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Numerical and Experimental Analysis of Damage Evolution and Martensitic Transformation in AISI 304 Austenitic Stainless Steel at Cryogenic Temperature

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ABSTRACT: In this research, properties of ductile damage evolution and martensitic phase transformation in an AISI 304 stainless steel at cryogenic temperature has been studied experimentally and numerically. Simple loading-unloading tension tests for specimens floating in liquid nitrogen have been performed. Accordingly, the cryogenic chamber has been designed and constructed to plunge the tensile test samples into the liquid nitrogen. From simple loading-unloading tension tests, the graph of force-deformation and the evolution of damage parameter during elastic unloadings have been determined. Afterwards, the x-ray diffraction tests have been performed on the stretched sample tests to evaluate the evolution of martensite phase in the resultant biphase material. In the numerical analysis, combining the phase transformation model of Garion and Skoczen and isotropic damage model of Lemaitre, a constitutive model for monotonic loadings has been introduced. The Garion and Skoczen model has been developed based on the assumption of small strains (under 0.2) for cryogenic condition. Furthermore, the hardening law for the biphase material has been obtained from the Mori-Tanaka homogenization. The numerical analysis in this study was carried out implementing the combined constitutive model by means of a user-defined material model subroutine in Abaqus/Standard. Finally, comparing the numerical simulation with the experimental data, parameters of the model has been calibrated.

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1- Introduction

Structural Materials, such as austenitic stainless steels, preserve their ductility even at cryogenic temperatures. Prediction of the behavior of these materials is important due to their wide and sensitive application in this range of temperature. Two main phenomena observed in plastic behavior of austenitic stainless steels at cryogenic temperatures are $\gamma \rightarrow \alpha'$ strain-induced martensitic phase transformation and the evolution of ductile damage [1].

Until now, some models have been introduced to predict the behavior of stainless steels at cryogenic temperature. Garion and Skoczen [2] have developed the first model for phase transformation particularly in cryogenic temperature. In this model, assuming a linear phase transformation kinetic model, a model for hardening of plastic behavior of bi-phase material based on the Mori-Tanaka homogenization scheme have been developed.

Although many researches have been developed on the phase transformation and damage evolution separately, a few works were dedicated to study both phenomena. Most of these studies, engaged with the behavior of materials at cryogenics, have developed the model by Garion and Skoczen [2] (GS model) accompanied with different continuum damage models. Some of these works are [1, 3-6]. In addition, two different constitutive models have been developed to consider the effect of strain rate on damage evolution and phase transformation [7, 8].

In the present paper, experimental and numerical analysis of damage evolution and martensite transformation of AISI 304 stainless steels at cryogenic temperature (77 K) has been represented. Isotropic continuum damage model of Lemaitre [9] in conjunction with the (GS model) have been applied. Loading-Unloading tensile tests and X-Ray Diffraction (XRD) method have been used in experiments to evaluate damage and martensite respectively. Numerical analysis has been performed in Abaqus/Standard, using a User-defined MATerial model (UMAT) code. Comparing the numerical and experimental results, parameters of the model have been determined.

2- Governing Equations

In this section, governing equations of the coupled model of damage evolution and martensitic transformation are represented briefly.

Garion and Skoczen [2] proposed a simplified evolution law for the volume fraction of martensite as follow:

$$\dot{\xi} = A(T, \dot{\varepsilon}_p, \sigma)\dot{p}H\left((p-p_{\xi})(\xi_L-\xi)\right) \tag{1}$$

where p_{ξ} represents the threshold plastic strain for phase transformation, ξ_L is the martensite content limit and H is the Heaviside function. Material parameter A generally depends on temperature and stress state. Also, $\dot{p}$ denotes the accumulated

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Table 1. Values of the parameters of the model

Parameter	Value	How to determine	Parameter	Value	How to determine
E	213.7 GPa	Directly from experiments	p_ξ	0.017	Directly from experiments
σ_y	595 MPa	Directly from experiments	ξ_L	0.74	Directly from experiments
C_0	2345 GPa	Directly from experiments	h	0.4	Calibrating the numerical with experimental results
A	4.095	Directly from experiments	S'	1 MPa	Calibrating the numerical with experimental results

plastic strain rate.

Considering isothermal condition, the general constitutive relation can be described as Eq. (2):

$$\boldsymbol{\sigma} = (1-D)\mathbb{E}:(\boldsymbol{\varepsilon}-\boldsymbol{\varepsilon}_p-\boldsymbol{\varepsilon}_{bs}) \tag{2}$$

where σ denotes the stress tensor, D the scalar damage variable, $\boldsymbol{E}$ the fourth-order elasticity tensor, ε the total strain tensor, ε_p the plastic strain tensor and ε_{bs} denotes the, so called, Bain strain tensor which can be expressed in terms of relative volume change Δv of the crystal due to phase transformation as $\varepsilon_{bs} = \frac{1}{3}\Delta V I$.

The Von Mises yield surface, coupled with damage through effective stress concept, has been used to describe the plastic behavior:

$$f_y = J_2(\tilde{\boldsymbol{\sigma}}) - \sigma_y - \tilde{R} \quad where \quad \tilde{R} = R/(1-D) \tag{3}$$

The rate of damage development with plastic deformation in the model of Lemaitre [9] could be expressed as:

$$\dot{D} = \frac{\sigma^2{}_{eq}}{2ES'(1-D)^2}\dot{p} \quad where \quad D = 1 - \frac{E(D)}{E_0} \tag{4}$$

where S' is a material constant and σ_{eq} is the von Mises equivalent stress. $E(D)$ represents the change of the Young modulus as the result of damage growth

Also, the evolution of isotropic hardening in the plastic behavior of biphase material based on the Mori-Tanaka homogenization method is presented by Garion and Skoczen [2]:

$$dR = C_m dp = 2(\mu_{MT} - \mu_{ta})dp \tag{5}$$

Where the μ_{ta} is shear modulus defined in Eq. (6)

$$\mu_{ta} = \frac{E_t}{2(1+\nu)}; \; k_{ta} = \frac{E_t}{3(1-2\nu)}$$
$$E_t = \frac{EC}{E+C}; \; C = C_0(1+h\xi) \tag{6}$$

and μ_{MT} is the homogenized modulus which is calculated by following equations [2]:

In Eq. (6), C_0 is the initial hardening parameter and h represents the increase in hardening of austenite due to harder martensite content. C_0 can be obtained from stress-strain curve of the material as the slope of the curve at the point of triggering the phase transformation.

$$\mu_m = \frac{E}{2(1+\nu)}; \; k_m = \frac{E}{3(1-2\nu)}$$
$$2\mu_{MT} + 2\mu^* = \left[\frac{1-\xi}{2(\mu_{ta}+\mu^*)} + \frac{\xi}{2(\mu_m+\mu^*)}\right]^{-1} \tag{7}$$
$$2\mu^* = \frac{\mu_{ta}(9k_{ta}+8\mu_{ta})}{3(k_{ta}+2\mu_{ta})}; \; k^* = \frac{4}{3}\mu_{ta}$$

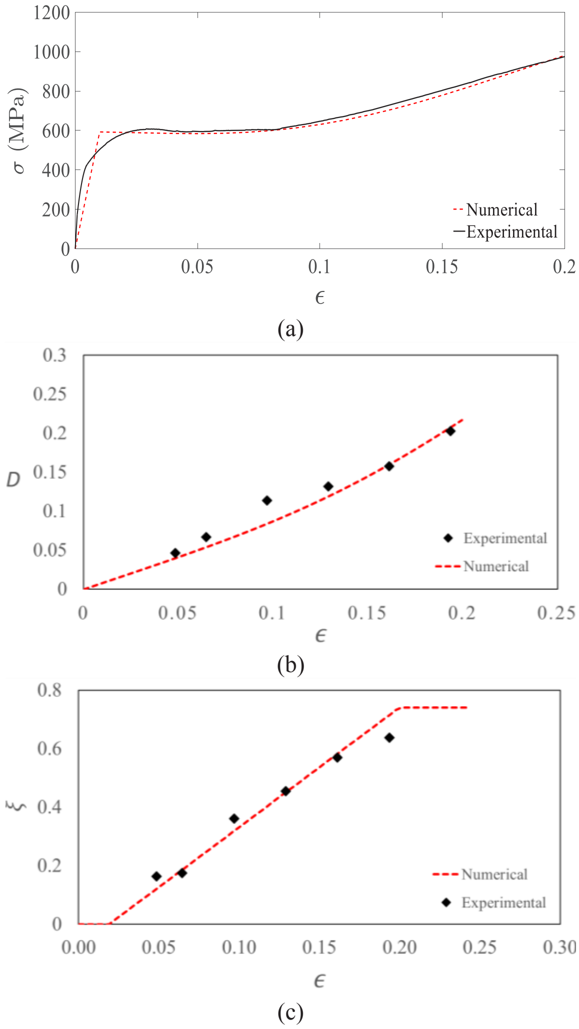

Fig. 1. Comparison of the numerical and experimental results for plastic behavior of AISI 304 stainless steel at cryogenic temperature

3- Experimental Test Procedure

The tensile tests have been performed at temperature 77K. In the present work, the specimens have been immersed in liquid nitrogen for at least 60s considering the ISO 6892-3 standard. A three-layered cryogenic chamber has been used in which the outer layer is made of AISI 304 stainless steel, the inner layer of PolyVinyl Chloride (PVC) and the middle layer is filled with polyurethane as a great insulation. The grip velocity is assumed as 0.75 mm/s in accordance with the ISO 6892-3 standard. Six levels of deformation (3, 4, 6, 8, 10, and 12 mm) have been specified to assess the martensite transformation and damage evolution. At each level of deformation, samples were unloaded and removed from the nitrogen bath in order to evaluate the damage parameter and to perform the X-Ray Diffraction test evaluating the amount of martensite formed in the sample.

4- Results and Discussion

In this section, numerical analysis has been performed implementing the constitutive model, represented in section 2, as a UMAT code in Abaqus/Standard. This analysis is used accompanied by experimental results to calibrate the parameters of the model. Some parameters of the model can be extracted from experimental results directly and other parameters should be obtained comparing numerical and experimental results. In Table 1, the value of these parameters has been specified. Using these parameters, the numerical response of represented constitutive model in comparison with experimental results has been shown in Fig. 1. It can be seen that the constitutive model represents a good agreement with experimental data.

5- Conclusions

A simplified constitutive model of plastic strain-induced phase transformation coupled with damage growth was presented for AISI 304 austenitic stainless steel at cryogenic temperature (77 K). Phase transformation model of Garion and Skoczen [2] and isotropic damage model of [9] was implemented in the constitutive equations. The model was developed on the basis of rate-independent small strain plasticity. In addition, experiments performed in order to identify the parameters in the model at cryogenic temperature (77K). The results show that the model can predict the plastic behavior of the material in monotonic loadings effectively.

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