Finite element implementation of SC11-TN coupled damage law for porous orthotropic hcp materials

University of La Frontera
Faculty of Engineering and Sciences
Department of Mechanical Engineering

LIÈGE université Sciences Appliquées

Carlos Rojas-Ulloa[1] Víctor Tuninetti[1] Anne Marie Habraken[2]

[1]: Department of Mechanical Engineering, University of La Frontera, Temuco, Chile.
[2]: ArGEnCo Department, MSM team, University of Liège, Liège, Belgium.

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Abstract

In this research, the new coupled SC11 damage model is extended and validated adding both micromechanical laws of nucleation and coalescence to describe the damage mechanisms of Ti-6Al-4V alloy. An experimental quasi static characterization for Ti-6Al-4V specimens was performed considering data from previously published in-situ X-ray tomography and novel Scanning Electron Microscopy (SEM) measurements. The implementation of SC11-TN extended damage law into the finite element (FE) research software Lagamine and was validated by benchmarking experimental and numerical results. The prediction capabilities of SC11-TN exhibited for large strains are in good agreement with experimental results, while the near-fracture strain results open new doors for further enhancement.

SC11-TN coupled damage law

The SC11-TN extended coupled damage law is of the form: [1]

$$\Phi(\boldsymbol{\sigma}, \bar{\epsilon}^p) = \left[\frac{\bar{\Sigma}_{CPB06}}{\sigma_y}\right]^2 + 2q_1 D\cosh\left[\frac{3q_2(\Sigma_m - X_m)}{h\sigma_y}\right] - 1 - q_3 D^2 \leq 0$$

Where:

- $\bar{\Sigma}_{CPB06}$ is the CPB06 effective stress:[2]
- σ_y is the yield stress, modeled as the Voce's isotropic hardening law:
- D is the effective porosity ratio.

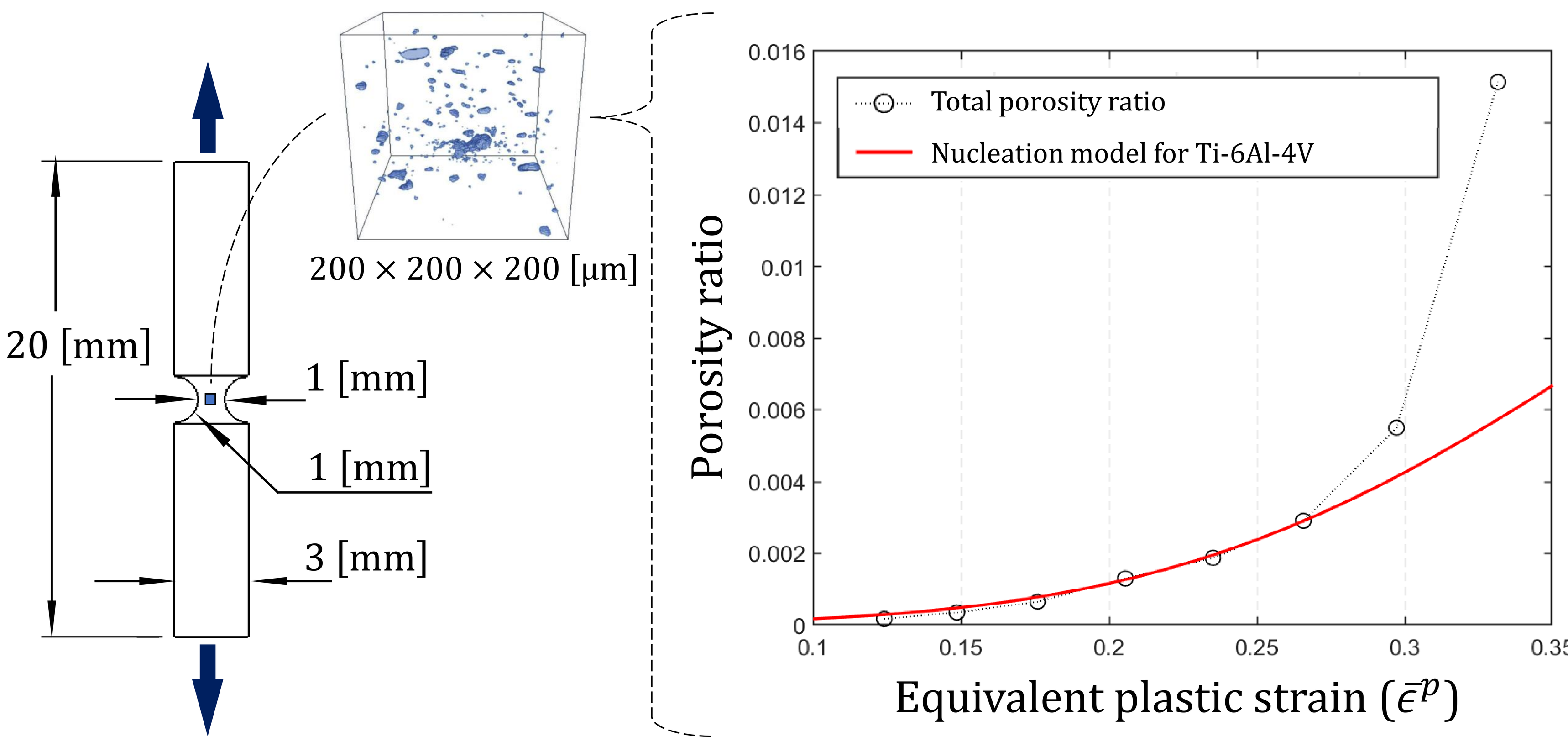
The increment of D is ruled by growth, nucleation and coalescence of voids as applied. The analytical formulations for each damage mechanism in their incremental configuration are:

- Growth: $\dot{f}_g = (1 - q_1 D)tr(\dot{\boldsymbol{\epsilon}}^{\mathbf{p}})$
- Nucleation: $\dot{f}_n = \dfrac{F_N}{S_N\sqrt{2\pi}}\exp\left[-\dfrac{1}{2}\left(\dfrac{\bar{\epsilon}^p - \epsilon_N}{S_N}\right)^2\right]\dot{\bar{\epsilon}}^p$
- Coalescence: $\dot{D} = \begin{cases} \dot{f} = \dot{f}_g + \dot{f}_n & if \quad f \leq f_{cr} \\ \dfrac{(f_u - f_{cr})}{(f_F - f_{cr})}\dot{f} & if \quad f > f_{cr} \end{cases}$

Damage characterization on Ti-6Al-4V

In-situ X-ray tomography[3]

This experimental imaging technique results in a continuous depiction of the porosity ratio measurement within a selected volume sample.

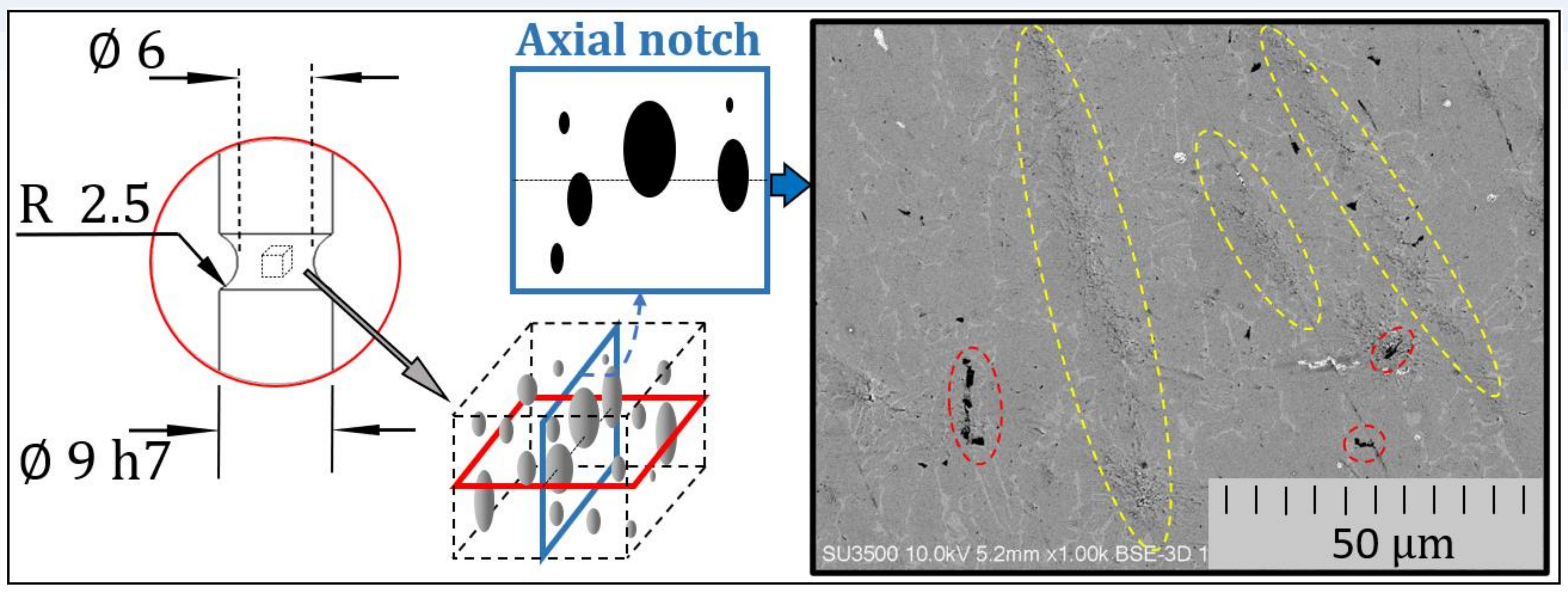


As a result, the parameters for modeling the nucleation of voids were successfully identified:

F_N	S_N	ϵ_N
0.016	0.12	0.375

Near-fracture SEM imaging

In order to identify the damage mechanisms patterns and the coalescence model parameters, SEM images were captured in transversal and axial samples from Ti-6Al-4V notched bar submitted to a near-fracture tensile test.

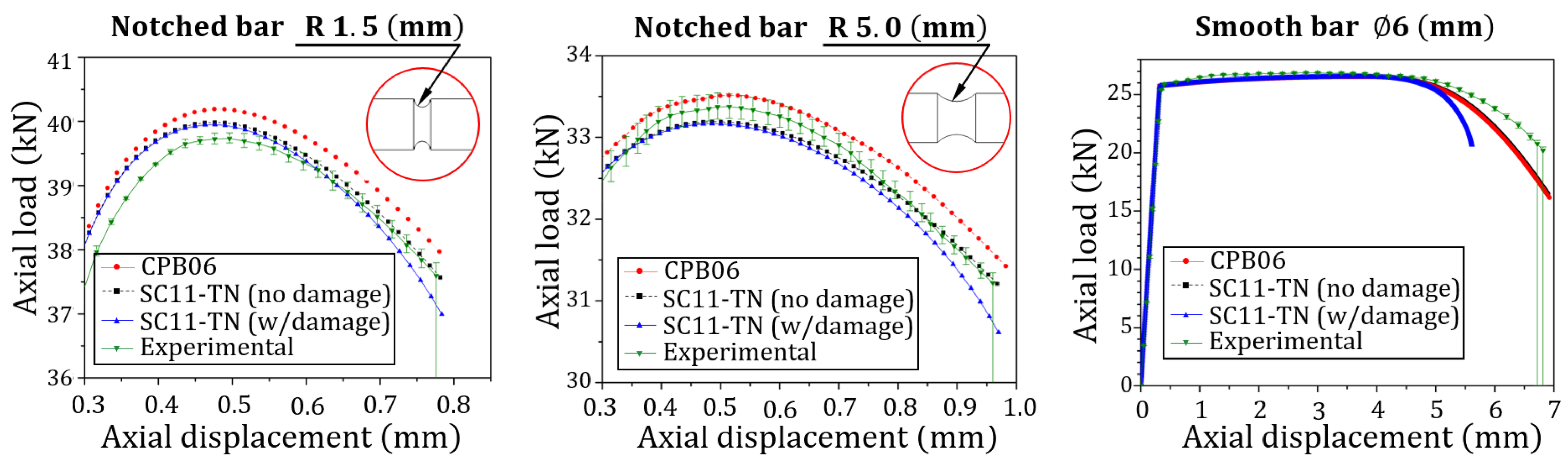


The parameters for modeling the coalescence of voids, and the initial porosity ratio f_0 are :

f_0	f_u	f_F	f_{cr}
5×10^{-5}	0.40	0.20	0.003

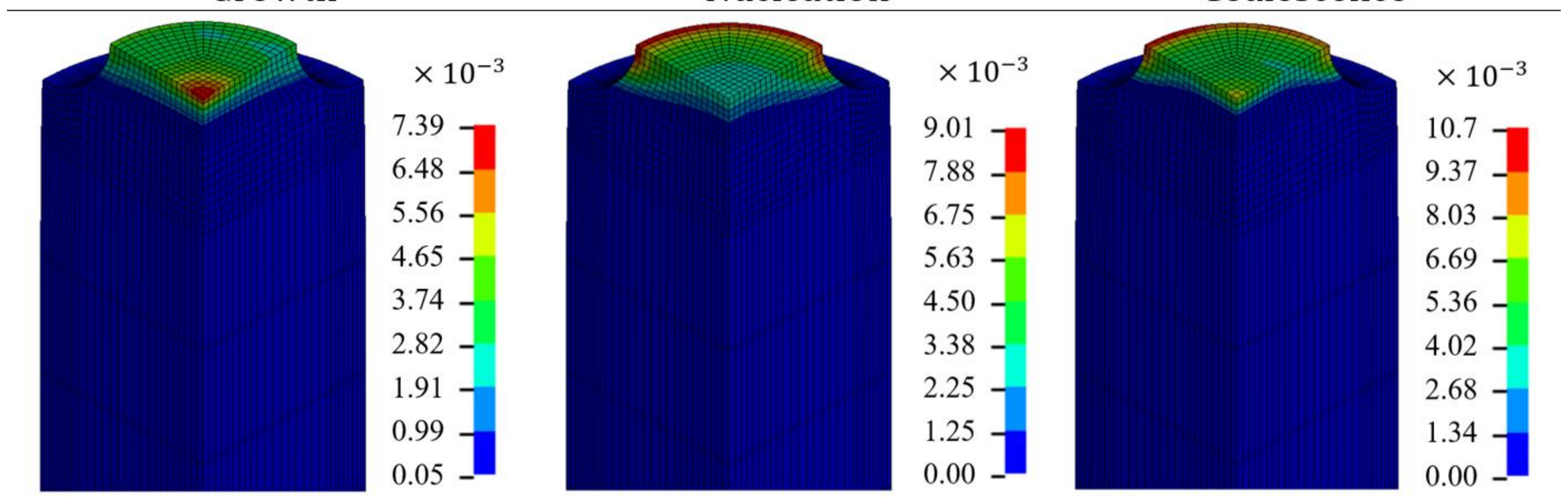
Numerical results and validation

The validation of the recently implemented SC11-TN damage law was carried out by benchmarking the numerical and experimental load-displacement curves. In addition, the previously implemented and validated[4] CPB06 yield criterion[2] is also considered.



As the highest triaxiality specimen, the R 1.5 (mm) notched bar is hereafter assessed for a damage analysis in fracture configuration.

Effective porosity ratio contributions in Ti-6Al-4V notched bar R1.5 (mm) due to:



Conclusions

- The continuum micromechanics based SC11-TN model has proven to be suitable for describing the elastoplastic and damage behavior of Ti-6Al-4V alloy.
- In comparison with the CPB06 yield criterion, the SC11-TN capability of modeling distortional hardening through the increment of effective porosity ratio has proven to be physically accurate.
- In order to enhance the prediction ability of the SC11-TN damage model, further work must be focused on performing new identification procedures of the elastoplastic and damage parameters in one step, acknowledging near-fracture strains. In addition, neural networks approach could be explored.

References

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