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NUMERICAL SIMULATION OF THE PORTEVIN – LE CHATELIER EFFECT IN VARIOUS MATERIAL AND AT DIFFERENT SCALES

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Abstract. The Portevin Le Chatelier (PLC) effect appears in many metallic materials at different temperatures. Some numerical simulations of this effect for different alloys (aluminium, steel, nickel based superalloy) are presented in this article. The mechanical model remain the same for all studied materials but the behavior parameters and identification methods differ. The scale at which this effect is investigated also varies from the microstructure to aeronautic components.

Introduction

Many metallic materials exhibit serrations on their global tensile strain – stress curve in a given range of temperature and deformation rate [1,2]. The so-called called Portevin – Le Chatelier effect is due to the interaction between mobile dislocations and solute atoms diffusion denoted dynamic strain aging [3,4]. This strain ageing induce in a given range of temperature and deformation rate a negative strain rate sensitivity. This negative sensitivity lead to a strain localization phenomenon characterized by bands of plastic strain rate propagating in specimens, and by serrations appearing on the global strain/stress curve.

The Portevin Le Chatelier effect has been observed in aluminium alloys [5,6], in steels [7,8] or in nickel based superalloys [9,10]. It has also been observed in aluminium-ceramic composites with a low [11,12] or high [13] volume fraction of reinforcement. Concerning the mechanical model, strain ageing has been mainly described using two elastoviscoplastic models simulating the negative strain rate sensitivity. These models proposed on the one hand by MacCormick [14], on the other by Kubin and Estrin [15], have till now mainly been used to simulate PLC effect in tensile specimens [2,16,17].

Several works about PLC effect simulation are presented in this article in order to show how the MacCormick model can describe this effect for different materials, different temperatures, and at different scales. The PLC effect is then simulated in an aluminium alloy, in an aluminium-ceramic composite, in a steel, and in a nickel based superalloy; temperature varies from 20°C to 650°C, and scale from microstructure to aeronautical components.

Model

The simulation of the negative strain rate sensitivity requires to choose a suitable elastoviscoplastic model among both existing in literature. The first one used in this work and proposed by MacCormick [14] is based on an internal variable t_a called ageing time. The second one developed by Kubin and Estrin [15] describes the experimental localization phenomena using a more macroscopic approach of instabilities. The first of these model has been implemented in the finite element code Zset. The numerical local integration of the behavior constitutive equations has been carried out using a mixed approach between classical Runge-Kutta and Mid-Point methods. This original method allows to avoid local divergences and provides for global integration a coherent tangent matrix, that improves convergence of the global non-linear process. The interested reader can find more informations about this method, and about the constitutive equations presented below, in [18].

$$\varepsilon = \varepsilon_e + \varepsilon_p \tag{1}$$

$$\sigma = E : \varepsilon \tag{2}$$

$$f(\sigma, p, t_a) = J_2(\sigma) - R(p) - P_1 Cs(p, t_a) \tag{3}$$

$$R(p) = R + Q\,(1 - \exp(-b.p)) \tag{4}$$

$$dp/dt = p_0.\sinh(f/K) \tag{5}$$

$$dt_a/dt = 1 - (t_a/w).dp/dt \tag{6}$$

$$\varepsilon_p = p.n \tag{7}$$

$$n = \partial f / \partial \sigma = 1.5\ s / J_2(\sigma) \tag{8}$$

where $J_2(\sigma)$ is the second invariant of stress tensor, s is the deviatoric part of the stress tensor σ, R(p) is the nonlinear hardening law, and $P_1Cs(p,t_a)$ is the extra hardening induced by strain ageing [8,16].

A stability analysis of this model has been performed by Maziere [10] using a 1D linear perturbation method. This analysis provides for a given prescribed strain rate the critical strain where serrations will appear during finite elements simulations of tensile test on smooth specimens. The corresponding experimental value can then be taken into account during the material parameters identification.

Al-Mg Alloy, Al-Mg/Al_2O_3 Composite -- Microstructure scale

The elastoviscoplastic behavior of an Al-Mg alloy has been identified from tensile test performed on rectangular plates at room temperature for three different prescribed strain rates [11]. The model parameters have been identified on a representative volume element accounting for : (i) the average hardening level, (ii) the strain rate sensitivity, (iii) the critical plastic strain for which serrations occur. Then, these parameters have been used to simulate experiments on the three plates. The experimental and simulated tensile curves at $10^{-3}\ s^{-1}$, $10^{-4}\ s^{-1}$, $10^{-5}\ s^{-1}$ are respectively given on figures 1(a), 1(b), 1(c). The shape of oscillations of each tensile curve, and the critical plastic strains have been accurately described.

The behavior of a Al-Mg/Al_2O_3 composite showing PLC effect [11,12,13] has then been simulated using periodic structures; firstly in 2D (see figure 1(e)), and then using the tetrakaidecahedron drawn on figures 1(f) and 1(g). The 2D structure composed by an elastic inclusion in an Al-Mg matrix (behavior previously identified) has been used to simulate the tensile behavior at different strain rates of different composites presenting different reinforcements volume fractions.

The tensile behavior of this structure is given on figure 1(d) for different prescribed strain rates, and for a 2% volume fraction of ceramic inclusion. Some 3D simulations with different volume fraction and different strain rates are actually carried out in order to investigate the influence of these two parameters on the critical strain and on the shape of serrations.

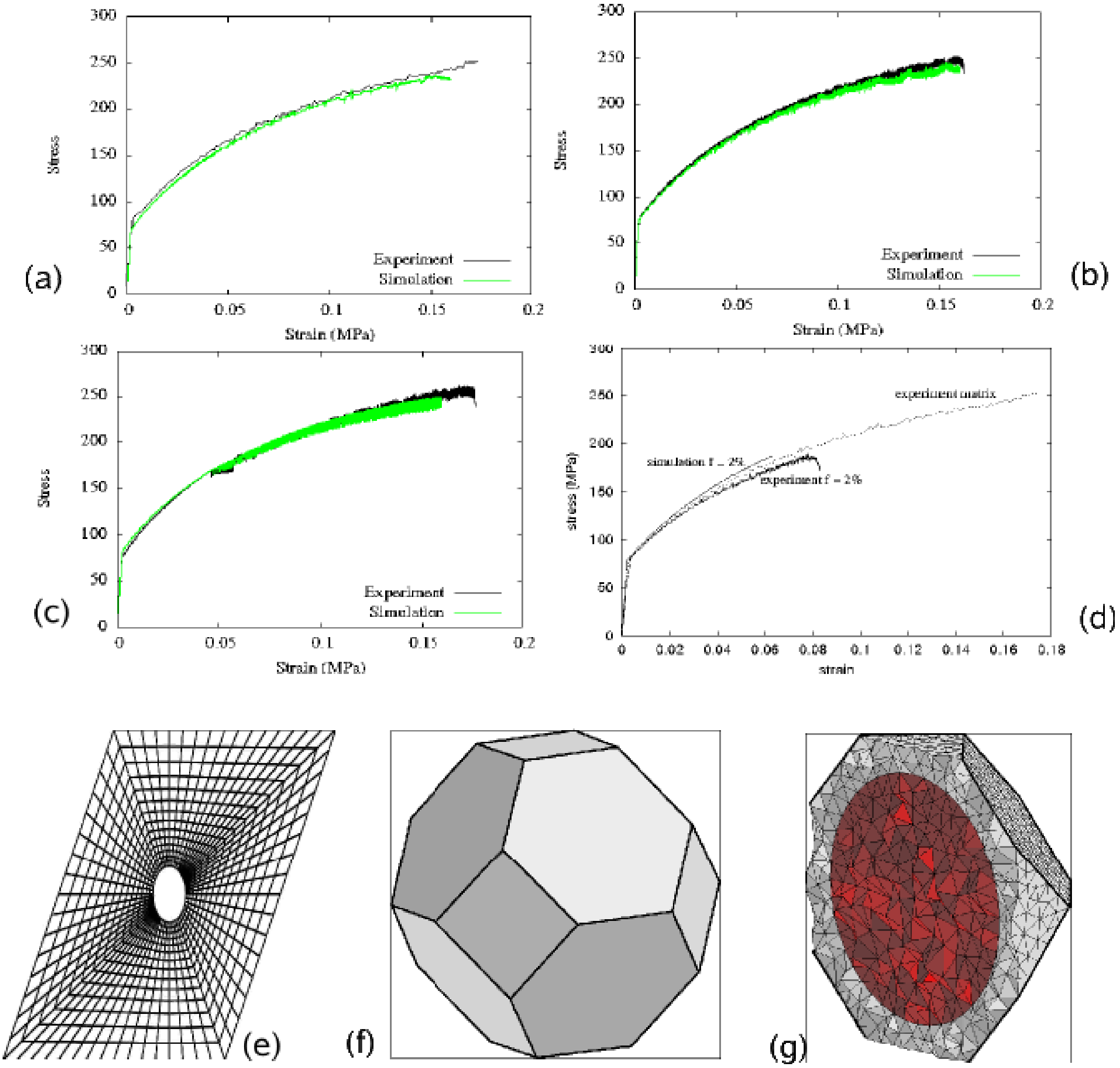

Figure 1: Experimental and numerical tensile curves for a plate in Al-Mg for prescribed strain rates equal to (a) 10^{-3} s^{-1}, (b) 10^{-4} s^{-1}, (c) 10^{-5} s^{-1}.(d) Simulated tensile curves for an Al-Mg/Al_2O_3 composite with 2% of ceramic inclusions for different prescribed strain rates [12]. (e) Periodic 2D structure with 2% of ceramic inclusions. Tetrakaidecahedron used for 3D periodic simulations with 59% of ceramic (f) general view, (g) cross-section view.

C-Mn Steel -- Specimen scale

The PLC effect has been observed for different temperatures (150°C – 250°C) and for different prescribed strain rates during tensile tests on a C-Mn steel used in the pipeline of the secondary circuit of a Pressurized Water Reactor (PWR) [19]. The identification has been carried out in order to get a physical evolution of some material parameters with respect to temperature (such as P_1 on figure 2(a)), while some other remain free (like Q on figure 2(a)).

The mechanical behavior has then been simulated on smooth, and U and V notched tensile specimens. One can observes on figure 2(b) that numerical results match quite accurately experimental ones at 200°C for two different strain rates (10^{-2} s^{-1} and 10^{-4} s^{-1}). The localization bands of plastic strain rate are also drawn on this figure for the simulation at 10^{-4} s^{-1}. Some complementary works are currently performed in order to get more experimental data and to improve the multi-temperature identification of model parameters.

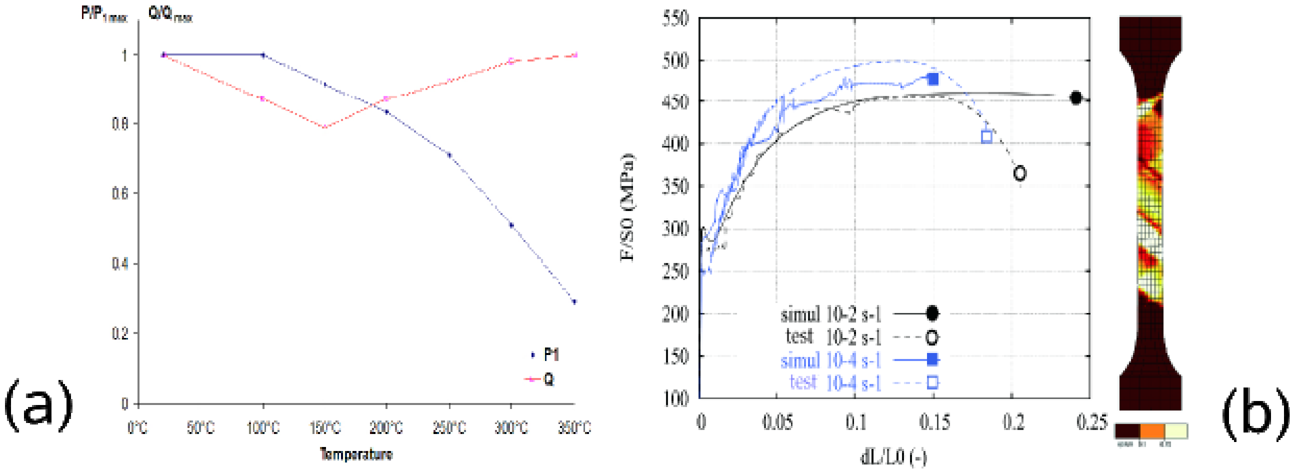

Figure 2: (a) Variation of identified parameters Q and P_1 with temperature.(b) Experimental and simulated tensile curve for a C-Mn steel at 200°C for two prescribed strain rates [BelotteauPhD].

Nickel based Superalloy -- Structure scale

Udimet 720 is a nickel based superalloy used to manufacture some turbine disks of helicopter engines. The PLC effect has been observed in this material between 300°C and 600°C [10,18], that is to say in the range where disks are used during flights. Model parameters have been identified in order to simulate as for previous materials the strain localization in tensile specimens at the average temperature of disk, 500°C. This behavior has firstly been tested on notched cylindrical specimens (see figure 3), in order to prove that serrations on equilibrium curves, and strain localization appears not only on smooth tensile specimens but also on other types of structure that are less suitable for instabilities development.

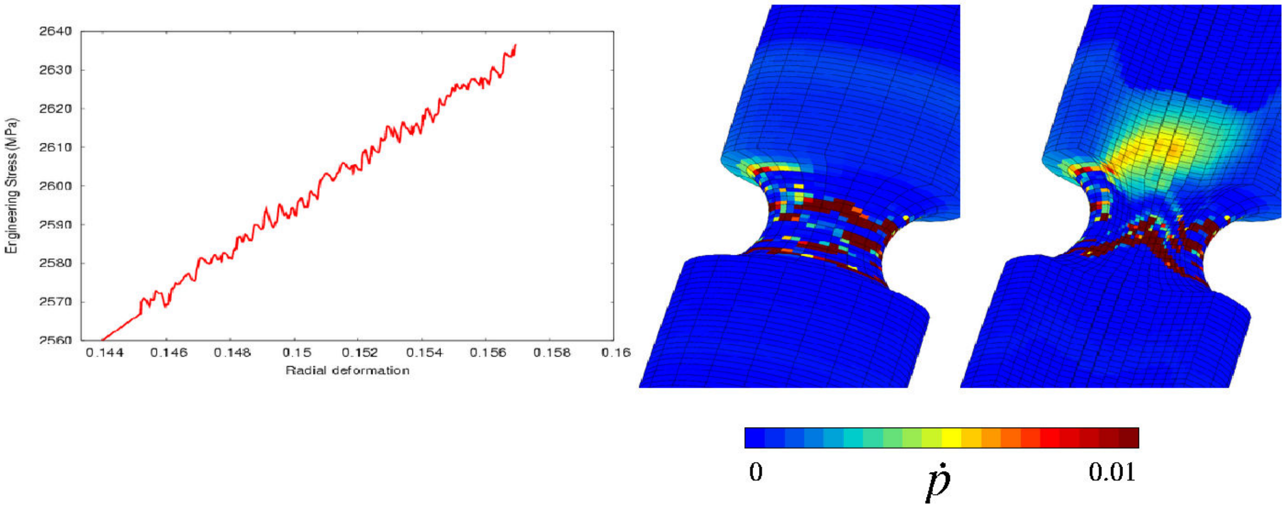

Figure 3: Simulation of Portevin Le Chatelier effect in a cylindrical notched specimen in Udimet 720.

Rotating turbine disks in Udimet 720 at 500°C have then been simulated to observe that for an enough high rotation rate, plastic strain rate bands of localization appear. One can observe this localization on figure 4. The main result of this study developed in [18] is that if PLC effect increase local stresses in disks, it does not seems to make the burst rotation rate (the maximum of equilibrium curve) decreasing.

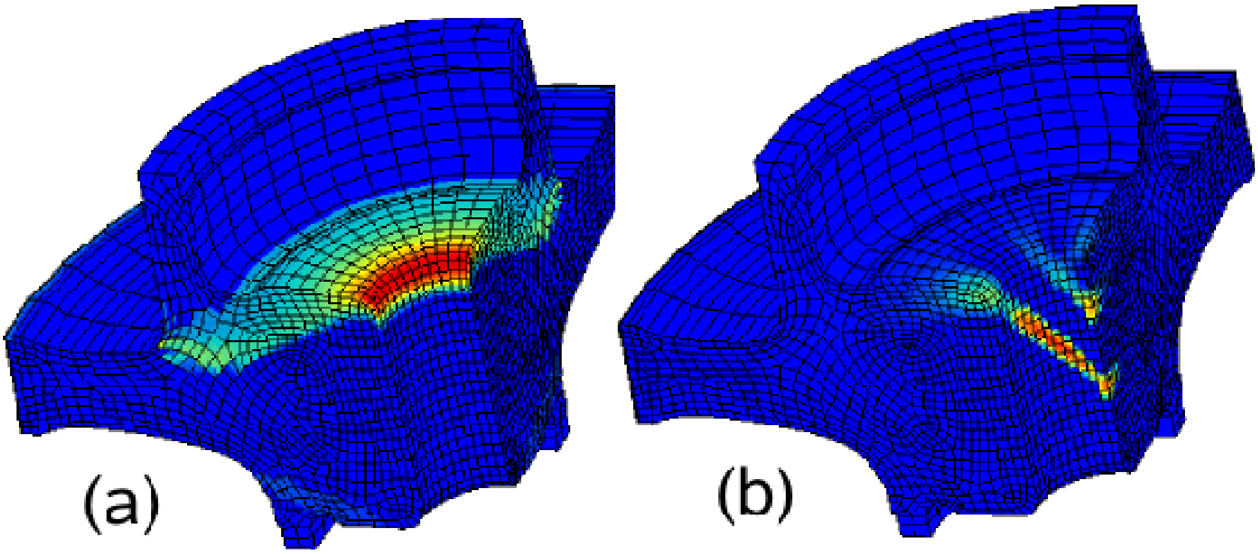

Figure 4: Simulation of Portevin Le Chatelier effect in a turbine disk in Udimet 720 for a (a) low (b) high rotation rate. Localization of plastic strain rate appears while increasing the rotation rate.

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