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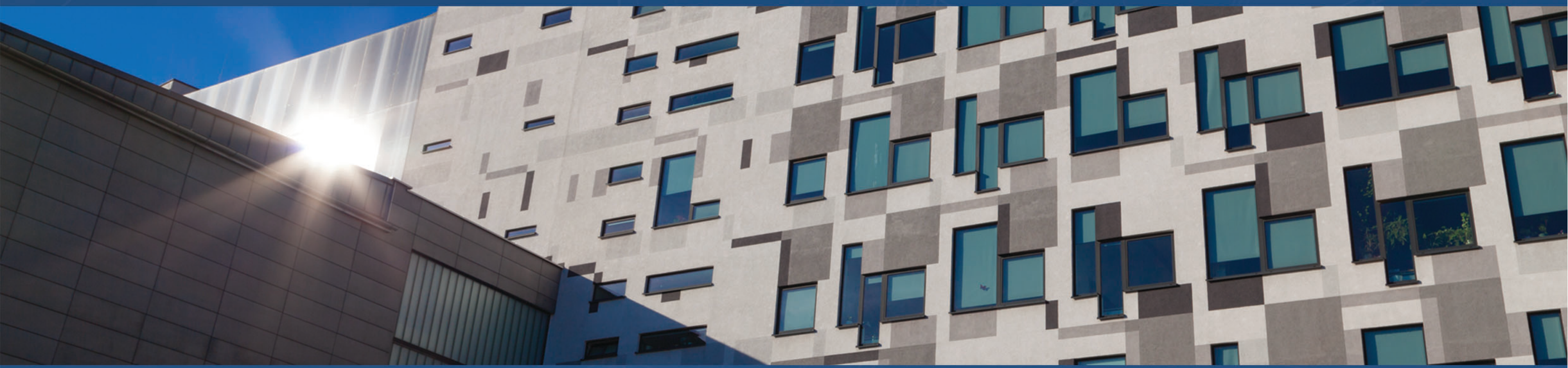

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VISCO-PLASTIC EFFECTS DUE TO DEFORMATION ALONG CIRCULAR LOADING PATH

T. Szymczak[1], Z.L. Kowalewski[2]

[1] *Motor Transport Institute, Warsaw, Poland*
[2] *Institute of Fundamental Technological Research, Warsaw, Poland*

e-mail: zkowalew@ippt.pan.pl

1. Introduction

Cyclic circular loading path is classified as a non-proportional deformation. Experimentally it can be obtained by the use of two out-of-phase sinusoidal signals of strain or stress: axial and shear [1, 2]. The phase shift between the signals should be equal to 90 degrees. An influence of circular path on material behaviour is investigated by many research groups [1-4]. They analyse variations of stress state components versus time. The results enable analysis of a cyclic softening or hardening of materials [1, 2, 4], variations of principal strain directions [3], and effective strain evolution [2]. For better understanding of material behaviour under non-proportional cycles further systematic investigations are required.

2. Experimental procedure and results

All tests were carried out at room temperature using thin-walled tubular specimens and servo-hydraulic testing machine. The wall thickness and gauge length of the specimens were equal to 0.75 mm and 60 mm, respectively. The 2024 aluminium alloy, widely used in aircraft industry, was selected for investigations. Strain gauges, cemented on the specimen measurement length, were used to control the testing machine. Two strain signals: axial and shear were applied to create circular strain path, Fig 1. Four values of the effective strain amplitude were selected in the experimental programme: ±0.2, ±0.4, ±0.6 and ±0.8%. The frequency was constant (0.02Hz).

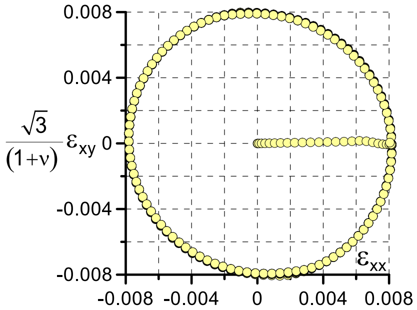


Fig. 1. Circular strain path for effective amplitude of ±0.8%

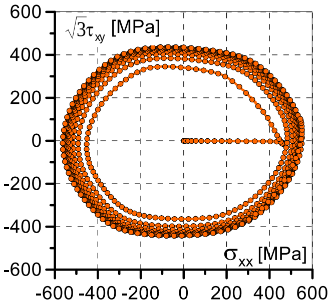


Fig. 2. Stress response into the programme shown in Fig. 1

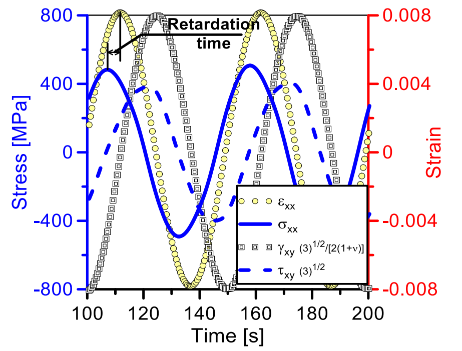


Fig. 3. Retardation time between strain and stress signals during cyclic deformation along circular strain path

Material behaviour during deformation along circular strain path was elaborated on the basis of: stress response (Fig. 2); retardation time and retardation angle (f) (Figs. 3, 4c); dynamic modulus (Fig. 4a); and modulus variation (Fig. 4b). For the strain amplitude of ±0.8% the stress response identifies material hardening, Fig. 2. A comparison of the stress and strain signals as a function of time makes it possible to determine a retardation time, Fig. 3. This phenomenon becomes more significant with increasing number of cycles and tends asymptotically to the constant level. Dynamic modulus (Fig. 4a) for axial and torsional directions can be expressed by the proportion of stress and strain amplitudes:

(1a, b) $$E_{d\_xx} = \frac{\sigma_a}{\varepsilon_{xx\_a}}; \quad E_{d\_xy} = \frac{\tau_a}{\varepsilon_{xy\_a}}.$$

Stress and strain amplitudes, that are used for calculation of dynamic modulus increment (Fig. 4b) in both directions considered may be defined by the following equations:

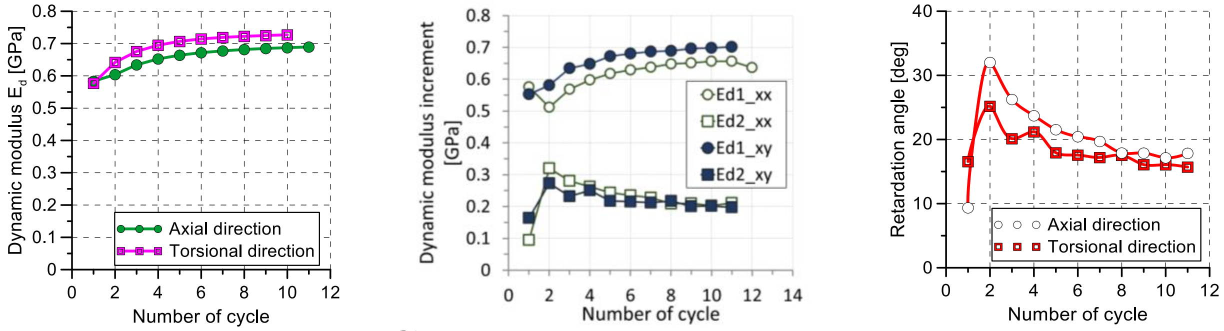
(2a, b) $$E_{d1\_xx} = E_{d\_xx} \cos(\varphi); \quad E_{d2\_xx} = E_{d\_xx} \sin(\varphi);$$

(3a, b) $$E_{d1\_xy} = E_{d\_xy} \cos(\varphi); \quad E_{d2\_xy} = E_{d\_xy} \sin(\varphi).$$

Retardation angle can be represented by the following relationships:

(4a, b) $$\tan(\alpha)_{\_xx} = \frac{E_{d2\_xx}}{E_{d1\_xx}}; \quad \tan(\alpha)_{\_xy} = \frac{E_{d2\_xy}}{E_{d1\_xy}}.$$

It achieved the highest value at the beginning of cyclic loading, and finally took almost constant magnitude, Fig. 4c.



(a) (b) (c)

Fig. 4. Visco-plastic effects observed during deformation along circular strain path: (a) dynamic modulus; (b) dynamic modulus increment; (c) retardation angle

Gradual increase of dynamic modulus (E_d) versus number of cycles identifies the material hardening. For the final stage of cyclic loading it takes constant level, close to the Young's modulus of the aluminium alloy tested. The same effect is observed for the variations of E_{d1_xx} and E_{d1_xy}, Fig. 4b. The variations of E_{d2_xx} and E_{d1_xy} moduli represent an opposite tendency. In the case of the retardation angle one can notice lowering of its value up to 17° for both directions taken into account, Fig. 4c. It means that the phase shift between stress and strain signals did not vanish, however, the saturation state was achieved (Fig. 2 and 4c).

3. Summary

An influence of circular strain path on the material behaviour can be studied on the basis of: (a) variations of principal strain directions, phase shift and retardation angle between stress and strain signals; (b) increase of dynamic moduli.

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