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Experimental Validation of the Multiphase Extended Leblond's Model.

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Abstract. Transformation induced plasticity is a crucial contribution of the simulation of several forming processes involving phase transitions under mechanical loads, resulting in large irreversible strain even though the applied stress is under the yield stress. One of the most elegant and widely used models is based on analytic homogenization procedures and has been proposed by Leblond *et al.* [1-4]. Very recently, a simple extension of the Leblond's model has been developed by Weisz-Patrault [8]. Several product phases are taken into account and several assumptions are relaxed in order to extend the applicability of the model. The present contribution compares experimental tests with numerical computations, in order to discuss the validity of the developed theory. Thus, experimental results extracted from the existing literature are analyzed. Results show a good agreement between measurements and theoretical computations.

INTRODUCTION

When phase transformations occur under applied mechanical loads that can be much lower than the yield stress, significant plastic strains are observed. This phenomenon called transformation induced plasticity received particular attention (see for instance [1-7]) since the eighties because of numerous applications in mechanical engineering. Two different mechanisms have been proposed to explain transformation plasticity namely: Greenwood & Johnson and Magee mechanisms. One of the most fruitful model has been proposed by Leblond *et al.* [1] and relies on a homogenization procedure without adding a priori contributions in the plastic strain tensor that would be proportional to phase proportion rate. This classic contribution results directly from the homogenization procedure itself and both Greenwood & Johnson and Magee mechanisms are thus identified. In order to give a more specific and usable form to the homogenized model, a morphological assumption which consists in an idealization of the microstructure has been proposed and solved analytically by Leblond *et al.* [2-4]. Because of its solid theoretical basis and simple explicit formulas for the overall plastic strain increment, this model has been intensively used for various engineering applications and has been included in a commercial Finite Element software dedicated to welding applications. However, forming processes often involve multiphase transitions. This aspect being not addressed in the original papers [1-4], an extension has been developed and submitted recently by Weisz-Patrault [8] and differs from the attempt proposed in [9]. Several product phases are taken into account and several assumptions are relaxed in order to extend the applicability of the model. In particular, the classic singularities arising in the original model are naturally smoothed. The present contribution compares experimental tests with numerical computations, in order to discuss the validity of the developed theory. Thus, experimental results performed on a 16MND5 low carbon steel and extracted from the existing literature are analyzed.

TRANSFORMATION INDUCED PLASTICITY

Weisz-Patrault [8] developed a simple transformation induced plasticity model by using homogenization procedures. The calculation relies on analytic developments and assumptions related to the microscopic morphology of the different phases. Namely, the representative volume element (RVE) is constituted of a sphere of parent phase that contains a sphere gathering all product phases. Basic equations are briefly stated in this section without proof. For

more details and more complete equations and proofs, the reader is referred to [8]. The hydrostatic thermo-metallurgical strain rate $\underline{\dot{\epsilon}}^{thm}$ is shown to be:

$$\underline{\dot{\epsilon}}^{thm} = \underline{1} \sum_{k=2}^N \frac{1}{3} \left(\frac{\rho_1(T)}{\rho_k(T)} - 1 \right) \dot{X}_k + \left(\sum_{k=1}^N \alpha_k X_k \right) \dot{T} \quad (1)$$

where T is the temperature, α_k are the thermal expansion coefficients, X_k the phase proportions and ρ_k the densities of the different phases (the parent phase being labelled by 1). The total product phase proportion is given by:

$$X = \sum_{k=2}^N X_k \quad (2)$$

There are three possible situations in equation (3) for the evaluation of the transformation induced plasticity strain rate, depending on the overall product phase proportion. First, the hydrostatic eigenstrain $\underline{\epsilon}^{thm}$ (due to phase transition) may be not sufficient to generate plastic deformations in the matrix of parent phase, or the eigenstrain may create a plastic zone that do not cover all the parent phase, or the parent phase may be entirely plastic. According to these three possible situations, the transformation induced plasticity strain rate is given by:

$$\underline{\dot{\epsilon}}^{tp} = \begin{cases} 0 & \text{if } \frac{\Delta\sigma^Y}{\zeta|\underline{\epsilon}^{thm}|} > 1 \\ -\frac{3|\underline{\epsilon}^{thm}|\underline{s}_1}{\sigma_1^Y} \ln\left(\frac{\Delta\sigma^Y}{\zeta|\underline{\epsilon}^{thm}|}\right) \sum_{\substack{m=2 \\ \dot{X}_m > 0}}^N \dot{X}_m & \text{if } X \leq \frac{\Delta\sigma^Y}{\zeta|\underline{\epsilon}^{thm}|} \leq 1 \\ -\frac{3|\underline{\epsilon}^{thm}|\underline{s}_1}{\sigma_1^Y} \ln(X) \sum_{\substack{m=2 \\ \dot{X}_m > 0}}^N \dot{X}_m & \text{if } X > \frac{\Delta\sigma^Y}{\zeta|\underline{\epsilon}^{thm}|} \end{cases} \quad (3)$$

where $\underline{s}_1$ is the deviatoric part of the applied stress tensor in the parent phase, which can be identified in this contribution to the macroscopic deviatoric stress tensor. Moreover $\Delta\sigma^Y$ quantifies the distance between the yield stress of the parent phase (austenite) and the von Mises equivalent stress in the parent phase:

$$\Delta\sigma^Y = \sqrt{(\sigma_1^Y)^2 - (\sigma_1^{eq})^2} \quad (4)$$

where ζ is the following material parameter (where λ_1 and μ_1 are the Lamé coefficients of the parent phase):

$$\zeta = \frac{(3\lambda_1 + 2\mu_1)2\mu_1}{\lambda_1 + 2\mu_1} \quad (5)$$

and where $\underline{\epsilon}^{thm}$ represents an approximation of the strain history:

$$\underline{\epsilon}^{thm} = \sum_{k=2}^N \frac{X_k}{1 - X_1} \left(\frac{1}{3} \left(\frac{\rho_1(T)}{\rho_k(T)} - 1 \right) + \frac{\rho_1(T)}{\rho_k(T)} (\alpha_k - \alpha_1) (T - T_{start,k}) \right) \quad (6)$$

where $T_{start,k}$ is the start temperature of each phase transition.

The model also describes the classic plastic strain rate due to temperature and equivalent stress variations. In this paper the latter contribution is negligible, thus only the classic plastic strain rate $\underline{\dot{\epsilon}}_T^{cp}$ due to temperature variations is addressed:

$$\underline{\dot{\epsilon}}_T^{cp} = \begin{cases} 0 & \text{if } \frac{\Delta\sigma^Y}{\zeta|\underline{\epsilon}^{thm}|} > 1 \\ -\frac{3\tilde{\alpha}\underline{s}_1}{\sigma_1^Y} X \ln\left(\frac{\Delta\sigma^Y}{\zeta|\underline{\epsilon}^{thm}|}\right) \dot{T} & \text{if } X \leq \frac{\Delta\sigma^Y}{\zeta|\underline{\epsilon}^{thm}|} \leq 1 \\ -\frac{3|\underline{\epsilon}^{thm}|\underline{s}_1}{\sigma_1^Y} X \ln(X) \dot{T} & \text{if } X > \frac{\Delta\sigma^Y}{\zeta|\underline{\epsilon}^{thm}|} \end{cases} \quad (7)$$

where $\tilde{\alpha}$ is the average thermal expansion coefficient of all the product phase (where α_k are the thermal expansion coefficients of all individual phases):

$$\tilde{\alpha} = \sum_{k=2}^N \frac{X_k}{1 - X_1} (\alpha_k - \alpha_1) \quad (8)$$

EXPERIMENTS WITH THERMAL CYCLES

The experiment is extracted from [14]. Dilatometry tests have been performed under loading on a 16MND5 low carbon steel. One of the key parameter involved in the transformation induced plasticity model is the temperature dependent yield stress of the parent phase. This contribution deals with structural changes in steel with applied loads during cooling. Thus, the parent phase is austenite that however becomes unstable below a certain temperature. Consequently, measuring directly the yield stress of pure austenite is difficult on the whole temperature range of interest. This difficulty is discussed by Grostabussiat-Petit [15] who performed tensile tests at different temperatures on microstructures that contain metastable austenite. The following linear expression is obtained:

$$\sigma_1^Y(T) = -0.147 \times T + 183.14 \quad (9)$$

where σ_1^Y is given in MPa and T in °C. Furthermore the Young modulus is also given as a function of temperature after [15]:

$$E(T) = 2.08 \times 10^5 - 1.9 \times 10^2 T + 1.19 T^2 - 2.82 \times 10^{-3} T^3 + 1.66 \times 10^{-6} T^4 \quad (10)$$

where E is given in MPa and T in °C.

Several phases may be produced even though they have been interpreted as only one product phase in the original paper. However it has been verified that ferrite-pearlitic phase transitions do not occur during cooling. Thus, only austenite, bainite and martensite are considered. The experiment is focused on identical thermal cycles in order to determine if re-austenitization erases transformation induced plasticity. Free dilatometry tests enable us to quantify phase proportions as a function of temperature on the one hand and to calibrate thermal expansion coefficients and densities of each phase on the other hand (listed in Table 1). The identified phase proportions along with material parameters are then used to evaluate transformation induced plasticity, thermo-metallurgical strain and classic plasticity due to thermal variations as described in the previous section. Finally, by integrating all strain increments over time, the total strain can be computed and compared with strain measurements. Thermal and stress cycles are presented in Figure 1. The proposed theoretical model is compared with experiments. Thus, cyclic dilatometry tests are presented in Figure 2. Good agreement is observed between measurements and computations. Furthermore re-austenitization clearly does not erase transformation induced plasticity that cumulates at each cycle. Beside this experimental comparison, a theoretical comparison can be done between the original Leblond's model [1-4] and the extended model [8], as presented in Figure 3. Transformation induced plasticity is underestimated by the original model. However, it should be mentioned that one can fit the original model and the experimental measurements by modifying the yield stress of the parent phase even though the obtained value does not seem very realistic compared to the yield stress identified in [15].

Table 1 Material parameters

Austenite start temperature (K)	AC ₃	1000
Bainite start temperature (K)	BS	845
Martensite star temperature (K)	MS	673
Thermal expansion coefficient of austenite (K ⁻¹)	α_A	23.5×10^{-6}
Thermal expansion coefficient of bainite (K ⁻¹)	α_B	15.7×10^{-6}
Thermal expansion coefficient of martensite (K ⁻¹)	α_M	15.7×10^{-6}
Heating rate (K.s ⁻¹)	H_R	100
Cooling rate (K.s ⁻¹)	C_R	3
Applied stress (MPa)	σ_A	23

Figure 1 Thermal and stress cycles

Figure 2 Free dilatometry (left) and cyclic dilatometry under loading (right). Theoretical evaluation and experiments

Figure 3 Comparison between extended model [8] and the original model [1-4]

CONCLUSION

This contribution is dedicated to an experimental validation of the transformation plasticity model proposed recently by Weisz-Patrault [8]. Experiments have been extracted from the existing literature in order to compare with theoretical computations. Taleb and Petit [14] performed dilatometry tests under thermal and stress cycles in order to determine if re-austenitization erases transformation induced plasticity. Material parameters have been extracted from Grostabussiat-Petit [15] and inferred directly from the free dilatometry test. A very good agreement between measurements and the theoretical model is observed.

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