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Thermomechanical Behavior by Martensitic Transformation in Single and Polycrystals of Metallic Alloys

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The phenomenon of Transformation Plasticity is a particular behavior observed in some alloys when a phase transformation occurs under applied stress. The kinematic study for the overall behavior may determine the strain induced by transformation and the strain caused by other mechanisms (e.g. motion of dislocations, thermal expansion ..). According to this distinction we recognize two classes of behavior [1] :

- Coupled Transformation Plasticity (C.T.P.) : in this case, characteristics of transformation are modified by the other mechanisms of deformation (e.g. in steels, martensitic transformation induces plastic flow in the parent phase and this plastic flow changes the transformation characteristics).

- Pure Transformation Plasticity (P.T.P.) where strain is exclusively produced by phase transformation.

In thermoelastic martensitic transformation, we observed a phenomenon called pseudoelasticity which is characterized by a large reversible inelastic strain (more than ten per cent for single crystal). This phenomenon may be considered as Pure Transformation Plasticity and the aim of this work is to model it [2]. In P.T.P. the mechanism of transformation is composed with a shear part on the habit plane, and an extension part in the direction of the normal to the habit plane as shown in Fig. 1. So for a single crystal, the inelastic strain can be defined by the following expression :

$$\epsilon_{ij}^{AM} = \frac{1}{2}(m_i n_j + m_j n_i) g = R_{ij} g$$

where g denotes the shear magnitude in the direction of motion and R_{ij} is the orientation tensor of martensite variant.

Fig. 1. Unit volume transformation from parent phase to martensite.

This result may be generalized for the case where many variants are formed and also for a polycrystal.

In the single crystal case, we deduced a relation between external parameters and internal variables from a thermomechanical approach based on the Gibbs free energy. This study enables to define a pseudoelastic potential and to obtain the transformation criterion, so we are in the case of standard material and the potential allows to define the single crystal flow rule. The change of Gibbs free energy is expressed by :

$$\Delta G = \Delta G^C(T) V_M + \Gamma S + E_{ext} + E_{int}$$

where V_M is the volume of martensite. This relation is composed by four terms of different origins :

- $\Delta G^C(T)$ denotes the chemical free energy ;
- Γ denotes the free energy of interface ;
- E_{ext} is the interaction energy with externally applied stress ;
- E_{int} is the elastic energy associated with the inclusion.

Γ may be neglected for thermoelastic martensite, E_{ext} can be obtained by using Eshelby's relation [3] and E_{int} was calculated by Fassi-Fehri et al. [4]. So, we obtain the following expression for the potential :

$$\frac{\Delta G}{V} = \Delta G^C(T) - \sigma_{ij} g \sum_n R_{ij}^n F^n + g^2 \sum_n E_F^n + g^2 \sum_{n,m} H^{nm} F^n F^m$$

where F^n denotes the volume fraction of variant n , E_F^n denotes the interaction energy between variant n and parent phase and H^{nm} denotes the interaction matrix between the variants of martensite. So, for one variant, if we consider an inclusion with a plate shape ($E_F^n = 0$), the criterion which determines the beginning of the transformation is :

$$\sigma_{ij} R_{ij}^n = \frac{\Delta G^C(T)}{g}$$

This criterion is analogous to the Schmid one, but hydrostatic pressure is taken into account. Finally, the flow rule is expressed by :

$$dE_{ij}^{PT} = \sum_n R_{ij}^n \sum_m H^{nm} (R_{kl}^m d\sigma_{kl} - \frac{B^n dT}{g})$$

B^n denotes the coefficient which express the linear relation between ΔG^C and temperature.

To model pseudoelasticity in the polycrystal, we used a phenomenological approach based on a transformation criterion analogous to the Von Mises one :

$$\sqrt{J_2} + \frac{tg\alpha}{3} I_1 - \frac{\Delta G^C(T)}{g \cos \alpha} = 0$$

To obtain the flow rule, we consider that the polycrystal is a standard material and so we obtain :

$$dE_{ij}^{PT} = a \left(\frac{S_{ij}}{2\sqrt{J_2}} + \frac{tg\alpha}{3} \right) \left[\left(\frac{S_{kl}}{2\sqrt{J_2}} + \frac{tg\alpha}{3} \right) d\sigma_{kl} - \frac{BdT}{g \cos \alpha} \right]$$

where "a" denotes a function to be identified by a particular type of loading.

These flow rules are then compared with experimental results for uniaxial tension of a Cu-Zn-Al alloy. We observed a good agreement between experiments and theoretical values for the transformation point and for the transformation slope [2].

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