computer simulation were in close correlation with those obtained from the experimental study, with variations in any of these parameters being quite below the generally acceptable 10% value.

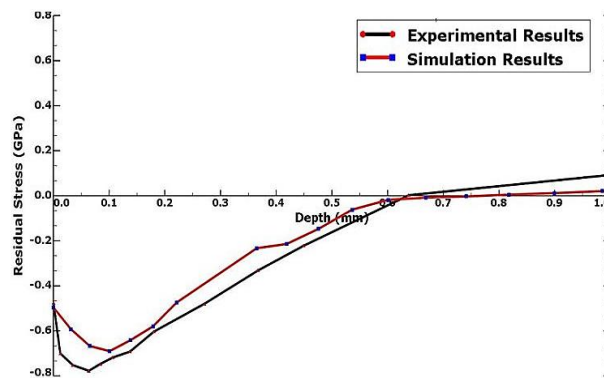


Figure 3. Superimposed simulated and experimental residual stresses against depth.

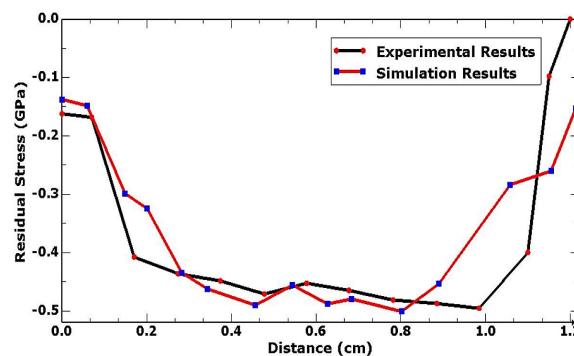


Figure 4. Superimposed simulated and experimental surface residual stresses profiles.

Figure 4 likewise presents a close call correlation in terms of distribution, magnitude and shape of the surface residual stress profiles obtained at the control area of 1 cm² subjected to laser shock peening. In this instance too, variance in values of the surface residual stresses obtained along the length of the peened area, with similarity in sharp transitions observable in results at both edges of the treated area. The values of the output parameters obtained are presented in table 2. This close correlation in experiment and numerical simulation results inadvertently lends credence to and validates the simulation method. Juxtaposing the analysis times of the CED method against the conventional explicit-implicit method also reveals a quicker solution time using the former, showing a 40% log time saving, which can be very crucial in practice, considering that the size and dimensions of the actual component may be much greater than the dimensions applied in both the experimental and simulation models. Further details of the analysis time comparisons between the two methods considered in this study are presented in table 3.

Table 2. Analysis results.

Parameter Description	Experiment	Simulation
Surface Residual Stress [SRS] (GPa)	-0.462	-0.481
Maximum Compressive Residual Stress [MCRS] (GPa)	-0.771	-0.723
Depth of MCRS (mm)	0.064	0.101
Maximum depth of CRS (mm)	0.64	0.70
Peened Area Core SRS (GPa)	-0.478	-0.484

Table 3. Analysis time comparisons.

CED Method		Conventional Explicit-Implicit Analysis Method	
Job Time Summary (Secs)		Job Time Summary (Secs)	
User Time	106.7	User Time	382.30
System Time	21.70	System Time	298.80
Total CPU Time	128.40	Total CPU Time	681.10
Wall Clock Time	210	Wall Clock Time	724
Log Time	8640	Log Time	12538

4. Conclusions

In conclusion, this study has presented the application of an alternate numerical method to simulate LSP process through a computational coupling of explicit integral systems of equations which describe the high intensity generation and propagation of shockwaves from impingement of laser power on a target surface, and the viscous damping and incremental integrative tolerance provided by an extending time-dependent damping period. The results show very close correlation with those obtained from experiments and thus lends credence to the validity of the model. Furthermore, this alternate method provides valuable computational time saving, which can be of crucial essence in its industrial application on plant components, when contrasted with the more conventional explicit-implicit method, providing a time-efficient and computationally cost effective solution to real time prediction and evaluation of the economic parameters of the laser peening steam turbine blades and other plant components. In a fast-paced world, where energy generation companies are constantly racing against time, and striving to balance the supply and demand scale, prompt solutions such as the technique discussed in this paper can improve the net time taken to implement condition-based monitoring and maintenance decision making. The results obtained has also shown promise, having been validated experimentally, to be able to provide improved surface and sub-surface enhancement of the mechanical properties of plant components and machinery parts which are susceptible to cracking, stress fatigue or failure while in service. Based on the foregoing, the following conclusions can be drawn;

1. The CED method is a valid, time-efficient and computationally cost-effective methodology for finite element modelling and simulation of laser shock peening.
2. Finite element simulations can effectively become viable alternative to experimental studies in the determination of the outcomes of LSP on engineering materials.

Acknowledgements

The authors wish to acknowledge the National Research Foundation (NRF Grant Reference No: SFH170720255948), ESKOM, Tshwane University of Technology (TUT), National Laser Centre (NLC-CSIR) and the Department of Science and Technology (DST), Republic of South Africa for their financial and technical support towards the success of this research.

References

- [1] IEA, *Preview of the world energy outlook* (2018) <https://www.iea.org/newsroom/news/2018/june/weo-2018.html>. Viewed on 20th June 2019
- [2] I. Chambers. The reliability and accuracy of remnant life predictions in high pressure steam plant, (148), 293–304 (2001).
- [3] D. Ziegler. Investigation of turbine blade failure in a thermal power plant. *Case Studies in Engineering Failure Analysis*. Elsevier Ltd., vol. **1(3)**, 192–99 (2013).
- [4] H. Amarchinta, R. Grandhi, K. Langer, and D. Stargel. Material model validation for laser shock peening process simulation. *Modelling and Simulation in Mat. Sci. and Eng.* **17(1)**, 0–15 (2009). <https://doi.org/10.1088/0965-0393/17/1/015010>
- [5] J. Pretorius, D. Desai, and G. Snedden, Effect of laser shock peening on fatigue life at stress

- raiser regions of a high-speed micro gas turbine shaft: A simulation-based study. *Intl Journal of Engineering Research in Africa*, **45**, 15–27 (2019). <https://doi.org/10.4028/www.scientific.net/JERA.45.15>
- [6] S. Kok, A. Beaudoin, and D. Tortorelli. A polycrystal plasticity model based on the mechanical threshold. *Intl Journal of Plasticity*, **18(5–6)**, 715–41 (2002). [https://doi.org/10.1016/S0749-6419\(01\)00051-1](https://doi.org/10.1016/S0749-6419(01)00051-1)
- [7] D. Armfield, Optimised Implementation of Physics-based Strain-rate Dependent Material Models for the Improved Simulation of the Laser Shock Peening Process. University of Pretoria, South Africa, (2018).
- [8] S. Keller, S. Chupakhin, P. Staron, E. Maawad, N. Kashaev, and B. Klusemann, Experimental and numerical investigation of residual stresses in laser shock peened AA2198. *Journal of Materials Processing Tech.*, **255**, 294–307 (2018). <https://doi.org/10.1016/j.jmatprotec.2017.11.023>
- [9] R. Purohit et al. Simulation of shot peening process. *Materials Today: Proceedings*, **4(2)** 1244–51 (2017). <https://doi.org/10.1016/j.matpr.2017.01.144>
- [10] S. Ki, et al. ScienceDirect Optimization of Laser Shock Peening For Titanium. *Materials Today: Proceedings. Elsevier Ltd*, **5(5)** 12174–86 (2018).
- [11] Z. Ran, et al. Finite Element Analysis of Surface Roughness Generated by Multiple Laser Shock Peening. *Rare Metal Materials and Engineering*, **47(1)** 33–38 (2018).
- [12] K. Kuvaya, C. Polese, and M. Newby. Laser Peening versus Shot Peening Effects on Residual Stress and Surface Modification of X12CrNiMo12 Turbine Blade. *6th International Conference on Laser Peening and Related Phenomena*, (November), 6–11 (2016).
- [13] D. Glaser, M. Newby, C. Polese, L. Berthe, and A.M. Venter, Evaluation of Residual Stresses Introduced by Laser Shock Peening in Steel using Different Measurement Techniques, **4** 45–50 (2018). <https://doi.org/10.21741/9781945291678-7>