SHAKEDOWN OF FUNCTIONALLY GRADED STRUCTURES SUBJECTED TO PLASTIC STRAIN INDUCED PHASE TRANSFORMATION

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Summary Metastable, type FCC metals and alloys are often applied at extremely low temperatures because of their excellent ductility over the whole temperature range, practically down to the absolute zero. These materials (like stainless steels) are frequently characterised by the low stacking fault energy and undergo at low temperatures the plastic strain induced transformation from the parent phase γ to the secondary phase α'. The phase transformation process consists in creation of two-phase continuum, where the parent phase coexists with the inclusions of secondary phase in thermodynamic equilibrium. The evolution of material micro-structure induces strain hardening related to interaction of dislocations with the inclusions and to increase of equivalent tangent stiffness as a result of evolving proportions of both phases, each characterised by different stiffness. The corresponding hardening model is based on micromechanics and on the Hill concept (1965) supplemented by Mori and Tanaka (1973) homogenisation scheme. The model has been used to describe phase transformation in rectangular beams and circular rods subjected to cyclic loads at cryogenic temperatures. New feature of structures made of metastable materials has been observed. As soon as the γ→α' phase transformation begins, the evolution of material micro-structure accelerates the process of adaptation (shakedown) of structure to cyclic loads.

KINETICS OF PLASTIC STRAIN INDUCED FCC-BCC PHASE TRANSFORMATION

In consequence of the plastic strain-induced phase transformation, platelets of secondary phase (bcc) dispersed in the austenitic matrix (fcc) are formed. In Fe-Cr-Ni austenitic steels the martensite embryos are created at the intersection of shearbands. The volume fraction of martensite ξ depends on the temperature due to the relation with chemical energy. However, in the case of strain-induced transformation, both the plastic deformation and the stress field influence the transformation driving force and determine the amount of new-created martensite. The transformation curves are usually sigmoidally shaped. Transformation processes occurring at the temperatures close to room temperature have rather flat characteristics, whereas at cryogenic temperatures the thermodynamic driving force is stronger. Therefore, the phase transformation process has more dynamic course. Kinetics of the phase transformation process at very low temperatures can be subdivided into three stages: low rate transformation (I), fast transformation with a high and nearly constant transformation rate (II) and asymptotically vanishing transformation with the rate decreasing to 0 (III). A simplified evolution law for the volume fraction of martensite ξ has been introduced for the linear part (II) of the sigmoidal curve by Garion and Skoczeń (2002):

$$\dot{\xi} = A\left(T, \underline{\underline{\dot{\varepsilon}}}^{p}, \underline{\underline{\sigma}}\right) \dot{p} H\left(\left(p - p_{\xi}\right)\left(\xi_{L} - \xi\right)\right) \tag{1}$$

Here p denotes the accumulated plastic strain, A is a function of temperature, stress state and strain rate, p_{ξ} denotes the accumulated plastic strain threshold, ξ_L stands for the martensite content limit and H represents the Heaviside function.

RVE BASED CONSTITUTIVE MODEL OF FCC-BCC PHASE TRANSFORMATION

Formulation of the constitutive model of a material subjected to the plastic strain induced phase transformation is based on multiscale considerations [1]. The general constitutive law includes plastic, thermal and transformation strains:

$$\underline{\underline{\sigma}} = \underline{\underline{\underline{\underline{E}}}} : \left(\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon}}^{p} - \underline{\underline{\varepsilon}}^{th} - \xi \underline{\underline{\varepsilon}}^{bs}\right) \quad ; \quad \underline{\underline{\varepsilon}}^{bs} = \frac{1}{3} \Delta \upsilon \underline{\underline{I}} \tag{2}$$

The model of plastic flow is based on the rate independent plasticity. The hardening model is represented by the kinematic part related to the back stress $\underline{\underline{X}}$ and the isotropic part represented by the hardening parameter R. Since the hardening variables are affected by the presence of secondary phase, the corresponding evolution laws are postulated in the following incremental form:

$$d\underline{\underline{X}} = d\underline{\underline{X}}_{a} + d\underline{\underline{X}}_{a+m} = \frac{2}{3} C_{X}(\xi) d\varepsilon^{p} \quad ; \quad dR = C_{R}(\xi) dp \tag{3}$$

It is assumed that the back stress increment is composed of the classical term which corresponds to the behaviour of the austenitic phase (dX_a) in the presence of localized small inclusions, uniformly distributed and randomly oriented in the RVE, and a term related to the combination of austenite and martensite via the homogenization algorithm (dX_{a+m}). Based on the micromechanics, the back stress increment corresponding to the behaviour of austenite in the presence of highly localized martensite inclusions can be decomposed in the following way:

$$d\underline{\underline{X}}_{a} = d\underline{\underline{X}}_{a0} + d\underline{\underline{X}}_{a\xi} = \frac{2}{3} C_0 d\underline{\underline{\varepsilon}}^{p} + \frac{2}{3} C_0 h \xi d\underline{\underline{\varepsilon}}^{p} = \frac{2}{3} C(\xi) d\underline{\underline{\varepsilon}}^{p} \tag{4}$$

The second contribution to the hardening model is based on the principle of homogenization applied by means of the current linearized tangent stiffness moduli of the matrix and the inclusions. As the matrix (fcc) is elastic–plastic, the relevant local linearized tangent stiffness tensor is derived. The inclusions are assumed to be ellipsoidal in shape (type Eshelby) and elastic, therefore, the elastic tangent stiffness is applied. The process of step-by-step homogenization, based on the local tangent stiffness moduli, involves Mori-Tanaka algorithm:

$$d\underline{\underline{X}}_{a+m} = 2(\mu_{MT} - \mu_{ta})d\underline{\underline{\varepsilon}}^{p} = (2C_{a+m}/3)d\underline{\underline{\varepsilon}}^{p} \tag{5}$$

where C_{a+m} denotes surplus tangent stiffness modulus. Finally, the mixed hardening is described by the following model:

$$d\underline{\underline{X}} = \frac{2}{3}C_X(\xi)d\underline{\underline{\varepsilon}}^{p} = \frac{2}{3}\left[C(\xi) + \beta C_{a+m}(\xi)\right]d\underline{\underline{\varepsilon}}^{p} \quad ; \quad dR = C_R(\xi)dp = (1-\beta)C_{a+m}(\xi)dp \tag{6}$$

SHAKEDOWN OF STRUCTURES SUBJECTED TO STRAIN INDUCED PHASE TRANSFORMATION

The FGMs can be easily obtained within the structural members made of metastable austenitic steels by loading them beyond the yield point and inducing the γ→α' phase transformation [2]. It is possible to obtain various distributions of mechanical properties, generated by two-phase micro-structure of the material, depending on the distribution of plastic strain fields as a function of the shape of structure.

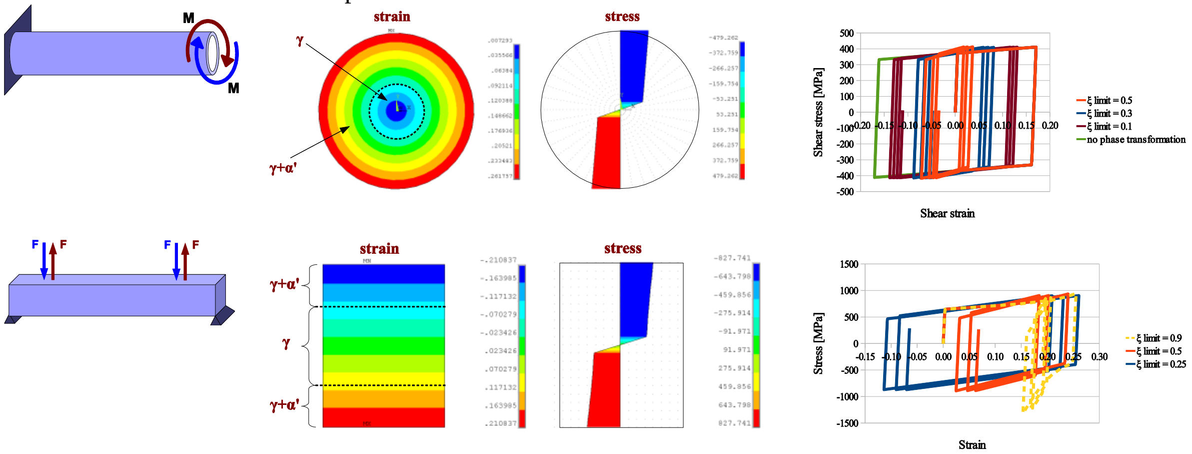

Fig. 1 Shakedown of functionally graded structural members subjected to cyclic loads: cyclic torsion and bending

The above presented constitutive model has been implemented in order to solve several one-dimensional problems: tension/compression of bars, twisting of rods of circular cross-section and bending of rectangular beams at cryogenic temperatures. The results were compared with the closed form solutions, previously obtained by means of purely analytical approach [3]. Moreover, the model has been validated with respect to the available experimental data. The structural members were subjected to cyclic loads and to combined loads in order to evaluate their response. One of the most important features consists in the fact that an accelerated shakedown is observed due to the phase transformation process [4]. It results from the structural evolution of two-phase continuum, where the elastic–plastic matrix is gradually replaced by the elastic inclusions. In the limit case, where 100% of primary phase has been replaced by the secondary phase, the material becomes purely elastic and the shakedown occurs by definition. This important and new conclusion has very practical meaning. As soon as the phase transformation begins, the evolution of material structure accelerates the process of adaptation of structural members to cyclic loads and enhances therefore their fatigue life when compared to classical elastic–plastic members. Finally, this particular feature of structures made of metastable materials is explained in the framework of Melan and Koiter adaptation/inadaptation theorems.

CONCLUSIONS

The main aim of the present paper consists in showing that the phase transformation process may substantially accelerate the shakedown of structures subjected to cyclic loads at cryogenic temperatures. In all the cases solved analytically and numerically of tension/compression, torsion and bending, the accelerated shakedown has been clearly demonstrated. Moreover, such a structural behaviour is justified in the framework of Melan and Koiter adaptation and inadaptation theorems, which forms rather solid basis for better understanding of lifetime of structures made of metastable materials.

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References

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