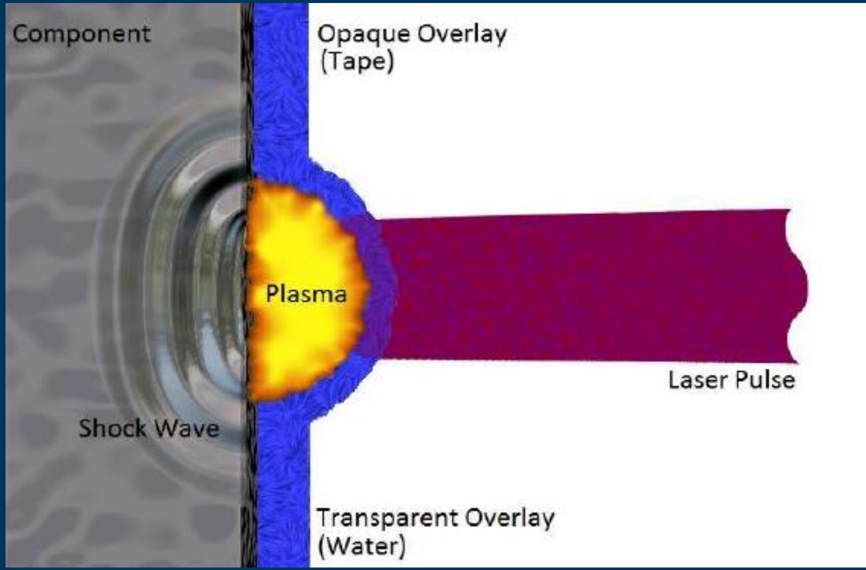
Virtual Seminar Series – Tuesday 2, 9, 16 November



Residual Stress Generation Using Laser Shock Peening and Applications to Improve Aircraft Fatigue Performance

Presented by Dr. Niall Smyth
Coventry University

Tuesday, November 9, 2021

Residual Stress Generation Using Laser Shock Peening and Applications to Improve Aircraft Fatigue Performance

Abstract

Laser shock peening (LSP) is a surface treatment used for enhancement of the fatigue performance of safety critical components and structures. This is achieved through introduction of a compressive residual stress field in the material that counteracts applied tensile stresses thus potentially extending the fatigue life. This presentation will provide an overview of the recent applications of LSP studied at Coventry University such as use of peening strips as a replacement for bonded crack retarders providing a potential weight saving, and using laser peened residual stress fields as a tool to control the crack growth direction away from safety critical areas. Finally, some of the application challenges for laser peening that hinder wider industrial application will be discussed.

About the presenter, Dr. Niall Smyth, Coventry University

Dr. Niall Smyth is a research fellow at Coventry University. He has worked in the area laser shock peening since 2009 and his research interests are in the areas of fatigue and fracture mechanics, residual stress, finite element analysis, advanced materials and structural integrity. He is a member of the editorial board of the “International Journal of Microstructure and Materials Properties” and the “International Journal of Peening Science and Technology”.

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Residual Stress generation using Laser Shock Peening and applications to improve Aircraft Fatigue Performance
9th November 2021

Dr. Niall Smyth, Dr. Marco Pavan, Mitchell Leering, Prof. Michael Fitzpatrick

Laser Shock Peening – Areas of Research

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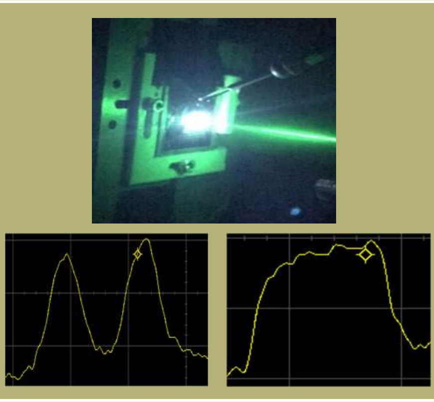
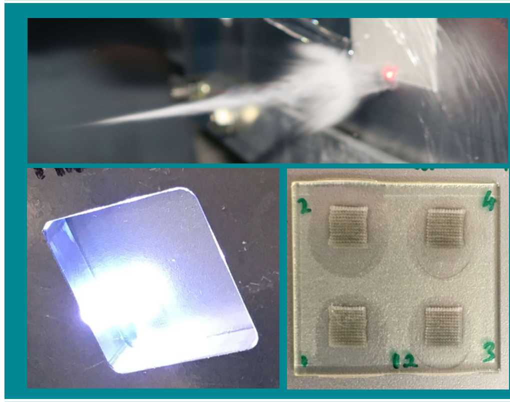
Fundamental Laser Peening Parameters



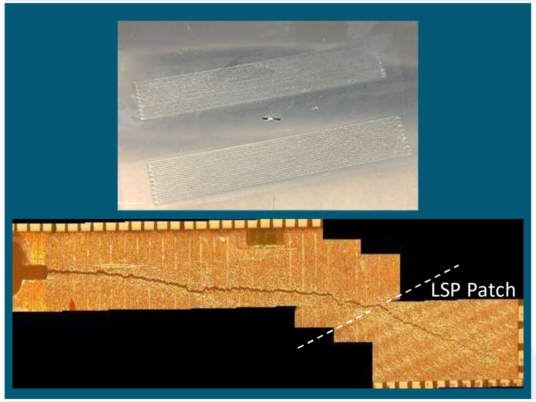
- Laser temporal profile influence on residual stress formation.
- Laser parameter influence on residual stress.
- LSP induced surface degradation.

Laser Peening Process Development



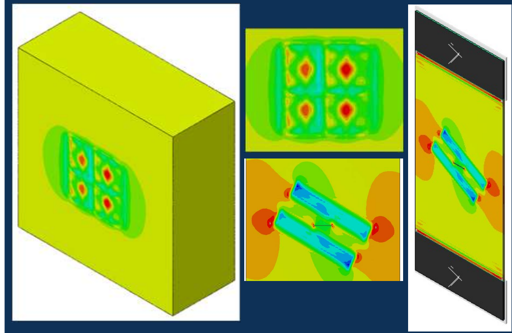
- Development of novel confinement mediums to remove water in the LSP process.
- Defining operational procedures for implementing novel confinement mediums.

Novel Laser Peening Applications



- Fundamental study of crack redirection by LSP residual stress.
- Material life extension by LSP residual stress.

Laser Peening Simulation & Modelling



- Pulse by pulse dynamic simulation of LSP to predict residual stress and material interaction.
- Modelling of fatigue crack growth in residual stress fields.

Laser Shock Peening

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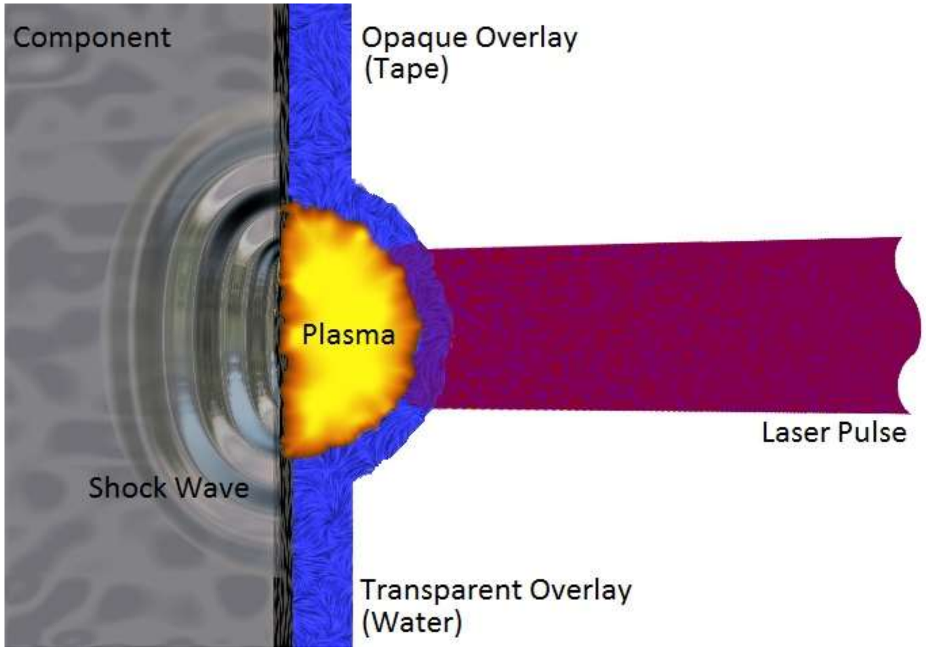

Laser spot diameter : mm
Laser pulse duration : ns
Laser pulse energy : mJ – J

LSP is already successfully applied to structural components such as

- ✓ **wing lugs**
- ✓ **rotor assemblies**
- ✓ **fan blades**

subject to **crack initiation** due to high loads, foreign object damage and fretting fatigue

Laser Shock Peening

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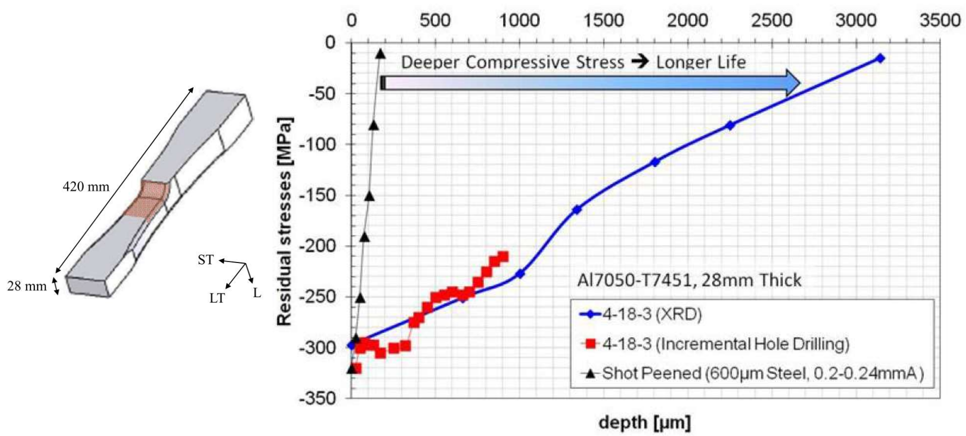
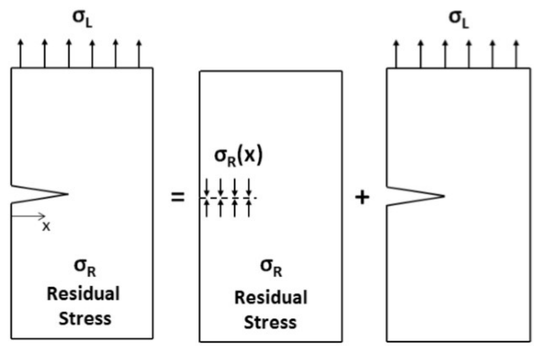
LSP vs Shot Peening



Comparison of the residual stress profiles in LT-direction for LSP and SP treatments[1]

Deeper compressive residual stress than shot peening

Superposition Principle



[1] Ulrike C. Heckenberger, Elke Hombergsmeier, Vitus Holzinger and Wolfgang von Bestenbostel, Laser shock peening to improve the fatigue resistance of AA7050 components, *International Journal of Structural Integrity. 2* (2010) 22 - 33.

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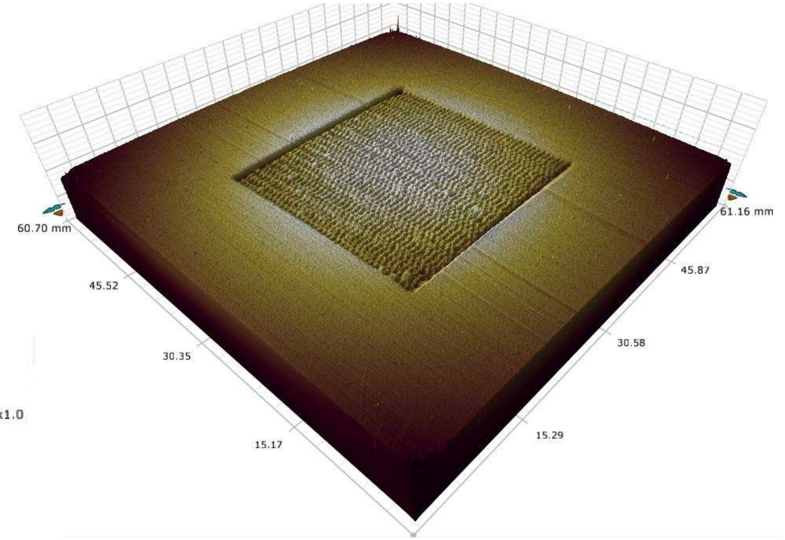
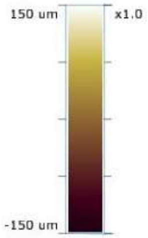
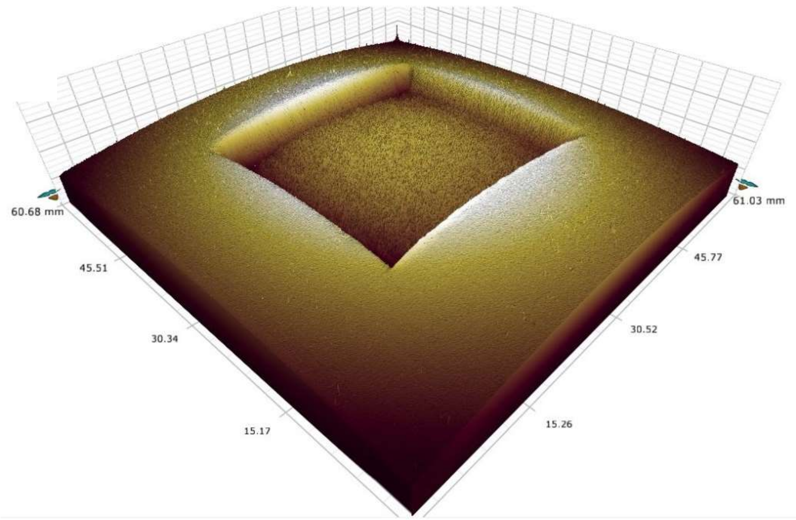
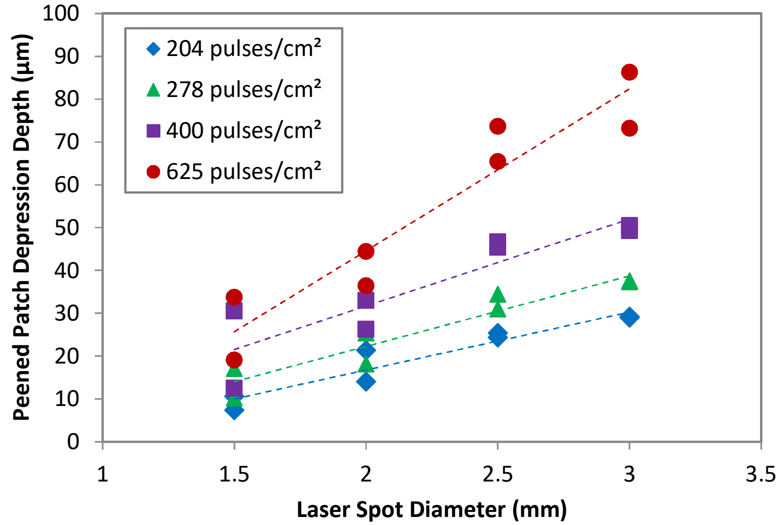




204 pulses/cm², spot Ø 1.5 mm



625 pulses/cm², spot Ø 3.0 mm



Incremental Hole Drilling (IHD)

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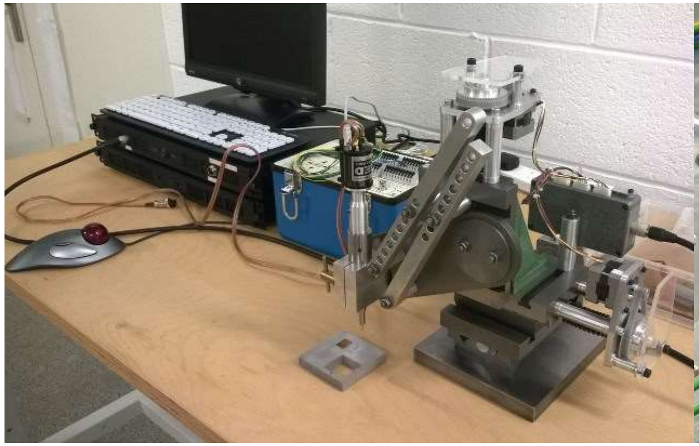
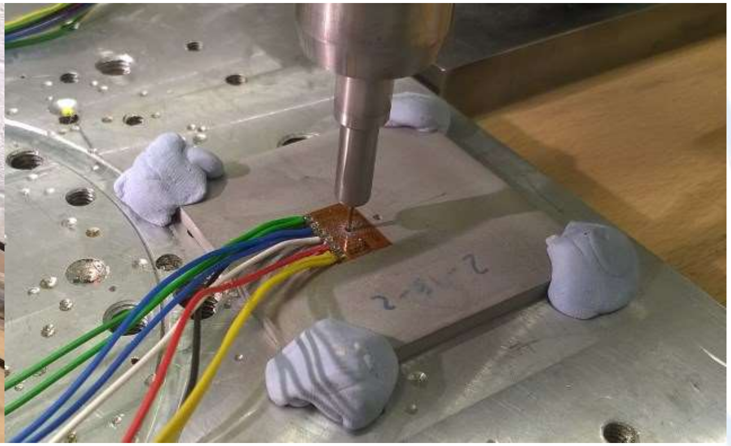
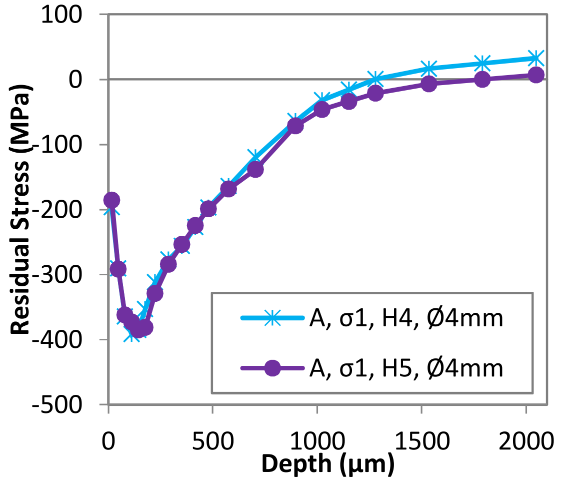
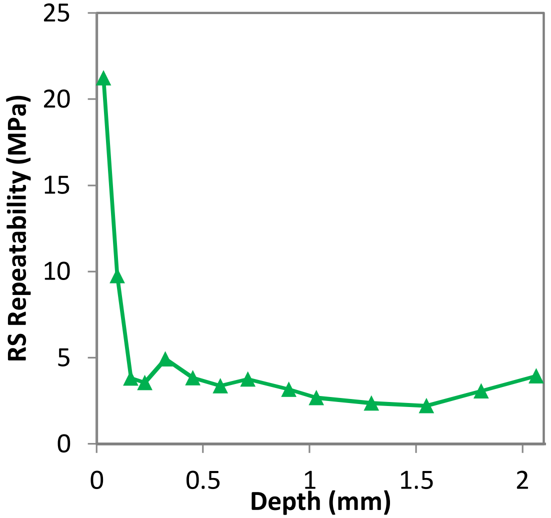
- The IHD method of measuring residual stress is based on drilling a small hole in the material surface.
- This relieves the residual stresses and the associated deformations around the hole.
- The relieved deformations are measured in 3 direction using a strain gauge.
- The original residual stress in the material is then evaluated based on the measured deformations and using calibration coefficients.









XRD Analysis – cos α method

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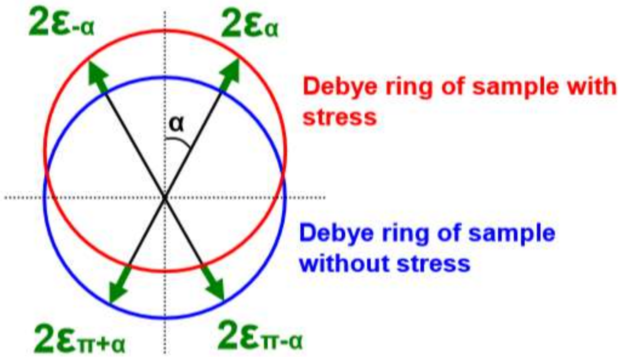
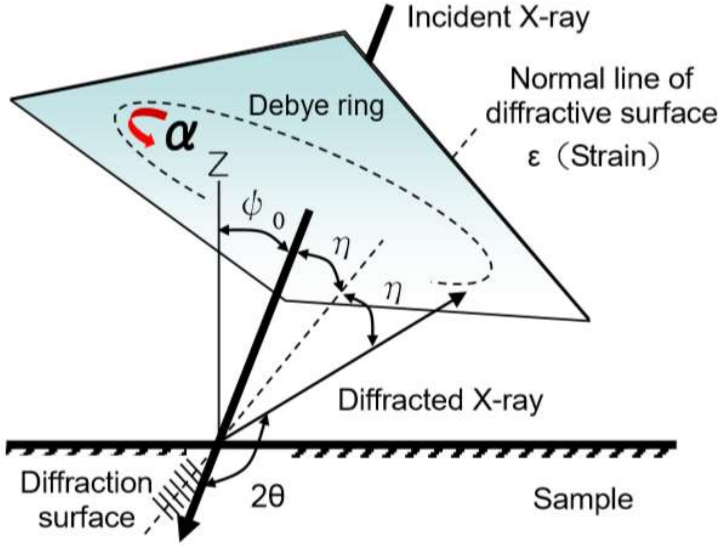


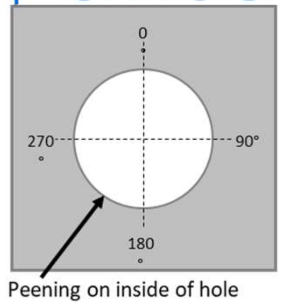


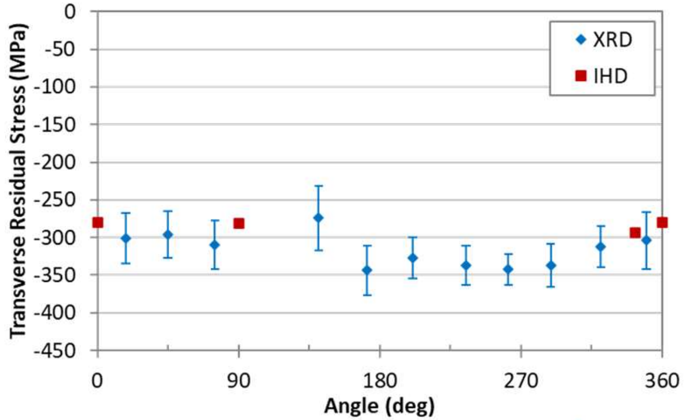
$$\varepsilon_{\alpha} = -\frac{1}{\tan\theta}\Delta\theta \qquad (0 \leq \alpha \leq 2\pi)$$

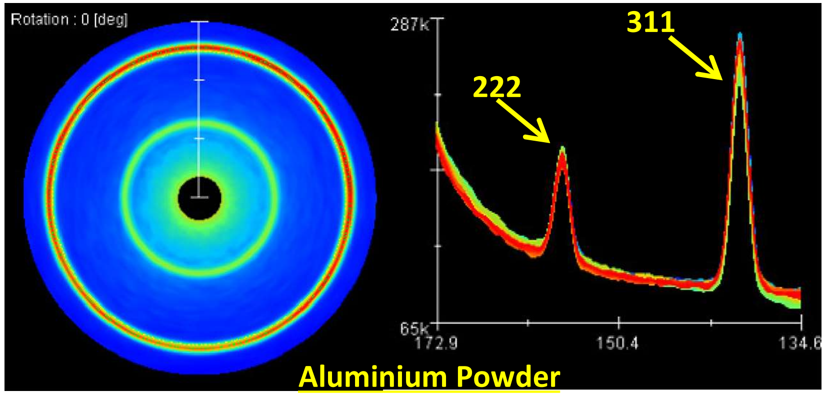
$$\varepsilon_{\alpha}1 = \frac{1}{2}\{(\varepsilon_{\alpha} - \varepsilon_{\pi+\alpha}) + (\varepsilon_{-\alpha} - \varepsilon_{\pi-\alpha})\}$$

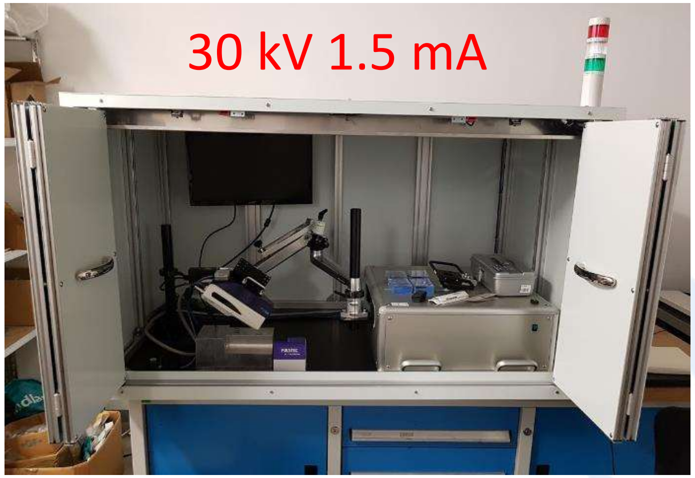
$$\sigma_x = -\frac{E}{1+\nu} \cdot \frac{1}{\sin 2\eta} \cdot \frac{1}{\sin 2\psi_0} \cdot \left(\frac{\partial \varepsilon_{\alpha}1}{\partial \cos_{\alpha}}\right)$$

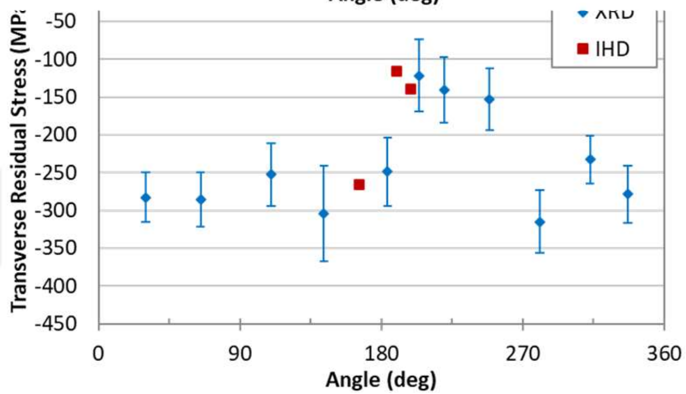
* E is Young's modulus. ν is poisson's ratio.











RS measured using Slitting Method

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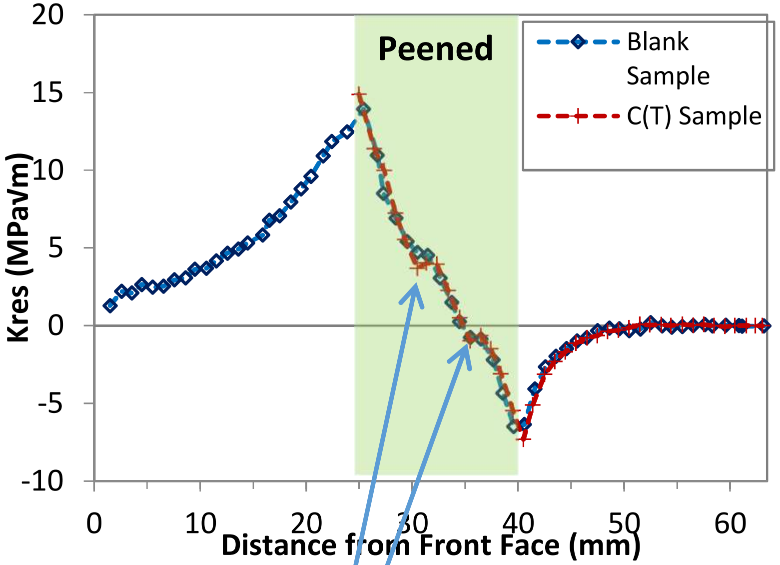
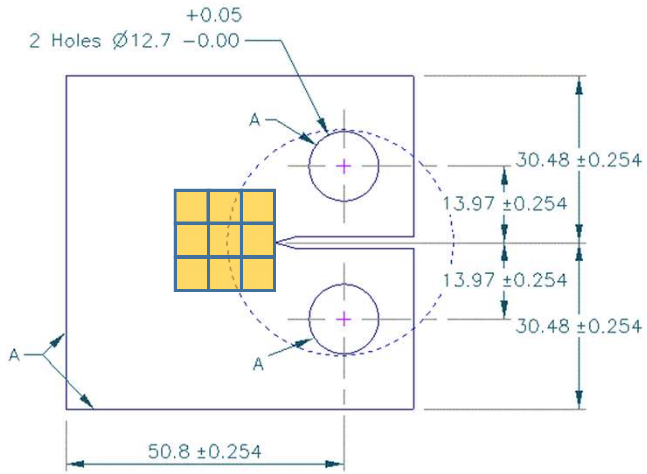
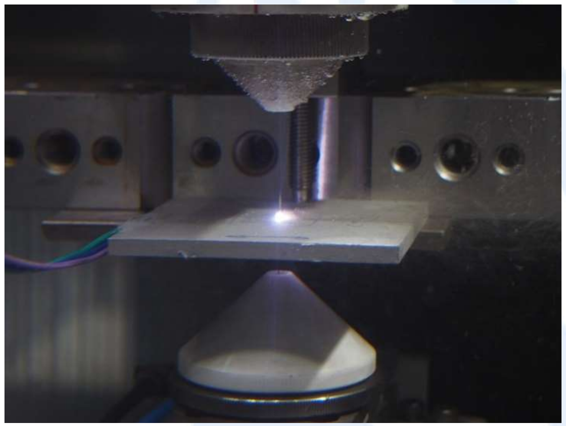
RS measured along crack path using slitting method. Two experiments performed

- RS measured in compact tension samples
- RS measured in 'blank' sample



LSP Spot Overlap





Contour Method for Residual Stress Measurement

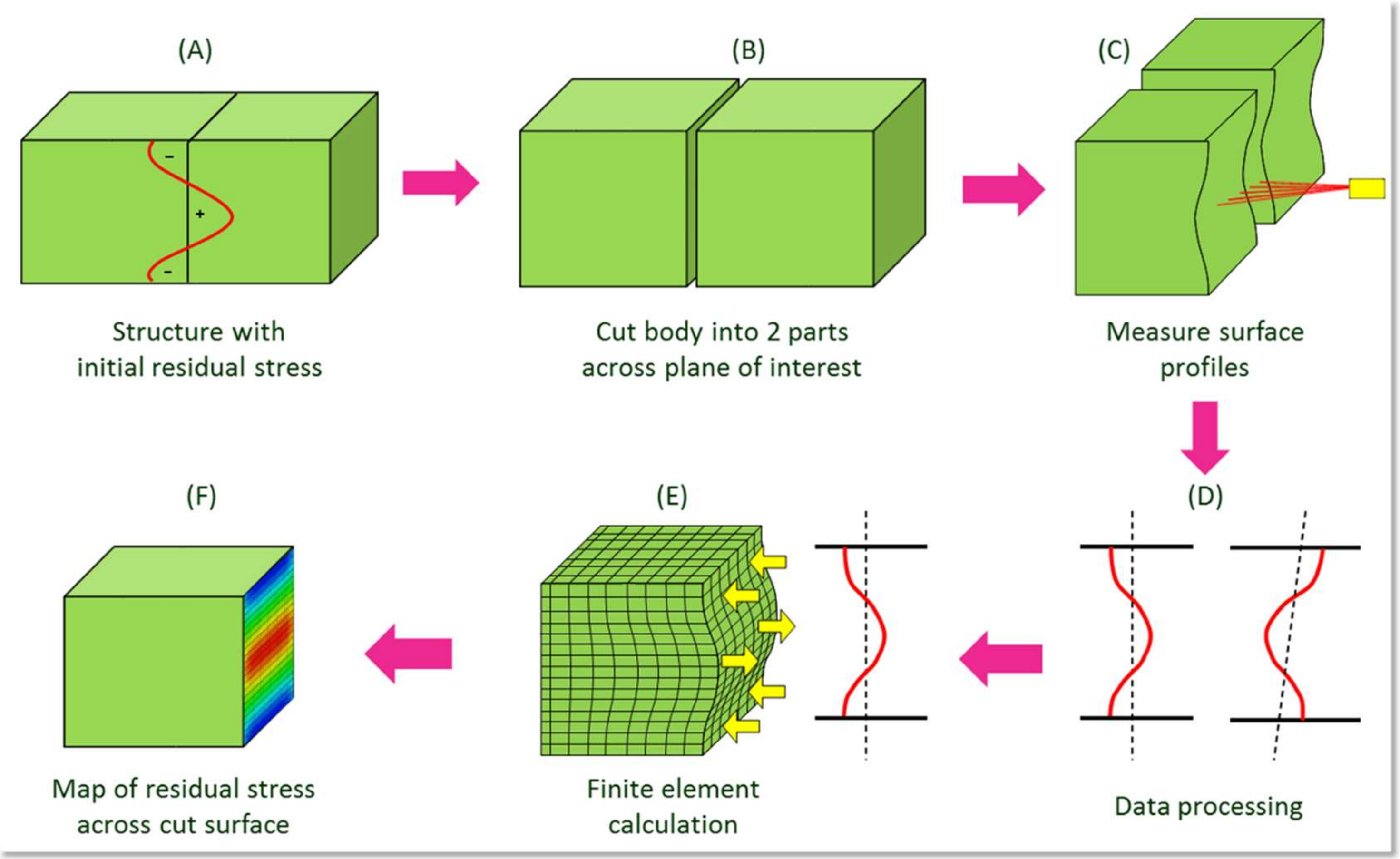


Image taken from www.stressmap.co.uk/contour-method/

Laser Shock Peening – Areas of Research

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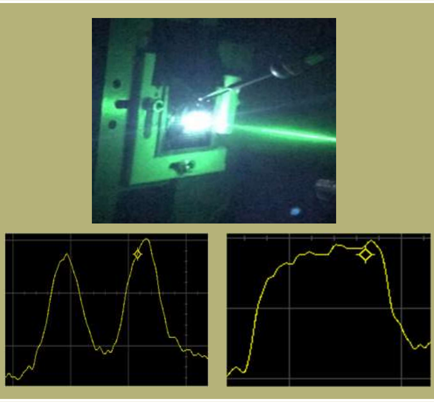
Fundamental Laser Peening Parameters



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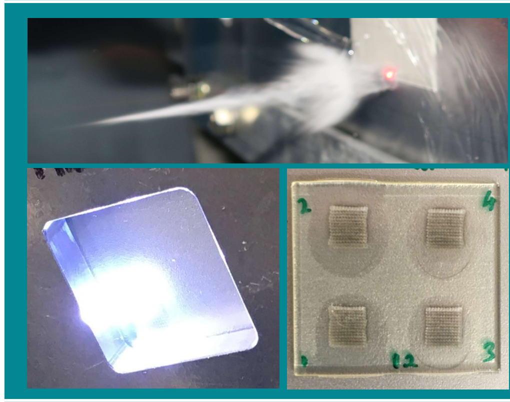
Laser Peening Process Development



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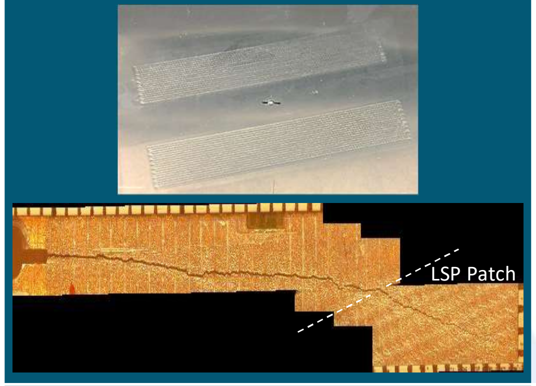
Novel Laser Peening Applications



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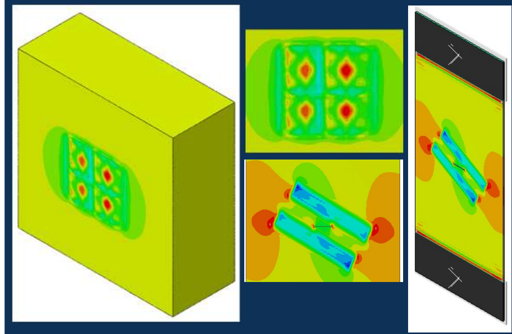
Laser Peening Simulation & Modelling



- Pulse by pulse dynamic simulation of LSP to predict residual stress and material interaction.
- Modelling of fatigue crack growth in residual stress fields.

Fundamental Laser Peening Parameters

Temporal profile effects on LSP residual stress

- Time dependency of the laser energy delivery defines the strength of the plasma pressure.
- The plasma pressure acts to create the plastic deformation of the material, introducing the residual stress.
- The effects on residual stress of samples LSP with a Gaussian, Flat Top and two variants of a double Gaussian pulse were studied.
- Peak beam energy and pulse width at the profiles half width full maximum was set to be equivalent across all profiles.
- At short pulse widths, the temporal profile does not have a significant influence on the outcome of the residual stress.
- This is important for the future design of LSP systems, as the industry moves into smaller and cheaper laser systems.

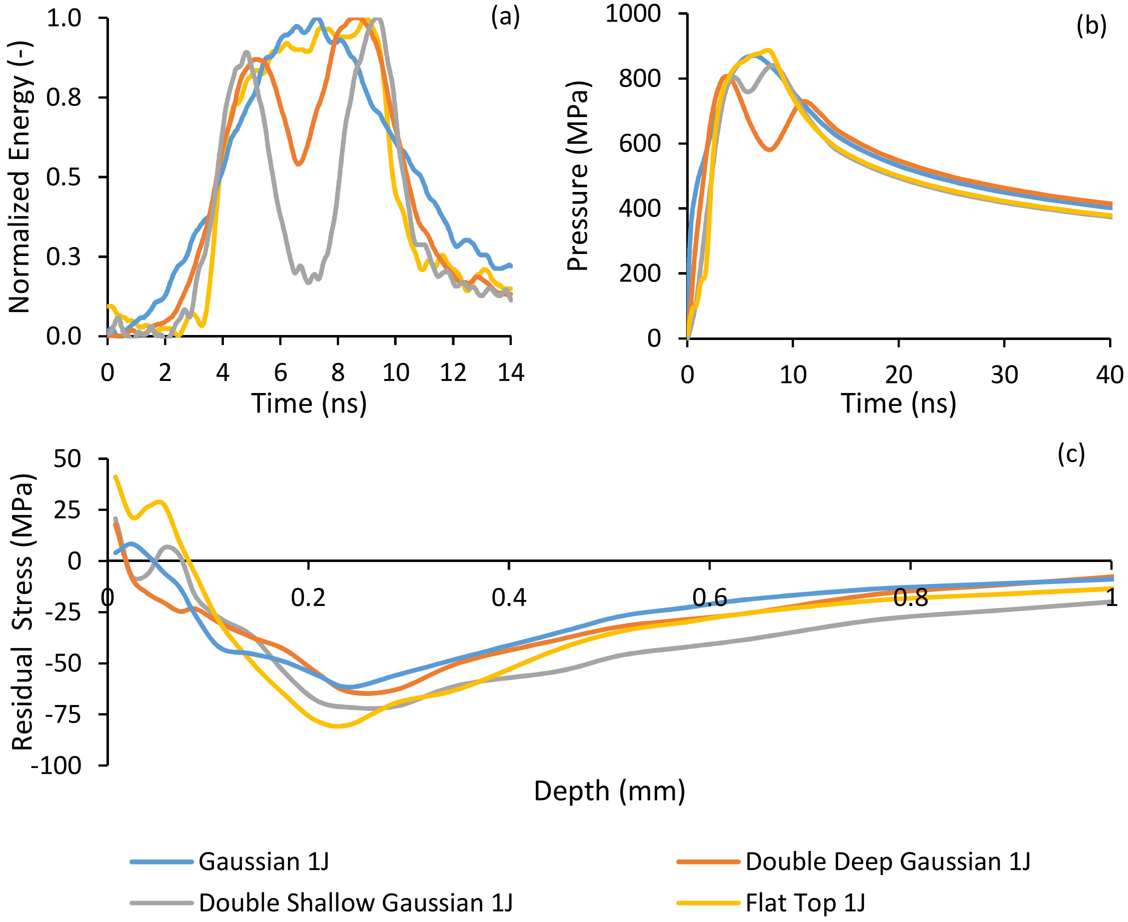


Figure – Effect of temporal profile on the formation of residual stress, (a) measured temporal profiles, (b) analytically determined effect of temporal profile on plasma pressure and (c) measured residual stress using incremental hole drilling

Laser parameter influence on residual stress

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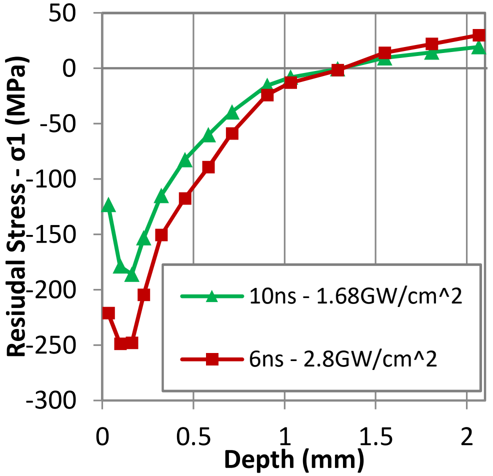
Effect of Pulse Duration

Energy: 4.2J

5×5 mm spot

3 peen layers

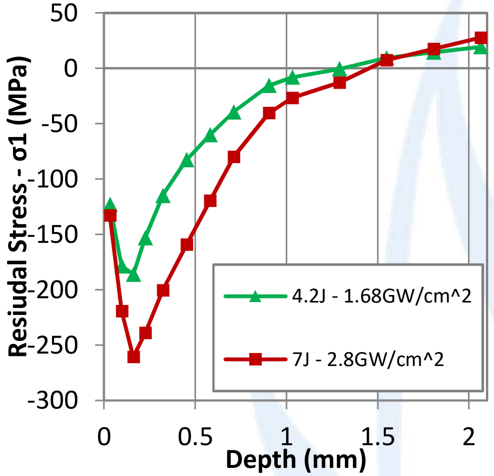


Effect of Laser Energy

Pulse Duration: 10 ns

5×5 mm spot

3 peen layers



$$\text{Power Intensity (GW/cm}^2) = \frac{\text{Energy (J)}}{\text{Pulse Duration (s)} \times \text{Laser Spot Area (cm}^2)}$$

Fundamental Laser Peening Parameters

Effect of LSP parameters on residual stress and surface quality

- Power intensity is the most critical factor in the formation of deep compressive stresses.
- A higher power intensity increase the peak and depth of the compressive stress.
- As a consequence, the post LSP surface is significantly degraded, even when an ablative coating is used during processing.
- Surface effects can then work against the compressive stress as the damage is prime area for crack initiation and corrosion sites.

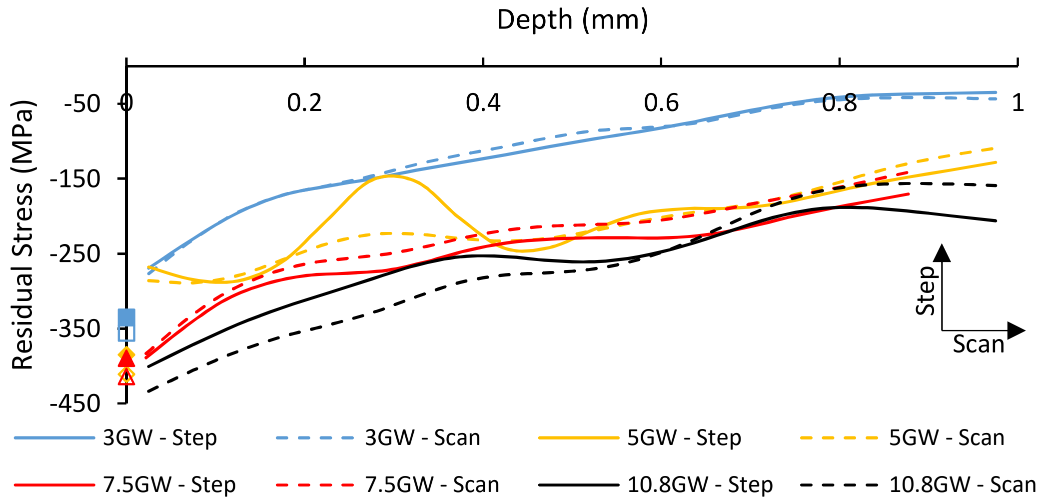


Figure – Increase in residual stress due to increased power intensity

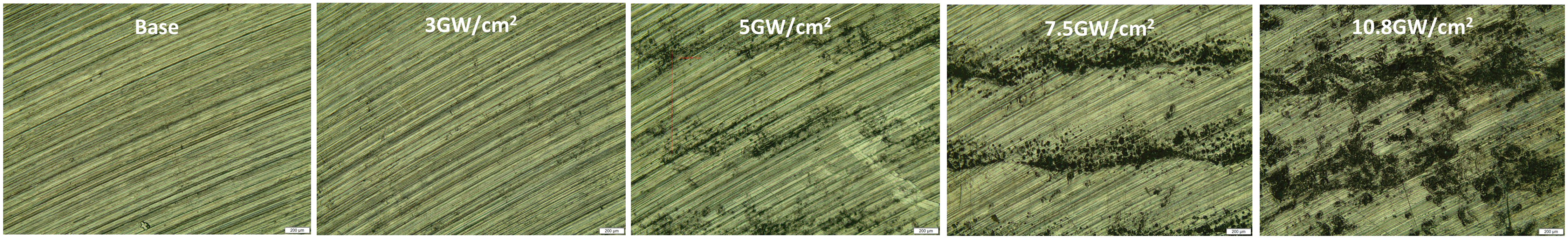


Figure – Surface degradation due to laser processing overlap with increasing power intensity

Laser Shock Peening – Areas of Research

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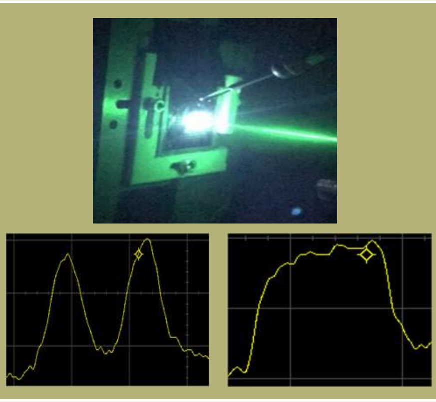
Fundamental Laser Peening Parameters



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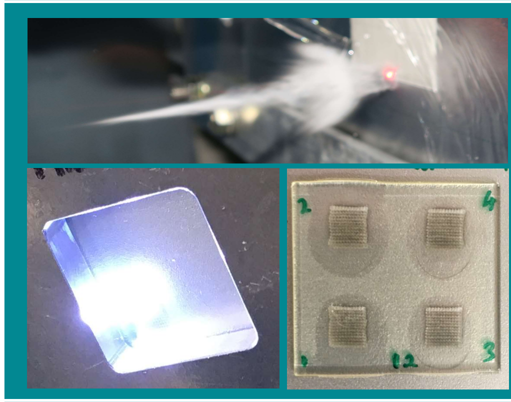
Laser Peening Process Development



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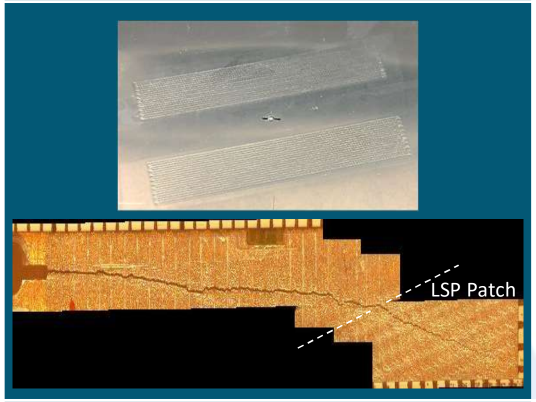
Novel Laser Peening Applications



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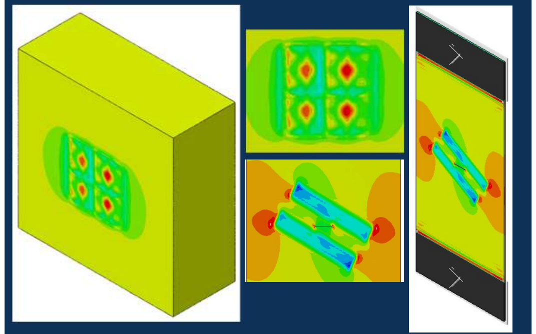
Laser Peening Simulation & Modelling



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3D Printed Solid Confinement

Introduction

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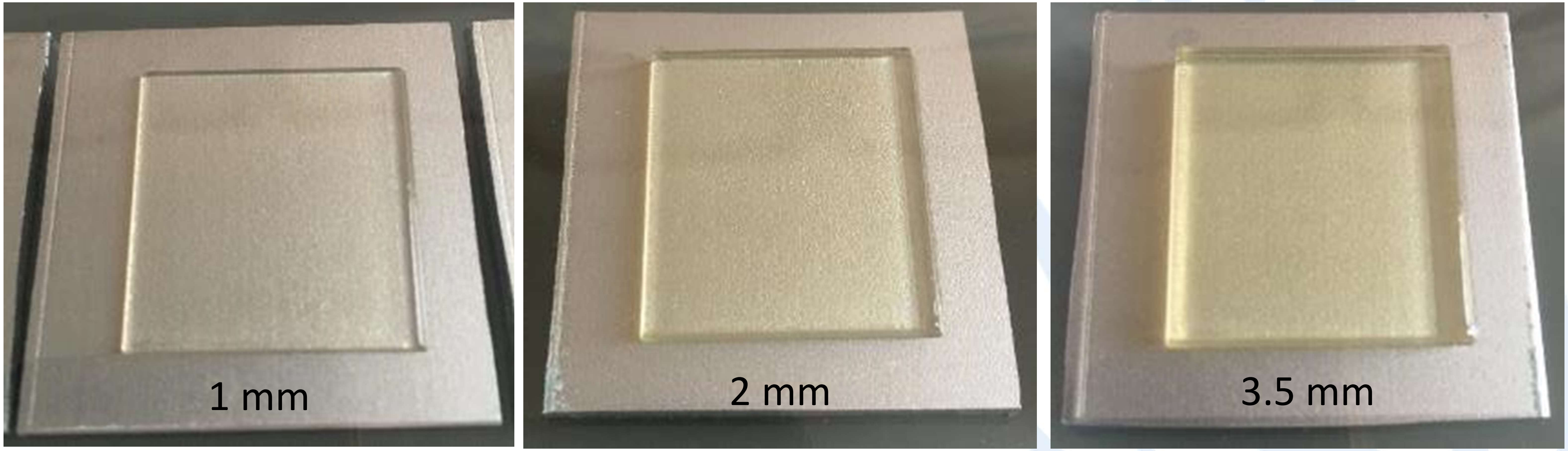
- Water is used as a confinement medium in LSP and acts to increase the intensity of the pressure pulse experienced by the sample.
- However water is seen as a barrier to wide scale adoption of LSP as delivery and containment of water is problematic on manufacturing lines and repair facilities.
- The aim of this research is to investigate the replacement of water confinement with a 3D printed solid confinement medium.
- Confinement medium is made from 3D printed pliable polymer material deposited and cured directly to the substrate.

Figure – Ejected water jet during a single LSP pulse



3D Printed Solid Confinement

Energy Transmission and Damage Threshold

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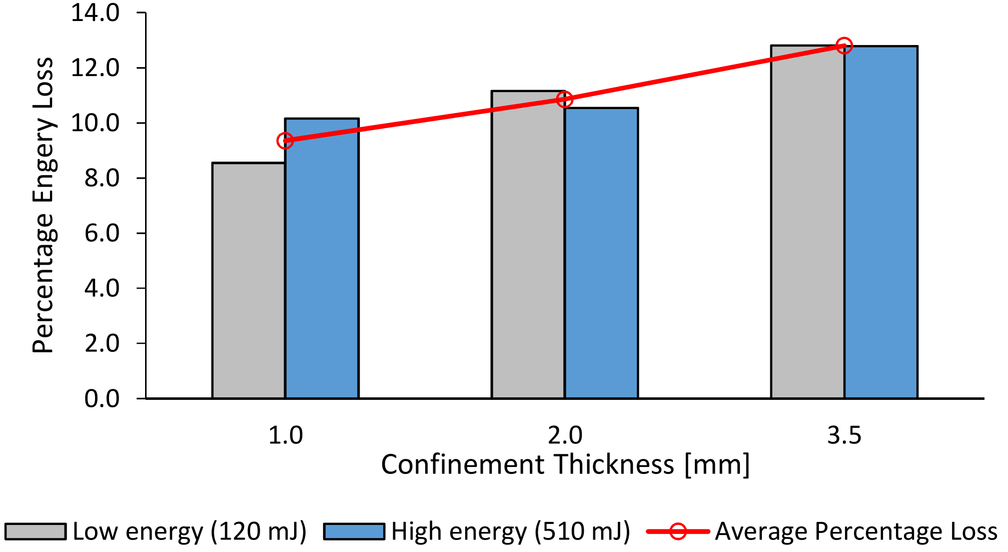
As built:

- ±11% energy loss due layer light reflection and absorption.
- Material exhibited 0.87-0.9 energy transmission.
- Energy loss tended to increase with layer thickness.

Table 1 – Energy lose in as built material

Confinement thickness [mm]	Energy in [mJ]	Energy out [mJ]	Ave. energy lose [%]	Energy in [mJ]	Energy out [mJ]	Energy lose [%]	Ave. energy lose [%]
1.0	117.0	107.0	8.5	571.0	513.0	10.2	9.4
2.0	121.0	107.5	11.2	572.0	511.7	10.5	10.9
3.5	121.0	105.5	12.8	571.0	498.0	12.8	12.8

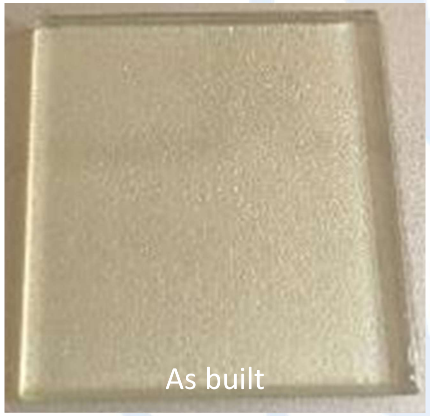


Post-LSP:

- Post-LSP energy through put dropped by a further ±60% due to extensive damage of the confinement medium.

Table 2 – Further energy lose due to Laser Peening damage

Confinement thickness [mm]	Energy in [mJ]	Energy out [mJ]	Ave. energy lose [%]	Energy in [mJ]	Energy out [mJ]	Energy lose [%]	Ave. energy lose [%]
2.0	200	78	61	642	215	66.5	63.75



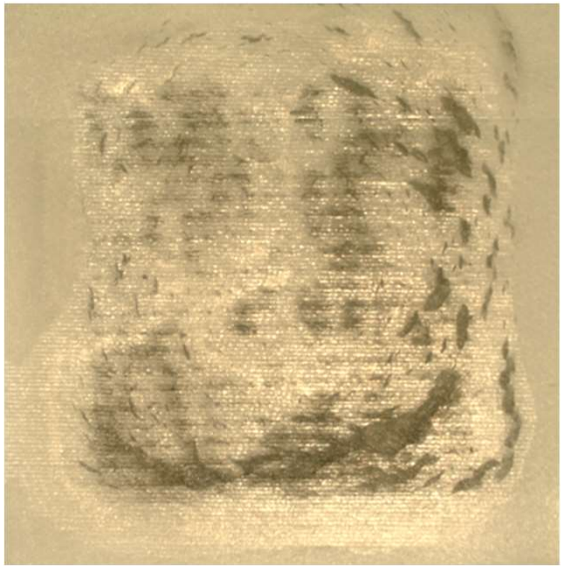
3D Printed Solid Confinement

Energy Transmission and Damage Threshold

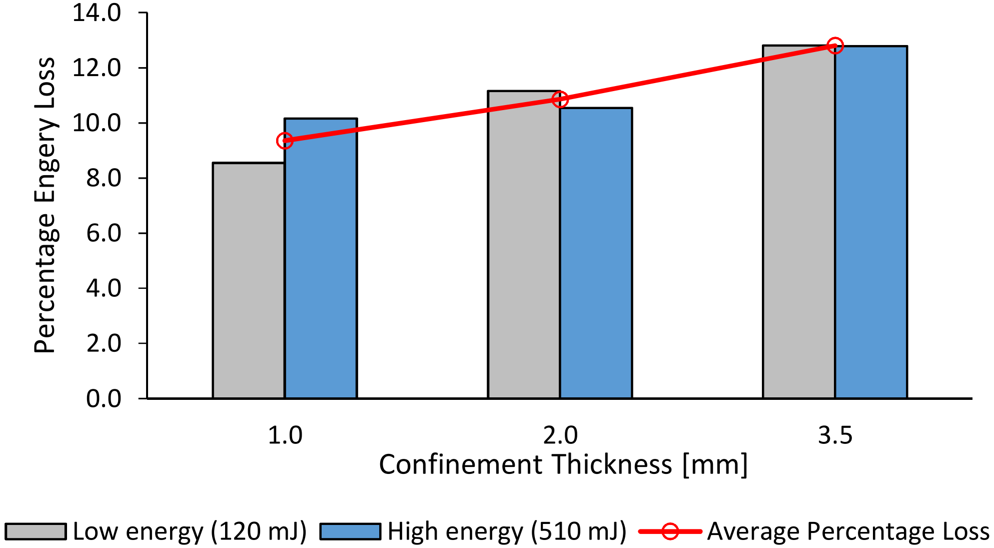
Damage Threshold:

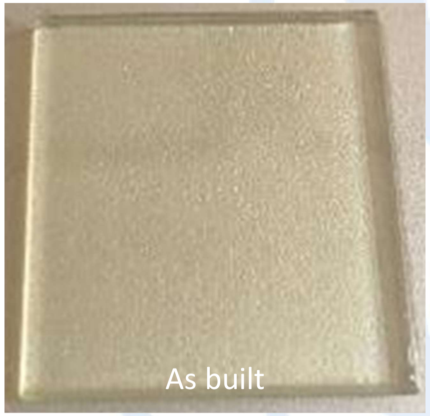
- Cracking and flaking occurred on external surface (laser in surface).
- Burning and blackening occurred on confinement/substrate interface surface.
- No cracking or fracture occurred on confinement/substrate interface surface.

External surface (laser in)



Confinement / Substrate interface





3D Printed Solid Confinement

Low Energy and Small Spots

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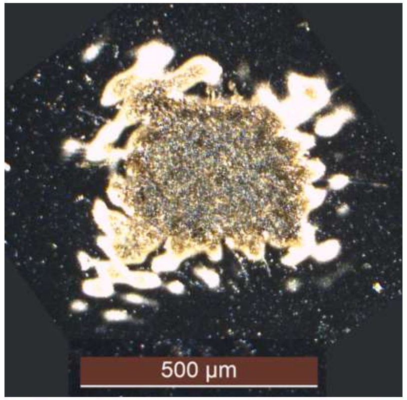
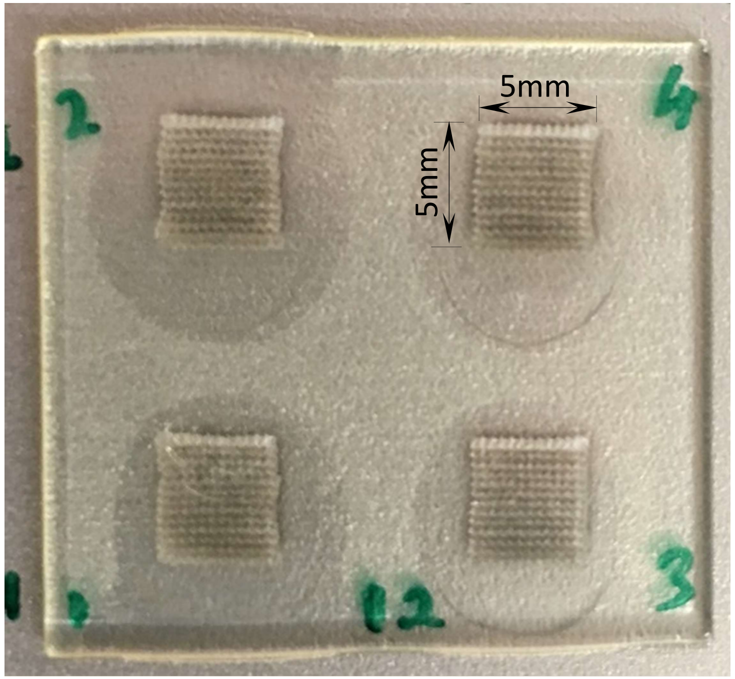
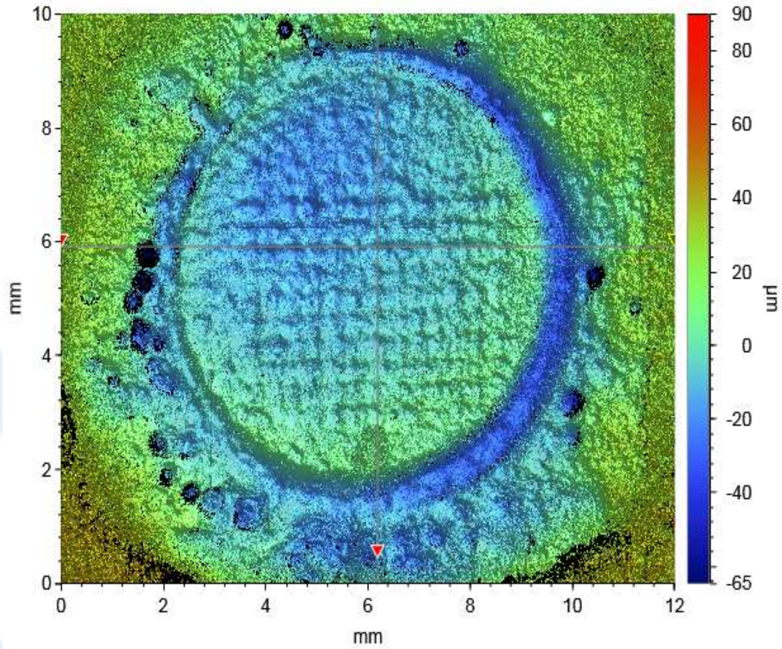
- Power intensity was fixed at 1 GW/cm^2 ±0.25 GW/cm^2 , single layer and no spot overlap.
- A single ±400 µm square spots did not locally delaminate confinement from the substrate.
- Delamination in the surrounding area occurs only when a LSP patch is applied.
- Compressive residual stress of -196 MPa after peening





0.016J – 0.4x0.4mm spot


50 µm removed by electro polishing



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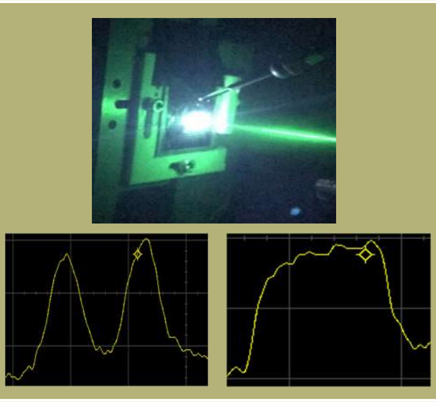

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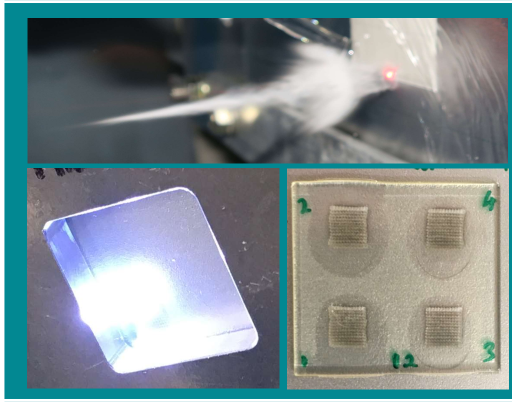
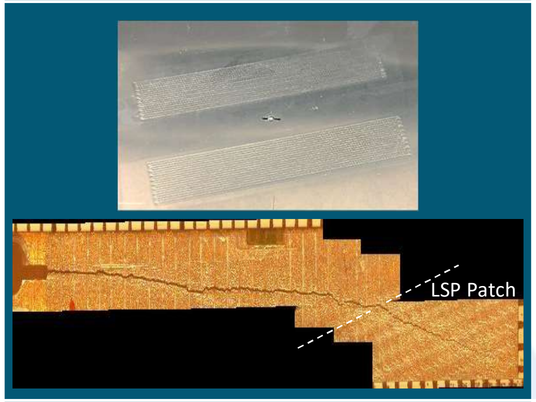
- LSP induced surface degradation.

Laser Peening Process Development



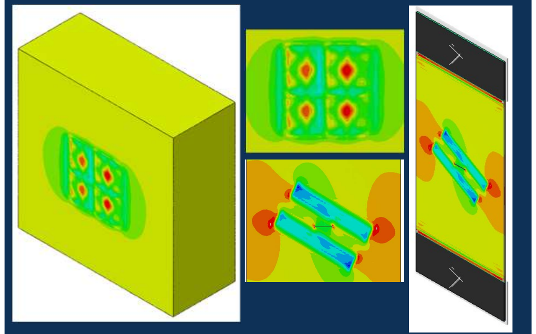
- Development of novel confinement mediums to remove water in the LSP process.
- Defining operational procedures for implementing novel confinement mediums.

Novel Laser Peening Applications



- Fundamental study of crack redirection by LSP residual stress.
- Material life extension by LSP residual stress.

Laser Peening Simulation & Modelling



- Pulse by pulse dynamic simulation of LSP to predict residual stress and material interaction.
- Modelling of fatigue crack growth in residual stress fields.

Fatigue Testing (Effect of Power Density)

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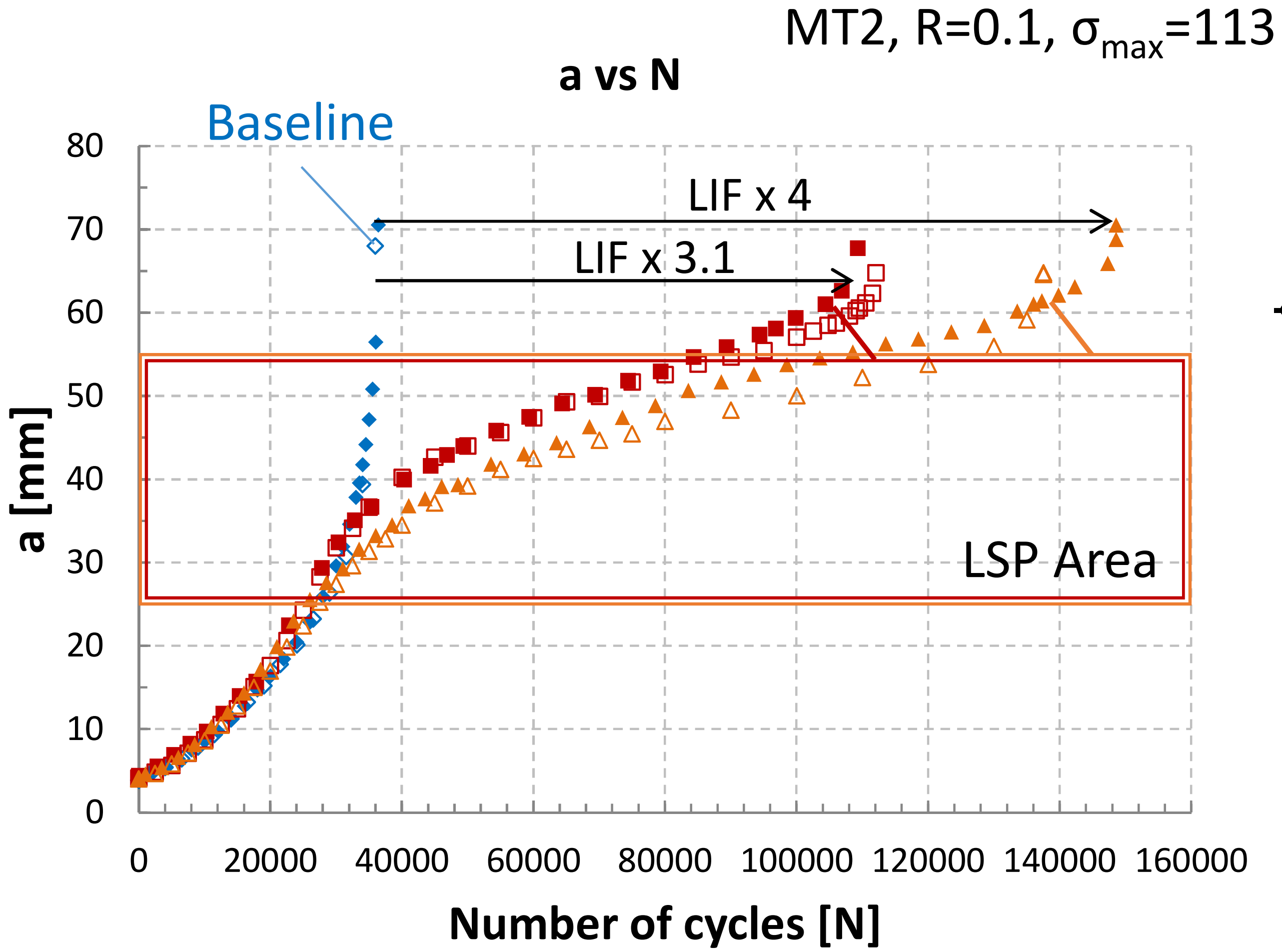

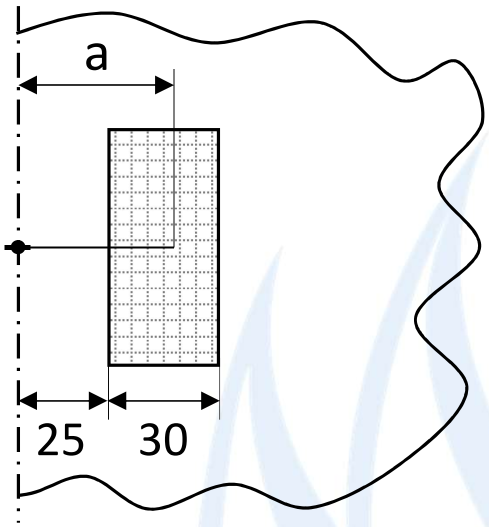

LSP	Power Intensity [GW/cm²]	Spot Size [mm]	Spot Offset	Layers
3-18-4	3	5.5 x 5.5	50%	4
4-18-4	4	4.7 x 4.7	50%	4

Fatigue Testing (Effect of wLSP)

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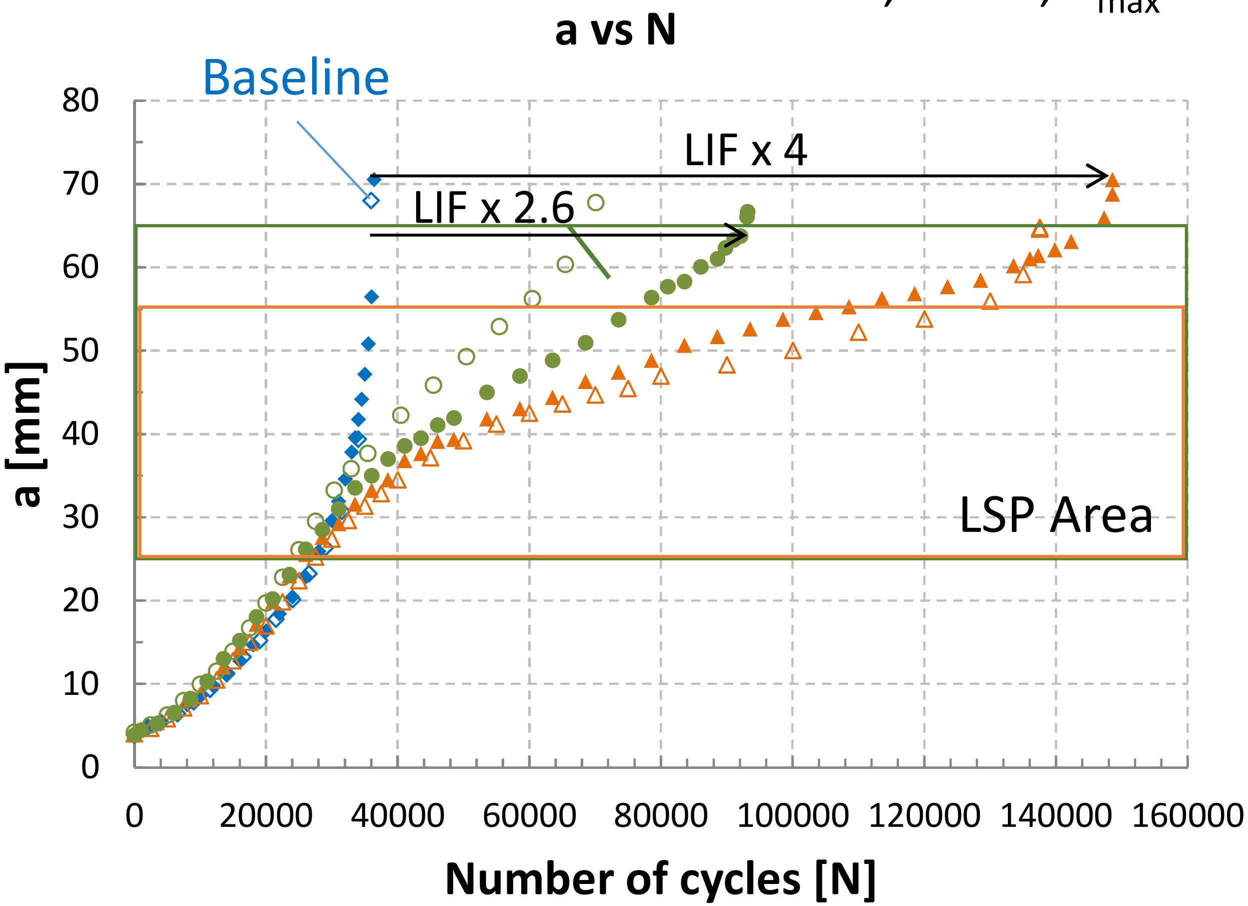
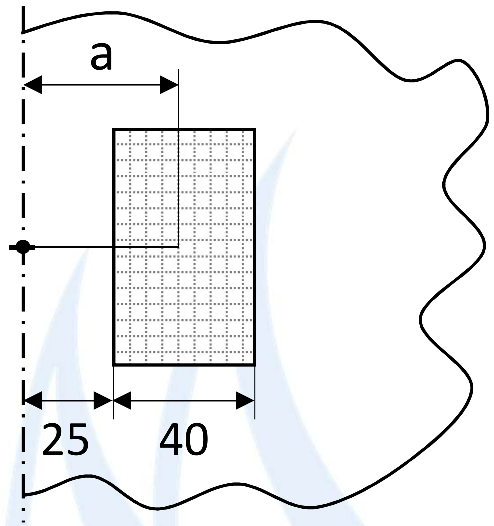
MT2, R=0.1, σ_{max}=113





LSP	Power Intensity [GW/cm²]	Spot Size [mm]	Spot Offset	Layers
3-18-4	3	5.5 x 5.5	50%	4
3-18-4	**3**	**5.5 x 5.5**	**50%**	**4**

Residual Stress Measurements

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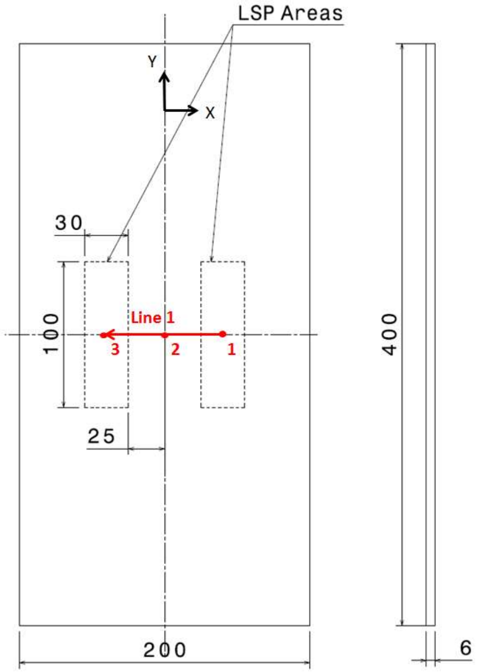
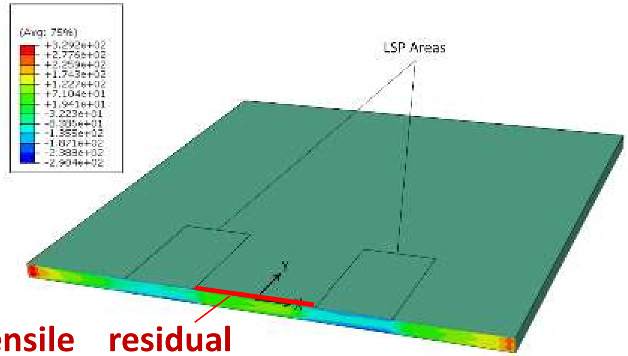


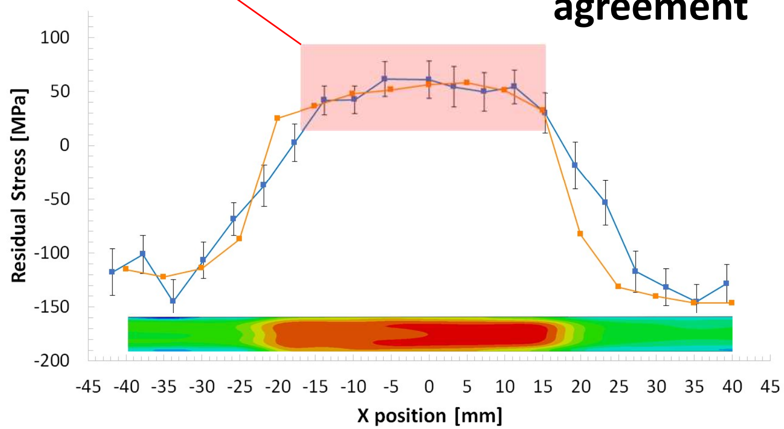
Neutron Diffraction
Canadian Neutron Beam Centre (CNBC)

Contour Method
Coventry University



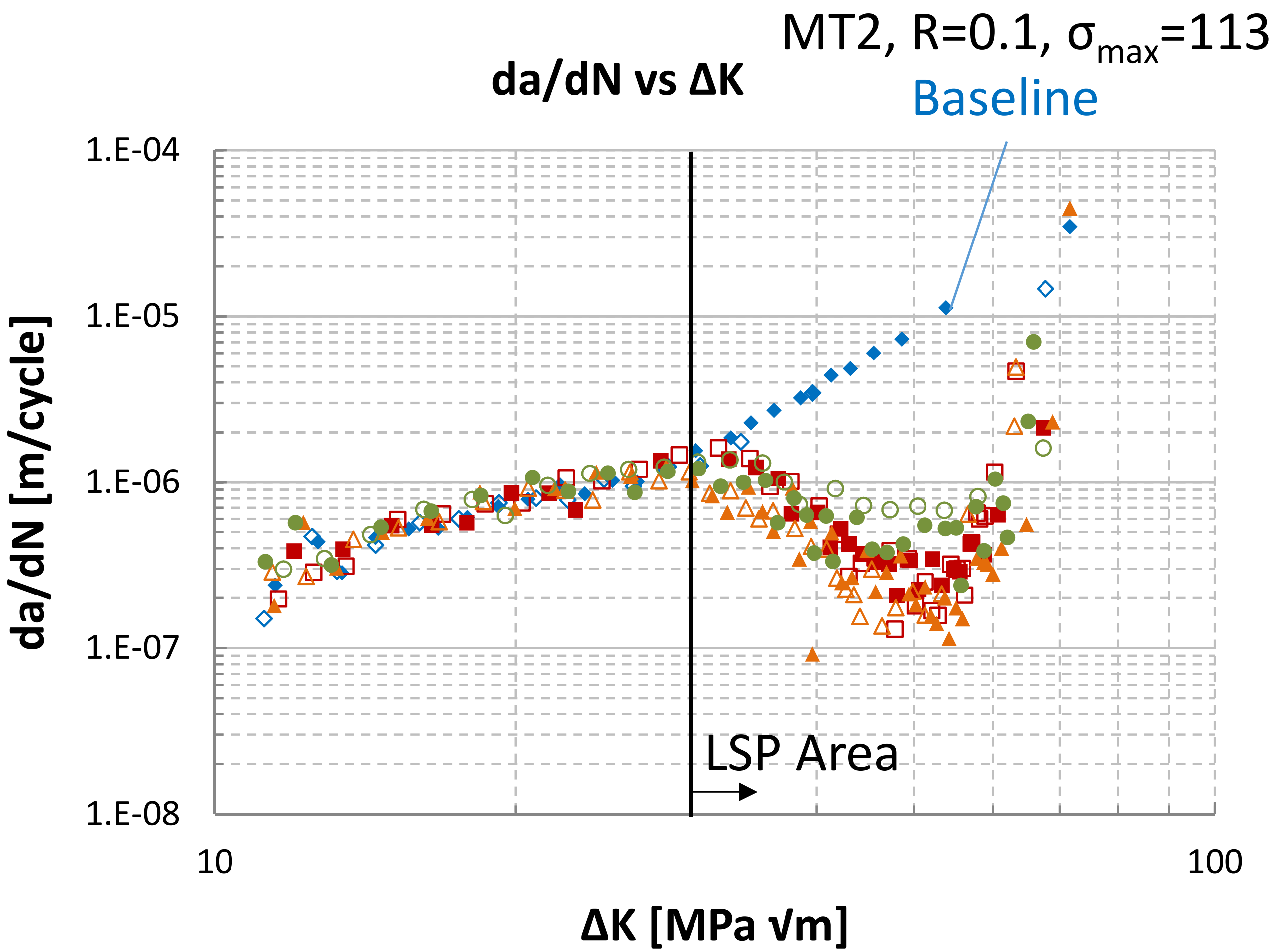
Balancing tensile residual stress generates outside the LSP Areas

Good agreement

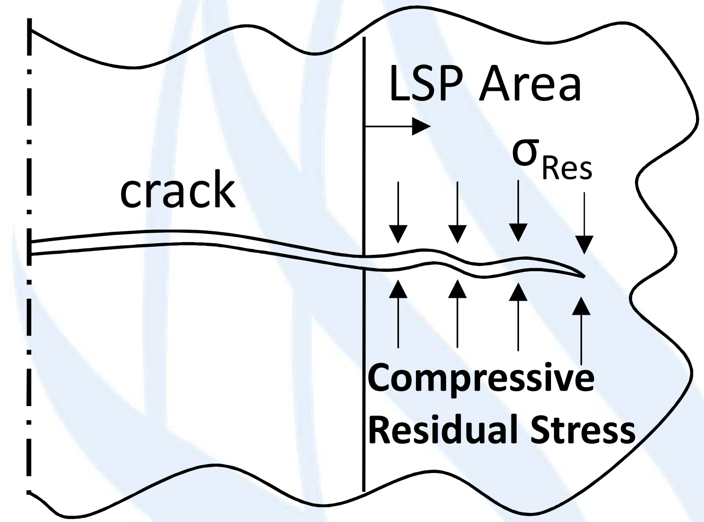


Average through the thickness

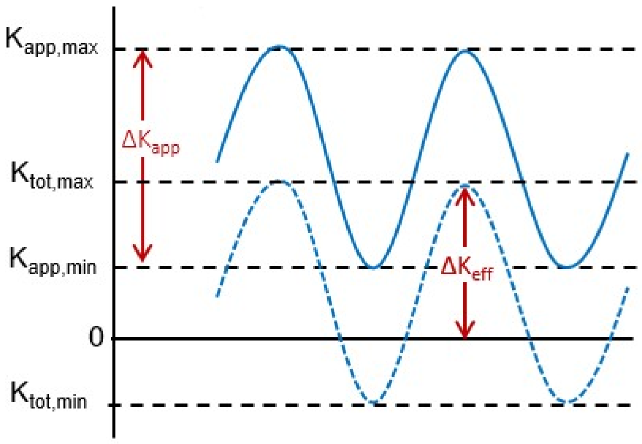
Fatigue Testing Results



Fatigue Crack Growth Rate (FCGR) decreases when the Laser Shock Peened area is approached.



Numerical Modelling



Applied Loading Only

$$\Delta K_{app} = K_{max} - K_{min}$$

$$R = \frac{K_{min}}{K_{max}}$$

Applied Loading & Residual Stress Field

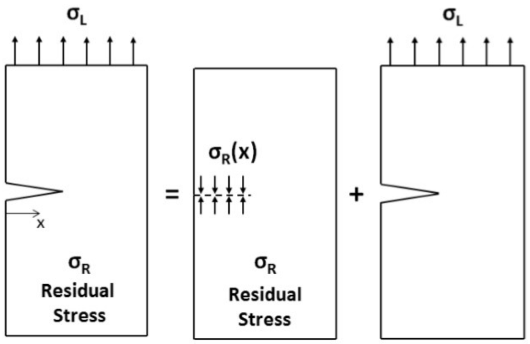
$$K_{tot,max} = K_{app,max} + K_{res}$$

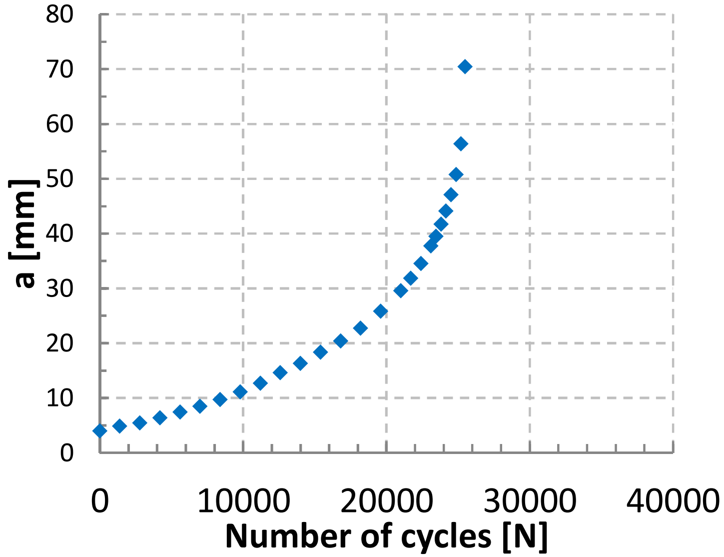
$$K_{tot,min} = K_{app,min} + K_{res}$$

$$\Delta K_{eff} = \begin{cases} K_{tot,max}, & \text{if } K_{tot,min} \leq 0 \\ K_{tot,max} - K_{tot,min}, & \text{if } K_{tot,min} > 0 \end{cases}$$

$$R = \begin{cases} 0, & \text{if } K_{tot,min} \leq 0 \\ \dfrac{K_{tot,min}}{K_{tot,max}}, & \text{if } K_{tot,min} > 0 \end{cases}$$

Superposition Principle





Paris Equation

$$\frac{da}{dN} = C\Delta K^{n}$$

Walker Equation

$$\frac{da}{dN} = C(\Delta K(1-R)^{m-1})^{n}$$

Numerical Modelling

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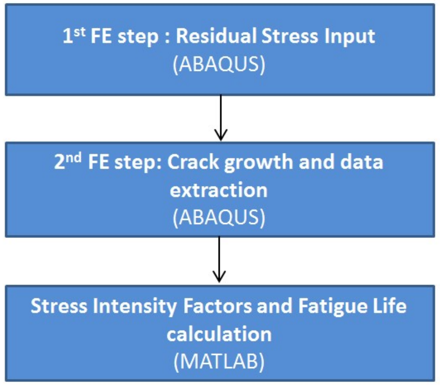
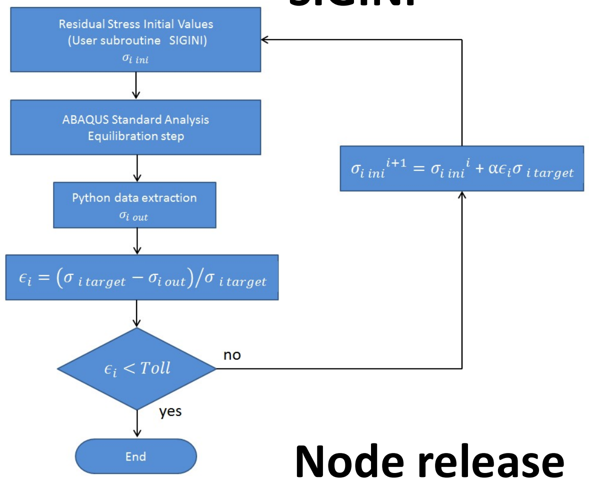
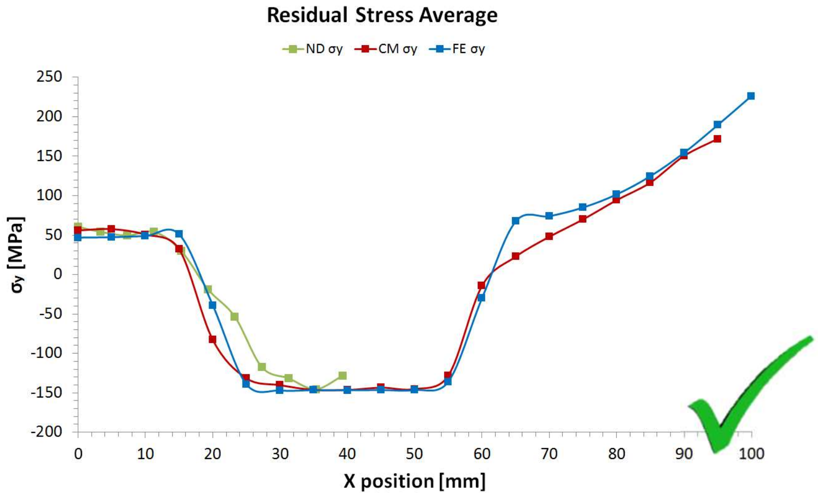
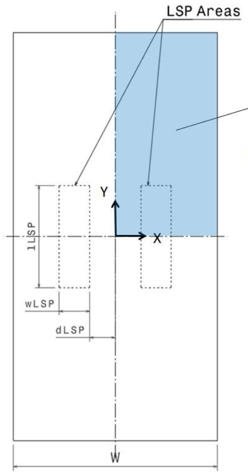


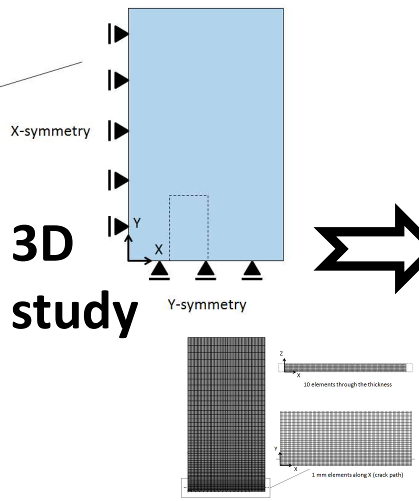
SIGINI

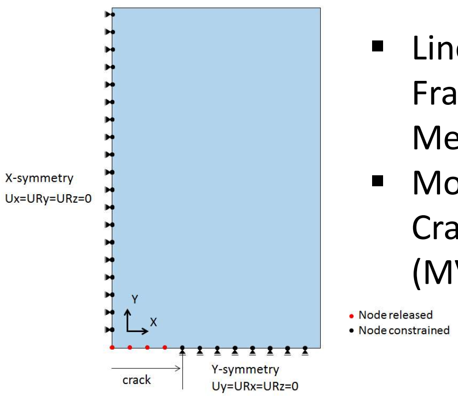






3D study

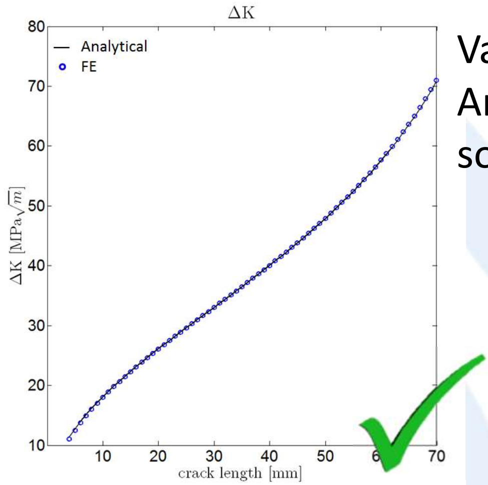




Node release advance scheme

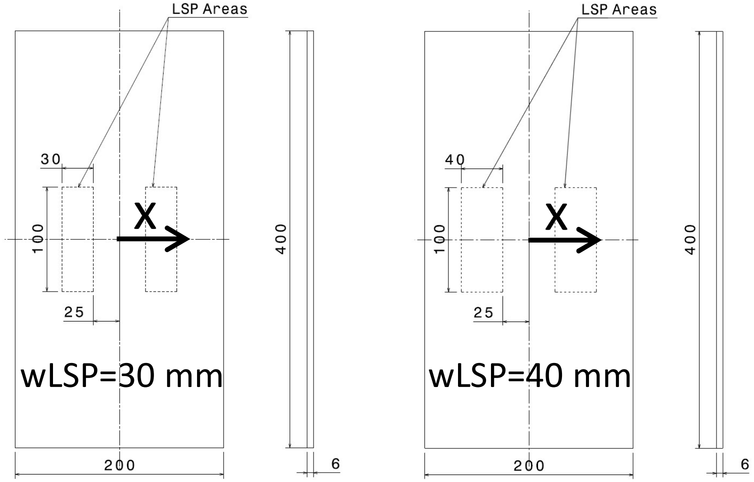
- Linear Elastic Fracture Mechanics (LEFM)
- Modified Virtual Crack Closure (MVCCT)

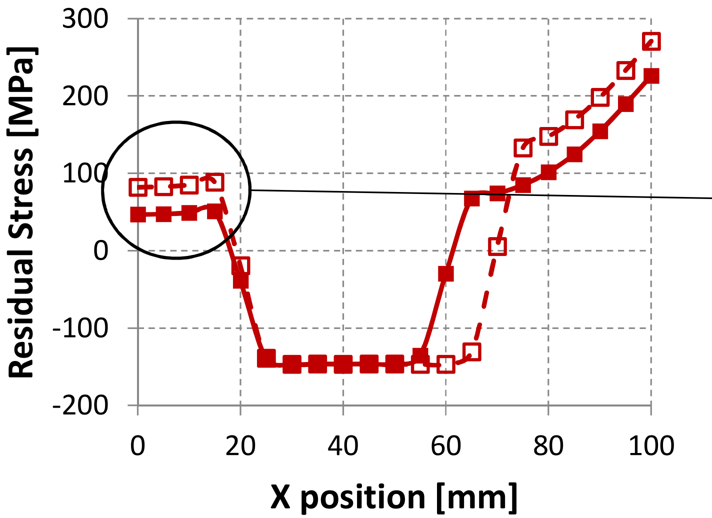
• Node released
• Node constrained



Validated with Analytical solution

Numerical Modelling

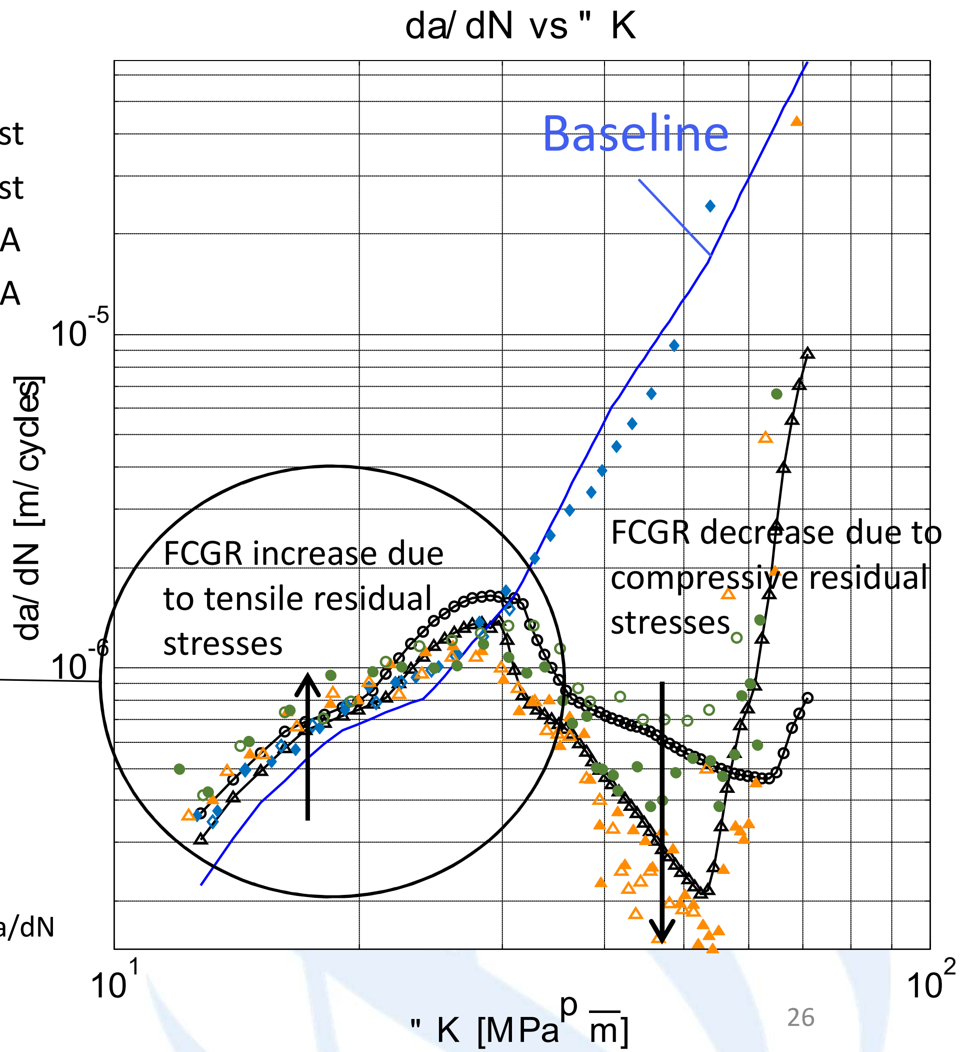




Baseline
wLSP=30 mm, Test
wLSP=40 mm, Test
wLSP=30 mm, FEA
wLSP=40 mm, FEA

Good agreement between FEA and experimental results

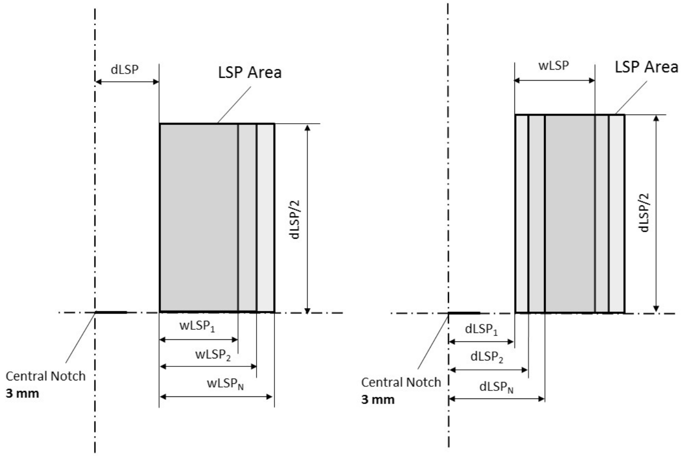
FCGR = Fatigue Crack Growth Rate da/dN

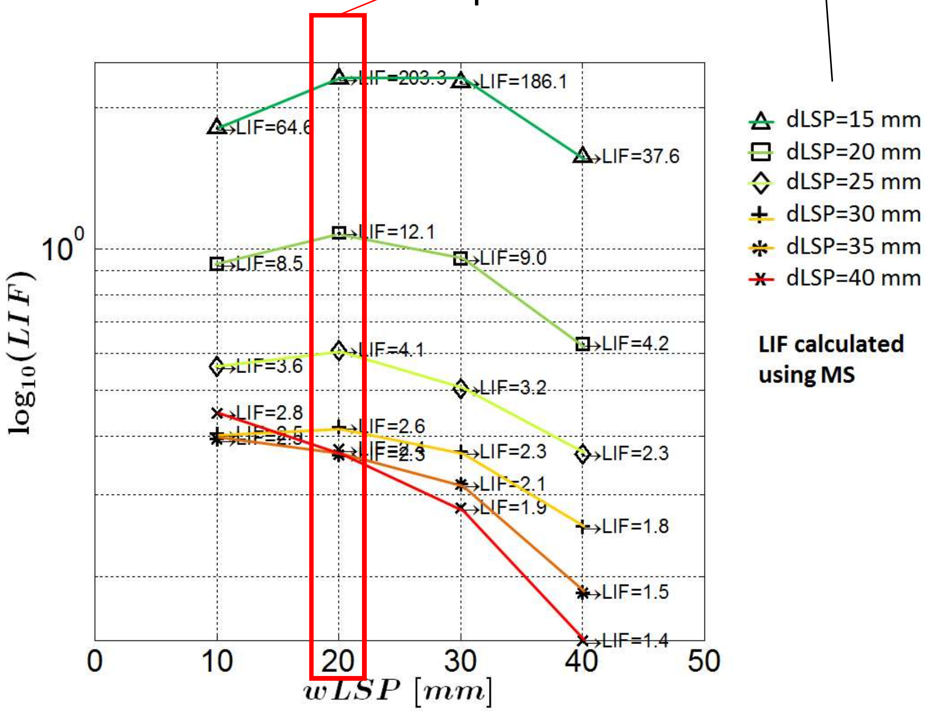


Optimised LSP Patch Position

MT-2524-200-400-6, R=0.1, σ_{max}=113 MPa

for dLSP≤ 10 mm, crack is arrested





LIF calculated using MS

wLSP=10,20,30,40 mm
dLSP=10,15,20,25,30,35,40 mm
σ_y=-146 MPa

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Novel Laser Peening Applications

Life extension and crack redirection by LSP residual stress

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- Angled LSP patches are used to attempt to alter the crack trajectory away from the preferred fracture orientation.
- This is a useful concept to drive concealed cracks, such as those occurring in fuselage skin overlaps, to easily inspected areas.
- By altering the crack trajectory, titanium crack stopper sizes can be reduced.
- Average through thickness residual stresses that are equivalent to the applied loads are introduced to slow the crack and establish mixed mode loading.

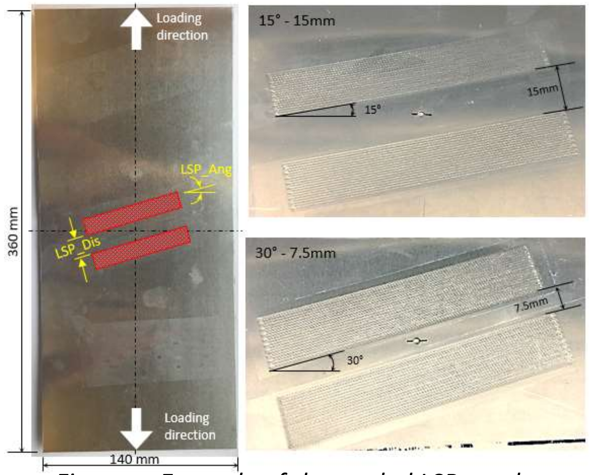
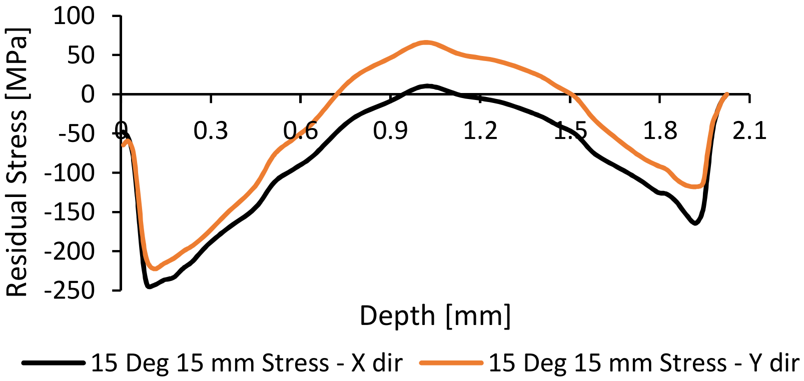


Figure – Example of the angled LSP patches



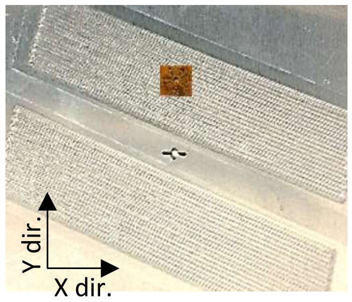


Figure – Through thickness residual stress profile of angled patched LSP processed AA2024-T3

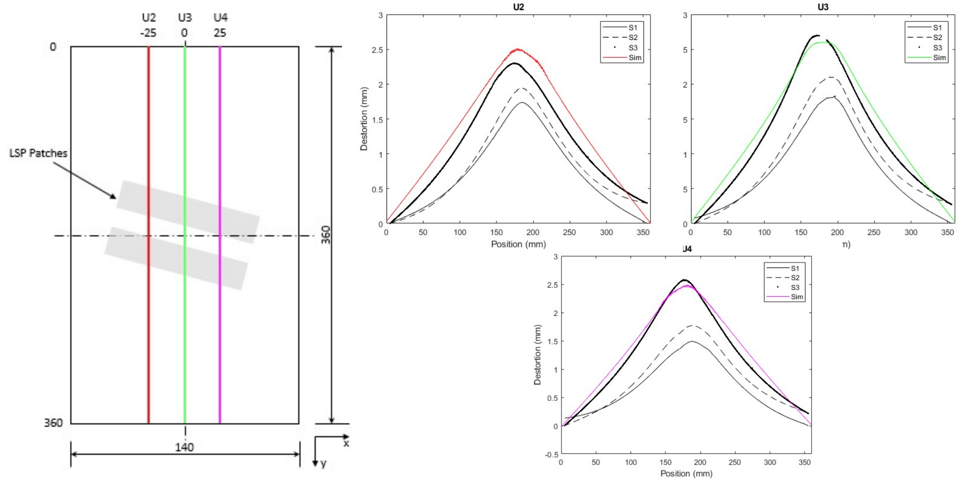


Figure – Cauterisation of samples deflection due to LSP

Novel Laser Peening Applications

Life extension and crack redirection by LSP residual stress

- The cracks trajectory is perpendicular to the applied load and is pulled towards the residual stress patch.
- LSP significantly reduces the effective loading and prolongs the life of the component by as much as x24 times the original life.
- **Extend service life** – place the LSP patch as close to the crack tip.
- **Alter crack trajectory** – place the LSP patch further away.

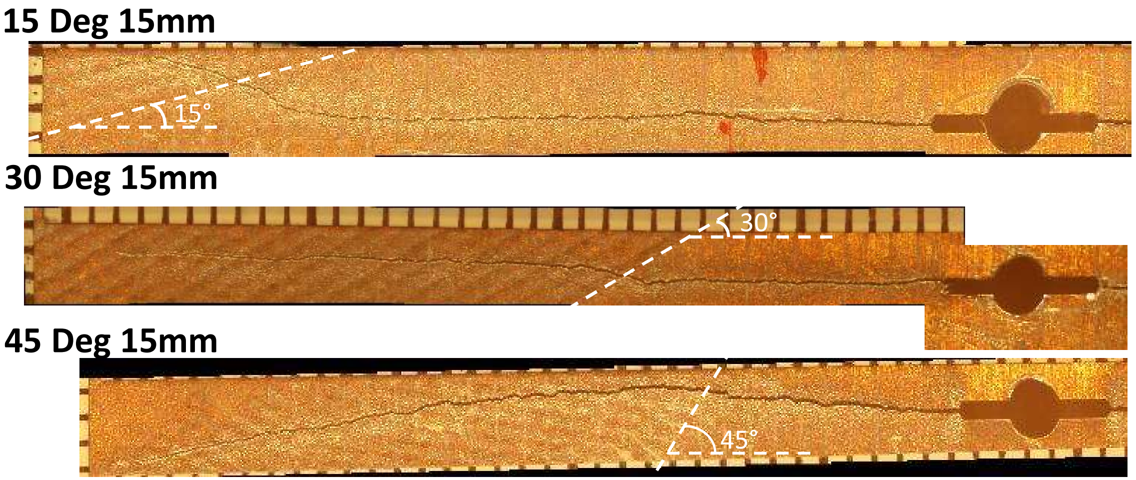


Figure – Crack trajectory modification by LSP residual stress

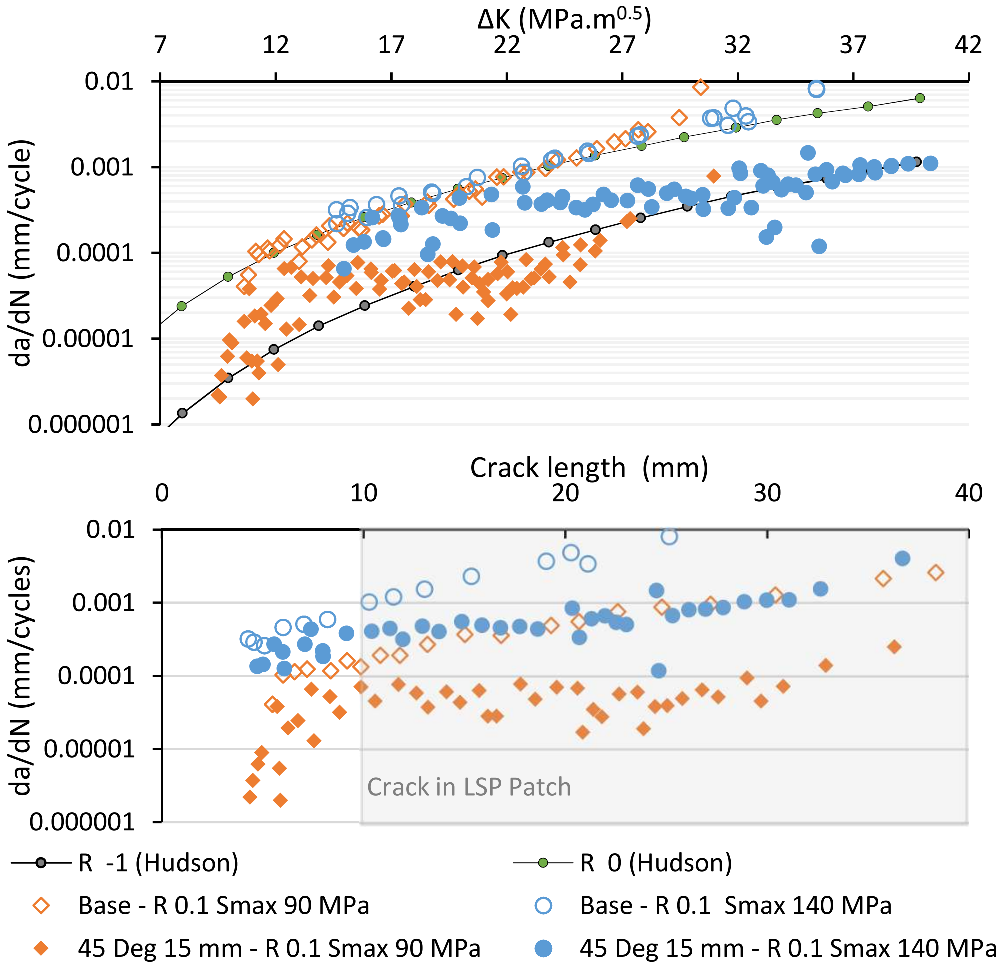


Figure – Influence of LSP patches at two maximum stresses (a) FCGR comparison of LSP samples at 45 Deg & 15 mm, (b) effective loading due to LSP compressive stress

Laser Shock Peening – Areas of Research

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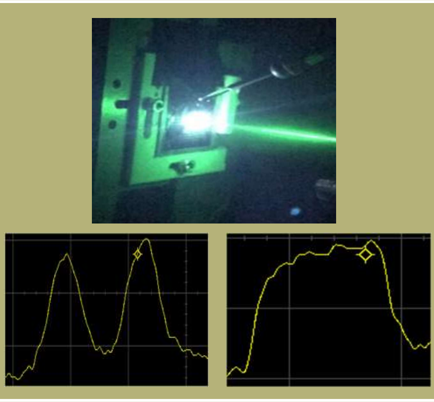
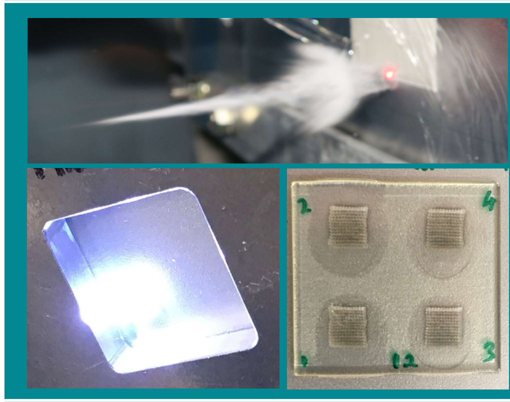
Fundamental Laser Peening Parameters



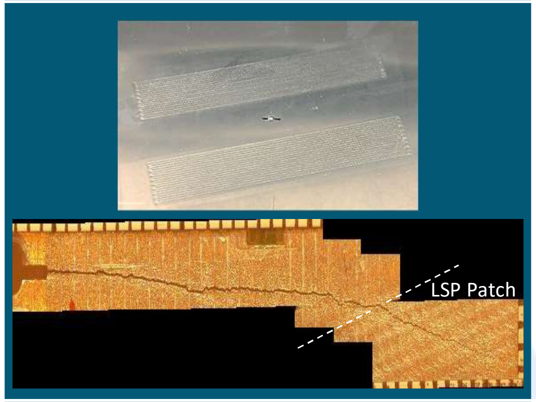
- Laser temporal profile influence on residual stress formation.
- Laser parameter influence on residual stress.
- LSP induced surface degradation.

Laser Peening Process Development



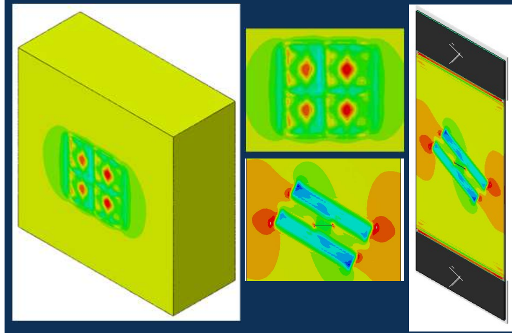
- Development of novel confinement mediums to remove water in the LSP process.
- Defining operational procedures for implementing novel confinement mediums.

Novel Laser Peening Applications



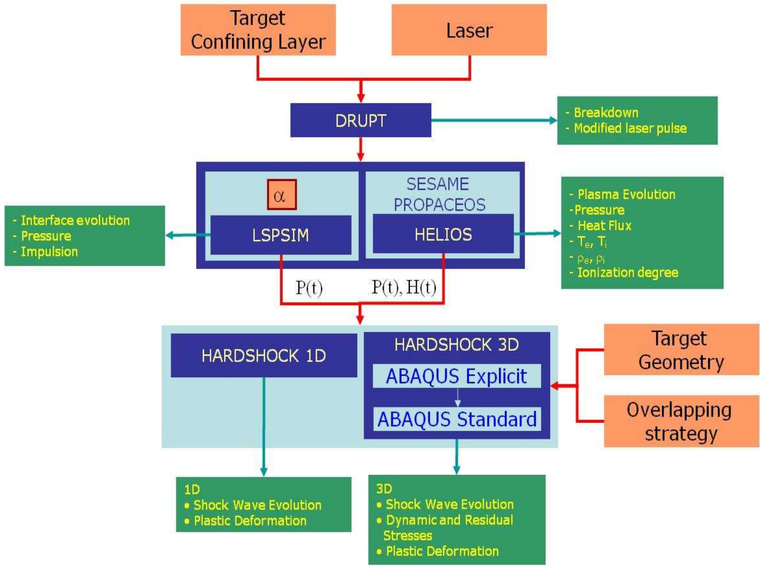
- Fundamental study of crack redirection by LSP residual stress.
- Material life extension by LSP residual stress.

Laser Peening Simulation & Modelling

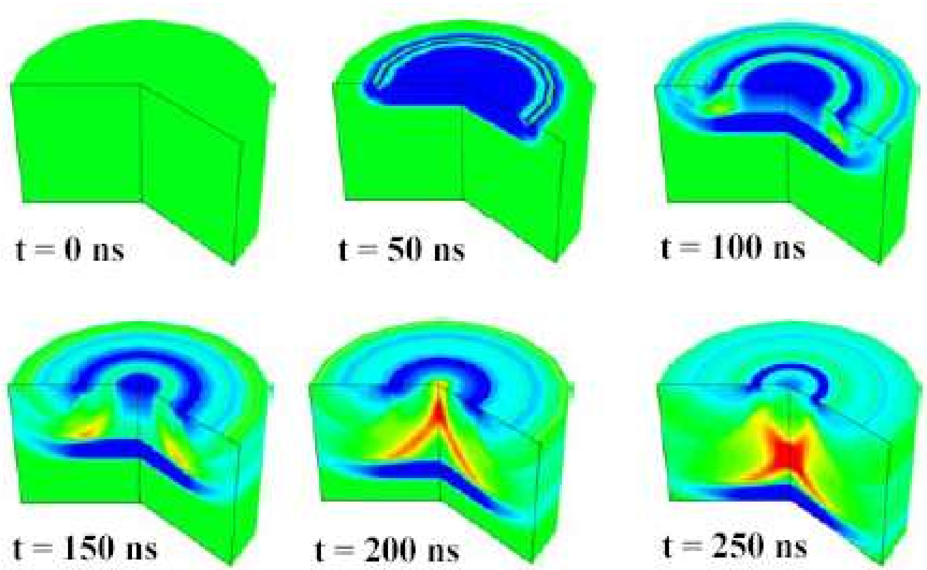


- Pulse by pulse dynamic simulation of LSP to predict residual stress and material interaction.
- Modelling of fatigue crack growth in residual stress fields.

FE Modelling of LSP Process & prediction of induced residual stress field - UPM

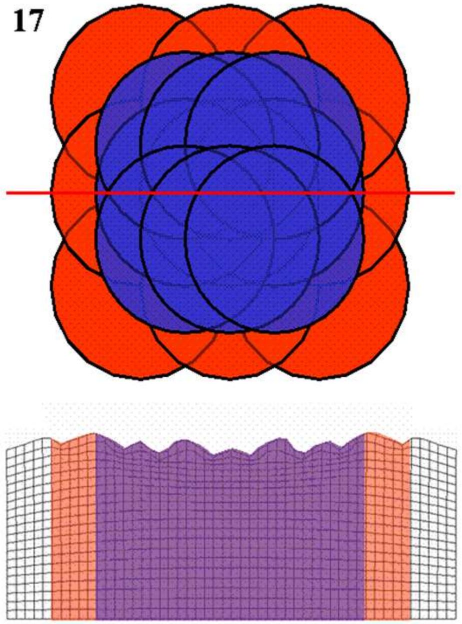


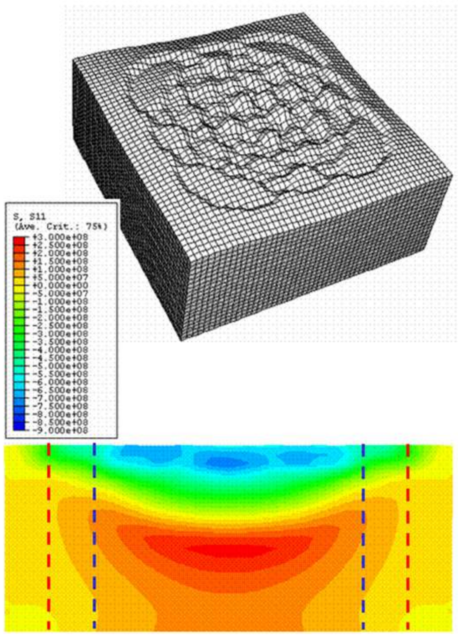
General scheme of the SHOCKLAS calculation system used for the modelling of the LSP processes.

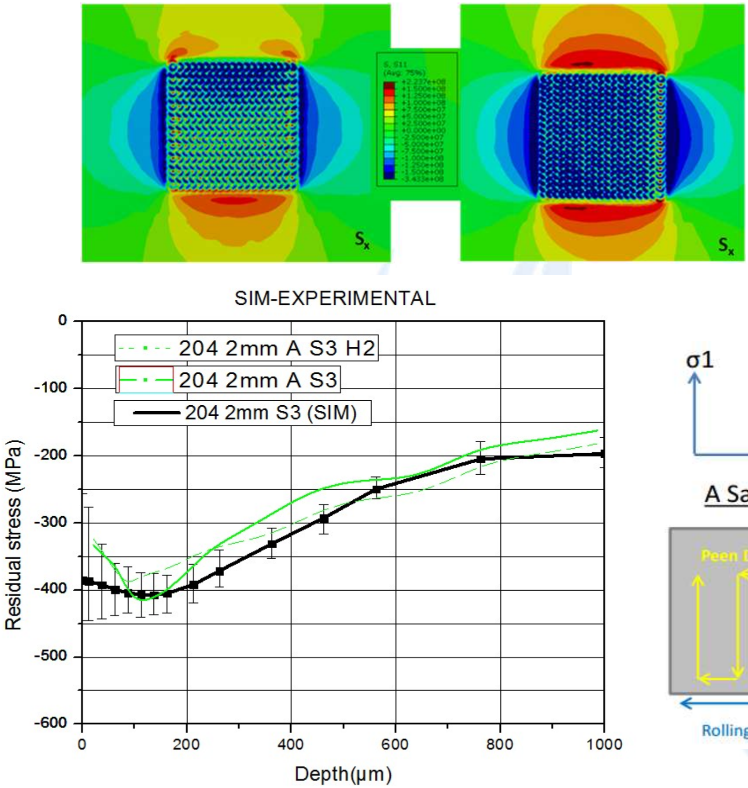


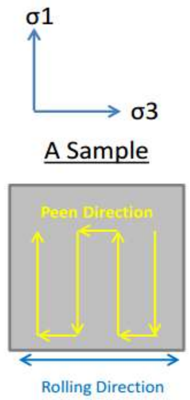
Sample result of the HARDSHOCK calculation system showing the temporal evolution of the thermo mechanical stresses in an Al target as a result of the incidence of a 10 ns FWHM, 8 GW/cm^2 peak intensity laser pulse with water as the confining medium.

FE Modelling of LSP Process & prediction of induced residual stress field - UPM









Sample result of the HARDSHOCK calculation system showing the final residual stress field and induced surface deformation after application of the LSP pulses following a typical surface-sweeping strategy.

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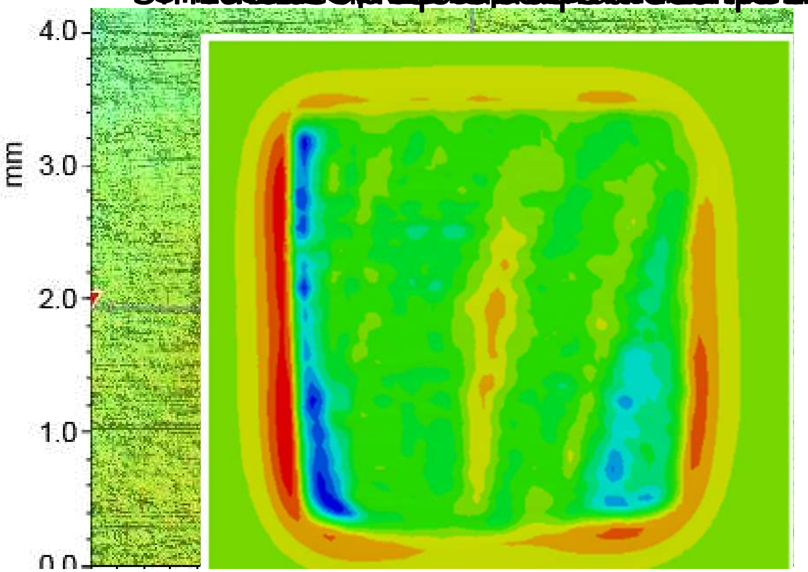
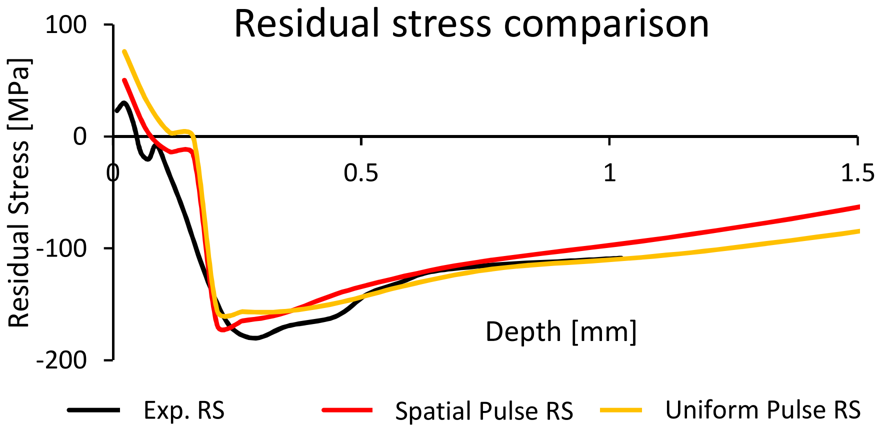
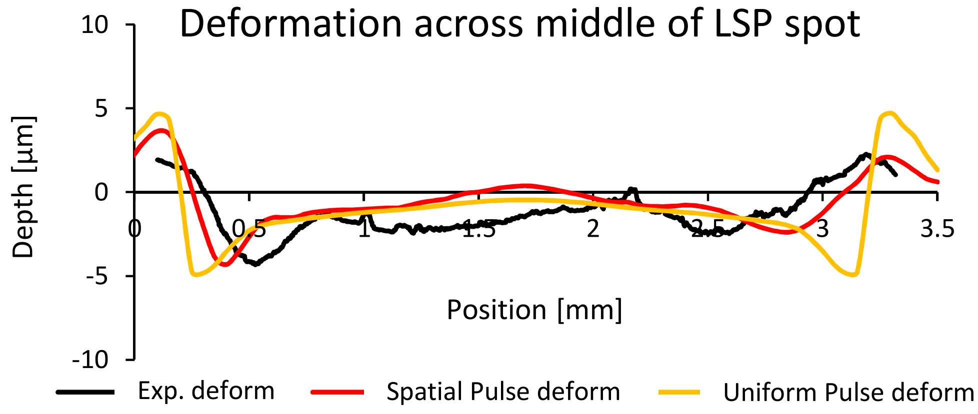
Laser Peening Simulation & Modelling

Dynamic LSP pulse by pulse simulations



- Using analytical methods to predict the plasma pressure, the effects of the LSP processing can be estimated through dynamic simulations of each LSP spot.
- The estimated surface roughness of the peened surface can be estimated by including the laser beam 2D spatial intensity profile.
- This method improves the accuracy of the LSP predictions.



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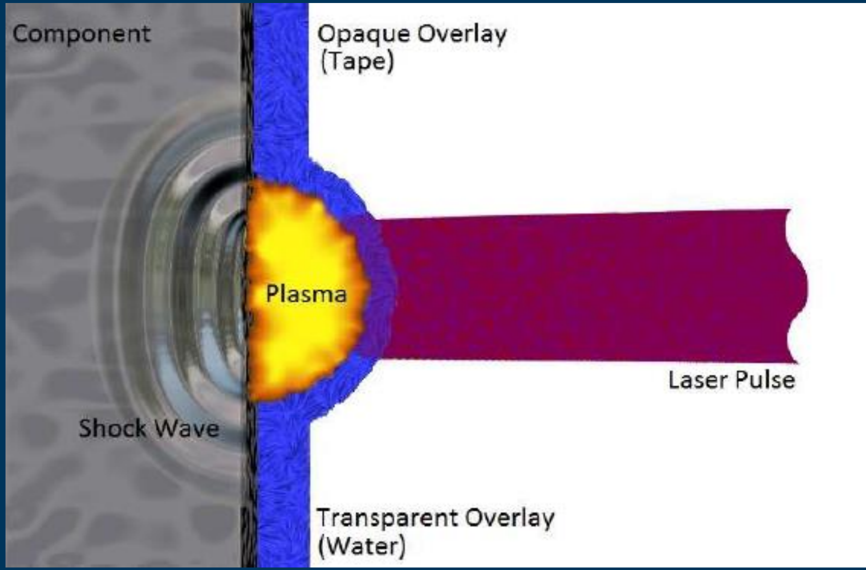

Residual Stress Generation Using Laser Shock Peening and Applications to Improve Aircraft Fatigue Performance

Presented by Dr. Niall Smyth
Coventry University

Tuesday, November 9, 2021