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Yield-point phenomenon in constitutive models of cyclic plasticity

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A B S T R A C T

This paper describes the yield-point phenomenon in rate-independent constitutive models of cyclic plasticity. This phenomenon is typical of annealed low-alloy steels and related alloys as well as of some aluminium and titanium alloys and occurs at first transition from the elastic into the elasto-plastic region. The effects of cyclic plasticity are described with constitutive equations of kinematic and cyclic hardening or softening. The advantage of the presented model is that it requires a small number of material parameters which describe the yield-point phenomenon and can be defined using simple uniaxial monotonous experiments. In order to define material parameters and establish the stress–strain response of the constitutive model in comparison with the actual state, uniaxial monotonous and uniaxial cyclic tension–compression experiments were carried out. The model is included in the finite element code the use of which helps to simulate the contribution of the model to the development of the stress–strain state in a real structure.

1. Introduction

At first transition from the elastic into the elasto-plastic region, annealed low-alloy steels and some related alloys exhibit a typical sharp yield point and an immediate stress drop followed by a stress plateau (called the Lüders strain) and further hardening (Fig. 1). In the literature, this phenomenon is described as the yield-point phenomenon. Most existing constitutive models of cyclic plasticity [1,2] take no account of the yield-point phenomenon which is typical of the aforementioned metals. In most cases of cyclic loading, the plastic zone is covered by the elastic zone. Since the yield-point phenomenon is not taken account of, the models predict a degree of plastic deformation different from the real one. Precise stress–strain analyses require a model which accurately describes the yield-point phenomenon as well as the subsequent cyclic plasticity.

In the past, the yield-point phenomenon was described by many authors [3–20]. Despite a relatively large number of researchers in this field of work, only a few models of cyclic plasticity with the yield-point phenomenon were presented. The first to describe the uniaxial model of the yield-point phenomenon was Hahn [16]. The presented model described the stress drop based on Johnston's and Gilman's [4] concept of a rapid increase in the number of mobile dislocations at the transition of the yield point. Shioya and Shioiri [17] later expanded Hahn's model to a multiaxial one, while Itoh [18] was the first to implement Hahn's model to the finite element code. In the recent period, contribution in this field of work has been made by Yoshida [19,20], who has presented two rate-dependent models of cyclic plasticity. He describes the stress drop on the basis of rapid dislocation multiplication after the transition of the yield point.

The paper presents the yield-point phenomenon in elasto-plastic rate-independent constitutive models. The model is based on the phenomenological approach. The effects of cyclic plasticity such as the Bauschinger effect, cyclic hardening or softening as well as the changing of the centre of the yield stress surface are described with constitutive equations of kinematic and cyclic hardening or softening. The model is included in the finite element code by means of modern algebraic and symbolic methods which makes the model easy to use in more complex applications. The advantage of the presented model is that it requires a small number of material parameters which describe the yield-point phenomenon and can be defined using simple uniaxial monotonous experiments.

In order to define material parameters and establish the stress–strain response of the constitutive model in comparison with the actual state, uniaxial monotonous and uniaxial cyclic tension–compression experiments were carried out. For the purpose of observing the yield-point phenomenon and verifying the model under different material conditions, experiments were carried out on specimen under annealed and tempered conditions. A comparison of cyclic simulation with the application of the presented model shows good agreement with the performed experiments.

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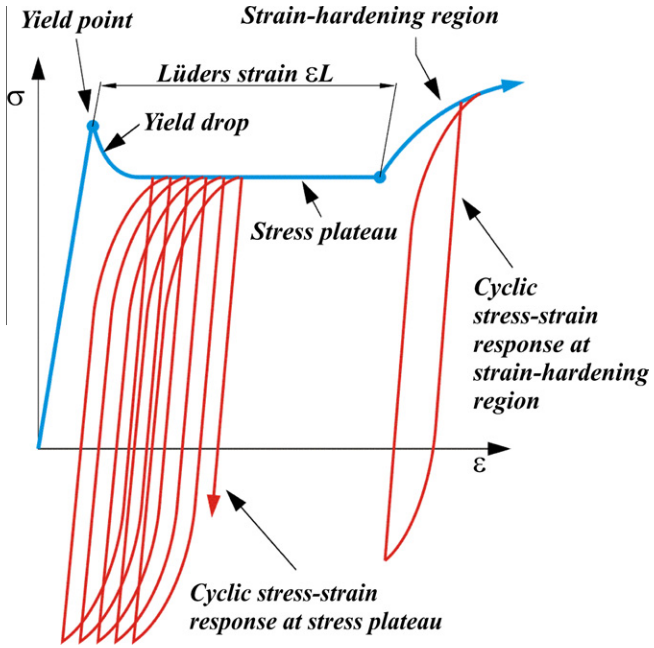

Fig. 1. Schematic presentation of the yield-point phenomenon in the stress–strain region.

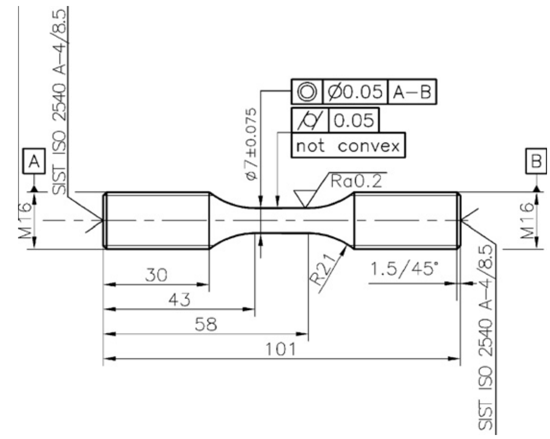

Fig. 2. Shape of a specimen.

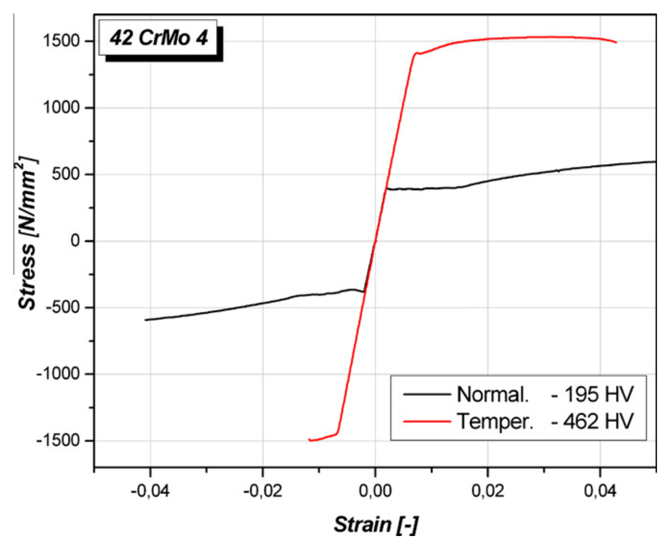

Fig. 3. Stress–strain curves obtained from monotonous experiments.

2. Experimental observations

For the purpose of observing cyclic elasto-plastic characteristics of the material, uniaxial monotonous tension and compression experiments as well as uniaxial cyclic tension–compression experiments were carried out. Specimens were made of low-alloy steel ISO 42 CrMo 4 (W. Nr. 1.7225, VCMO 140). Its chemical composition is presented in Table 1. The shape of the specimens (Fig. 2) was axial symmetric and in accordance with ASTM E 606 [21]. The specimen steel was annealed at 840 °C for 2 h and then slowly cooled in a stove. The hardness of steel was 195 HV. With the purpose of observing the size of the stress plateau and its reduction due to subsequent thermal treatment, experiments were carried out on the specimen made of annealed steel (195 HV) and on the specimen made of annealed steel the hardness of which was tempered to 462 HV by means of the heating process in the stove at 830 °C and quenching in oil followed by tempering at 400 °C for 1 h.

The experiments were carried out on a servo-hydraulic purpose-built test rig. Elongation of the observed region of the specimen was measured with a clip-on extensiometer with gauge length of 10 mm. Monotonous tension and monotonous compression experiments were carried out for annealed and tempered material. The crosshead speed during monotonous experiments was 0.2 mm/min. All experiments were carried out at a temperature of 20 °C.

Fig. 3 shows the flow of the stress–strain curve obtained during monotonous experiments for annealed and tempered material. With both annealed and tempered material, in the beginning the material response is elastic and ends with a yield point followed by a slight stress drop and inhomogeneous plastic strain. Deformation takes place during the formation of the entire stress or the Lüders plateau. Once the entire material part under observation is plastically deformed, the material is homogeneously deformed. The yield stress increases in accordance with the hardening of the material. The aforementioned yield-point phenomenon occurs during tension as well as compression experiments. It can be noted that the Lüders plateau is much bigger when the material is annealed than when it is tempered. According to the results obtained, it can be concluded that the yield-point phenomenon is significantly less distinctive after the material is tempered.

For the purpose of observing cyclic characteristics of the material, cyclic experiments with strain control were carried out at different mean values of the elongation and different elongation amplitudes. For experiment purposes both the annealed and tempered material was tested. All cyclic experiments were carried out at the speed of 2 Hz and at a temperature of 20 °C.

The results of cyclic experiments for annealed material are shown in Fig. 4. The curves in the figure apply to the strain ampli-

Table 1
Chemical composition of steel 42 CrMo 4.

	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Al	Sn
42 CrMo 4	0.43	0.26	0.65	0.015	0.021	1.07	0.19	0.16	0.16	0.021	0.006