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## Thermomechanical modeling of distortional hardening fully coupled with ductile damage under non-proportional loading paths

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### ABSTRACT:

In order to capture, as accurately as possible, the complex physical effects during texture evolution of high strength materials subject to non-proportional loading paths at high temperature, a macroscale thermo-mechanical model is developed. This model accounts, in the framework of large inelastic strains, for anisotropic thermo-elasto-viscoplasticity with isotropic, kinematic and distortional hardenings strongly coupled with isotropic ductile damage. Following the footsteps of François (2001), induced anisotropy is modeled to predict the behavior under complex non-proportional loading paths. The initial plastic anisotropy and tension-compression asymmetry are considered through two different temperature dependent fourth-rank tensors. The full coupling of thermo-mechanical model with ductile damage is considered based on the total energy equivalence assumption. The proposed constitutive equations are implemented into finite element code ABAQUS/Explicit using appropriate user subroutine VUMAT. The local integration algorithm (at each Gauss point) of the developed model is based on a fully-implicit scheme. Applications have been made to three different materials (aluminum alloy AU4G T4 (2024), titanium alloy Ti-6Al-4V and magnesium alloy AZ31) to demonstrate the predictive capabilities of the proposed model.

*Keywords:* thermomechanical coupling; anisotropy; asymmetry; distortional hardening; damage

### Notation

-First-rank tensor or vector:  $\vec{x}, x_i$ ,

-Second-rank tensor:  $\underline{x}, x_{ij}$ ,

-Fourth-rank tensor:  $\underline{\underline{x}}, x_{ijkl}$ ,

-Second rank identity tensor:  $\underline{1}, \delta_{ij}$ ,

-Fourth-rank symmetric identity tensor:  $\underline{\underline{I}}, I_{ijkl} = \frac{1}{2}(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk})$ ,

-Fourth-rank symmetric deviatoric identity tensor:  $\underline{\underline{I}}^D, I_{ijkl}^D = \frac{1}{2}(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}) - \frac{1}{3}\delta_{ij}\delta_{kl}$ ,

-Transpose of 2<sup>nd</sup> rank tensor:  $\underline{x}^T, (x_{ij})^T = x_{ji}$ ,

-Symmetric and skew parts of second-rank tensor:  $\underline{x} = [\underline{x}]^S + [\underline{x}]^A$

$[\underline{x}]^S = \frac{1}{2}(\underline{x} + \underline{x}^T)$ ,  $[\underline{x}]^A = \frac{1}{2}(\underline{x} - \underline{x}^T)$ ,

-Hydrostatic part of second-rank tensor:  $[\underline{x}]^H = \frac{1}{3}tr(\underline{x})\underline{1}$ ,

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