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Material effects during monotonic-cyclic loading

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ABSTRACT

The effects commonly related with deformation caused by proportional and non-proportional loading types were identified experimentally. In the case of non-proportional cyclic loading along circular strain path the second order effects such as: phase shift between stress and strain signals was observed. An analysis of experimental data from tests under non-proportional cyclic loading along square strain path exhibited a significant reduction of stress independently on direction of deformation.

The paper also presents experimental results concerning evaluation of an influence of cyclic loading on stress variations during monotonic deformation carried out on the pure copper and X10CrMoVNb9-1 steel. All strain controlled tests were performed at room temperature using thin-walled tubular specimens. The experimental programme contained selected combinations of monotonic and cyclic loadings, i.e. the torsion-reverse-torsion cycles were superimposed on the monotonic tension. It is shown that such cycles associated with monotonic tension caused essential variations of tensile stress. For both materials, a significant decrease of the axial stress was visible. The effects observed during monotonic and cyclic loading combinations were theoretically described using the Mróz and Maciejewski model.

1. Introduction

Mechanical behaviour of structural materials under different kinds of cyclic loading was investigated in many laboratories (e.g. Lamba and Sidebottom, 1978; Pilo et al., 1979; Krempl and Lu, 1984; Tanaka et al., 1985; Benallal and Marquis, 1987; Ohashi et al., 1985; Khan and Wang, 1988; Murakami et al., 1989; Cheng and Krempl, 1991; Doong and Socie, 1991; Krempl and Cheng, 1993; Calloch and Marquis, 1997a,b; Cailletaud et al., 1991; Dietrich et al., 2000). Earlier experimental works in this research field were conducted on OFHC copper by the use of thin-walled tubular specimen (Lamba and Sidebottom, 1978). Their results demonstrated an additional hardening of the material expressed by much higher stress level at saturation state during deformation along circular loading path than that for simple tension–compression cycles observed (Lamba and Sidebottom, 1978). Also, this phenomenon was well reflected for the 316 stainless steel (Tanaka et al., 1985). In this case 200 MPa difference between the effective stress during deformation along proportional (tension–compression cycles) and non-proportional (circular) strain paths was obtained Fig. 1. Similar behaviour for the steel was observed during sequence of proportional and non-proportional deformation paths, Fig. 2. In the case of cyclic circular deformation 100 MPa increase of the effective stress was obtained, although the saturation state was achieved for an earlier cycles applied along the proportional loading path.

Later results, achieved for a range of materials tested under non-proportional cyclic loading, also demonstrated an additional hardening in comparison to the hardening observed under proportional loading path (e.g. Murakami et al., 1989a,b; Calloch and Marquis, 1997a). It is usually assumed that such effect is due to a higher number of slip systems activated by the non-proportional loading (Doong and Socie, 1991; Cailletaud et al., 1991).

Murakami et al. (1989a,b) conducted tests investigating the cyclic stress–strain relations of the 316 stainless steel subjected to tension–compression cycles and circular strain path under strain control at 873 K, Fig. 3. Besides of additional hardening observed during a circular deformation, the results show that the increase of the stress amplitude develops rapidly at the early stage of inelastic strain accumulation and then it tends asymptotically to a constant level (saturated stress state).

An influence of various type of loading paths, i.e. proportional and non-proportional on the 316 steel behaviour was examined by Calloch and Marquis (1997b). They analysed maximum equivalent stress at steady state for: tension–compression, hourglass, cruciform, square and circular paths. The largest value of the stress equal to 570 MPa was obtained during deformation along circular path, but the smallest one of 350 MPa was achieved for tension–compression. Other results (Colak, 2004) exhibited the higher

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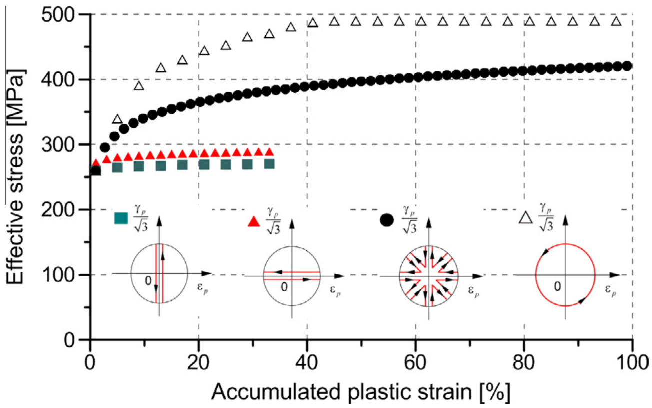

Fig. 1. Variations of effective stress for the 316 stainless steel during proportional and non-proportional loading (Tanaka et al., 1985).

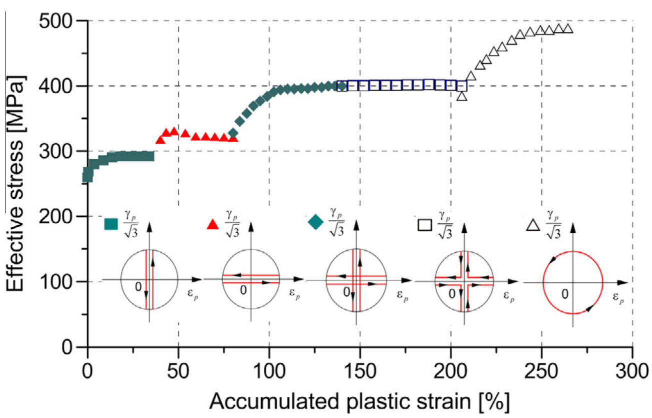

Fig. 2. An influence of loading path on the effective stress variations for the 316 stainless steel during sequence of proportional and non-proportional loading paths (Tanaka et al., 1985).

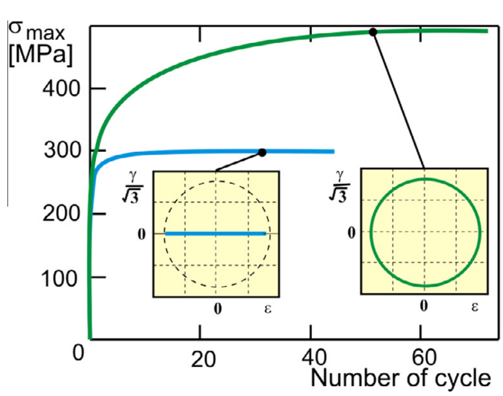

Fig. 3. Experimental data for the 316 stainless steel: cyclic stress–strain relations at 873 K under tension–compression cycles and circular cycles under total strain amplitude equal to 0.4% (Murakami et al., 1989a,b).

hardening for a square loading path than during deformation along a circle.

Some previous papers emphasised that the material behaviour is dependent on parameters of non-proportional loading paths (Benallal and Marquis, 1987; Xia and Ellyin, 1997). Besides of the amplitude, a retardation angle between strain signals can affect a material stress response. The results obtained for the 316 stainless steel exhibited 2.5 times increase of the maximum axial stress when the retardation angle was equal to 90° in comparison to that obtained for 33° (Benallal and Marquis, 1987). Experiments on the 304 stainless steel showed a slight decrease of the maximum equivalent stress from 270 to 230 MPa with a decrease of the retardation angle within the range of 90° ÷ 0° (Xia and Ellyin, 1997).

Taking into account experimental results mentioned above, it is reasonable to conclude that the cyclic loading of metals along non-proportional paths may have more significant influence on material properties than that usually observed for proportional ones.

From previous experimental works it is also known that for certain class of materials the softening effect can be observed under non-proportional cyclic loadings (Lamba and Sidebottom, 1978; Dietrich et al., 2000; Shamsei et al., 2010). Such difference between material behaviour under cyclic loading leads to the essential difficulties in the constitutive modelling. Therefore, for the rational formulation of multiaxial cyclic constitutive equation, it is necessary to study a series of representative non-proportional cyclic tests, and to identify the property of the multiaxial cyclic hardening/or softening mechanisms. In this paper the representative results will be given.

Among many topics taking place in analysis of cyclic loading effects of engineering materials one can distinguish experimental evaluation of an influence of different forms of shear deformation of engineering materials on their mechanical parameters variation during parallel or subsequent loading processes (Bochniak and Korbel, 1999, 2000, 2003; Kong and Hodgson, 2000; Correa et al., 2003; Gronostajski and Jaśkiewicz, 2004; Korbel and Bochniak, 2004; Bochniak et al., 2006; Niewielski et al., 2006; Kowalewski and Szymczak, 2007, 2008, 2009a,b). The results achieved from such investigations are important from technological point of view because they are providing a knowledge necessary for modification of some metal forming processes, such as drawing, extrusion or forging (Bochniak and Korbel, 1999, 2000, 2003; Kong and Hodgson, 2000; Korbel and Bochniak, 2004; Bochniak et al., 2006).

For example in the case of forging the loading was programmed in such a way, that the torsion cycles were activated during the stamp movement (Bochniak et al., 2006), Fig. 4a. A magnitude of the cyclic loading amplitude was dependent on the forging force. It was gradually increased as the forging force achieved bigger values. This type of loading enabled to reduce the axial force more than four times. Similar effect was achieved during extrusion, however, it was much weaker (Kong and Hodgson, 2000), Fig. 4b. Since the differences in reduction of forces in technological processes and their microscopic reasons are not fully recognised up to now, further experimental and theoretical analyses are necessary.

The analytical solution for tensile, or compressive deformation of cylinders or tubes of a perfectly plastic material with assistance of cyclic torsional strain was provided by Mróz et al. (2006), where the steady state stress paths and axial load reductions were discussed in detail. The well known technology of severe plastic deformation (SPD) to generate nano-size grain structure by cyclic non-proportional loading (such ECAP- equal channel angular pressing) certainly belongs to this class of problems, that is cyclic plasticity for kinematically induced large localised plastic straining, varying cyclically within the material element. The analysis of axisymmetric extrusion assisted by cyclic torsion was presented by Maciejewski and Mróz (2008). The subject is important not only from technological point of view, but also is essential for researchers developing new numerical codes and constitutive equations (Bochniak et al., 2006).

The paper presents an identification of effects due to complex loading being combination of cyclic and monotonic loading, and moreover, gives an attempt to model the phenomena observed. The results of such type experiments were mainly achieved for large deformations. In order to fill a gap in data for small deformations in this paper only such results will be reported.