The effect of residual stress on fatigue and other failure mechanisms

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Engineering Integrity of Structures & Components Subjected to Degradation Mechanisms
Measurement services business unit of the Open University, founded in 2013. Dedicated to providing specialist stress/strain measurement services to clients worldwide. Specialise in the Contour Method of residual stress measurement and testing, which we combine with other techniques to provide the most reliable and useful information possible.
Our team

Prof John Bouchard, Director

Dr Foroogh Hosseinzadeh, Assistant Director

Dr Sanjoo Paddea, Executive Director

Dr Jeferson Oliveira, Business & Research Manager

Dr Ho Kim, Project Engineer

Damian Flack, EDM Specialist
Our Facilities

Large wire EDM (Wire Ø 0.1-0.25 mm)

CMM with laser triangulation

XRD with Sin² Ψ

Micro wire EDM (Wire Ø 0.02-0.1 mm)

Leica 3D confocal microscope

ICHD with StressCraft kit
• Fatigue is the degradation of a structure caused by the repeated application of subcritical stresses or strains.
• Fatigue crack growth process can be divided in nucleation and propagation.
• Nucleation characterises a microstructural degradation up to the formation of cracks.
• Propagation begins when these micro-cracks coalesce to form dominant macroscopic cracks.
Low-cycle vs. high-cycle fatigue

- LCF (typically <= 10,000 cycles)
  - Residual stress has little effect.
- HCF >> 10,000 cycles.
  - Applied stress generally does not induce bulk plastic deformation.
  - Can be highly sensitive to RS.

In HCF, residual stress can affect both nucleation and propagation phases of the fatigue crack growth.
Effect of Residual Stress on Fatigue

Nucleation

Residual stress will drive changes to the mean stress. Tensile RS will increase the effective mean stress, accelerating crack nucleation. Compressive RS will decrease the mean stress, slowing down the nucleation process.
Effect of Residual Stress on Fatigue

Propagation

RS will drive changes to the mean applied stress intensity factor ($K_{m,\text{eff}}$), thus changing the R ratio and it may also change the effective cyclic SIF ($\Delta K_{\text{eff}}$).

**Tensile RS** will increase the effective mean SIF, which may prevent crack closure, increasing crack growth rate. It also increases $K_{\text{max}}$, which can speed up crack growth and prevent crack arrest.

**Compressive RS** decreases the mean SIF, and may reduce $\Delta K_{\text{eff}}$, significantly slowing down or even halting crack growth.

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Effect of Residual Stress on Fatigue

Propagation

- **Tensile RS** can prevent crack closure.
- It may also prevent crack arrest.
- Or simply speed up the crack growth rate.
- **Compressive RS** reduce the $K_{\text{max}}$, and may also reduce the $\Delta K_{\text{eff}}$, which may reduce or even halt crack growth.
RS Effect on Other Failure Mechanisms

Stress corrosion cracking (SCC)
• Tensile residual stresses increases corrosion rates.
• While compressive residual stresses can slow down the process.

Buckling
• Residual stresses may cause uneven plastic deformations, increasing the risk of buckling.

Distortion
• Residual stresses can cause unacceptable distortions during manufacture or operation.
Residual stresses are self-equilibrating stresses retained within a body in the absence of external forces.

They arise due to shape misfits (eigenstrains) within materials and are present in virtually all solids.

They are divided into three types:

- Type I macrostresses: continuum mechanics
- Type II microstresses: intergranular
- Type III microstresses: intragranular.

The main mechanism for changes in crack growth rate is crack closure, thus residual stresses of type I are the most important for fatigue analyses.
Residual stress engineering offers a great opportunity to add value to structures with little to no added production costs, in some cases, production can become cheaper.

Industries that have considered RS and others that are starting to realise this potential include:

• Aerospace
• Power (nuclear and non-nuclear)
• Advanced manufacturing
• Offshore
• Medical
• Rail
• Automotive
Residual stress engineering is all about optimising the manufacturing processes to enhance the mechanical performance of the structure by modifying the RS.

In order to understand how the manufacturing processes affect the residual stresses, it is necessary to measure these stresses, often after each manufacturing step.

Here I will present the main techniques that we use for characterising the RS.

Each has its advantages and limitations, but being able to combine them gives us a significant advantage.
Contour Method - Basics

Undisturbed body which contains residual stress

Sever body into 2 parts

Map of residual stress on surface where severed

Data analysis
Contour Method - Advanced

Multiple Cut Contour

Multiple Method Contour

Electropolishing + XRD
Why the Contour Method?

2D map & can measure multiple residual stress components

- Longitudinal
- Transverse
- Normal

Not sensitive to microstructural variations

Can be applied to small, large and complex structures
A selection of examples..

Simple welded block

Pipes/Dissimilar metal weld

Small sample

Complex sample

Additive manufacturing

Near surface stresses
Dissimilar metal weld
Dissimilar metal weld

Flow element of a nuclear reactor
Inconel 600 - Carbon steel outlet feeders (SA-106B)

Susceptible to Primary Water Stress Corrosion Cracking (PWSCC), driven principally by welding residual stresses.
Dissimilar metal weld
Dissimilar metal weld

Cutting direction
Dissimilar metal weld

Welding direction

View from SA-106 Grade B end

S, S33
(Avg: 75%)

-4.539e+02
+4.000e+02
+3.333e+02
+2.667e+02
+2.000e+02
+1.333e+02
+6.667e+01
-4.578e-05
-6.667e+01
-1.333e+02
-2.000e+02
-2.667e+02
-3.333e+02
-4.000e+02

3 o’clock

9 o’clock
Dissimilar metal weld

Weld centre-line

HAZ

Cut 4

Cut 5
Dissimilar metal weld
Dissimilar metal weld
Dissimilar metal weld

SA-106 Grade B

Alloy 600

Weld H
Dissimilar metal weld

- Measured Contour Method
- Predicted Isotropic Hardening
- Predicted Averaged Isotropic+Kinematic
- Predicted Kinematic Hardening

Stress Map

S, S\textsubscript{33} (Avg: 75%)

- +4.0e+08
- +3.0e+08
- +2.0e+08
- +1.0e+08
- +0.0e+00
- -1.0e+08
- -2.0e+08
- -3.0e+08
- -4.0e+08
Additive manufacturing

Additive layer

Base plate
Additive manufacturing

1st contour cut to measure longitudinal stress
Additive manufacturing
Additive manufacturing
Additive manufacturing
Additive manufacturing

- XRD + Contour Method
- Multiple Cut

Stress (MPa) vs. Distance from top surface (mm)
Laser peening

Low Pressure Steam turbine rotor

→

turbine blade

→

Fir tree attachment location

Coupon with coating before processing

LSP Coupon after removal of coating
Laser peening

LSP Surface

Sample thickness co-ordinate (mm)

Distance across sample LSP surface (mm)
Laser peening
Laser peening

Residual Stress (MPa) vs. Depth Below Surface (mm)

- SXRD
- XRD + Electro-polishing
- Contour Measurement
- Hole drilling
- Neutron Diffraction
Laser Hybrid weld

Map of longitudinal stress
Laser Hybrid weld

Stress [MPa] vs. Distance from weld centre-line - 8mm below the groove [mm]

- Blue line: Longitudinal - Simulation
- Red line: Longitudinal - Contour method
Laser Hybrid weld

![Stress Map](image)

**Graph:**
- **Y-axis:** Stress [MPa]
- **X-axis:** Distance from the top of the weld [mm]

- **Lines:**
  - Blue: Longitudinal - Simulation
  - Green: Longitudinal - DHD method
  - Red: Longitudinal - Contour 2

**Legend:**
- Laser Hybrid weld

**Note:**
- The graph illustrates the stress distribution along the distance from the top of the weld.
Swiss high voltage cable
Swiss high voltage cable
Swiss high voltage cable
Swiss high voltage cable
Femoral knee implant
Femoral knee implant

Material: ASTM F75, a Cobalt-Chrome-Molybdenum alloy.
Why: Excellent wear, corrosion and bio-compatibility properties.
Problem: Distortion when cutting ligaments and shot blasting.
Femoral knee implant

Shot-blasting used to clean the parts, i.e. remove the casting shell.

Uses a centrifugal-wheel to accelerate stainless steel shots at the femorals whilst they are tumbled on a rubber belt.

Before

After
Femoral knee implant

As-cast

After shot blasting
Nuclear waste canister
Nuclear waste canister

![Graph showing stress (MPa) vs. distance from outer surface (mm) for Contour Method and DHD.](Image)

- Stress (MPa) on the y-axis.
- Distance from outer surface (mm) on the x-axis.

- Red line represents Contour Method.
- Black line represents DHD.
Wire arc additive manufacturing
Wire arc additive manufacturing
Wire arc additive manufacturing

As-deposited

Rolled

Rolled & Laser Processed
THANK YOU

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