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VARIATION OF MECHANICAL PARAMETERS OF ENGINEERING MATERIALS UNDER TENSION DUE TO CYCLIC DEFORMATION BY TORSION

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The paper presents experimental results of investigations carried out under complex stress state on the 2024 aluminium alloy (used by aircraft industry) and P91 steel (used at power plants). Second-order effects associated with cyclic loadings enforced by the trapezoidal signals in the two mutually perpendicular directions are identified. It is shown, how the cyclic loading and its parameters (strain amplitude and frequency) influence the simultaneous monotonic loading in the direction perpendicular with respect to the cyclic one. Moreover, the paper presents an analysis of the selected mechanical properties variations on the basis of an initial yield locus evolution.

1. Introduction

The influence of different forms of shear deformation of engineering materials on their mechanical parameters variation during parallel or subsequent loading processes has been investigated by many research groups, e.g. [1, 7, 9, 10, 12, 13]. The experimental results of these tests reflect a great role of the shear deformation connected with location and distribution of material grains [12], enforcing of slip lines direction [13] or identification of characteristic dislocation structures associated with cyclic loading, for a range of shear stress amplitudes. There is also a strong interest in experiments evaluating the influence of torsion cycles on the materials behaviour after prestraining due to monotonic deformation [6], or tension-compression cycles carried out up to the saturation state [2]. Looking at the available publications, a new trend in material testing can be observed in the last decade. It is related to the cyclic loading application for a modification of some well-known forming processes [3–5]. Such an approach is important not only from the technological point of view, but also is essential for researchers developing new FEM codes and constitutive equations [8].

The paper presents the identification of material effects due to various combinations of cyclic and monotonic loadings.

2. Identification of cyclic loading influence on the material deformation in the perpendicular direction

2.1. *A role of torsion cycles for cyclic deformation in axial direction of the 2024 aluminium alloy*

All strain-controlled tests were carried out on the 2024 aluminium alloy under the biaxial stress state, being a combination of an axial force and twisting moment, both varying cyclically. The control signals were designed to form a square in the strain plane. It was achieved by the combination of two trapezoidal loading signals mutually delayed (when the first signal attained the maximum, then the second one started to increase linearly while the first one kept the constant value; when the second signal attained the maximum, the first one started to decrease up to the minimum while the second one kept the constant value, and so on). The main purpose of the programme was to identify second-order effects associated to the non-proportional cyclic loading along the square strain path.

An interesting feature can be easily noticed looking at the courses of stress and strain signals, Fig. 1a; 1b. A significant reduction of stress components magnitude takes place. It is visible when one of the control loading signals changes the direction (i.e. turns back). The second-order effects mentioned above are

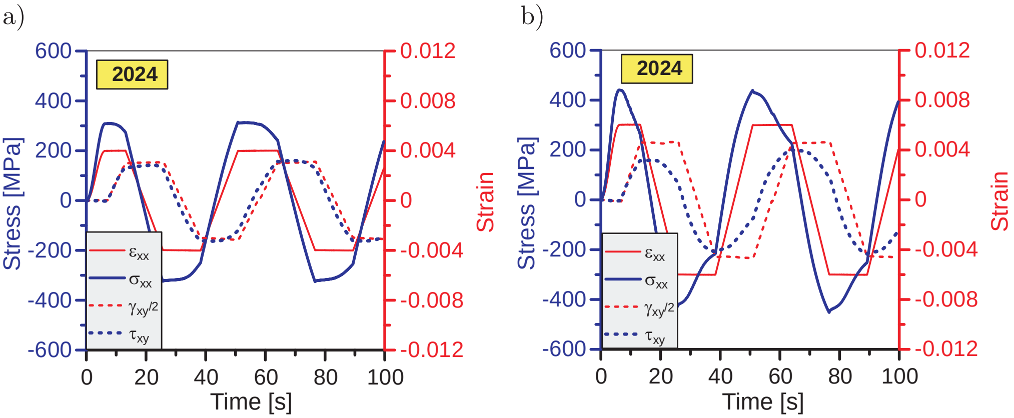

Fig. 1. Variations of the strain and stress signals due to cyclic loading realized along the square strain path. Effective strain amplitude: a) ±0.4%; b) ±0.6%.

especially considerable when the amount of strain amplitude increases. For example, in the case of the cyclic strain amplitude equal to ±0.4% a drop of the axial stress reaches about 100 MPa, whereas for ±0.6% it equals 250 MPa.

The influence of complex cyclic loadings acting along square strain path on the mechanical behaviour of the 2024 aluminium alloy can be evaluated on the basis of the data shown in Fig. 2, where the selected experimental results are presented. The results exhibit a hardening effect of the material. It is expressed by a gradual increase of stress amplitude and hysteresis loops. The effect increases with the strain amplitude increase. Moreover, the material does not reach the saturation state after the applied number of cycles. Both diagrams in Fig. 2 also well identify the axial stress reduction. Direct reason of that effect is connected with unloading in the torsion direction.

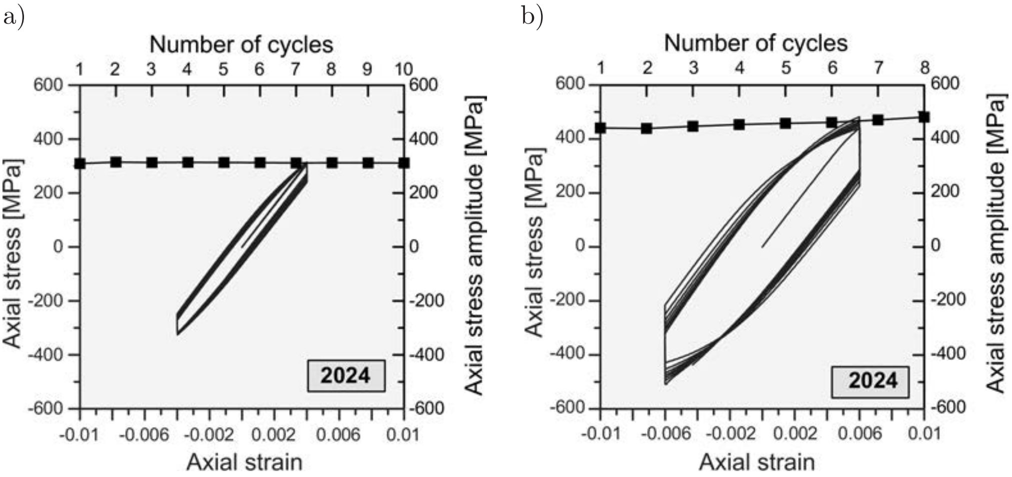

FIG. 2. Stress-strain variations and stress amplitude evolution due to the loading programmes shown in Fig. 1. Effective strain amplitude: a) ±0.4%; b) ±0.6%.

A rapid stress drops observed during cyclic loading along a square strain path was further investigated on the P91 steel, using the experimental programme in which torsion cycles were superimposed on monotonic tension. The representative experimental results of these tests are presented in the next point of this paper.

2.2. *An influence of torsion-reverse-torsion cycles on uni-axial tension of the P91 steel*

The experimental programme was carried out for a small value of the total strain, less than 1%. The main experimental objectives were focused on evaluation of:

- the influence of torsion-reverse-torsion cycles on the tensile characteristic and conventional mechanical parameters of engineering materials;
- the role of delayed torsion cycles on the behaviour of materials during the monotonic tension;
- an influence of the cyclic loading frequency on the tensile characteristics.

The P91 steel, commonly applied in the power industry, was investigated. A control parameter in the form of cyclic strain amplitude was designed to have a triangular shape and frequency equal to 0.5 Hz or 1 Hz.

All tests were carried out at room temperature using thin-walled tubular specimens with 1.5 mm wall thickness. The biaxial stress state was obtained using various combinations of axial force and twisting moment. All loading programmes were strain-controlled. The experimental programme contained selected combinations of monotonic and cyclic loadings, i.e. the torsion-reverse-torsion cycles were superimposed on the monotonic tension.

In the last part of the experimental programme, the subsequent yield surfaces for a plastic offset strain equal to 10^{-5} were determined. It enabled investigation of the initial yield surface evolution due to the loading history applied.

The representative loading programme is shown in Fig. 3. It presents some variations of the axial and shear strain components versus time. Stress responses in the programme are illustrated in Fig. 4. Variations of the axial stress express the material hardening in the direction of tension, while those for the shear stress observed identify a lack of any significant effects.

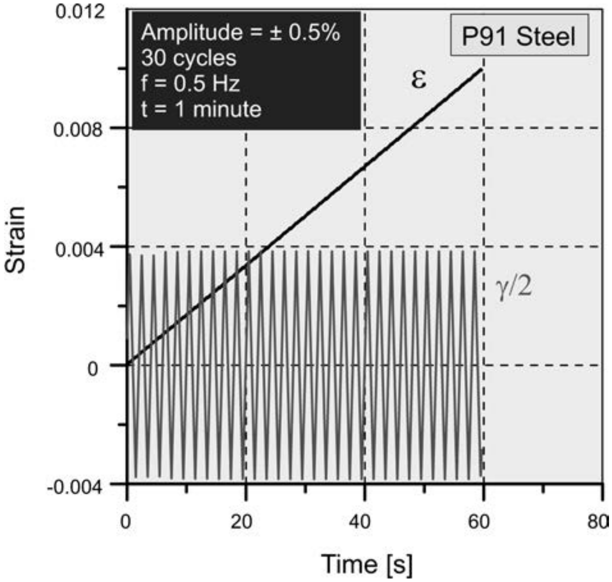

Fig. 3. Strain-controlled loading paths (ε – axial strain, $\gamma/2$ – shear strain).

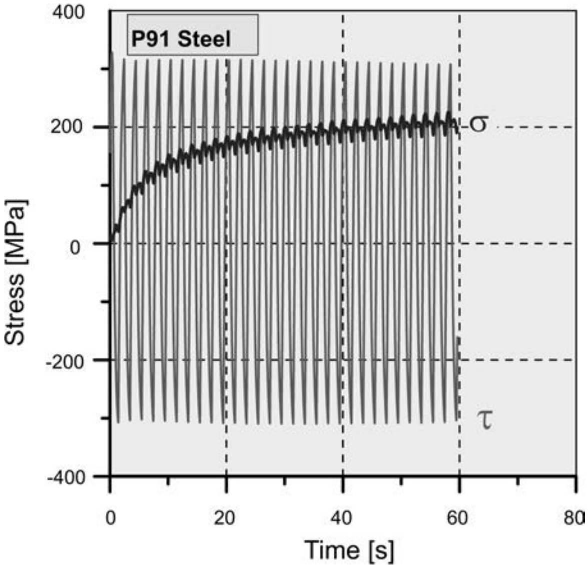

FIG. 4. Stress responses in the loading program shown in Fig. 3
(σ – axial stress, τ – shear stress).

In the first part of experiment, an influence of the cyclic strain amplitude on the basic mechanical parameters evolution was investigated. As it is shown in Fig. 5, the torsion-reverse-torsion cycles associated with monotonic tension

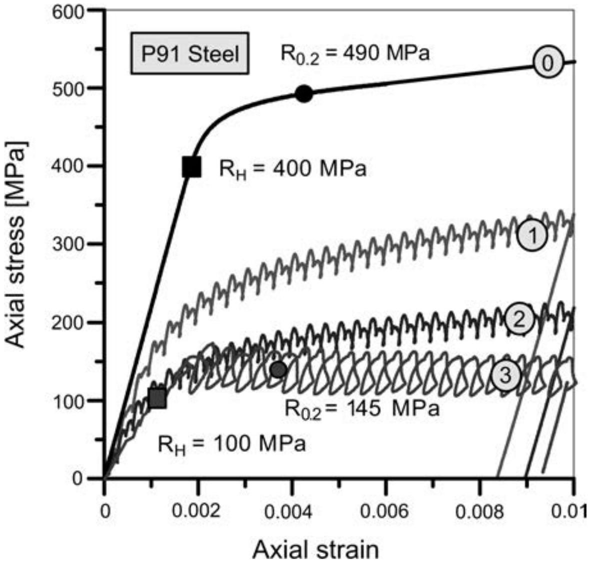

FIG. 5. Comparison of typical tensile characteristic (0) with tensile characteristics due to monotonic tension, superimposed on the torsion-reverse-torsion cycles for strain amplitude equal to: ±0.3% (1), ±0.5% (2), ±0.7% (3).

caused variations of the tensile characteristic. 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 stress-strain characteristic. As a consequence, due to the cyclic loading applied, the conventional mechanical parameters, such as the proportional limit and yield point, were significantly reduced. It is expressed by an essential drop of the yield point from 490 MPa to 145 MPa (Fig. 5).

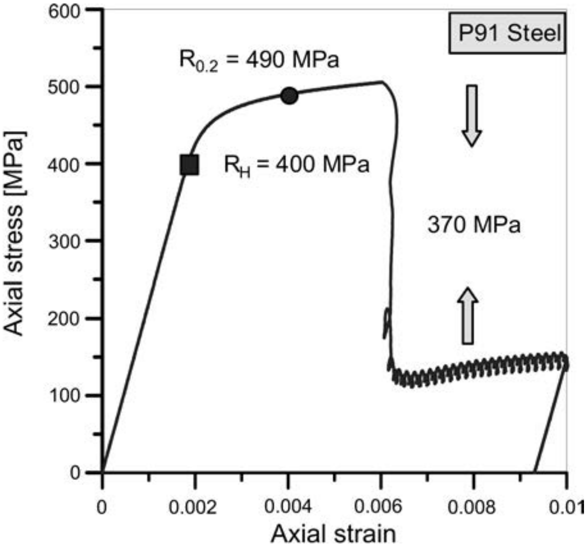

Fig. 6. Tensile characteristic of the P91 steel determined in assistance of torsion cycles (±0.5%), delayed with respect to monotonic axial loading.

The stress-strain diagrams showing the results of tests for the 2024 aluminium alloy identify a transient character of the axial stress reduction during tension associated with cyclic loading [9, 11]. This conclusion can be proved by determination of the yield surfaces for materials after standard tension tests and after the tension carried out in the presence of torsion cycles.

Thus, the next step of the experimental programme comprised the tests, the main aim of which was to check whether the axial stress reduction (as a consequence of the axial force lowering) during tension had a permanent character. The yield surface concept was applied. For each yield surface determined it was assumed that the total strain in the axial direction must be the same. The representative results for the P91 steel are presented in Fig. 7. As it is clearly seen, the subsequent yield surfaces for the material confirm that the axial stress reduction is related only to torsion cycles during monotonic tension. Looking at the magnitudes of tension stress achieved for the same offset strain, instead of reduction their increase can be observed. Therefore, it can be concluded that the comparison of the subsequent yield loci with the initial yield surface exhibits only an influence of the loading history applied, and moreover, it proves a transient character of the axial force reduction, which can be solely attributed to cycles acting in the perpendicular direction.

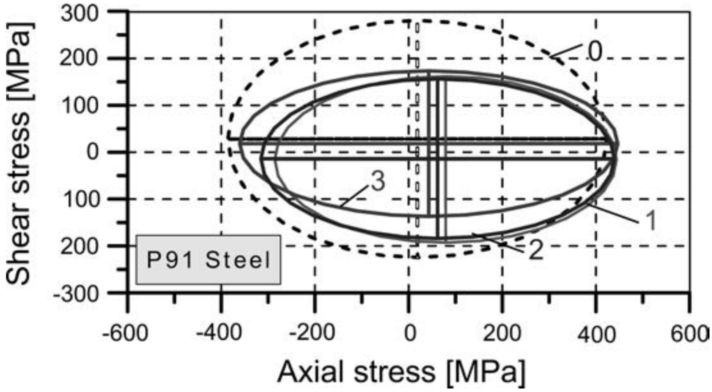

Fig. 7. Evolution of the initial yield surface (0) for the P91 steel due to torsion-reverse-torsion cycles for strain amplitude equal to: ±0.3% (1), ±0.5% (2), ±0.7% (3).

Taking into account the evolution of the initial yield surface origin, it is easy to see a reduction of the residual stresses in the torsion direction for the material subjected to the highest value of the torsion cyclic strain amplitude. In order to check whether a further increase of the cyclic strain amplitude may further eliminate the residual stresses from the material, additional tests were carried out. They were performed for two combinations of cyclic and monotonic loading having the same value of strain amplitude equal to ±0.8%, Fig. 8. At first, the material was subjected to monotonic torsion (up to 1% prestrain) assisted by tension-compression cycles and then, using another specimen, it was loaded monotonically by increasing axial force (leading to 1% prestrain) and by reversible twisting moment. In the next step, directly after termination of these loading programmes, the yield surfaces were determined. Their comparison with the initial yield locus confirms the transient character of a stress reduction observed on the monotonic loading direction when cycles were in progress. Also, a tendency to residual stresses reduction due to the increase of cyclic strain amplitude was approved. The results presented in Fig. 8 delivered an additional important knowledge on the material behaviour, namely, the P91 steel subjected to cyclic loading exhibits the softening effect observed on the directions corresponding to those of the cycles applied. Similar conclusions can be formulated on the basis of the results presented in Fig. 9. It shows a comparison of the initial yield locus with the subsequent yield surface determined after termination of the loading programme illustrated in Fig. 6. Despite the delay of cyclic

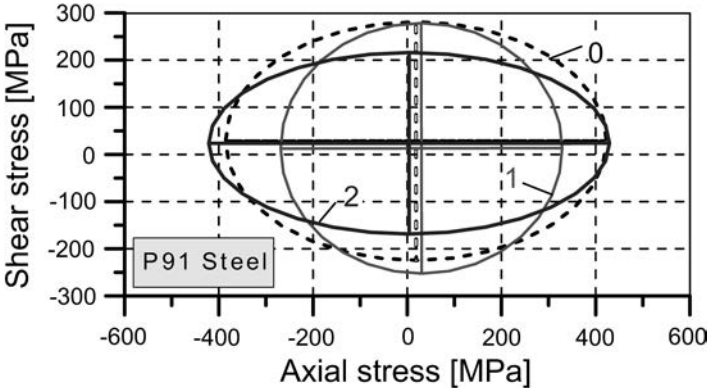

Fig. 8. Comparison of the initial yield surface (0) with the subsequent yield surfaces determined after monotonic torsion combined with tension-compression cycles (1) and after monotonic tension and by torsion cycles (2). For both cyclic loadings, the effective strain amplitude was equal to ±0.8%.

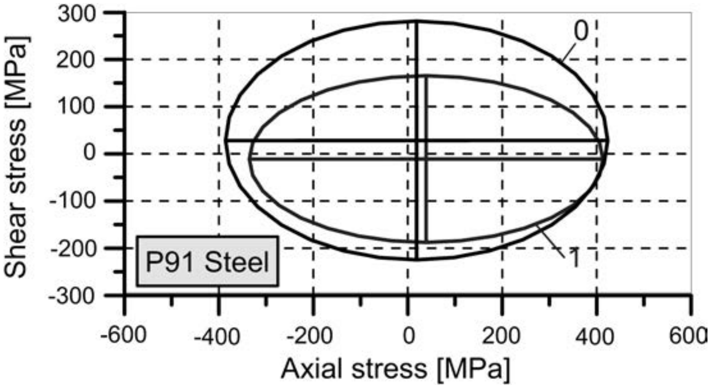

Fig. 9. Comparison of an initial yield surface (0) with a subsequent yield surface (1) after the test shown in Fig. 6.

torsion with respect to monotonic deformation due to tension, the same effects were obtained, i.e. softening of the steel in the directions of cyclic preloading and a lack of stress reduction observed during an acting of the torsion-reverse-torsion cycles.

The experimental programme also contained the tests evaluating the influence of the cyclic loading frequency on the tensile characteristics. As mentioned earlier, two values of the frequency were taken into account: 0.5 Hz and 1 Hz. The results are presented in Fig. 10.

As it is shown, only a small variation was achieved, and therefore further investigations in this matter are required. They should cover a much wider range of the frequency variation.

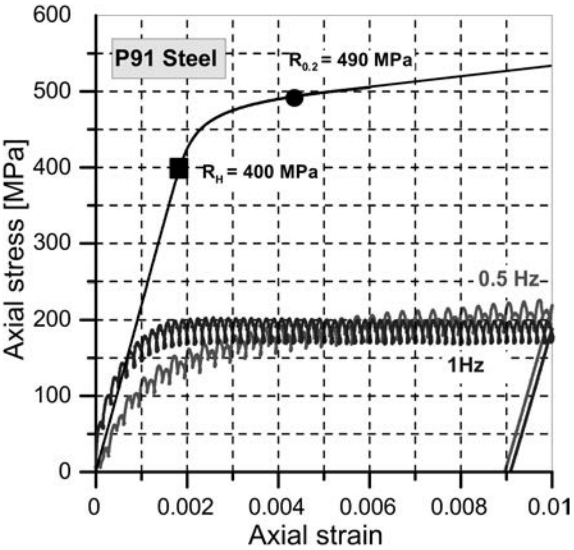

Fig. 10. Illustration of the effect of frequency variation on the tensile characteristics.

3. Final remarks

The effects presented in the paper are especially important for solid mechanics development, since they can be used to formulate new constitutive models. On the other hand, they provide an essential knowledge necessary for possible modification of some forming processes commonly applied in the industry.

The investigations carried out on the P91 steel and 2024 aluminium alloy allow to formulate the following conclusions and remarks:

- for the non-proportional cyclic loading along a square strain path, a significant reduction of stress components was identified. It was observed during each turn back of cyclic loading components;
- torsion-reverse-torsion cycles during monotonic tension cause a significant decrease of the proportional limit and yield point;
- an increase of the strain amplitude of torsion cycles improves material ductility in the tension direction;
- a reduction of the yield point and proportional limit increases with the cyclic strain amplitude increase;
- an axial stress reduction due to the presence of torsion cycles is not permanent, it vanishes after cyclic loading interruption;
- an initial yield surface evolution does not confirm rapid reduction of the selected mechanical parameters during tension assisted by cyclic torsion, it only points out their variations due to the loading history applied;

- the frequency variation of cyclic loading, within the range of values considered, caused only a little variation of the tensile characteristic.

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