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VARIATIONS OF MECHANICAL PARAMETERS AND STRAIN ENERGY DISSIPATED DURING TENSION-TORSION LOADING

ZMIANY PARAMETRÓW MECHANICZNYCH ORAZ ENERGII DYSYPOWANEJ PODCZAS JEDNOCZESNEGO ROZCIĄGANIA I SKRĘCANIA

The paper presents behaviour of materials under complex loading being combinations of torsion-reverse-torsion cycles superimposed on monotonic tensile deformation. The 2024 aluminium alloy, P91 steel and M1E copper were investigated under plane stress state using thin-walled tubular specimens. All tests were strain controlled and a total strain was less than 1%. An influence of torsion cycles on tensile characteristic was manifested by lowering of the proportional limit and yield point. This effect was increased with magnification of cyclic strain amplitude and in the case of copper a reduction of yield point was equal around 90%. A character of this effect was checked using the yield surface concept after each test. The papers also presents, variations of tangential hardening modulus and plastic strain energy dissipation.

Keywords: complex loading, biaxial stress state, cyclic loading, mechanical parameters

W pracy zamieszczono wyniki badań prezentujące zachowanie materiałów w warunkach złożonego obciążenia będącego kombinacją cyklicznego skręcania i monotonicznego rozciągania. Badaniom poddano stop aluminium 2024, stal P91 oraz miedź M1E w postaci próbek rurkowych zapewniających realizację płaskiego stanu naprężenia. Wszystkie testy zostały przeprowadzone przy sterowaniu sygnałem odkształcenia, przy czym odkształcenie całkowite nie przekraczało 1%. Badania wykazały znaczny wpływ obecności cykli skrętnych na przebieg jednocześnie realizowanego monotonicznego rozciągania widoczny w postaci obniżenia granicy proporcjonalności oraz granicy plastyczności. Efekt ten powiększał się wraz ze wzrostem amplitudy obciążenia cyklicznego, i w przypadku miedzi spadek wymienionych parametrów osiągnął ok. 90% w odniesieniu do wartości wyznaczonych na podstawie klasycznej próby rozciągania. Trwałość tego efektu została sprawdzona na podstawie analizy wymiarów powierzchni plastyczności. W pracy zaprezentowano także zmiany stycznego modułu wzmocnienia oraz energii odkształcenia plastycznego.

1. Introduction

Complex loading may have a significant influence on the mechanical properties variations of engineering materials exploited in many branches of industry.

A typical example of such situation is a gas rotor turbine, for which the highest stress values and the largest phase differences between the load components are obtained during start-up period [1]. Therefore, the start-up is regarded as crucial with respect to variations of the mechanical properties of the material. Since the mechanical parameters of materials can be modified by complex loading many research groups are actually looking at complex loading in an effort to optimize some of the manufacturing processes [2-10] in order to reduce costs and prolong the lifetimes of engineering components. Therefore, it can be concluded that knowledge of loading history applied has at least a twofold role. It is important for adequate choice of materials of structural elements, and moreover, it allows the design of forming processes to guarantee optimal mechanical parameters for particular applications. Hence, many laboratories for strength of materials are involved in such research programs, which would be able to provide new knowledge related to the influence of complex loading on the selected material parameters of importance in industry.

2. Experimental procedure

All strain controlled tests were carried out at room temperature under biaxial stress state using thin-walled tubular specimens (the thickness 1.5 mm). Behaviour

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and variations of mechanical parameters of three materials: P91 steel, 2024 aluminium alloy and M1E pure copper, due to complex loading were investigated. Representative mechanical parameters of the materials are shown in Tab. 1. The loading program was designed in such a way that the cyclic loading was superimposed on monotonic deformation, i.e. torsion-reverse-torsion cycles were combined with monotonic tension, Fig. 1. The total cyclic strain amplitude was less than 1%. After the main loading program the yield surface concept was applied to check whether the effects observed during cyclic loading have a permanent character. Other details of experimental procedure and test results were presented in [11-13].

TABLE 1

Selected mechanical parameters of: P91 steel, 2024 aluminium alloy, M1E copper; R_H – proportional limit, $R_{0.2\%}$ – yield point

P91 Steel		**2024 Alloy**		**M1E Copper**	
R_H	$R_{0.2\%}$	R_H	$R_{0.2\%}$	R_H	$R_{0.2\%}$
[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]
400	490	400	460	175	240

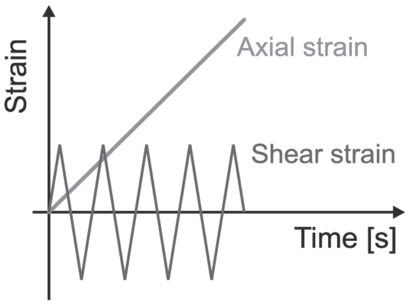

Fig. 1. Loading program

3. The results of tension-torsion loading

The influence of torsion cycles on the tensile characteristic is presented in Fig. 2 for all materials investigated. Comparing the initial mechanical parameters shown in Tab. 1 with their variations stimulated by cyclic loading illustrated in Fig. 2, it is easy to see a significant reduction of the proportional limit and yield point. This effect is visible for cyclic strain amplitude in either elastic (±0.3%) or plastic (±0.7%) ranges. A drop of mechanical parameters is clearly seen in Fig. 3. The results exhibit a significant reduction of the selected mechanical parameters. The effect is very strong and depends on the amplitude of cyclic loading. An increase of the cyclic strain amplitude led to the further decrease of the mechanical parameters. For example, in the case of P91 steel tested for the highest amplitude applied the reduction of proportional limit and yield point was equal to 300 MPa and 350 MPa, respectively. Variations of the mechanical parameters of M1E copper for cyclic strain amplitude equal ±0.7% illustrate a drop of proportional limit and yield point equal to 160 MPa and 230 MPa, respectively. A comparison of the variations of selected mechanical parameters shows characteristic tendency for all materials tested. Namely, it easy to noticed a decrease of the mechanical parameters to a certain asymptotic value, of course different for each material in question.

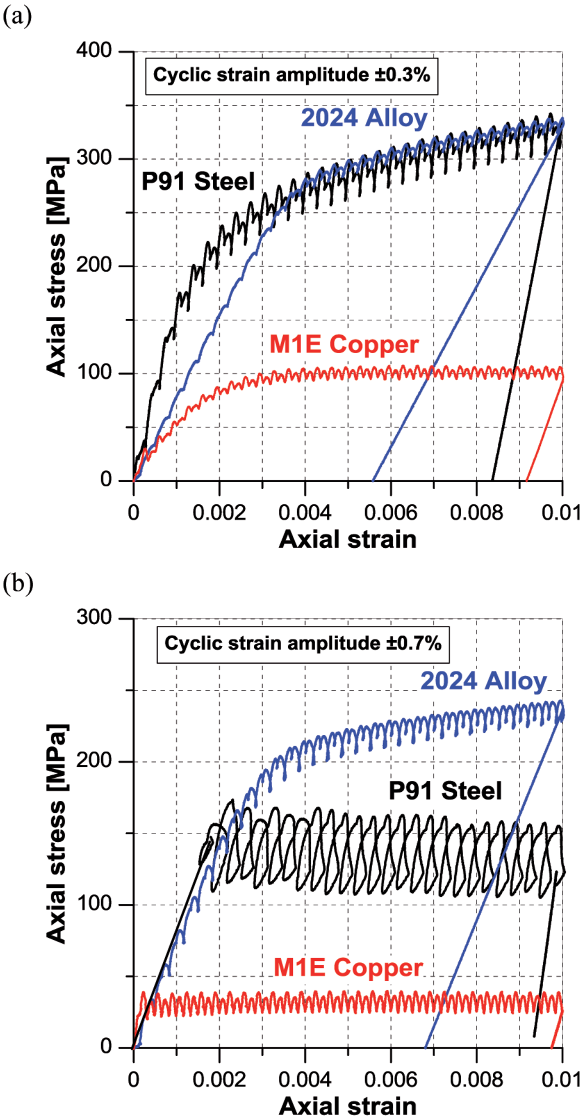

Fig. 2. Characteristics of monotonic tension carried out simultaneously with torsion cycles for ampli-tude equal to: (a) ±0.3%, (b) ±0.7%

Calculations of an energy balance have been performed to compare plastic strain energy dissipated during a typical monotonic test and that of a monotonic-cyclic loading combination, Figs. 4-5. The plastic strain energy dissipated during uniaxial tension is significantly reduced, Fig. 4a. For greater cyclic strain amplitudes the plastic strain energy decreases for all materials. In the case of P91 steel and M1E copper variations of plastic strain energy are more non-linear, while in the case of 2024 aluminium alloy a linear relationship is visible. Variations of plastic strain energy evaluated on the basis of tests became stronger with an increase of cyclic strain amplitude, Fig. 4b. A similar tendency is observed for the total plastic strain energy, Fig. 5. Despite of the total strain energy increasing with increase of the cyclic strain amplitude we have to remember that superimposing cyclic loading on monotonic loading diminishes the stress parameters significantly. In many industrial applications such behaviour may extend the lifetimes of some engineering components. This is especially important taking into account those elements for which the manufacturing costs are extremely high. As supplement to the analysis of material behaviour, an evolution of tangential hardening modulus was also determined and representative results are shown in Fig. 6. Its variation expresses a lowering of the hardening curve especially for cyclic strain amplitude equal to ±0.9%.

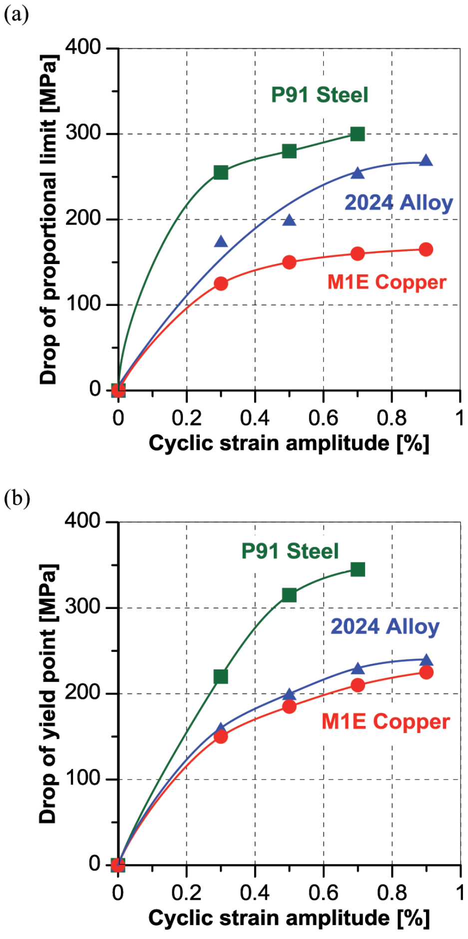

Fig. 3. Variations of tensile parameters: (a) proportional limit, (b) yield point, due to cyclic loading su-perimposed on monotonic tension, for amplitude from ±0.3% to ±0.9%

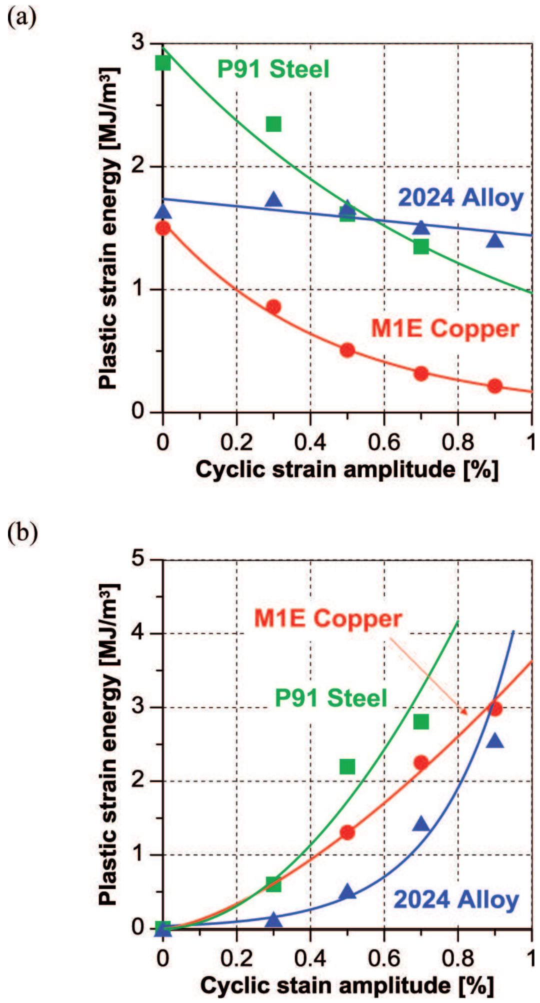

Fig. 4. Plastic strain energy versus cyclic strain amplitude for: (a) stress-strain characteristic; (b) hysteresis loop

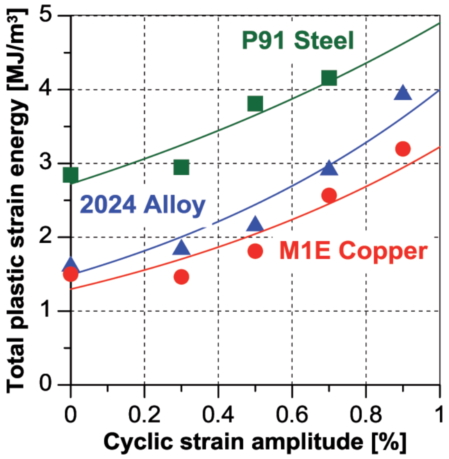

Fig. 5. Relationship between total plastic strain energy on the basis of adding of: stress-strain characteristic with hysteresis loop

The significant lowering of mechanical parameters during monotonic-cyclic loading was not a permanent and after termination of torsion cycles it disappeared. This was confirmed on the basis of the yield surface concept. Differences between the initial and subsequent yield surfaces are negligible, Figs. 7-8. Their dimensions indicate solely an influence of loading history applied. This fact is important from technological point of view, since it may serve as an effective method for modification of metal forming processes by reduction of acting forces, what as a consequence, may lead to the lifetime extensions of manufacturing tools. It can be also helpful during elaboration of new constitutive equations and for modelling of materials behaviour under complex loadings using numerical algorithms in the framework of Finite Element Method.

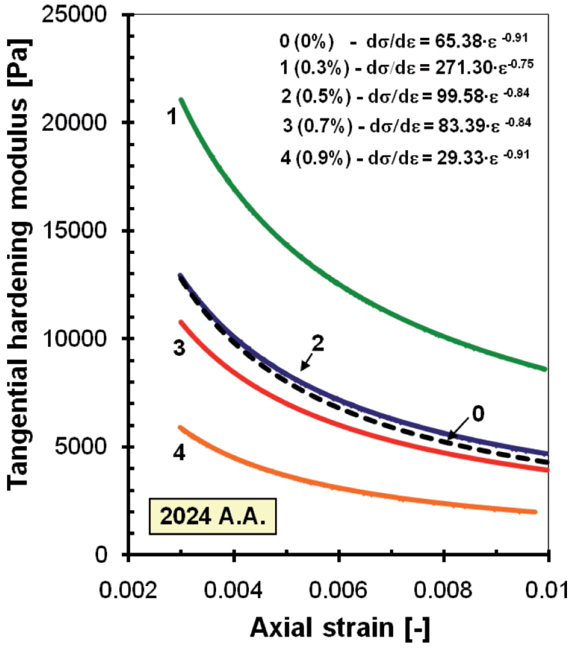

Fig. 6. Tangential hardening modulus calculated for the 2024 aluminium alloy on the basis of monotonic tension and cyclic torsion characteristic for strain amplitude within the range of ±0.3% ÷ 0.9%

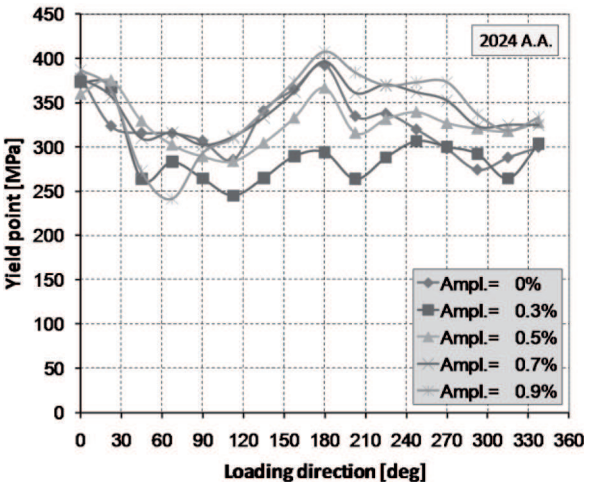

Fig. 7. Variations of yield point determined on the basis of yield surface for the 2024 aluminium alloy

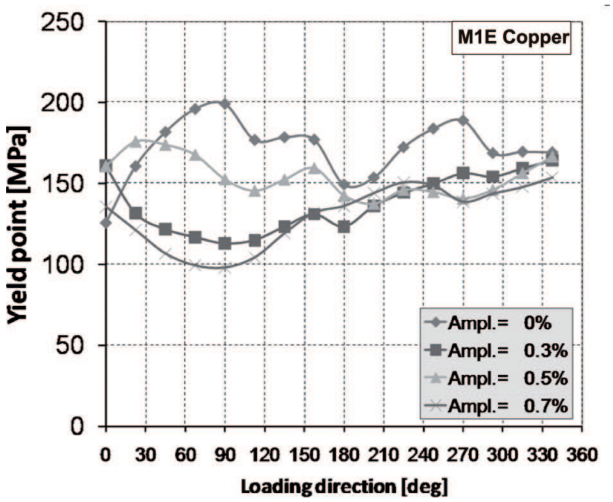

Fig. 8. Variations of yield point determined on the basis of yield surface for the M1E copper

4. Final remarks

The paper presents variations of selected mechanical parameters and evolution of plastic strain energy due to a complex loading being combination of monotonic tension and torsion-reverse-torsion cycles. Experimental results and calculations have enabled to formulate the following conclusions:

- the materials during monotonic loading shown a significant sensitivity to cyclic loading applied simultaneously,
- an increase of cyclic strain amplitude during torsion led to gradual lowering of the initial stress-strain tensile characteristic obtained without the associated cyclic loading,
- a rapid drop of the proportional limit and yield point did not has a permanent character. It existed only during torsion cycles superimposed on monotonic tension,
- a decrease of tangential hardening modulus with an increase of cyclic strain amplitude was observed.

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