A ROLE OF CYCLIC LOADING AT MODIFICATION OF SIMPLE DEFORMATION PROCESSES OF METALLIC MATERIALS

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Abstract: The paper presents experimental results of investigations carried out on the 2024 aluminium alloy and P91 steel under biaxial stress state. The loading programme comprised a monotonic tension assisted by torsion-reverse-torsion cycles. An influence of the cyclic loading and its delay with respect to uniaxial tension on the selected mechanical parameters taken on the basis of tensile characteristics was investigated. Additionally, a relative variation of the proportional limit and yield point due to the loading history applied was analyzed. A permanency of effects observed during combination of tension and cyclic torsion was experimentally assessed on the basis of an initial yield surface evolution.

1. INTRODUCTION

An activity of many research groups is focused on experimental evaluation of an influence of cyclic loading on material behaviour under complex stress states being combination of an axial force and twisting moment (Niewielski et. al. 2006; Xiang, 2003; Correa et. al., 2003; Gronostajski and Jaśkiewicz, 2004; Kowalewski and Szymczak, 2007, 2008, 2009). 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 (Kong and Hodgson, 2000) or forging (Bochniak et al. 2006).

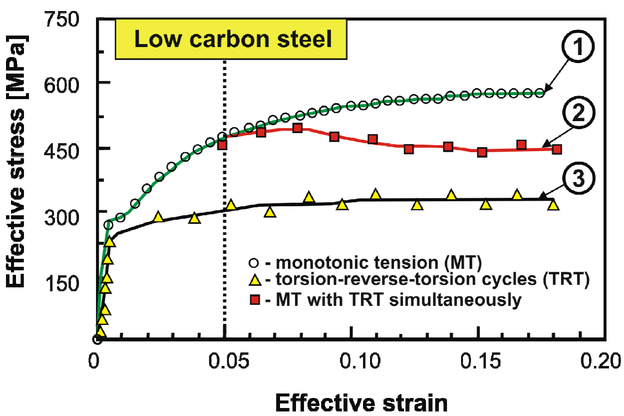

Fig. 1. Variations of the effective stress-effective strain characteristics due to different types of loading: 1 – monotonic tension, 2 – monotonic tension and torsion-reverse-torsion cycles, 3 – torsion-reverse-torsion-cycles (Correa et. al. 2003)

Moreover, these results are also important for developing of a new theoretical formulas and modelling of material effects observed (Kong and Hodgson, 2000).

An essential change of the stress-strain characteristic in the form of stress drop for the same magnitude of strain is the typical material effect associated with cycles acting in the perpendicular direction with respect to the monotonic loading (Correa et. al., 2003; Gronostajski and Jaśkiewicz, 2004; Kowalewski and Szymczak 2007, 2008, 2009), Fig. 1. As it is presented in Fig.1, a switching on of the cyclic loading caused 33% drop of the monotonic tension curve. However, a comparison of the stress-strain curve for the tests carried out under combination of monotonic tension and cyclic torsion against to the curve representing a cyclic torsion only, exhibits a hardening effect.

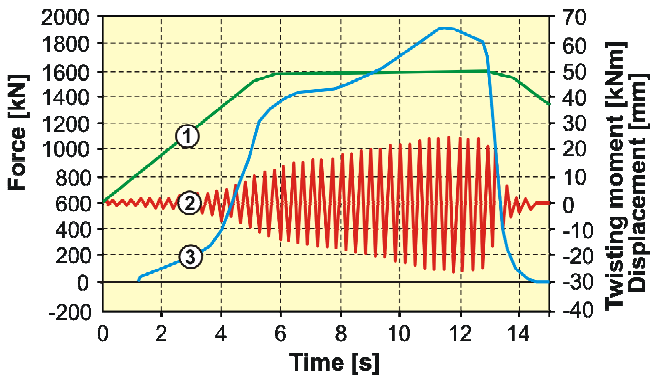

Fig. 2. A scheme of loading programme for optimisation of forces during the bevel gears forging at temperature equal 850^{o}C, 1 – displacement of stamp, 2 – twisting moment, 3 – forging force (Bochniak et. al. 2006)

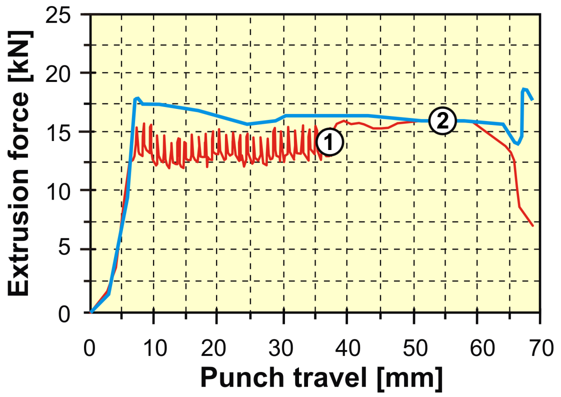

Fig. 3. Force variations during extrusion process by application of the KOBO method, 1 – using torsional loading, 2 – without torsional loading (Kong and Hodgson, 2000)

A cyclic loading was successfully applied to improve forging processes, Fig. 2 (Bochniak et. al.). The loading was programmed in such a way, that the torsion cycles were activated during the stamp movement. A magnitude of the cyclic loading amplitude was dependent on the forging force. It gradually increased as the forging force was increased. This type of loading reduced the axial force during forging more than four times. Similar effect was achieved during extrusion, however, it was much weaker, Fig. 3. (Kong and Hodgson, 2000).

2. DETAILS OF EXPERIMENTAL PROCEDURE

The main 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:

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

Three materials were tested: P91 steel (commonly applied in the power industry), 2024 aluminium alloy from aircraft industry and M1E pure cooper (mainly used in the electronic industry). A control parameter in the form of the cyclic strain amplitude was designed to have a triangular shape and frequency equal to 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 an 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 subsequent yield surfaces for a plastic offset strain equal to 10^{-5} were determined. It enabled investigation of an initial yield surface evolution due to the loading history applied.

3. THE EXPERIMENTAL RESULTS

At the beginning of the main experimental programme a material behaviour was investigated under torsion-reverse-torsion. Figure 4 presents representative variations of shear stress for two tested materials. The results for the pure copper exhibit a significant cyclic softening effect (Fig. 4a), but in the case of steel a little cyclic hardening takes place (Fig. 4b). These effects are also well visible in Fig. 5 which presents hysteresis loops evolution for both materials.

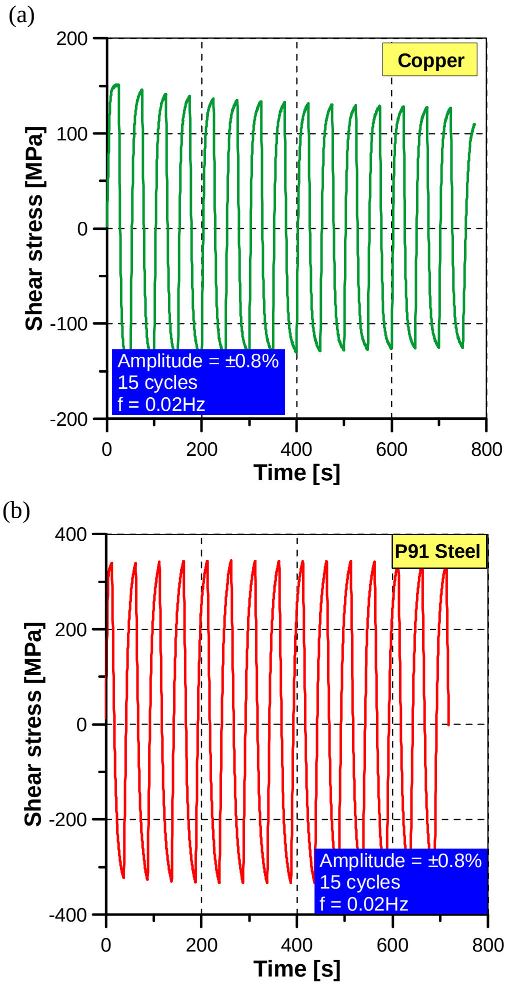

Fig. 4. Variations of a shear stress due to torsion-reverse-torsion cycles for: (a) M1E copper; (b) P91 steel

The main representative loading programme is shown in Fig. 6a for the P91 steel. It presents some variations of the axial and shear strain components versus time. Stress responses into the programme are illustrated in Fig.6b. Variations of the axial stress express the material hardening in the tension direction, while those for the shear stress observed identify a lack of any significant effects.

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 Figs. 6-10, the torsion-reverse-torsion cycles associated with monotonic tension caused variations of the tensile characteristic. For both materials, 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.

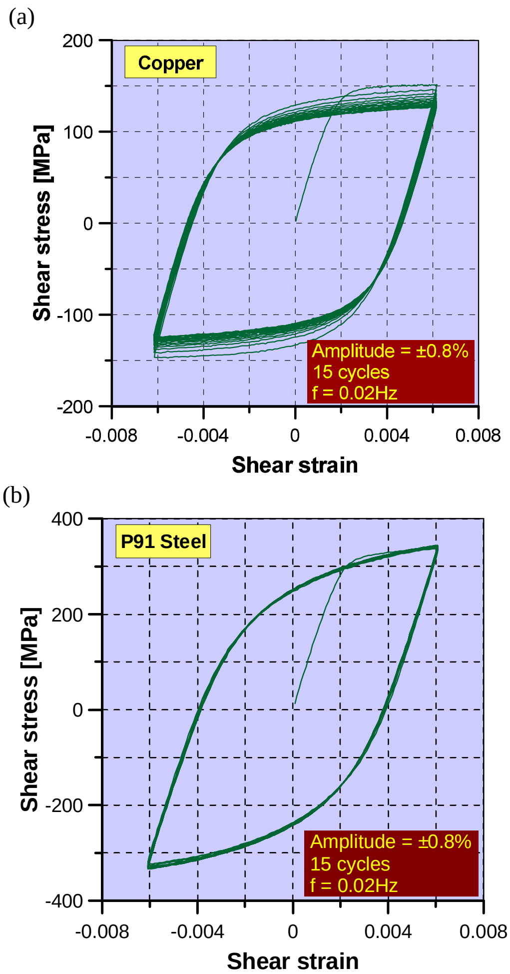

Fig. 5. Hysteresis loops evolution due to torsion-reverse-torsion cycles for: (a) M1E copper; (b) P91 steel

As a consequence, due to the cyclic loading applied the conventional mechanical parameters, such as the proportional limit and yield point, were reduced significantly. It is expressed by an essential drop of the yield point from 240 MPa to 25 MPa for the cooper (Fig. 7) and from 550 MPa to 125 MPa for the steel (Fig. 9). The effect is much stronger for the copper, since the yield point reduction (8 times) is greater than that for the steel achieved (more than 4 times).

Taking into account a percentage decrease of the proportional limit and yield point in comparison to their magnitudes determined from standard tension test it corresponds to around 90% drop of these parameters in the case of copper (Fig. 8), and around 70% for the steel, Fig.10.

The next part of the experimental programme was focused on investigations evaluating an influence of the torsion-reverse-torsion cycles delay on the tensile characteristic. The results for the P91 steel are presented in Fig. 11. It is clearly seen, that a drastic axial force drop is related to the assistance of cyclic loading. The axial force decreased rapidly (370 MPa) directly after switching on of the torsion cycles. Similar effect was earlier observed for the 2024 aluminium alloy, Fig.12 (Kowalewski and Szymczak 2007).

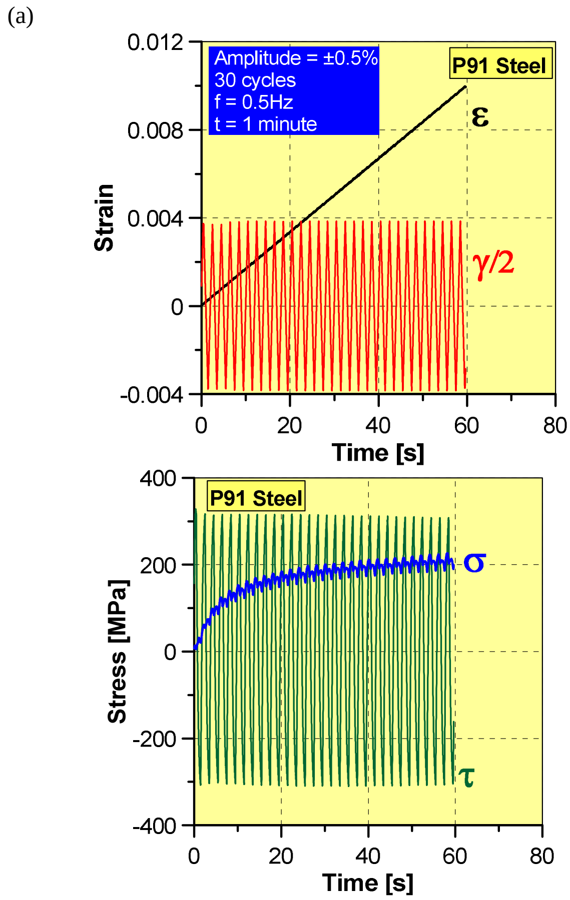

Fig. 6. Strain controlled loading paths (a), (b) – stress responses into the loading program shown in (a), ε – axial strain, γ/2 – shear strain, σ – axial stress, τ – shear stress

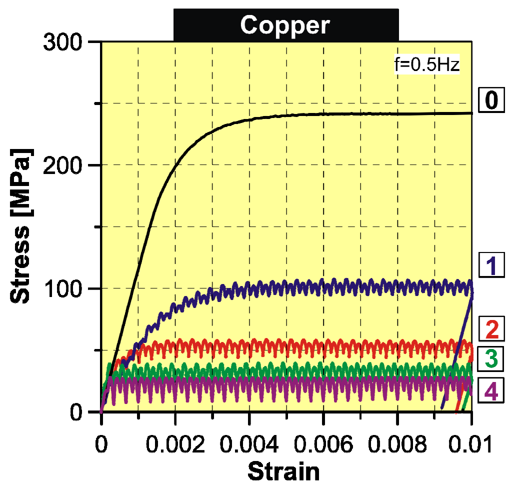

Fig. 7. A comparison of typical tensile characteristic (0) with tensile characteristics due to monotonic tension superimposed on the torsion-reverse-torsion cycles for strain amplitude equal to: ±0.3% (1), ±0.5% (2), ±0.7% (3), ±0.9% (4)

The stress – strain diagrams showing the results from tests 2024 aluminium alloy identify a transient character of the force reduction during tension associated with cyclic loading (Fig.12). This conclusion can be proved by determination of the yield surfaces for materials after standard tension tests and after tension carried out in the presence of torsion cycles.

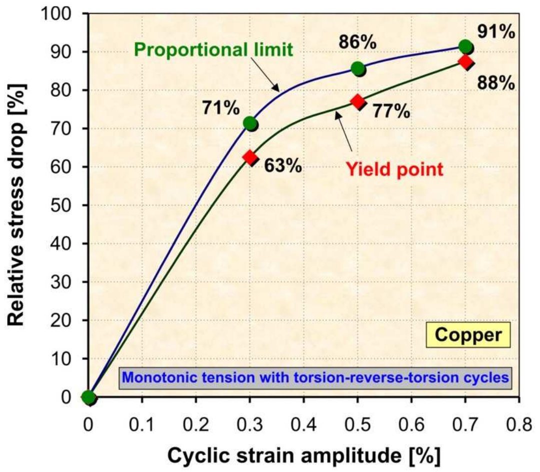

Fig. 8. Variations of the relative stress drop versus cyclic strain amplitude during monotonic tension superimposed on the torsion-reverse-torsion-cycles for strain amplitude varying from 0% to 0.7%

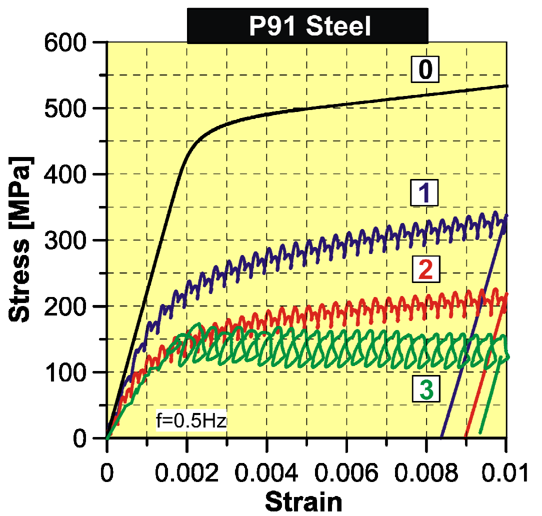

Fig. 9. A comparison of typical tensile characteristic (0) with tensile characteristics due to monotonic tension superimposed on the torsion-reverse-torsion cycles for strain amplitude equal to: ±0.3% (1), ±0.5% (2), ±0.7% (3)

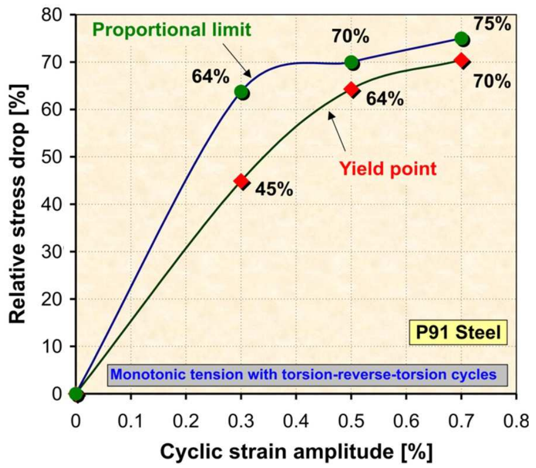

Fig. 10. Variations of the relative stress drop versus cyclic strain amplitude during monotonic tension superimposed on the torsion-reverse-torsion-cycles for strain amplitude varying from 0% to 0.7%

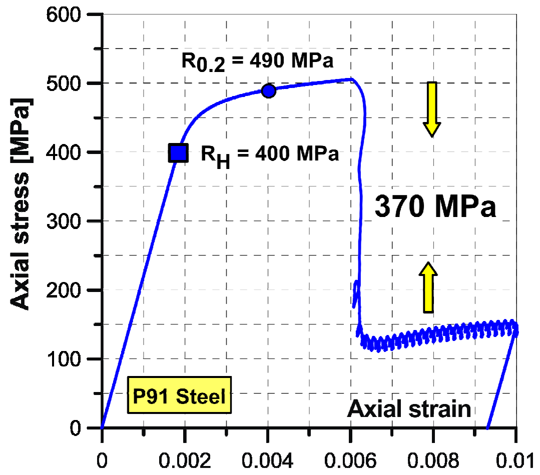

Fig. 11. Tensile characteristic of the P91 steel determined in assistance of torsion cycles delayed with respect to monotonic axial loading

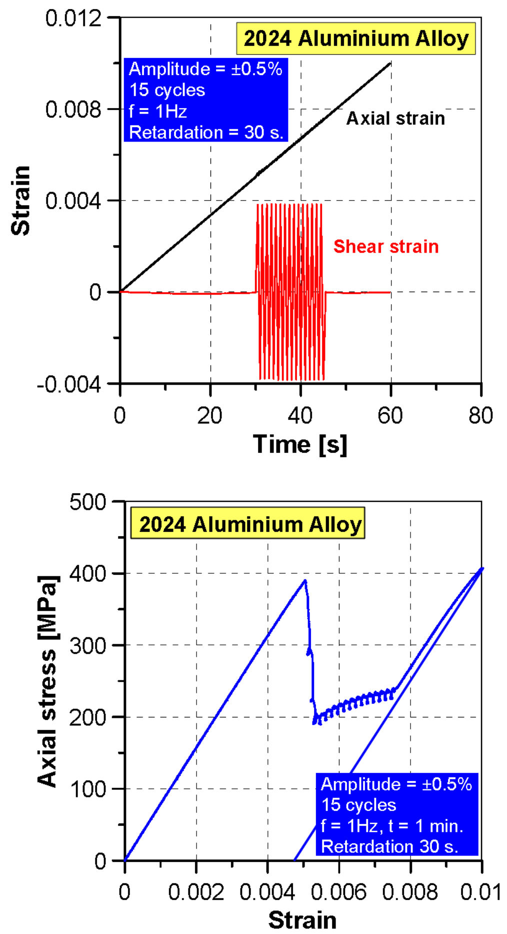

Fig. 12. Tensile characteristic of the 2024 aluminium alloy characteristic determined in assistance of torsion cycles delayed with respect to monotonic axial loading (programme of monotonic and cyclic loads is shown in the upper diagram)

Thus, the last step of the experimental programme comprised tests the main aim of which was to check whether the force reduction during tension had the 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 copper and P91 steel are presented in Figs. 13 and 14, respectively. As it is clearly seen the subsequent yield surfaces for both materials confirm that the axial force reduction is only related to torsion cycles during monotonic tension. Looking at the magnitudes of tension stress instead of reduction an increase can be observed (little for the P91 steel, but significant for the copper). 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, proves a transient character of the axial force drop, which can be solely attributed to cycles acting in the perpendicular direction.

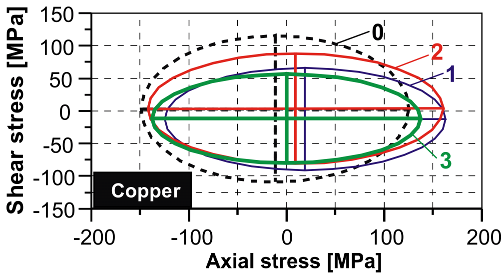

Fig. 13. An evolution of the initial yield surface (0) for the M1E copper due to torsion-reverse-torsion cycles for strain amplitude equal to: ±0.3% (1), ±0.5% (2), ±0.7% (3)

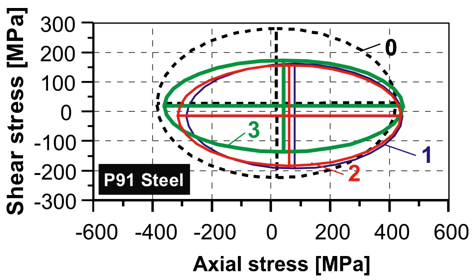

Fig. 14. An evolution of the initial yield surface (0) for the P91 steel due to torsion-reverse-torsion cycles for strain amplitude equal to: ±0.3% (1), ±0.5% (2), ±0.7% (3)

4. CONCLUSIONS

The investigations carried out on both materials allow to formulate the following conclusions and remarks:

– 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;
– axial force reduction due to presence of the torsion cycles is not permanent, it vanishes after cyclic loading interruption;
– an initial yield surface evolution does not confirm rapid reduction of selected mechanical parameters during tension assisted by cyclic torsion, it only points out their variations due to loading history applied.

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