DAMAGE AFFECTED DISCONTINUOUS PLASTIC FLOW

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1. General

Discontinuous plastic flow (DPF), characteristic of extremely low temperatures, is strongly coupled to mechanical and radiation induced damage. DPF is usually observed in fcc metals and alloys strained in cryogenic conditions. Such materials like copper and its alloys, aluminium alloys or different grades of stainless steel are applied in particle accelerator installations (including superconducting magnets, interconnection systems or detector elements). These elements are often subjected to cyclic loads as well as to intensive irradiation at near-0K temperatures, that lead to evolution of local micro-damage fields and finally to inevitable failure. The physically based constitutive model of DPF, coupled with both types of damage, can be helpful in design of superconducting accelerator components.

2. Kinetic law of damage evolution

The DPF model developed by Skoczeń et al. [1] is extended to cover the evolution of mechanical and radiation damage. Driving force of the mechanical damage evolution is the plastic strain. Thus, increment of mechanical damage (D_m) is strictly related to the increment of plastic strain ε_p or accumulated plastic strain p (cf. Lemaitre-Chaboche , extended by Garion and Skoczeń to anisotropic version [2]):

(1) $$\dot{D}_m = \left(\frac{\tilde{\sigma}^2}{2ES}\right)^s \dot{\varepsilon}_p \quad ; \quad \underline{\underline{\dot{D}}}_m = \underline{\underline{C}}\,\underline{\underline{Y}}\,\underline{\underline{C}}^T \dot{p} H(p - p_D)$$

where S and s are material and temperature dependent constants, whereas $\underline{\underline{C}}$ is 2nd order symmetric tensor containing material moduli. For what concerns radiation damage evolution, the Rice-Tracey formula is used. The increment of radiation damage D_r is related to increment of plastic strain [3]:

(2) $$\dot{D}_r = q_A 2\pi r_{c0}^2 \exp\left[\alpha_r \int_0^{\tilde{p}} \exp\left(\frac{3\sigma_m}{2\sigma_{eq}}\right) dp\right] \alpha_r \exp\left(\frac{3\sigma_m}{2\sigma_{eq}}\right) \dot{p}$$

where q_A denotes surface density of clusters of voids, r_{c0} is the size of clusters cross-section and α_r is a scalar multiplier. By tracing the evolution of unloading modulus during loading-unloading uniaxial tests, the damage parameter is obtained:

(3) $$D = 1 - \frac{\tilde{E}}{E}$$

where E and $\tilde{E}$ denote the initial and the current (effective) elasticity moduli, respectively. The evolution of effective modulus for different stainless steels at 4.2 K and at room temperature is presented in Fig. 1 (mechanical damage). Identification of initiation and evolution of radiation induced damage under mechanical loads in the irradiated materials is presented in [3].

3. Computational aspects of DPF coupled with damage

The concept of coupling of damage with discontinuous plastic flow is presented in Fig. 2. Single serration during DPF in the stress-strain curve shows similar pattern: after initial elastic process, smooth plastic flow occurs until the abrupt drop of stress. It is worth pointing out that in austenitic stainless steels also relaxation is observed, after which the beginning of next elastic stage is immediately observed with new effective modulus. The model assumes additive rule to compute the total value of damage parameter (or tensor): $D = D_m + D_r$. It is worth pointing out that the analysis does not include the strain-induced phase transformation which is observed in loading-unloading uniaxial tests of austenitic steels at 4.2K (hardening effect).

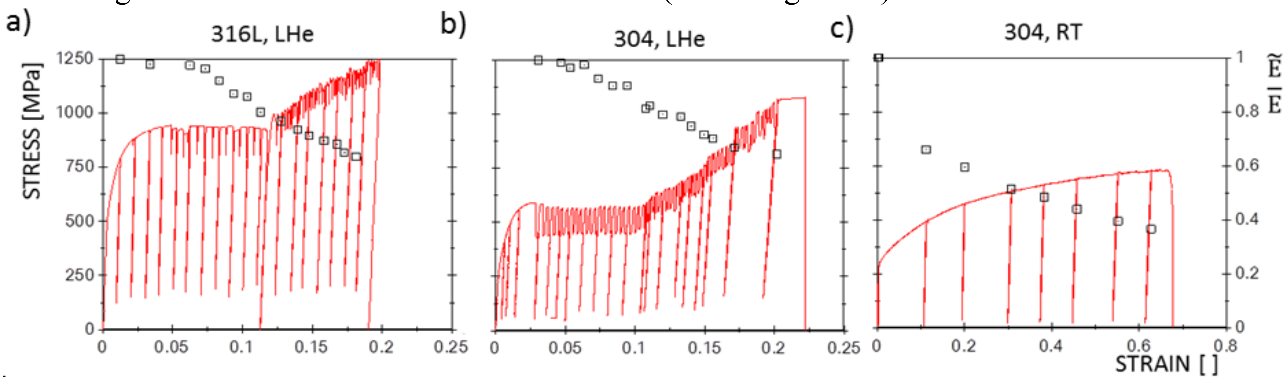

Figure 1 Evolution of effective modulus for a) 316L at 4.2K (LHe), b) 304 at 4.2K (LHe), c) 304 at 293K (RT).

Numerical simulation of effective modulus evolution for 304 austenitic stainless steel is presented in Fig. 2b. Step-like change of the effective modulus associated with serrations during DPF is observed (Fig. 2c).

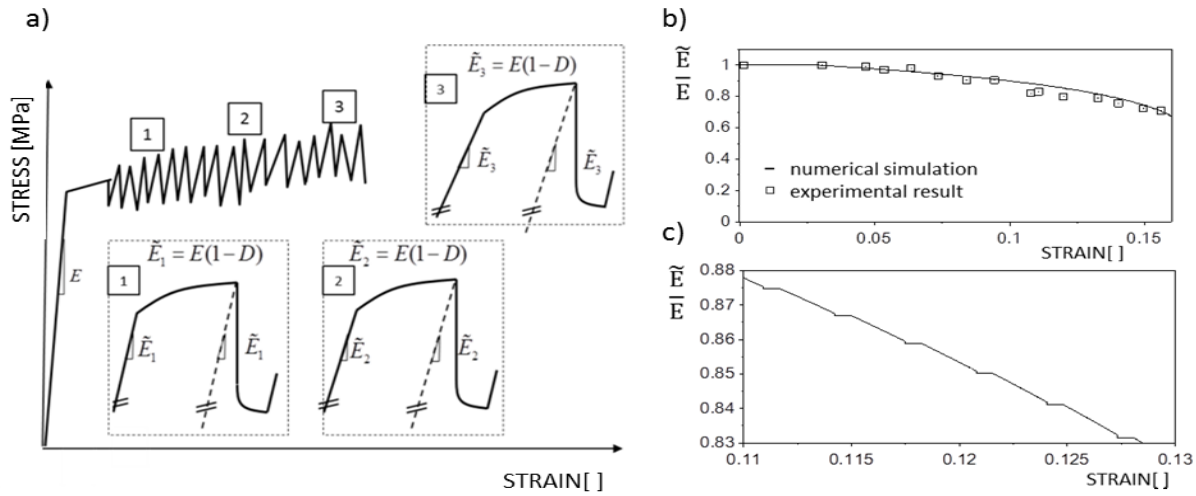

Figure 2 a) The concept of damage affected discontinuous plastic flow (DPF), b) effective modulus evolution for 304 stainless steel (numerical and experimental results), c) step-like change of effective modulus in the course of serrations during DPF (radiation and mechanical damage).

4. Conclusion

Physically based constitutive model of discontinuous plastic flow (DPF), which typically occurs in fcc materials applied at near-0K temperatures, has been substantially improved by introducing coupling of the DPF with the mechanically and the radiation induced micro-damage.

5. References

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[2] C. Garion, B. Skoczeń (2003). *Combined model of strain-induced phase transformation and orthotropic damage in ductile materials at criogenic temperatures*. Int. J. Damage Mech. **12**, 331-356.

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