LOW CYCLE FATIGUE PREDICTIONS OF A SPACE THRUSTER BUILT WITH A NEW REFRACTORY HIGH ENTROPY ALLOY

S. Valvano[a], G. Canale[b], A. Maligno[c], P. Wood[d]

[a] Associate Professor at IISE, University of Derby, s.valvano@derby.ac.uk
[b] Mechanical Integrity Engineer, Rolls-Royce Derby, giacomo.canale@rolls-royce.com
[c] Professor at IISE, University of Derby, a.maligno@derby.ac.uk
[d] Professor at IISE, University of Derby, p.wood7@derby.ac.uk

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Institute for Innovation in Sustainable Engineering (IISE)

Dr Stefano Valvano
Dr Giacomo Canale
Professor Angelo Maligno
Professor Paul Wood

Work motivation

- Directional thrusters are designed to provide force for short time periods.
- New generation of thrusters could be made using a High Entropy Alloy (HEA).
- Predicting fatigue damage initiation for this kind of metallic structure subjected to cyclic loads is important.
- Design for fatigue resistance relies on empirical with high financial costs.
- Unified Mechanics Theory (UMT) will be used to predict fatigue damage initiation of a material system without having experimental fatigue data.

B20 Thruster

Small satellite applications

Material currently used is Inconel 718

Unified Mechanics Theory (UMT)

C. Basaran, “Introduction to Unified Mechanics Theory with Applications”, Springer, 2021

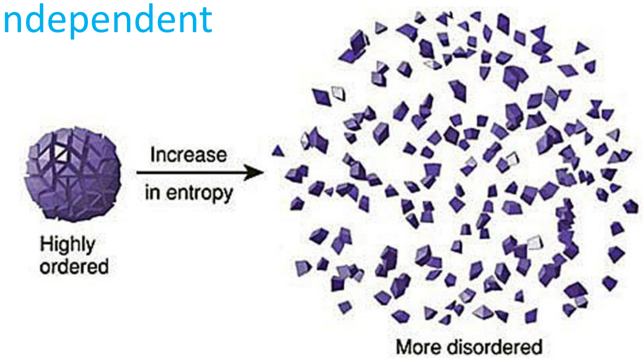
Why Entropy?

i. Entropy can model multiple competing degradation processes leading to damage

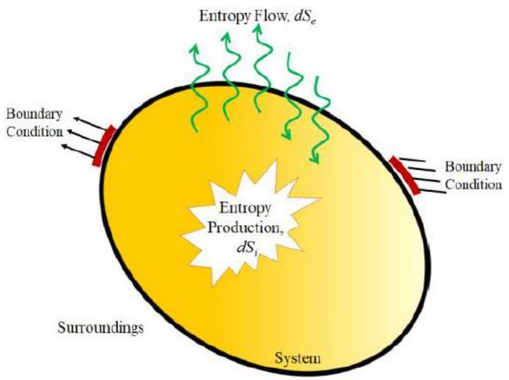
ii. Entropy is independent of the path to failure ending at similar total entropy at failure

iii. Entropy accounts for complex synergistic effects of interacting degradation processes

iv. Entropy is scale independent



Entropy increases in a non-reversible process



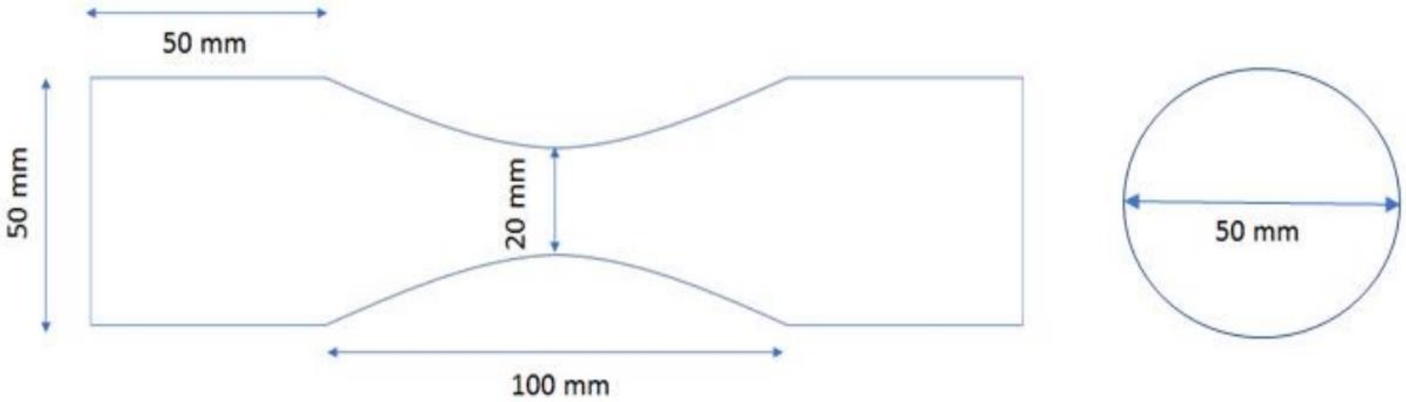
Entropy exchange in an open system. dSe is entropy flow through the boundaries of the open system and dSi is the entropy production within the open system.

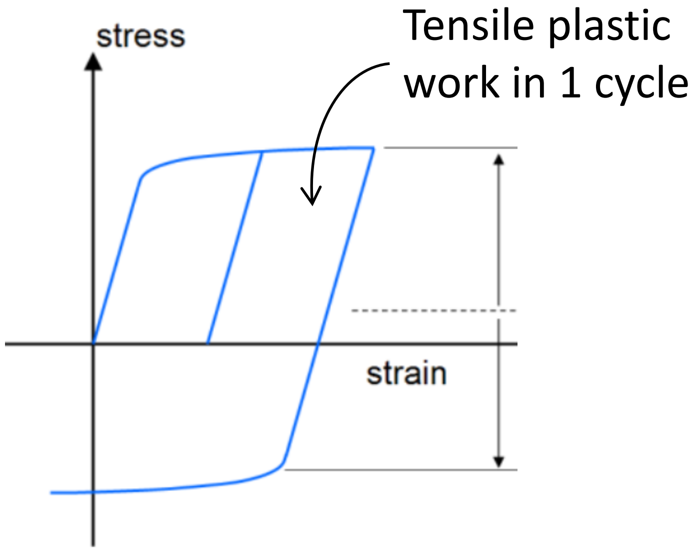
Sources of Dissipation

$$\sigma = \overbrace{\frac{1}{T^2}\boldsymbol{J}_q . \nabla T}^{\text{Thermal}} + \overbrace{\Sigma_{k=1}^{n}\boldsymbol{J}_k\left(\nabla\frac{\mu_k}{T}\right)}^{\text{Diffusion}} + \overbrace{\frac{1}{T}\boldsymbol{\tau} : \dot{\epsilon}_p}^{\text{Plastic deformation}} + \underbrace{\frac{1}{T}\Sigma_{j=1}^{r} v_j\, A_j}_{\text{Chemical reaction}} + \underbrace{\frac{1}{T}\Sigma_{m=1}^{h} c_m \boldsymbol{J}_m(-\nabla\psi)}_{\text{External fields}}$$

Entropy can be used to predict fatigue damage in materials

Assessment of UMT using forge grade stainless steel tensile and low cycle fatigue (LCF) test results

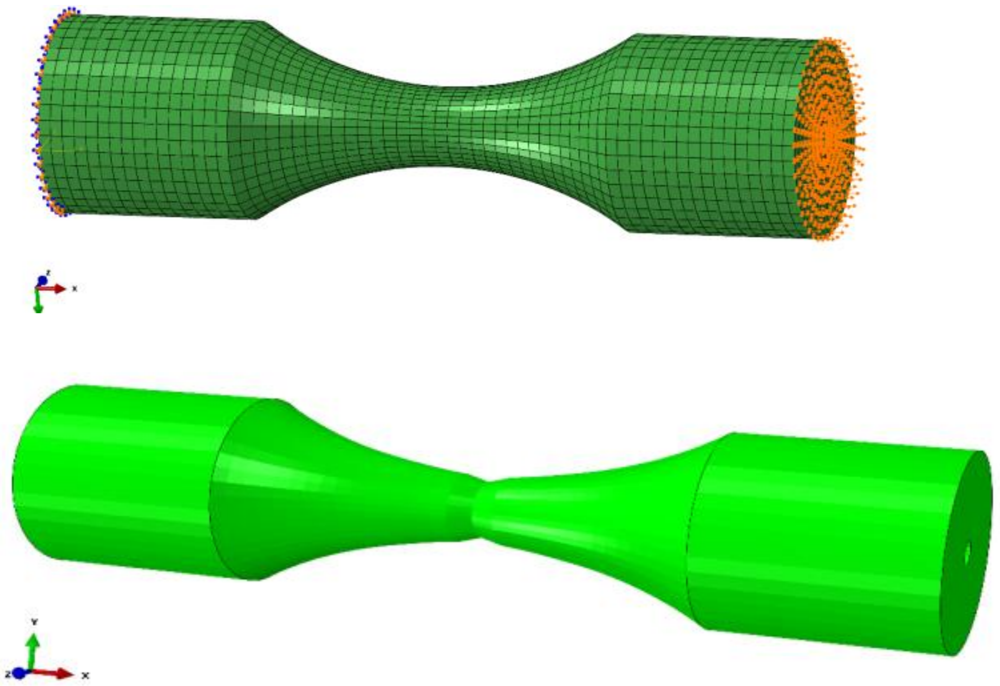


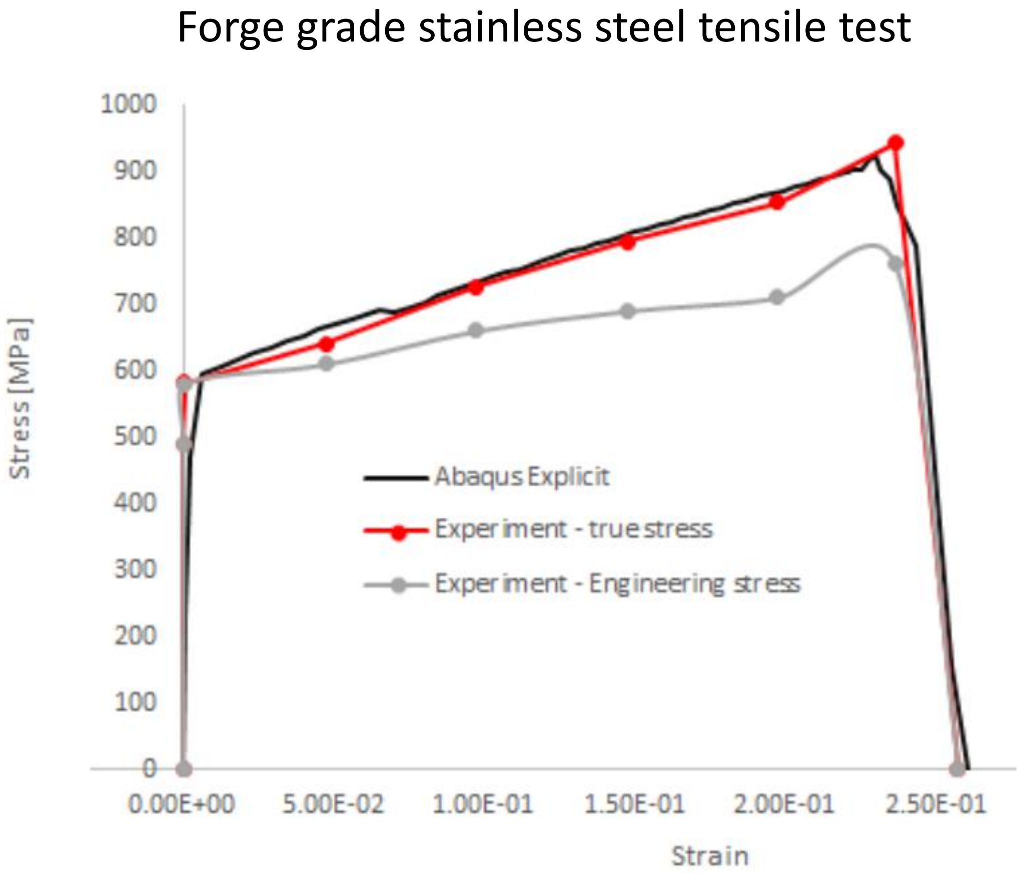


Development of elastic and plastic strain under LCF

Giacomo Canale, Marcello Lepore, Sara Bagherifard, Mario Guagliano, Angelo Maligno,
An experimental validation of unified mechanics theory for predicting stainless steel low and high cycle fatigue damage initiation.
Forces in Mechanics, https://doi.org/10.1016/j.finmec.2022.100162.

ABAQUS FE Model of Tensile Test and Quasi-static Simulation of LCF Sample





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Prediction of Fatigue Damage Initiation under LCF using UMT

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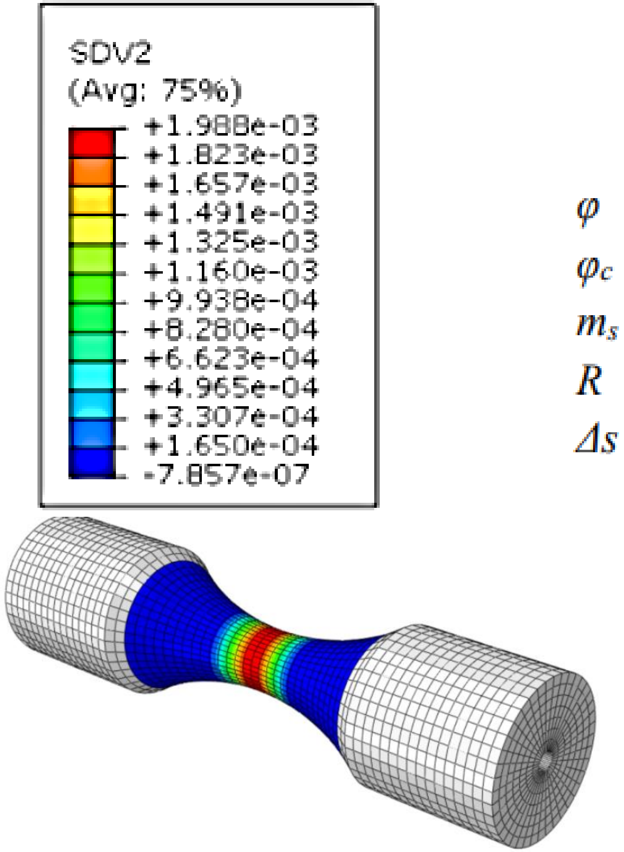

Algorithm of Jamal coded in VMAT

$$\varphi = \varphi_0 \left[1 - exp\left(-\Delta s \frac{m_s}{R}\right)\right]$$

Damage model with value between 0 and 1 on reaching 1, damage is initiated

φ	is the TSI (Thermodynamic State Index)
φ_c	is a fitting parameter defined for the specific problem
m_s	is the molar mass of the metal
R	is the gas constant
Δs	is the total change in entropy.

$$\Delta s = \frac{1}{\rho T} \int_{t1}^{t2} \sigma * d\varepsilon^p$$

T	is the material temperature
t_1	is the time at the beginning of the fatigue cycle
t_2	is the time at the end of the fatigue cycle
ε^p	is the plastic strain

$$\varepsilon^p = \varepsilon^{tot} - \frac{\sigma_0}{E}$$

ε^p	is the total strain (elastic and inelastic)
σ_0	is the yield stress.

$$N = \frac{1}{\varphi}$$

N	is the number of cycles to damage initiation

Noushad Bin Jamal M., Aman Kumar, Chebolu Lakshmana Rao and Cemal Basaran, "Low Cycle Fatigue Life Prediction Using Unified Mechanics Theory in Ti-6Al-4V Alloys", Entropy 2020, 22, 24; doi:10.3390/e22010024.

Giacomo Canale, Marcello Lepore, Sara Bagherifard, Mario Guagliano, Angelo Maligno,
An experimental validation of unified mechanics theory for predicting stainless steel low and high cycle fatigue damage initiation. Forces in Mechanics, https://doi.org/10.1016/j.finmec.2022.100162.

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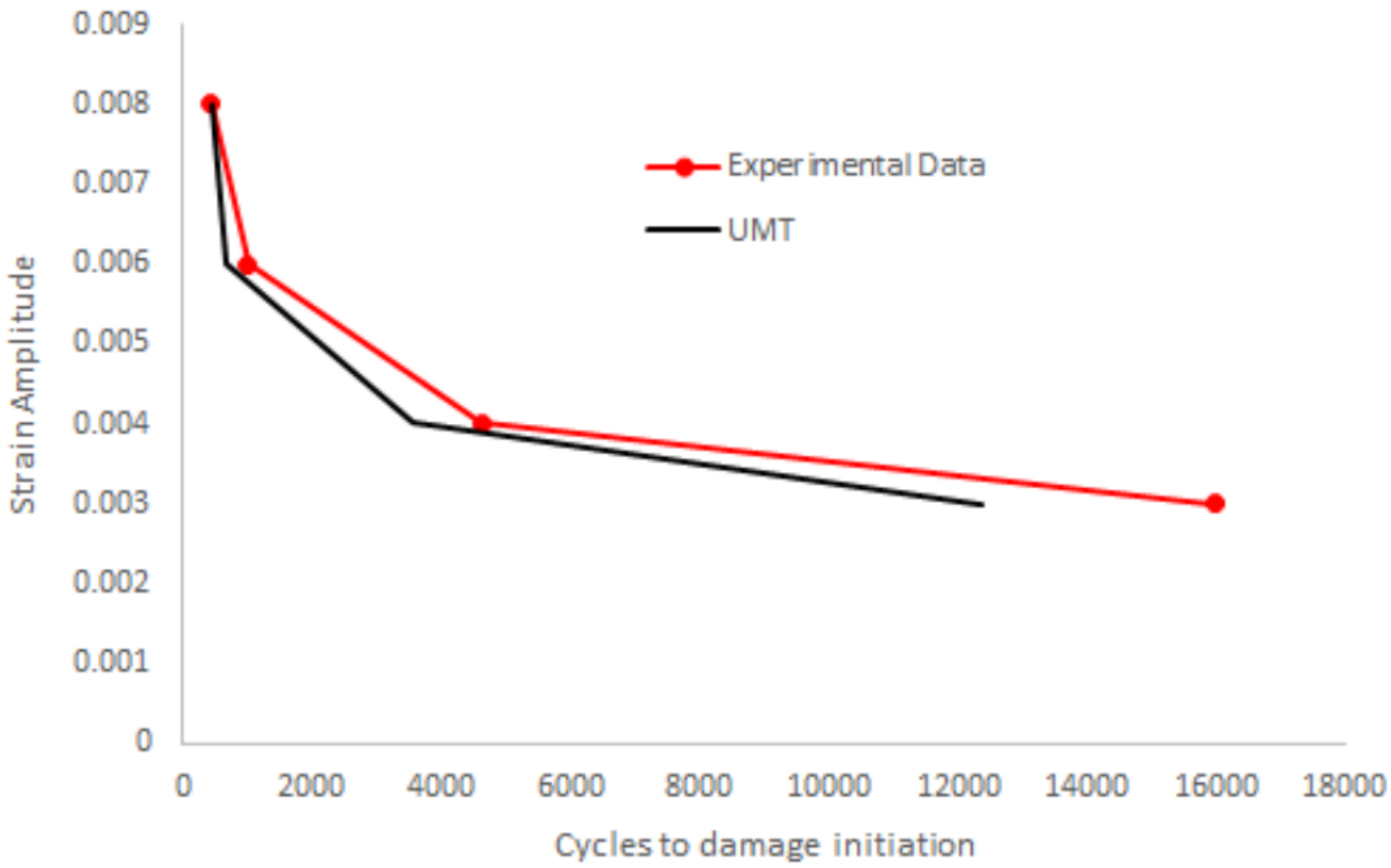
Assessment of UMT to Predict LCF Damage Initiation



Assumptions:
Plastic hysteresis in each cycle is stable
Therefore only one cycle is modelled

Using $N = \frac{1}{\varphi}$ predicts number of cycles to LCF damage initiation

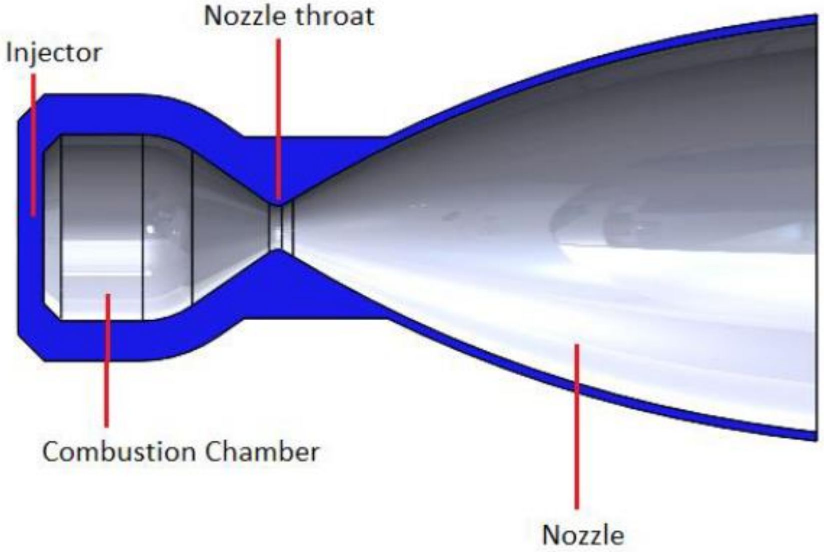
Thermo-mechanical Simulation of B20 Thruster

Figure 1: DA13-1

Design based on the following materials:

- Inconel 718
- High Entropy Alloy (Niobium based)

Blue = Wall material



For each material, determine how many ignition cycles lasting 5s can be performed before LCF fatigue damage initiation occurs?

Material properties

Inconel 718

Mechanical Properties

Temperature [°C]	Young Modulus [GPa]	Density [kg/m^3]	Poisson's Ratio
0	205	8190	0.3
650	163	7941	0.283
800	150	7884	0.31

Quasi-static Plastic Behaviour

Stress [MPa]	**Plastic Strain**	**Temperature [°C]**
950	0	0
1000	0.01	0
1100	0.02	0
1200	0.14	0
330	0	650
400	0.01	650
440	0.02	650
450	0.14	650

Thermal Properties

Temperature [°C]	Thermal Conductivity [W/m/°C]	Specific Heat [J/g/°C]	Thermal Expansion (1/°C)
0	8.8	0.43	1.3E-05
450	18	0.52	1.44E-05
750	24	0.61	1.6E-05

Material properties

High Entropy Alloy (HEA) - Designed in ATLAS

Mechanical Properties

Young Modulus [GPa]	Density [kg/m³]	Poisson's Ratio
230	11590	0.3

Quasi-static Plastic Behaviour

Stress [MPa]	**Plastic Strain**	**Temperature [°C]**
800	0	0
900	0.05	0
1000	0.1	0
1050	0.2	0
700	0	800
780	0.05	800
820	0.1	800
810	0.2	800

Thermal Properties

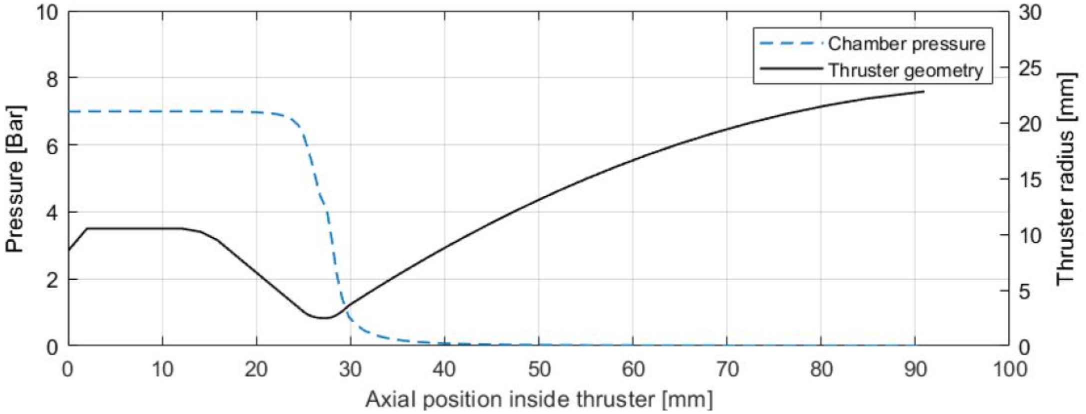
Temperature [°C]	Thermal Conductivity [W/m/°C]	Specific Heat [J/g/°C]	Thermal Expansion (1/°C)
0	18	0.21	6.98E-06
400	18	0.228	7.94E-06
800	18	0.25	8.91E-06

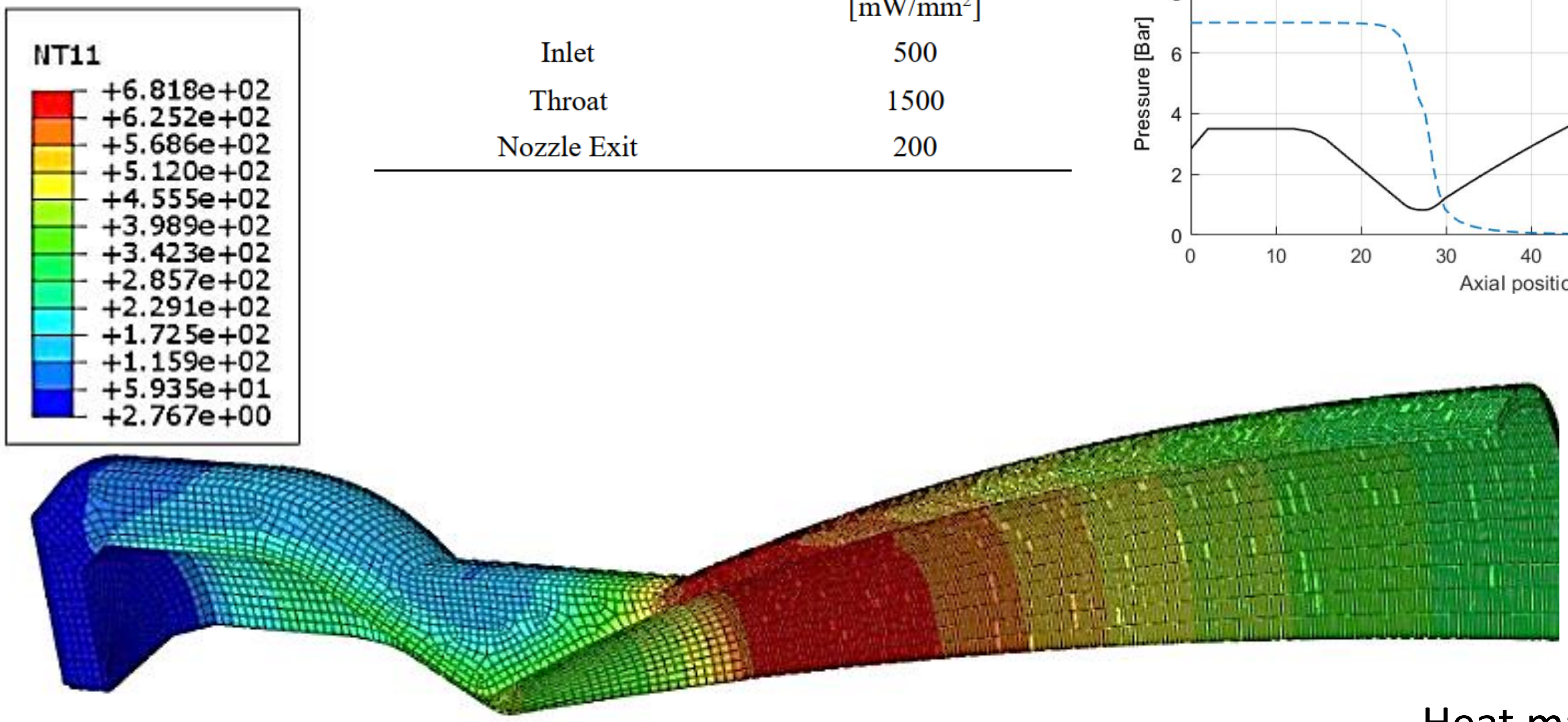
Model of B20 Thruster (Inco 718)

Thermal Flux

Axial Position	Heat Flux [mW/mm^2]
Inlet	500
Throat	1500
Nozzle Exit	200

Mechanical Load

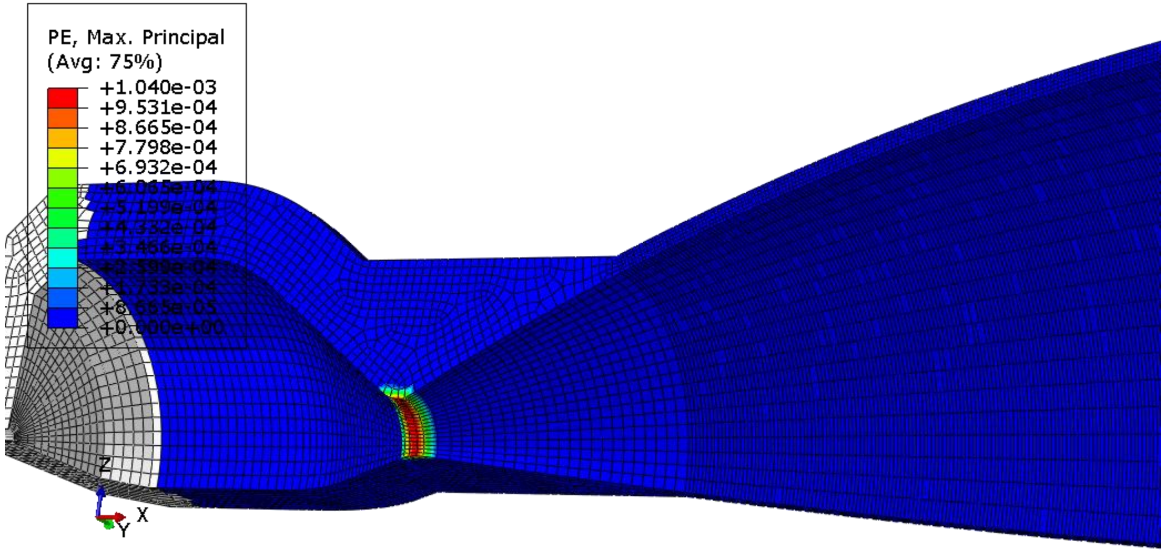




Heat map after 5s ignition

Predicted Max, Min Stress and Strain for both Materials

	Principal Plastic Strain	Temperature [°C]	Principal Stress [MPa]
Max strain Inco718	0.001	0	246
Min strain Inco718	-0.015	425	-705
Max strain HEA	0.00054	0	80
Min strain HEA	-0.00008	1034	-11



Plastic strain contours for Inco718

Strain versus Cycles to Failure (Inco 718)

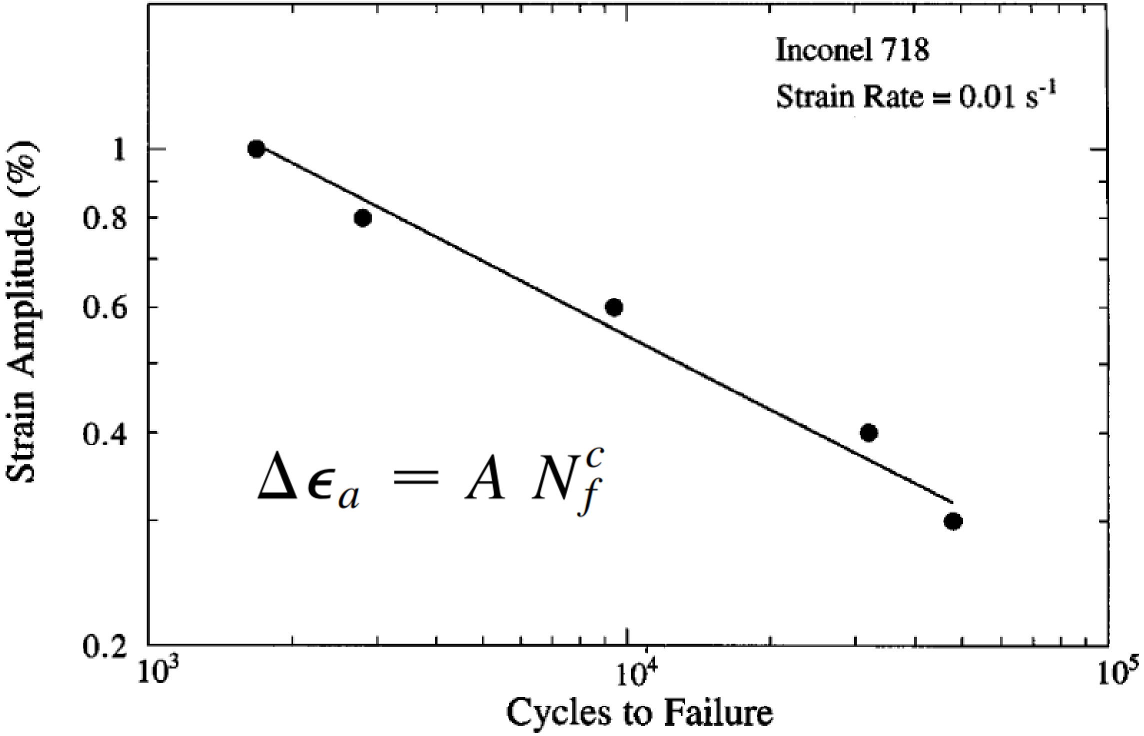
Empirical (traditional) approach

Walker equivalent medium strain:

$$\epsilon_w = (\epsilon_{max} - \epsilon_{min}) * \left(\frac{\sigma_{max}}{\sigma_{max} - \sigma_{min}}\right)^{(1-\gamma)}$$

Stress and strain are input from B20 simulation for Inco718

γ is the Walker exponent (0.47 in this example).



Low Cycle Fatigue Damage Initiation Predicted

UMT approach

$$\varphi = \varphi_0 \left[1 - exp\left(-\Delta s \frac{m_s}{R}\right)\right]$$

LCF damage initiation based on the entropy generation

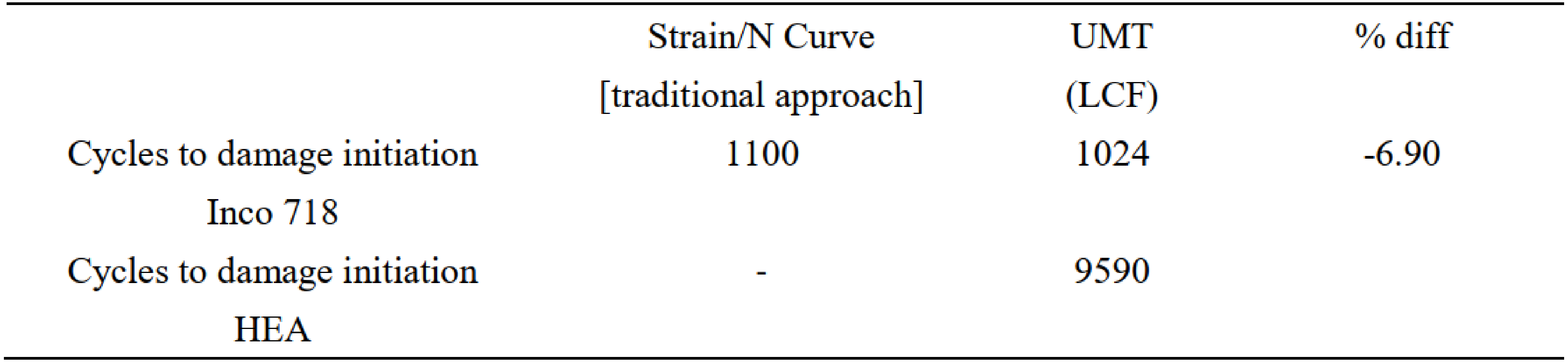
$$\Delta s = \frac{1}{\rho T} \int_{t1}^{t2} \sigma * d\varepsilon^p$$

Load cycle divided in small isothermal steps

$$\varepsilon^p = \varepsilon^{tot} - \frac{\sigma_0}{E}$$

$$N = \frac{1}{\varphi}$$

Comparing Predicted Cycles to Fatigue Damage Initiation in Thruster using Strain Based Approach and UMT for Inco 718



	Strain/N Curve [traditional approach]	UMT (LCF)	% diff
Cycles to damage initiation Inco 718	1100	1024	-6.90
Cycles to damage initiation HEA	-	9590	

Stress and strain due thermal loading dominates over mechanical

P. Wood, M. J. Qarni, J. Chippendale, A. Rosochowski. Numerical study on the effect of the thermo-mechanical properties of alloys on the behaviour of super plastic forming tools, 2014. https://doi.org/10.1002/mawe.201400289

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Conclusions

- UMT can make fatigue predictions when test data are not yet available.
- UMT does not take into account surface finish, fundamental in fatigue assessments.
- In this work the entropy generation is mechanical based.
- In future work the thermal contribution will be evaluated in the entropy calculation for damage initiation.

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University of Derby, Kedleston Road, Derby, DE22 1GB
T +44 (0)1332 591044 **E** opendays@derby.ac.uk

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