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Memorization and Other Transient Effects of ST52 Steel and Its FE Description

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Abstract. This contribution presents main results of experimental tests realized on smooth specimens made of ST52 steel under strain controlled uniaxial cyclic loading and compares these results with numerical simulations performed using a modified Chaboche model by finite element method. The effects of NonMasing's behavior, memorization, cyclic hardening/softening and mean stress relaxation have been studied at room temperature. The experiments were realized on the reconstructed hydraulic fatigue testing machine INOVA 100 at the Laboratory of modern materials testing and defectoscopy of VŠB-TU Ostrava. Developed mixed hardening material model includes a memory surface stated in stress-space, which makes possible to significantly improve prediction of effects studied.

Introduction

Even classical materials such as metallic materials could exhibit very complex behavior when are used out of their elastic state [1]. Many researchers focus their attention in studying physic of plastic deformation. Current research shows that the plastic deformation could be explained by dislocation theory. From the microscopic point of view metallic materials contain crystal grains of different sizes and orientations. Each of grains has different level of strain energy stored in the crystal lattice. When a metal material starts to accumulate plastic deformation, each grain is subject to slip and yields successively. In consequence it results in formation of the multislip structures during cyclic loading, which is the major reason for strain hardening. Due to high complexity mentioned above models describing material behavior based on its microstructure are too computationally demanding so other approaches have to be used. Complex behavior of metallic materials can be modeled by phenomenological models [2]. However, a robust cyclic plasticity model with higher number of parameters, which should be estimated using a lot of experimental fatigue test data, is often required for correct description of material behavior [3].

There are presented main results of tests performed on ST52 steel under uniaxial loading. The strain-controlled tests were designed to study mainly cyclic hardening/softening behavior of the steel, mean stress relaxation and memorization under sequential loading. A new concept of cyclic plasticity model is developed to describe all studied effects observed by experiments.

Description of realized tests

There were realized three low-cycle fatigue tests under strain control on specimens made from ST52 steel at the VSB-TU Ostrava. The specimens were subjected to tension-compression on the reconstructed test machine INOVA 100kN (Fig.1). The extensometer EPSILON 3550 with 25.4mm gauge length was used to measure axial strain. The testing specimen has round-solid testing part with diameter of 8 mm, see Fig. 2. Definitions of all tests are stated in the Table 1. The loading rate of strain cycling was about 1×10^{-3} in all tests. The test A was performed to show cyclic softening behavior for lower strain amplitude. Tests B were realized after test A on the same specimen to study memorization effect of the material. Finally, the test C was realized for four sequences with different non-zero mean strain value to show the effect of mean stress relaxation of the investigated material.

Fig.1 A photo from experiments

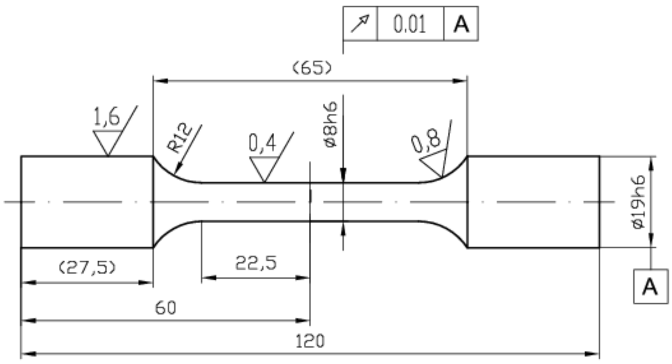

Fig.2 A scheme of used specimen

Table 1 – Tests definition

Strain controlled tests	**A**[b] ±0.22%	±0.5% (13c)[a]	+0.75% (1/2c)[a] -0.22%	+0.25% -0.22%
	B ±0.22%	±0.5% (13c)[a]	±0.75% (13c)[a]	±1% (13c)[a]
	C 0.75%	1.5%	2.25%	3%

[a] 13c represents number of cycles in the loadcase, the number of cycles of other unnoted loadcases is 25.

[b] (A) maximum and minimum of strain history; B) strain amplitude history with zero mean strain; (C) mean strain history with strain amplitude of 0.75%.

Cyclic plasticity modeling

In this paper we used classical incremental theory of plasticity with the concept of single yield surface. The rate-independent material models for metals mostly include von Mises yield criterion

$$f = \sqrt{\frac{3}{2}(\mathbf{s}-\mathbf{a}):(\mathbf{s}-\mathbf{a})} - Y = 0 \ , \ Y = \sigma_Y + R \, , \tag{1}$$

the associative flow rule

$$d\boldsymbol{\varepsilon}_p = dp\frac{\partial f}{\partial \boldsymbol{\sigma}} \ , \tag{2}$$

the kinematic hardening rule

$$d\mathbf{a} = g(\boldsymbol{\sigma}, \mathbf{a}, \boldsymbol{\varepsilon}_p, d\boldsymbol{\sigma}, d\boldsymbol{\varepsilon}_p, etc.) \tag{3}$$

and the isotropic hardening rule

$$dR = h(\mathrm{R}, \mathrm{dp}, \boldsymbol{\sigma}, \mathbf{a}, \boldsymbol{\varepsilon}_p, \boldsymbol{\varepsilon}_p, etc.) \ , \tag{4}$$

where $\boldsymbol{s}$ is the deviatoric part of stress tensor $\boldsymbol{\sigma}$, $\boldsymbol{a}$ is the deviatoric part of back-stress $\boldsymbol{\alpha}$, Y is the current size of the yield surface, R is the isotropic variable, σ_Y corresponds to the initial size of the yield surface, $\boldsymbol{\varepsilon}_p$ is the plastic strain tensor and dp is the equivalent plastic strain increment. The symbol ":" denotes the inner product between two tensors ($\mathbf{x}$:$\mathbf{y}$= $x_{ij}y_{ij}$).

The developed cyclic plasticity model is based on the kinematic hardening rule of Chaboche with the superposition of three backstress parts

$$\mathbf{a} = \sum_{i=1}^{M=3}\mathbf{a}_i \ , \ d\mathbf{a}_i = \frac{2}{3}C_i d\boldsymbol{\varepsilon}_p - \varphi(p)\gamma_i \mathbf{a}_i dp \ , \tag{5}$$

with the memory surface introduced by Jiang and Sehitoglu [4], but without contraction property. It means that the memory parameter R_M corresponds to the absolute maximum of backstress in previous history $|\alpha|$. The investigated steel shows kinematic and isotropic hardening, so the memory parameter is used in evolution equations for both hardening variables, the kinematic variable

$$\varphi(p) = 1 - (1 - \varphi_0(R_M)) \cdot e^{-\omega p} \tag{6}$$

and the isotropic variable

$$dR = b(Q(R_M) - R) \cdot dp \tag{7}$$

where ω end b are evolution parameters and suitable functions for φ_0 and Q are as follows

$$Q(R_M) = \sigma_Y a_k e^{c_k \cdot R_M} \quad , \tag{8}$$

$$\varphi_0(R_M) = \varphi_A \quad \text{for} \quad R_M \le R_M^L \ , \tag{9}$$

$$\varphi_0(R_M) = 1.5 - 0.0017 \cdot R_M \quad \text{for} \quad R_M \ge R_M^P \quad , \tag{10}$$

$$\varphi_0(R_M) = \varphi_A + \varphi_B R_M + \varphi_C R_M^2 + \varphi_D R_M^3 \quad \text{otherwise.} \tag{11}$$

All material parameters are shown in the Table 2. Calibration procedure of such model has been explained elsewhere [5].

Table 2 – Material parameters

σ_y=170MPa, C_1=2.5·10^{5}MPa, γ_1=2500, C_2=34860MPa, γ_2=273, C_3=1500MPa, γ_3=1.5, ω=20, b=10, a_k=0.03, c_k=0.007918, φ_A=0.135, φ_B=0.000513, φ_C=-4.28·10^{-5}, φ_D=4.31·10^{-7}, $R_M^L = 85$, $R_M^P = 175$

Results

Main results of experiments and performed simulations using developed cyclic plasticity model are shown at the Fig.2-4. As noted before the tests A and B were simulated together, because they were realized on the same specimen. Experimental and numerical results corresponding to the test A are presented at the Fig.2. It is clear from the comparison of prediction and experiment, that the third sequence of loading can be better modeled only by considering contraction of the memory surface or using other kinematic hardening rule. It is well known, that kinematic hardening rule significantly influence the relaxation prediction.

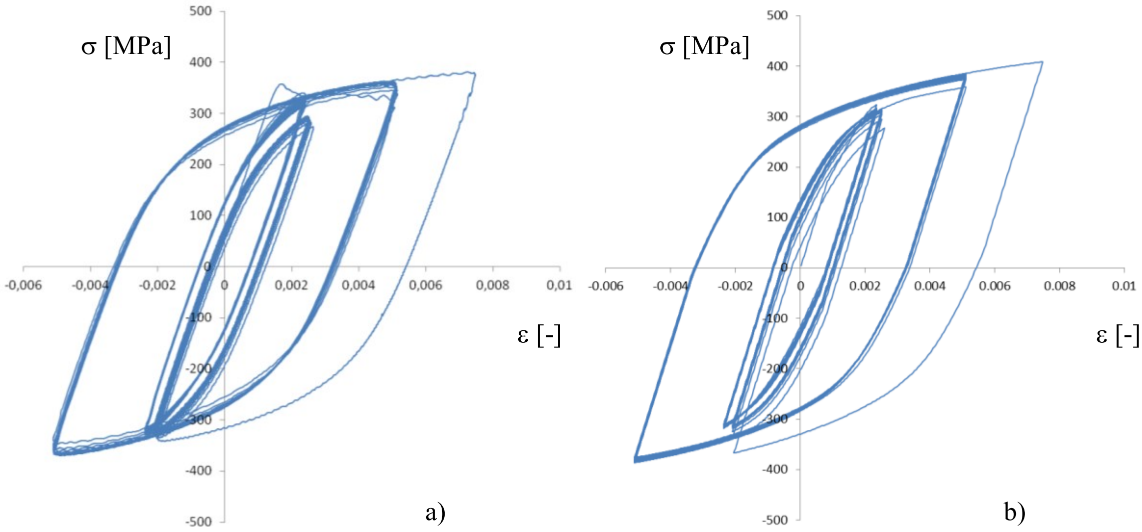

Fig.3 Experimental and predicted stress–strain hysteresis loops in the test A;
(a) experiment, (b) simulation.

Good correlation between shape of uniaxial hysteresis loops of experiment B and corresponding prediction is obvious from the Fig.4. Better accuracy of cyclic hardening behavior in this sequential test can be obtained for instance by use of memory parameter R_M to introduce dependency of evolution parameter ω on the amplitude of loading.

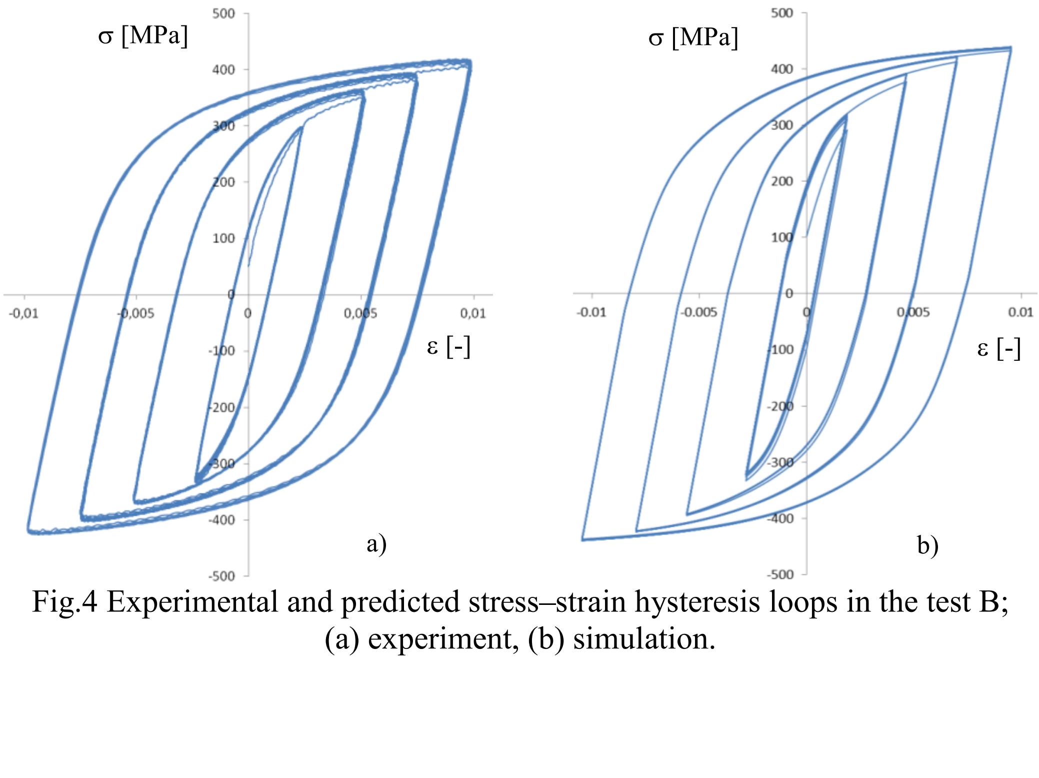

Fig.4 Experimental and predicted stress–strain hysteresis loops in the test B;
(a) experiment, (b) simulation.

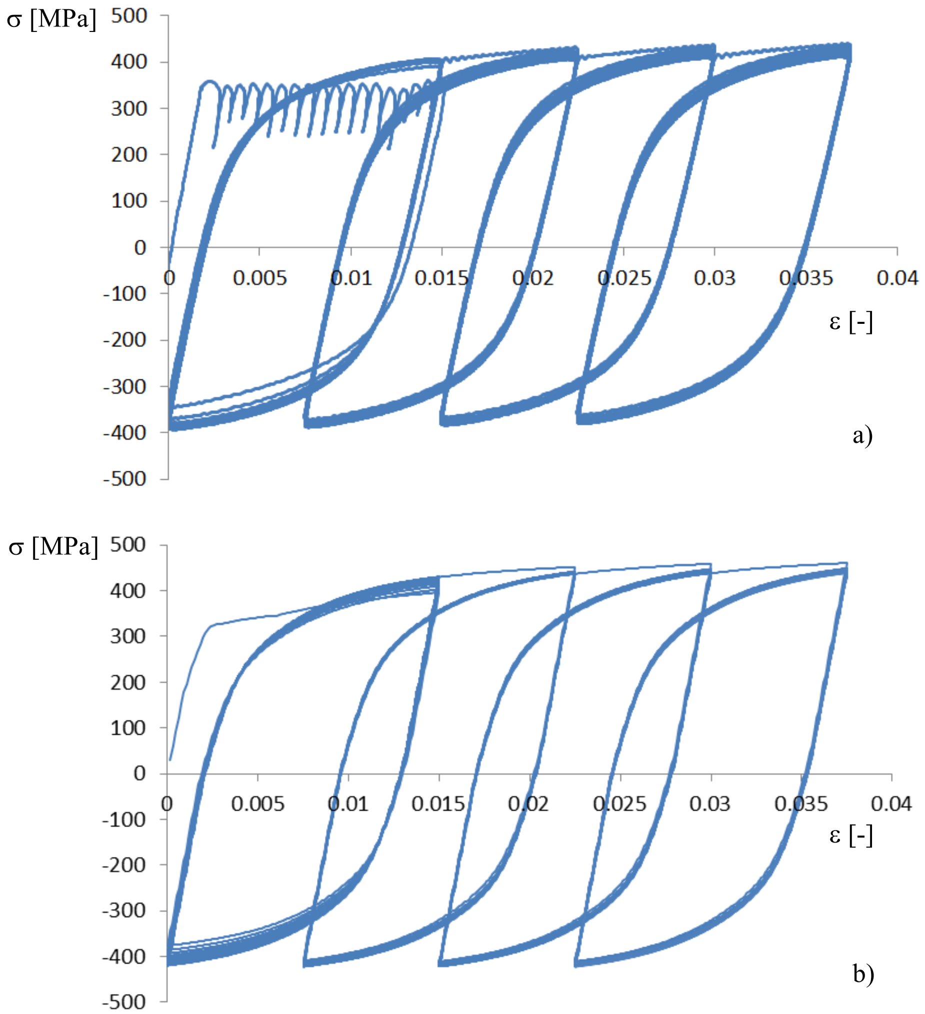

Fig.5 Experimental and predicted stress–strain hysteresis loops in the test C; (a) experiment, (b) simulation.

Good correlation between results of experiments and predictions is obvious in the case C too as can be seen in the Fig.5. The rate of mean stress relaxation can be influenced by the parameter γ_M. The same parameter is often used to improve accuracy of ratcheting prediction in the case of Chaboche model.

Summary

There were shown main experimental results of the stress-strain uniaxial behavior investigation of very popular constructional steel ST52. All three strain controlled experiments were simulated by a new cyclic plasticity model with the memory surface introduced in the stress space introduced by Jiang and Sehitoglu [4]. The model can describe transient softening/hardening behavior of the steel and its Non-Masing's behavior very well. Further possible improvements of the cyclic plasticity model to gain better prediction of the mean stress relaxation and memorization effects have been mentioned in the previous chapter. The concept of memory surface will be extended and applied to the MAKOC model [6] based on AbdelKarim-Ohno kinematic hardening rule in future.

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