MATERIAL EFFECTS DURING MONOTONIC-CYCLIC LOADING CONDITIONS

Zbigniew L. Kowalewski*, Tadeusz Szymczak, and Jan Maciejewski*****

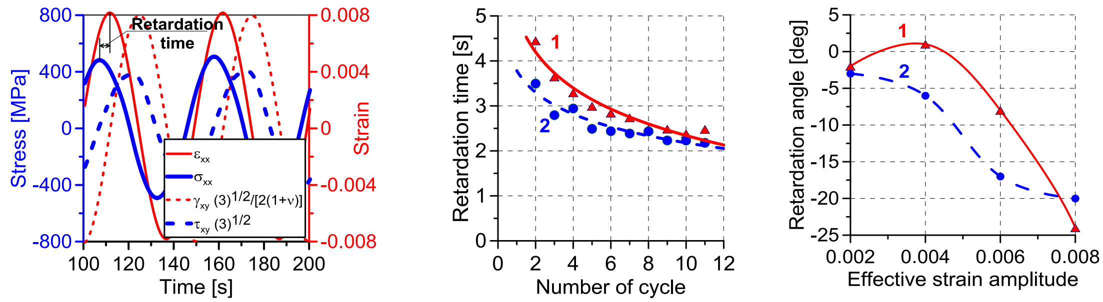
***Institute of Fundamental Technological Research,**
ul. Pawińskiego 5B , 02-106 Warsaw, Poland
zkowalew@ippt.pan.pl
**** Motor Transport Institute, ul. Jagiellońska 80, 03-301 Warsaw, Poland**
tadeusz.szymczak@its.waw.pl
*****Warsaw University of Technology, ul. Narbutta 84, 02-524 Warsaw, Poland,**
Jan.Maciejewski@simr.pw.edu.pl

ABSTRACT - The effects commonly taking place during proportional and non-proportional (circle and square) types of loading were identified experimentally. Experimental results of tests under cyclic loading assisted by monotonic deformation are compared to their predictions using the Mróz-Maciejewski model.

INTRODUCTION: Mechanical behaviour of structural materials under different kinds of cyclic loading was investigated in many laboratories. 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. Also, this phenomenon was well reflected by Tanaka *et al*. (1985). Later results also expressed an additional hardening in comparison to the effect observed under proportional loading path, e.g. [Murakami *et al.* 1989]. 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 [Kowalewski and Szymczak 2012].

PROCEDURES, RESULTS AND DISCUSSION: Three different commercial materials were investigated, i.e. the 2024 aluminium alloys, X10CrMoVNb9-1 steel and Cu 99.9 E copper. The experimental programme comprised two essential parts, i.e. combined tension-torsion cycles along the circular strain paths and combination of monotonic tension and torsion-reverse-torsion cycles.

A graphical presentation of the registered signals of strain and stress components as a function of time reveals remarkable phase shift between corresponding components of strain and stress. Typical example of this phenomenon is shown in Fig. 1a, b for the aluminium alloy. A difference between a time corresponding to the strain peak and that to the stress peak in a cycle defines so called retardation time, Fig. 1a, b. This parameter was used to calculate the retardation angle, Fig. 1c.



(a) (b) (c)

Fig. 1. The results for the 2024 alloy tested under cyclic loading along the circular strain path: (a) stress and strain signal components versus time at the cyclic strain amplitude equal to ±0.8%; (b) retardation time as a function of cycle number; (c) retardation angle versus effective strain amplitude; 1 and 2 - axial and shear components, respectively

As it is shown in Fig. 2, the torsion-reverse-torsion cycles associated with monotonic tension caused variations of the tensile characteristics. A significant decrease of the axial stress can be observed. An increase of the cyclic shear strain amplitude led to the further decrease of the tensile stress. It is expressed for example by an axial stress drop corresponding to the axial plastic strain equal to 0.2%, from 475 MPa to 125 MPa and from 240 MPa to 25 MPa in the case of steel and copper (Fig. 2a), respectively. The effect is much stronger for the copper, since such reduction (more than 8 times) is significantly greater than that for the steel achieved (more than 3 times).

Energy balance calculations were performed to compare total strain energy dissipated during typical monotonic test and that of a monotonic-cyclic loading combination, Fig. 2b. In the case of the steel and copper variations of the total strain energy calculated on the basis of tensile curves determined without or with torsion cycles exhibits a non-linear character. It decreases with an increase of the magnitude of cyclic strain amplitude.

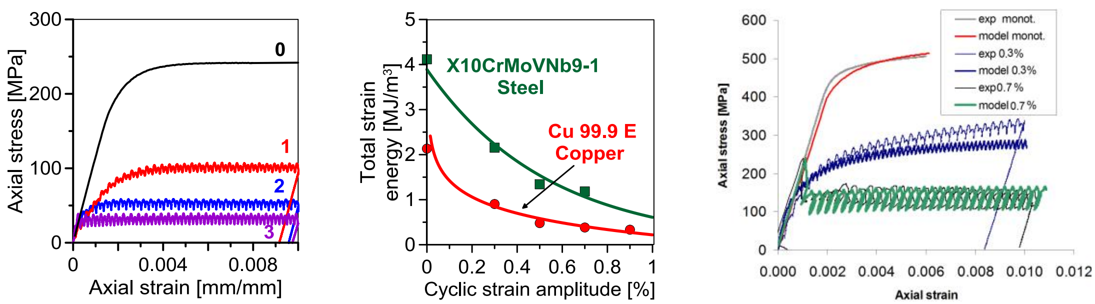
The Mróz-Maciejewski model was applied to simulate variations of stress-strain curve due to torsion cycles. Fig.2c. This concept based on the hardening (F_h) and limit (F_y) surfaces which can translate and expand. They are described by the following forms:

$$F_h = \sqrt{\tfrac{3}{2}\left(\boldsymbol{S}_l - \boldsymbol{Y}\right)\cdot\left(\boldsymbol{S}_l - \boldsymbol{Y}\right)} - \sigma_l\left(\xi\right) = 0,\ F_y = \sqrt{\tfrac{3}{2}\mathbf{Y}_l \cdot \mathbf{Y}_l} - R_l\left(\xi\right) = R - R_l = 0, \qquad (1)$$

where $\sigma_l(\zeta)$ $R_l(\zeta)$ are radiuses of the surfaces. Translation rule can be written as follows:

$$
\begin{aligned}
&\dot{\boldsymbol{Y}} = \dot{\lambda}\gamma_1\left(\boldsymbol{Y}_l - \boldsymbol{Y}\right) \quad \mathit{for} \quad r = \sqrt{\tfrac{3}{2}\boldsymbol{X}\cdot\boldsymbol{X}} > R_l\,,\\
&\dot{\boldsymbol{Y}} = \dot{\lambda}\gamma_1\left(\boldsymbol{X} - \boldsymbol{Y}\right) \quad \mathit{for} \quad r \le R_l\,,
\end{aligned}
\tag{2}
$$

where $\boldsymbol{Y}$ is the second level back stress, γ_1 is the material parameter, and $\boldsymbol{Y}_l$ is the limit convergence point. The limit, hardening and yield surfaces expand, but the ratio of their diameters is constant. The isotropic expansion of surfaces occurs when $F_h=0$, $f_p=0$, $F_y=0$, and depend on the amplitude of cyclic stress. Assuming that there is no isotropic hardening effect, then $l \le l_0$. The weighting parameter l connects with the distance of the stress point to the hardening surface. A comparison of experimental and numerical results, Fig. 2c, expresses applicability of the Mróz-Maciejewski model for material behaviour predictions under monotonic-cyclic deformation.



(a) (b) (c)

Fig. 2. Comparison of tensile characteristic (0) of the copper with stress-strain curves obtained during monotonic tension assisted by the torsion-reverse-torsion cycles for strain amplitude equal to: ±0.3% (1), ±0.5% (2), ±0.7% (3) - (a), total strain energy versus cyclic strain amplitude (b), comparison of experimental and numerical results (c).

CONCLUSIONS: The phase shift between strain and stress signals is typical for circular loading path. The total strain energy during tension decreases non-linearly with an increase of cyclic torsion strain amplitude. The Mróz-Maciejewski model can be used to simulate variations of tensile characteristic and phase shift effect as well.

REFERENCES:

Lamba, H.S., Sidebottom, O.M., 1978, Cyclic plasticity for non-proportional paths, Trans. ASME., J. Eng. Mat. Tech., **100**, 96.

Tanaka E., Murakami S., Ooka M., 1985, Effects of plastic strain amplitudes on non-proportional cyclic plasticity, J. Mech. Phys. Solids, **33**, 6, 559.

Murakami, S., Kawai, M., Aoki, K., Ohmi, Y., 1989, Temperature-dependence of multiaxial non-proportional cyclic behavior of type 316 stainless steel, J. Eng. Mat. Tech. **111**, 32.

Szymczak T., Kowalewski Z.L., 2012, Variations of mechanical parameters and strain energy dissipated during tension-torsion loading, Archives of Metallurgy and Materials, **57**, 1, 193.