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DEVELOPMENT OF RESEARCH METHODS AND EQUIPMENT FOR DETERMINING SUSCEPTIBILITY OF MATERIALS TO CHANGE IN DEFORMATION PATH

ROZWÓJ METOD BADAWCZYCH ORAZ URZĄDZEŃ DO OKREŚLANIA PODATNOŚCI MATERIAŁÓW NA ZMIANĘ DROGI DEFORMACJI

The growing demand for materials with better functional properties and improved manufacturing technologies inspires researches to search for new forming methods. Those, which involve deformation path change seem to be promising. The paper presents the laboratory equipment for research of effect of deformation path on the force and energy parameters, flow stress, limit strain and structure. Also some results concerning simultaneous cyclic torsion and tension are presented in the paper. Especially larger limit strains than in conventional processes and reduction of forming force can be obtained in simultaneous cyclic torsion and tensile deformations. However complex deformation processes need more plastic work than monotonic straining for production of product at the same degree of deformation.
Keywords: strain path, flow stress, plastic work, equipment

Rosnący popyt na materiały z lepszymi funkcjonalnymi własnościami oraz na wydajniejsze technologie inspiruje naukowców do poszukiwania nowych metod kształtowania plastycznego. Metody, które wykorzystują zmianę drogi deformacji, wydają się być najbardziej obiecujące. Artykuł przedstawia urządzenia laboratoryjne do badania wpływu drogi odkształcenia na siły i parametry energetyczne procesów oraz naprężenie uplastyczniające, odkształcenie graniczne i strukturę odkształcanego materiału. Również przedstawione zostały wyniki badań odkształcania materiału poprzez równoczesne cykliczne skręcanie i rozciąganie. Okazuje się, że poprzez tę metodę można uzyskać wzrost odkształceń granicznych oraz obniżenie sił kształtowania w porównaniu to metod odkształcania monotonicznego.

1. Introduction

Intensive research on the development of energy-saving plastic forming processes has been conducted for many years [1–4]. The research is based on findings indicating a potential for a considerable reduction in flow stress and increase in limit strain.

In sheet metal forming the influence of the strain path on the limit strain (corresponding to the loss of stability) has been known for a long time. In the case of bulk plastic forming, the strain path problem is much more complex since the possibilities for controlling the behaviour of materials through a change the strain path are much greater.

The complex strain paths can be observed in many industrial processes like rolling, ingot turning, forging, rotary swaging, extrusion, radial forging and other processes. However they are no intentionally applied in these processes. There are only a few processes, where change in strain path is purposefully used. One group of these processes concerns manufacture of material with ultra- or nanostructures [5–7]. They are called severe plastic deformation method – SPD. The dimensions of ultrafine grains obtained by these methods are very stable at elevated temperature. They are characterized also by very good ductility. The most popular method is ECAP (Equal Channel Angular Pressing). In this method, a material is cyclically pushed through a die with two intersecting channels and has a simple shear deformation. The amount of plastic strain in one pass depends on the channel angle and dimensions of die (Fig. 1a).

Other method is high-pressure torsion (HPT) where a material is simultaneously subjected to a high pressure and torsion. HPT has advantages over ECAP because it

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tends to produce both smaller grain sizes and additionally, HPT processing may be used for the consolidation of fine particles (Fig. 1b) [5].

In University of Mining and Metallurgy in Krakow cyclic – extrusion- compression (CEC) was developed, where the material is extruded cyclically through the die many times in order to obtain large plastic deformation (Fig. 2a) [7].

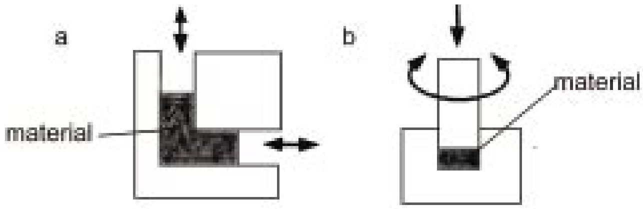

Fig. 1. Outlines of a) ECAP and b) HPT processes [5]

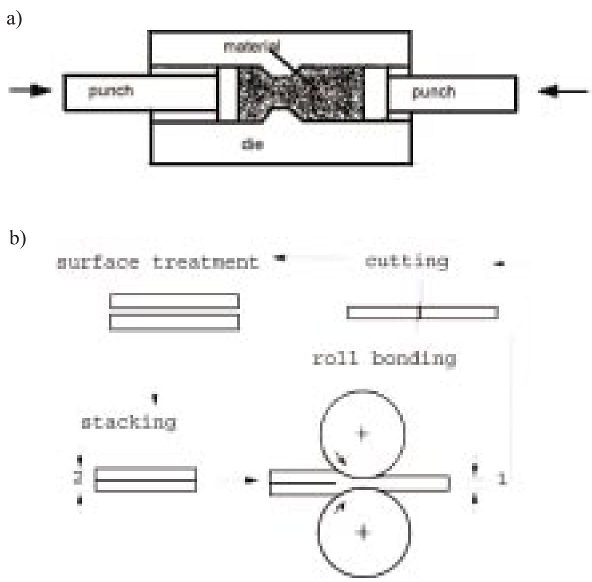

Fig. 2. Outline of a) CEC process and b) ARB process [7, 8]

Main disadvantage presented above SPD methods is small amount of obtained material and it limits this technology to laboratory application. Lager amount of ultrafine material can be obtained by others methods for example by: accumulative roll-bonding (ARB). In this process the 50% rolled sheet in first pass is cut into two, which are put together and then rolled again. Theses operations are repeated until required severe deformation is reached (Fig. 2b) [8].

In other group of new technology making use of complex strain paths the most important is to obtain larger limit strains and lower forming force than in conventional processes. Two such a processes are well-known: forward extrusion with die making additional cyclic movement around its axis (KOBO) and continues drawing with cyclic movement of central die (Fig. 3). Introduction additional shear deformation by cyclic movement of die causes decrease in extrusion and drawing forces (Fig. 4) [2, 9].

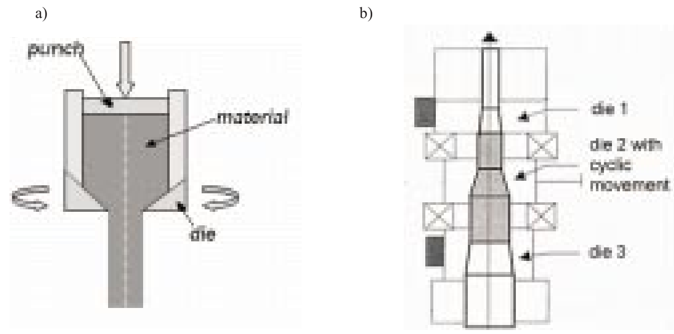

Fig. 3. Processes with complex strain path a) KOBO and b) Drawing with cyclic movement of central die [2, 9]

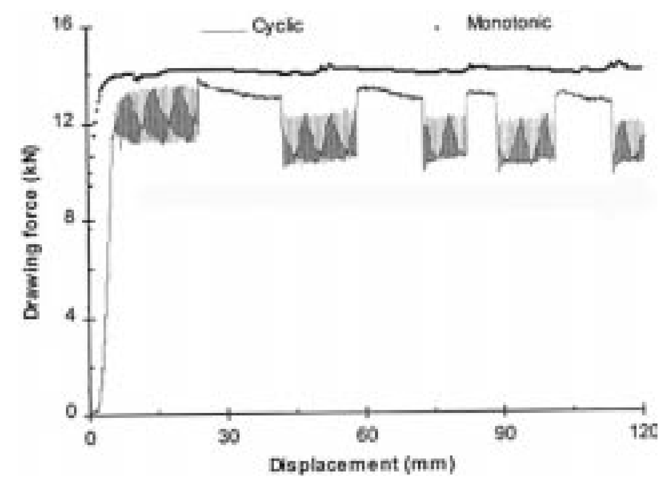

Fig. 4. Drawing force for monotonic and cyclic deformation [9]

Various other metal forming processes and original designs of devices exploiting the effect of a change in the strain path can be developed. However to make the most of it more detailed laboratory research is required.

2. Laboratory equipment for investigation of complex strain path

New laboratory equipment (mechanical and structural) aimed at explaining the peculiar behaviour of metallic materials in forced deformation path conditions has been elaborated in Department of Metal Forming Process Engineering, Wrocław University of Technology and in Department of Process Modelling and Medical Engineering, Silesian University of Technology [4, 10, 11].

The main objective of the equipment is to determine the technological plasticity characteristics of metallic materials in complex load conditions and to develop (through theoretical analyses) a method of identifying the plastic flow model in conditions when the deformation path is changed.

The test stand for complex loading, shown in Fig. 5 and built in Department of Process Modelling and Medical Engineering, can be used to test both solid and hollow specimens (additionally internal pressure can be applied).

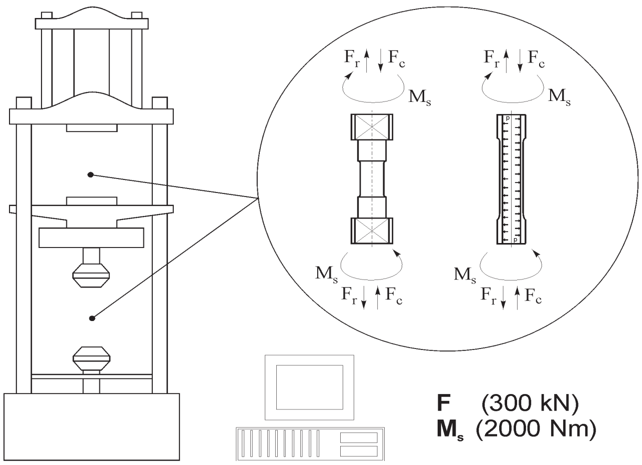

Fig. 5. Test stand for complex loading

The stand allows one to produce simple tension, compression and torsion and their combinations during deformation. Force F (tensile or compressive), torsional moment M, path l, torsional angle α and time t as well as temperature T and internal pressure p_w can be recorded during the test. The displacement parameters, i.e. path l and torsional angle α, are measured by digital optoelectronic displacement and rotation sensors collaborating with processing cards. Measuring parameter scanning frequency is continuously adjusted in a range of 0–100 Hz. The infinitely variable frequency adjustment allows one to optimally adjust the measuring parameter scanning frequency to test duration.

The test stand is equipped with a modern power hydraulics system. Hydraulic control ensures accurate pressure increment and servomotor plunger speed adjustment. The stand's operation can be controlled manually from a control panel or it can be computer programmed. The system makes it possible to control the test by setting general displacement parameters: path l and torsional angle α and traverse speed v_t. The set control parameters actuates the selected drive mechanisms in a fixed sequence. The software enables simultaneous tension and torsion or compression and torsion. During the tests the measurements can be visualized. The software includes a presentation graphics module with a print option.

The stand for compression+oscillatory torsion tests, shown in Fig. 6, is an integral part of a system of devices for testing materials in forced oscillatory-variable deformation path conditions. The stand is an original in-house design. It can be used to carry out the following deformation tests on metallic materials:

- oscillatory torsion;
- conventional compression in different friction conditions, e.g. frictionless compression, compression under dry friction;
- conventional compression in a closed die with an adjustable radial metal flow;
- compression with simultaneous oscillatory torsion in free radial metal flow conditions, compression with simultaneous oscillatory torsion under high quasi-hydrostatic pressures.

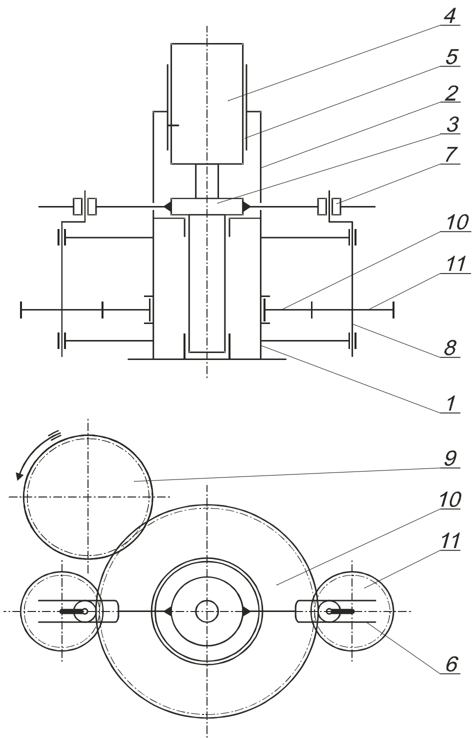

Fig. 6. Kinematics scheme of device for compression with oscillatory torsion. 1 – Lower casing, 2 – Upper casing, 3 – Lower punch, 4 – Upper punch, 5 – Sliding nonrotary bearing, 6 – Fork (lower punch arm), 7 – Roller, 8 – Crankshaft (eccentric), 9 – Driving toothed wheel, 10 – Toothed ring, 11 – Toothed wheel

The above tests can be performed thanks to the device's kinematic function enabling the oscillatory movement of the lower punch, which significantly increases the intensity of plastic deformation (Fig. 6). This action can be smoothly adjusted by changing the share of: the linear deformations caused by the plane motion of the punch and the non-dilatational strains caused by the rotation of the punch. The stand's accessories include a set for compression testing under high quasi-hydrostatic pressures. The set consists of a replaceable casing and a punch structurally integrated with the die. The instrumentation can be quickly replaced to adjust the stand to new test conditions.

The original kinematics of the device offers wide possibilities of testing materials' sensitivity to a change in the deformation path and performing the technological operation of upset forging. The rate of compression, the frequency of torsion and the amplitude of the torsion angle can be smoothly adjusted. The device's size and design allow it to operate in the working space of the test stand for complex loading. The controls for kinematic quantities allow one to change the torsional angle from 0° to ±8°. The frequency with which the lower punch oscillates is adjusted from 0 to 1.8 Hz (the maximum attainable frequency – 2.6 Hz) by an inverter. The maximum rate of travel of the lower punch is 0.4 m/min. The admissible compressive force is 300 kN. Compressive force F and deformation path Δh are recorded by the testing machine's computer system. The system can record and archive measurement data and allows one to program tests (set the displacement). Force curves can be visualized in real time during tests.

The stand for tension+oscillatory torsion, shown in Fig. 7, was designed and built in the Department of Metal Forming Process Engineering at Wrocław University of Technology. Thanks to two machine-tool electric motors with a very short starting time, controlled by an inverter, the device can realize complex deformation modes comprising any type of torsion with tension or compression and interruptions in deformation. The motors meet the rotational speed stability requirements: in a range of 0.5–1000 rpm the speed stability is +/−0.1% and a time of speed increase from 0 to 1000 rpm is not longer than 100 ms. The stand is equipped with a special oven for rapid cooling of test specimen.

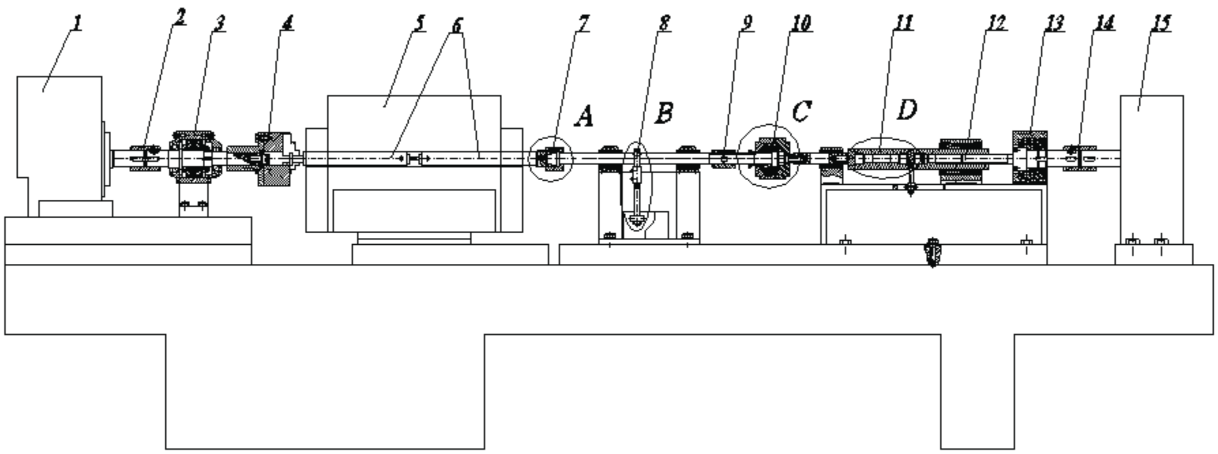

Fig. 7. Schematic of plastometer. 1 – 13 kW asynchronous machine-tool motor, 2 – sleeve coupling, 3 – fixed support, 4 – lathe head, 5 – oven, 6 – test piece grips, 7 – self-centring grip, 8 – torque meter, 9 – coupling, 10 – rotary head, 11 – dynamometer, 12 – screw gear, 13 – fixed support, 14 – sleeve coupling, 15 – 11 kW asynchronous machine-tool motor

The device's drive unit enables very large changes in stable deformation rates and easy adjustment of the rates. In order to simultaneously realize different deformation paths it was necessary to separate the drive system responsible for torsion from the one responsible for compression or tension. Also the ways of measuring the torsional moment and the axial force were so designed as not to interfere with each other. Another important factor which determined the plastometer's design were the proper dimensions and shape of the specimen's measuring part and its grip part (the latter must be able to carry both the torsional moment and the axial force). In order to reduce the inertial forces which occur during the deformation of test specimen, the moving bodies of the plastometer's components were minimized through the proper design of their shape and the selection of a suitable material for them.

The system's central unit is an IBM PC which:

- communicates with the experiment operator,
- carries out the control and measurement algorithm,
- archives and presents measurement data,
- converts measurement data to an Excel file.

3. Simultaneous cyclic torsion and tensile deformations

The presented devices can realize different strain path like: cyclic deformation, different sequential deformation and simultaneous cyclic torsion and tensile or compression deformations.

The research so far has shown that cyclic deformation leads to an improvement in the materials' formability. Small displacements obtained during cyclic deformation, limits the industrial application of this method. It seems that better practical results can be obtained either by sequential deformation, where the angle between the direction of forming rate vectors in the successive deformation stages is 90°, or by combining cyclic deformation with other deformation modes. The latter seems to be the most promising as far as industrial application is concerned. The Fig. 8 present scheme of simultaneous cyclic torsion with amplitude A and tensile deformation. The results of such a complex deformation are discussed below.

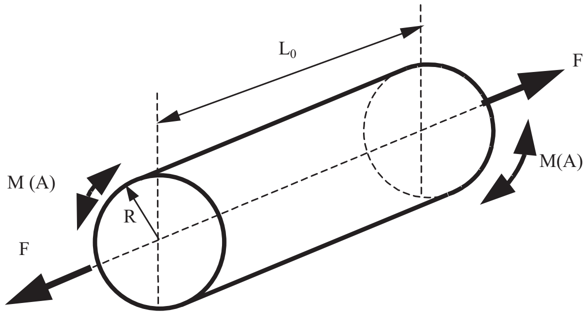

Fig. 8. Scheme of simultaneous cyclic torsion with amplitude A and tensile deformation

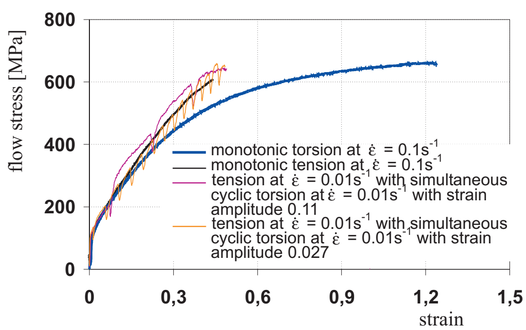

Fig. 9. Flow stress of silicon bronze CuSi3.5 at ambient temperature for simultaneous deformation at strain rates produced by tensile force and torsion moment – 0.01 s^{-1} ($\Phi = 1$) and for monotonic tension

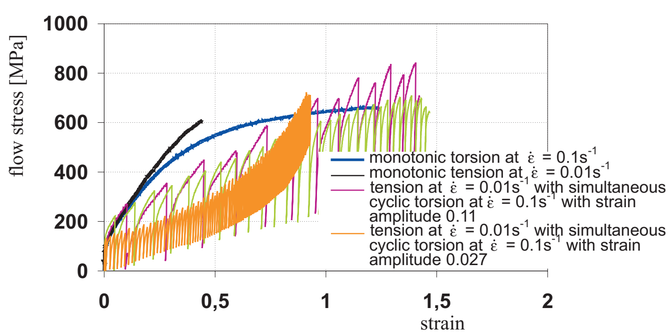

Fig. 10. Flow stress of silicon bronze CuSi3.5 at ambient temperature for simultaneous deformation by cyclic torsion and tension at different amplitudes and strain rates in tension – 0.01 s^{-1} and in torsion – 0.1 s^{-1} ($\Phi = 10$), and for monotonic torsion and tension

It has been found that as the ratio Φ of the strain rate at torsion to strain rate at tension is low, both the limit strain and the equivalent stress are close to the values obtained in the monotonic tension. (Fig. 9 – the ratio of the strain rate at torsion to strain rate at tension $\Phi = 1$).

An increase in this ratio, caused by an increase in the torsion strain rate, results in a reduction of equivalent stresses and in an increase of limit strains. Fig. 10 presents result for $\Phi = 10$ where change of mentioned parameters can be observed.

If the strain rate from torsion is further increased the significant improved of workability could be observed. For $\Phi = 100$ 10 times increase in limit plastic strain and twofold decrease in flow stress ware obtain comparing to such a strain in monotonic test (Fig. 11).

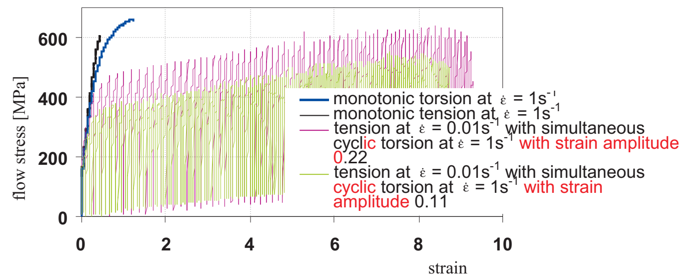

Fig. 11. Flow stress of silicon bronze CuSi3.5 at ambient temperature for simultaneous deformation by cyclic torsion and tension at different amplitudes and strain rates in tension – 0.01 s^{-1} and in torsion – 1 s^{-1} ($\Phi = 100$), and for monotonic torsion and tension

These experiments can simulate the actual loads in real industrial drawing processes additionally deformed by the cyclic torsion of die around its axis which is presented in the Fig. 3b. The drawing forces in the processes can be estimated from the axial stresses. Fig. 12 shows the relations between the tensile flow stress and tensile strain produced by simultaneous deformation shown in Fig. 11.

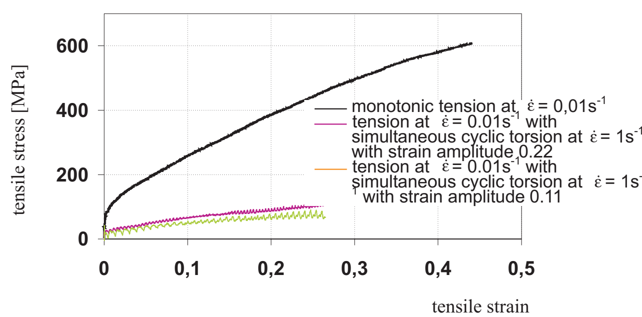

Fig. 12. Tensile stress-tensile strain relationship in the simultaneous cyclic torsion and tension on the background of flow stress in monotonic tension curve for silicon bronze CuSi3.5 at ambient temperature

One should conclude about the cost-effectiveness of complex deformation processes not only from equivalent stress and strain graphs, but also from the magnitude of plastic deformation work in the processes. The effect of different modes of complex deformation on plastic work in order to obtain 20% elongation of the sample is described below. The scheme of deformation is presented in the Fig. 13. The superposition principle is applied to determine the work. The work in torsion test and in tensile test is determined separately. The relative fall in the tensile stress for different deformation modes is calculated from the formula:

$$\Delta\sigma_{pr} = \frac{\sigma_{prm} - \sigma_{prz}}{\sigma_{prm}} 100\% \qquad (1)$$

where: σ_{prm} – stress in the monotonic tension test, σ_{prz} – stress produced by the tensile force in the complex deformation test.

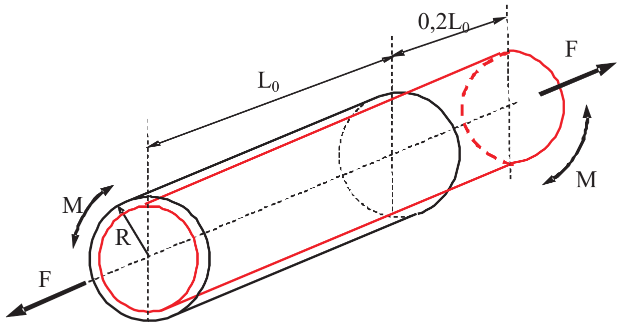

Fig. 13. Scheme of 20% elongation of the sample black – initial and red – final shape of sample

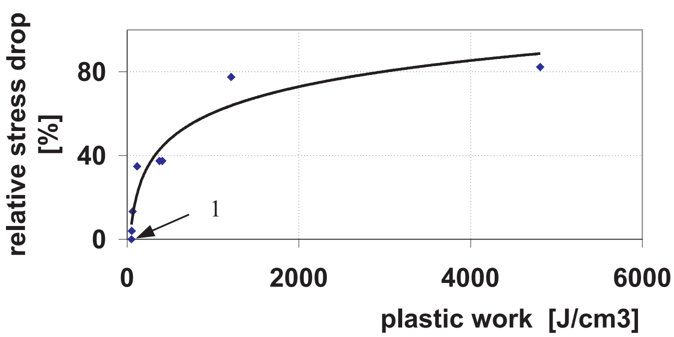

Fig. 14. Total plastic work for different complex deformation modes versus relative stress drop for silicon bronze CuSi3.5 at ambient temperature

For calculating the relative stress drop, the tensile stress obtained under the complex deformation schemes was compared with the stress determined in the monotonic tension test at similar strain rates. Fig. 14 shows the total plastic work for the different complex deformation processes versus the relative drop in stress at ambient temperature for silicone bronze CuSi3.5.

The smallest plastic deformation work at ambient temperature was obtained for monotonic tension (point 1). The introduction of additional low-cycle torsion results in an increase in this work in all the cases. It is seen from the figure that the greater the work of cyclic plastic deformation is, the larger the drop in stress produced by the tensile force is.

It has also been found that frequent changes in the direction of deformation, caused by cyclic torsion, are conducive to strain heterogenization leading to the formation of shear bands acrossing many grains (Fig. 15).

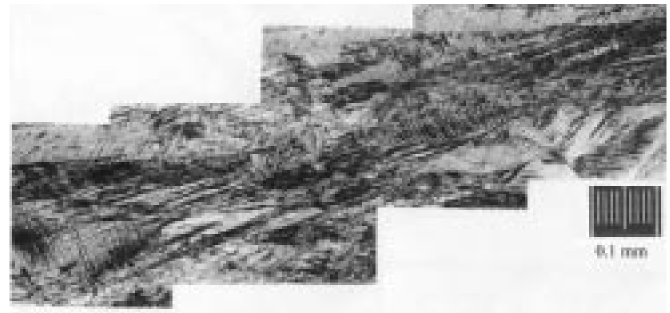

Fig. 15. Localized strain band for bronze CuSi3.5 at ambient temperature after tension ($\dot{\varepsilon}_{pr}$ = 0.01 s^{-1}) with simultaneous cyclic torsion ($\dot{\varepsilon}$ = 0.1 s^{-1}) at amplitude of 0.11 to equivalent strain of 0.8 at ambient temperature

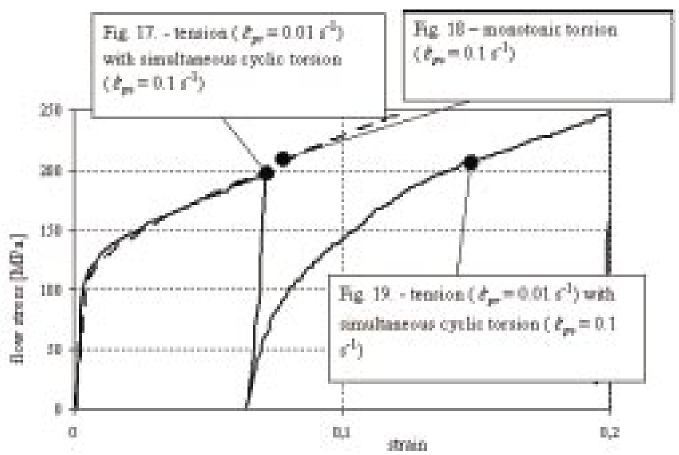

Fig. 16. History of deformation of samples, their structure are presented in Fig. 17–19, black circles represent moment of brake of individual experiment

One can concluded that if there are more micro and macro shear bends in material deformed with complex strain path than in material monotonic deformed, the dislocation substructure should be different in both material. In order to unveil it three testes were performed, which history of deformation is presented in Fig. 16. In spite of large differences in the way of deformation in these tests there were not observed significant changes in substructure. Fig. 17 presents substructure of bronze CuSi3 at ambient temperature after tension with simultaneous cyclic torsion to strain of 0.08, whereas Fig. 18 presents substructure for monotonic torsion to the same strain of 0.08. Only with increase in strain the increase in dislocation density occurs and distinct tangles of dislocation could be seen (Fig. 19). In all structure there are deformation twins in form bands crossing grains. Probably bigger differences between all structures would be visible if more analyses by electron microscope were performed.

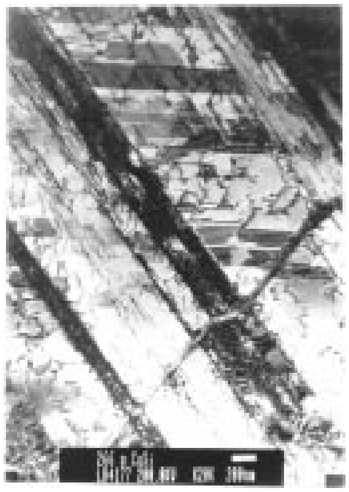

Fig. 17. Structure of sample after – tension ($\dot{\varepsilon}_{pr}$ = 0.01 s^{-1}) with simultaneous cyclic torsion ($\dot{\varepsilon}_{ps}$ = 0.1 s^{-1}) deformation to strain of 0.08 (TEM)

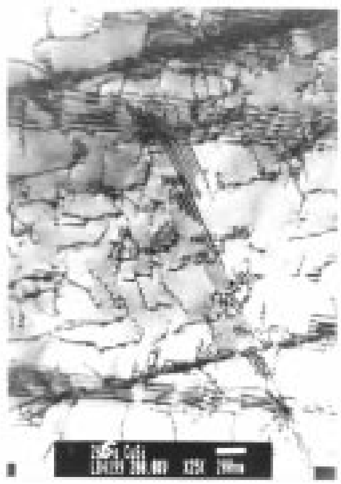

Fig. 18. Structure of sample after – monotonic torsion ($\dot{\varepsilon}_{ps}$ = 0.1 s^{-1}) deformation to strain of 0.08 (TEM)

Fig. 19. Structure of sample after - tension ($\dot{\varepsilon}_{pr}$ = 0.01 s^{-1}) with simultaneous cyclic torsion ($\dot{\varepsilon}_{ps}$ = 0.1 s^{-1}) deformation to strain of 0.15 (TEM)

4. Conclusions

There are some implementations of complex strain path in industrial processes, but complex strain path is nointentionally applied in these processes. To improve existing processes and elaborate new ones the more detailed laboratory researches of effect of strain path on structure and force parameters should be carried out.

The existing laboratory equipment allows to determine the appropriate way of deformation, amplitude, strain rate etc in order to improve workability of deformed material.

Especially larger limit strains and lower forming forces than in conventional processes can be obtained in simultaneous cyclic torsion and tensile deformations. However complex deformation processes need more plastic work than monotonic straining for production of parts with same final shape, but the more complex products can be manufactured.

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