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Influence of monotonic and cyclic deformation sequence on behaviour of CuSi3.5 silicon bronze

Z. Gronostajski*, K. Jaśkiewicz
Institute of Engineering and Automation, Wrocław University of Technology,
ul. Łukasiewicza 3/5, 50-371 Wrocław, Poland
* Corresponding author: E-mail address: zbigniew.gronostajski@pwr.wroc.pl

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Properties

ABSTRACT

Purpose: The main aim of the work is to investigate the effect of deformation sequence of low cyclic torsion, monotonic torsion and monotonic tension on the flow stress and structure. This knowledge can create possibility to elaborating and applying more energy and material saving technologies where final products have determined shape and properties.
Design/methodology/approach: Simultaneous deformation by cyclic torsion and tension was conducted in plastometer for complex strain paths. For micro structural observation, the optical, scanning and transition microscopes were used.
Findings: Obtained results shown that by change of direction of displacement velocity vector for about 90° it is possible to increase or decrease of the flow stress. Without such changes of this vector the dislocation structure is not enough disturbed and strain localization in shear bands is absent, so there is no softening of materials caused by increase of free distance of dislocation movement.
Research limitations/implications: The further investigations should be done especially at high temperature because at high temperature the investigated silicon bronze has large strain rate sensitivity that make difficulties to transform torque on the shear stress moreover the precise stabilization of temperature at high temperature is difficult.
Practical implications: On the base of performed investigation it can be stated that great progress in metal forming processes and new technologies, more effective from the point of view of energy and material consumption could be elaborated.
Originality/value: The effect of strain path in case of sheet metals forming processes has been investigated for a long time. In case of massive processes the effect of strain path on the plastic properties and structure of materials is less known because an investigations are more difficult and complex.
Keywords: Sequence of deformation; Silicon bronze; Torsion; Tension; Flow stress

1. Introduction

The flow stress-plastic strain relationship is basic plastic properties of materials in numerical simulation of materials behavior in forming processes. The effect of temperature, strain rate and strain on the flow stress strain relationship and structure has been widely investigated and well-known. Therefore, when new generation of computers and commercial FEM programmers create the possibilities to solve even very complicated forming processes with high accuracy, the meaning of proper work hardening curves is duly appreciated. Now the new factors effected work hardening curves were introduced into it. The base new factor is the strain path.

The effect of strain path in case of sheet metals forming processes has been investigated for a long time [1]. In case of massive processes the effect of strain path on the plastic properties and structure of materials is less known because an investigations are more difficult and complex.

The main categories for discussing the strain path effects on the flow stress and structure are:

- the value of strain rate vector direction
- the value of plastic strain in each strain path change.

Good solutions of this problem carry on to energy-saving and parallel to ecological effects from the one side and to obtain the products with good properties from the other side.

The softening as well as hardening during low cyclic deformation can be observed as a function of cumulative plastic strain in successive cycles or as a number of cycles (Fig. 1 and 2) [2]. If for constant strain amplitude ε_a the flow stress decreases with deformation ε_p until saturation stress σ_{an} is reached that is softening of materials (Fig. 3a), but when it grows that is hardening (Fig. 3b), and if it is constant that the steady state of flow stress is reached (Fig. 3c) [2].

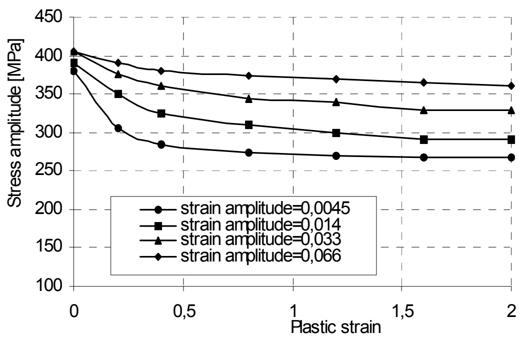

Fig. 1. Low cyclic softening of copper after initial deformation at ambient temperature [2]

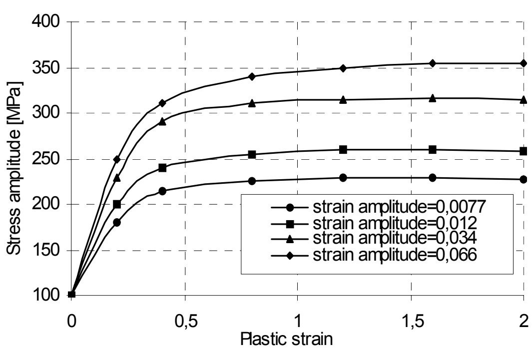

Fig. 2. Low cyclic hardening of annealing copper [2]

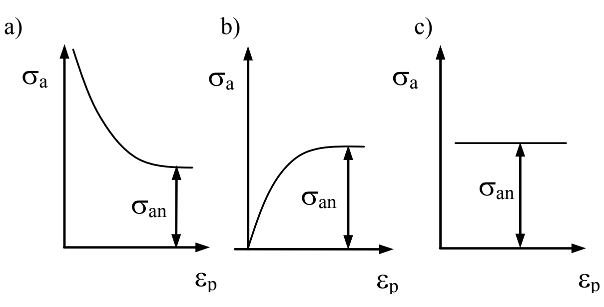

Fig. 3. Behavior of materials at ε_a=const: a) softening, b)hardening, c) steady state [2]

Recently the cyclic torsion [3-21] versus monotonic torsion has been used to show the effect of strain paths on behavior of metals and alloys during deformation. In the papers [3-6] the authors presented the stress-strain curves of commercial pure copper and interstitial free steel in hot cyclic torsion tests with a strain amplitude range of 0.015–0,4. The torsion test has shown that stress-strain curves for cyclic torsion are significantly different from those obtained in monotonic tests.

In order to analyse the mutual effects of monotonic and cyclic torsion, a composite test was carried out in which the sample was initially deformed under monotonic straining, then under cyclic loading with the amplitude ε_a=0.03, and finally under monotonic loading again. The results are shown in Fig. 4.

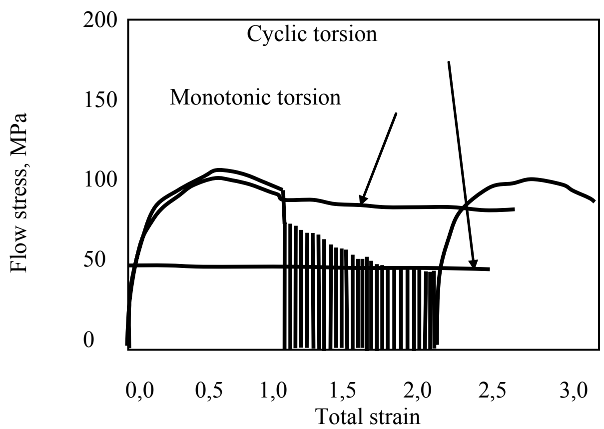

Fig. 4. The composite test: monotonic torsion till the strain of 1, next cyclic torsion till the strain of 2 and repeated monotonic torsion in comparison with monotonic and cyclic torsion in the whole range of deformation [5]

From this figure, it can be seen that cyclic torsion leads to extensive softening of the steel. Cyclic torsion applied after monotonic torsion at the strain equal to 1 causes decrease in the flow stress at a strain of 2 to the same level it would have reached under pure cyclic straining at the same amplitude [4].

Sometime there are opposite situation for hot deformation condition. For example at large deformation for CuAl8 aluminium bronze for the amplitude equal to 0.4, the cyclic steady state stress above the monotonic dynamic recrystallization steady state flow was observed [7, 9].

During cyclic deformation, each hysteresis loop contains elastic and plastic deformation and the relative fraction of elastic strain in the total deformation rapidly increases with diminution of the deformation amplitude and increase of the number of cycles in the whole deformation process. With the increase in deformation during the monotonic straining, the relative fraction of elastic strain in total deformation decreases. Therefore the stress–total strain relationship in cyclic deformation and monotonic deformation, where the relative fraction of elastic strain is quite different, cannot be compared. For a proper comparison of the above mentioned curves, the elastic deformation must be removed from the total deformation in case of cyclic stress-strain relationships but it is not so important in monotonic tests.

The other works [14, 22-26] contain the experimental characteristic of flow stress of metallic materials in various deformation conditions and theoretical analysis of plastic flow identification during change of the strain paths. Such information can be used in the numerical simulation of metal forming processes especially for no monotonic and no proportional flow of materials.

In the other work [27] the less hardening and the small strain hardening rates in the pure shear of FCC materials than in the simple tension can be attributed to the different distribution of strain in cross section of torsioned sample and connected with this various distribution of temperature.

In this literature review the investigations of the strain path changes on the behavior of metals and alloys were described. The works indicate that strain path effects are real and cannot be explained by simple formulation invoking cumulative strain. It is clear that microstructural evolution during the deformation is influenced by the strain path. The described works have been focused on sequential path changes mainly at room temperature, but the obtained results are not the same. The effect of high temperatures and strain rates is even less known and should be clarified because there is some incongnity between the results of various experiments and industrial practices as: rolling, ingot turning, rotary forging, rotary swaging, extrusion and other processes, where the strain path changes are observed [28-30].

From above discussion it is clear visible that by change of the strain path in a massive processes the great progress in metal forming processes can be obtain and new technologies more efficient from the point of view of energy and material consumption can be elaborated.

To obtain the final products with determined shape and properties made from metallic materials the large deformation must be applied. Realization of such processes need proper control of process parameters, it can be possible only on the base of knowledge of influence these parameters on the plastic deformation mechanism, structure and phenomena taking place during deformation and on the properties of manufacturing products. Development of enterprises competition forces them to elaborate and applied more energy and material saving technologies [31-34].

Analyzing the behaviour of materials in sequence processes containing torsion and tension, the main attention should be paid to changes of principal stress and strain directions.

The main aim of the work is to investigate the effect of deformation sequence of low cyclic torsion, monotonic torsion and monotonic tension on the flow stress. For comparison the pure monotonic torsion and monotonic tension and cyclic deformation in the whole range of deformation were applied. During transformation of torsion to tension the direction of displacement velocity vector to 90° is changed.

2. Experimental procedure

For the mechanical properties evaluation the plastometer for complex strain paths was used [36]. The specimens made from CuSi3.5 silicon bronze were deformed in the temperature range of 20-600 °C with strain rates equal to 0.01, 0.1 and 1 s^{-1}. The shape and size of specimen is shown in Fig. 5. The work hardening surface layer caused by mechanical turning was removed by heating of the specimens at high temperature. Each test in the same conditions was repeated at least three times until the results of three tests were very similar. The confidence interval at significance level of 0.05 was less than ±5%.

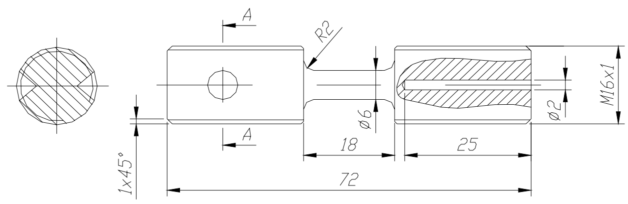

Fig. 5. Scheme of specimen used for torsion and tension

Precise determination of relationship between flow stress and plastic strain is dependent on the method of stress and strain calculations and an accuracy of deformation conditions control [37-41]. The differences obtained by using different conventional method are not so large, so for calculation of flow stress the simple classical method was applied [42].

Shear stress τ was calculated from following formula

$$\tau = \frac{(3+n+m)M}{2\pi R^3} \tag{1}$$

where:

M – torque,

$n = \frac{N}{M}\frac{\delta M}{\delta N}$ – hardening coefficient,

$m = \frac{\dot{N}}{M}\frac{\delta M}{\delta \dot{N}}$ – coefficient of strain rate sensitivity,

R – sample radius

plastic shear strain

$$\gamma_p = \frac{R\omega_p}{l} \tag{2}$$

and plastic twist rate

$$\gamma_p = \frac{R\dot{\omega}_p}{l} \tag{3}$$

Taking into account the Hubert-Misses the flow stress is given by

$$\sigma_p = \frac{(3+n+m)\sqrt{3}M}{2\pi R}, \tag{4}$$

the plastic strain by

$$\varepsilon_p = \frac{\gamma_p}{\sqrt{3}} = \frac{1}{\sqrt{3}}\frac{R\omega_p}{l}, \tag{5}$$

and plastic strain rate by following formula

$$\dot{\varepsilon}_p = \frac{\dot{\gamma}_p}{\sqrt{3}} = \frac{1}{\sqrt{3}}\frac{R\dot{\omega}_p}{l}, \tag{6}$$

where: M – torque, R – sample radius, l – gauge length of specimen, ω_p – plastic twist, $\dot{\omega}_p$ – plastic twist rate.

Because the shear strain is changed from zero in the middle of specimen to maximum value in outer layer the average value was used according to relation

$$\dot{\varepsilon}_p = \frac{2\dot{\gamma}_p}{3\sqrt{3}} = \frac{2}{3\sqrt{3}}\frac{R\dot{\omega}_p}{l} \tag{7}$$

Tensile flow stress σ_{pr} was determined by

$$\sigma_{pr} = \frac{F}{\pi R^2} \tag{8}$$

Plastic strain ε_{pr} caused by tensile force F was given by

$$\varepsilon_{pr} = \ln\frac{l}{l_p} \tag{9}$$

where: l_p - initial gauge length of sample,

The silicon bronze CuSi3.5 has following chemical composition: 0.001 % Al, 96.37 % Cu, 0.005 % Pb, 0.02 % Zn, 0.01 % Fe, 0.008 % Mn, 3.39 % Si, 0.01 % S, 0.001 % Sb, 0.005 % Pb and 0.18 others. The bronze has low stacking fault energy equal to 15 mJ/mm^2 and single structure of α phase.

Before investigations, bronze have been homogenously annealing at temperature 800°C during two hours. After such heat treatment bronze had α phase structure and the average grain size of 250 μm (Fig. 6).

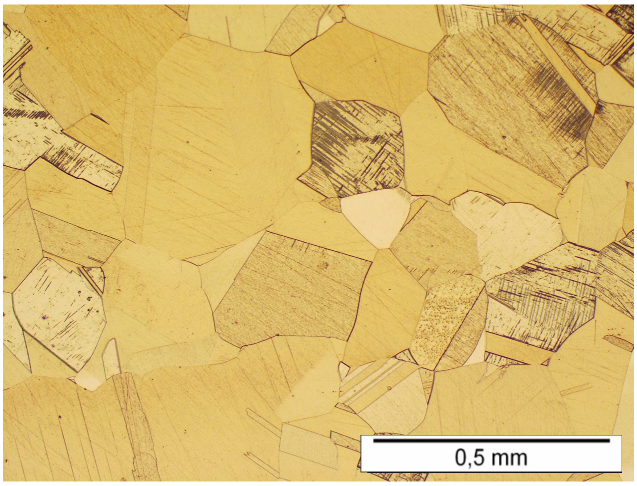

Fig. 6. Initial structure of silicon bronze CuSi3.5 after heat treatment

On the base of primary investigation, the following deformation processes have been chosen:

- monotonic torsion until fracture,
- monotonic tension until fracture,
- monotonic and cyclic deformation sequence.

The strain rate above 1 s^{-1} causes the growth of sample temperature as a result of plastic work change to heat, the increase in temperature is greater in the middle part of specimen than in its end parts because the heat is intensively removed by sample grip [27, 45, 46]. Because of heterogeneous distribution of temperature the middle part of specimen is more deformed than its end parts. To obtain the homogenous deformation along axis of sample the strain rate was limited to 1 s^{-1}.

For structural investigations, the sample was quenched in cold water. The optical microscope Olympus GX 51 with numerical camera Olympus DO12 and transmission electron microscope JRM 2010 ARP with micro analyzator OXFORD were used.

3. Separate monotonic torsion, monotonic tension and cyclic deformation

The flow stress–plastic strain relationships achieved in separate monotonic torsion and tension of CuSi3.5 silicon bronze at ambient temperature and different strain rates are shown in Fig. 7.

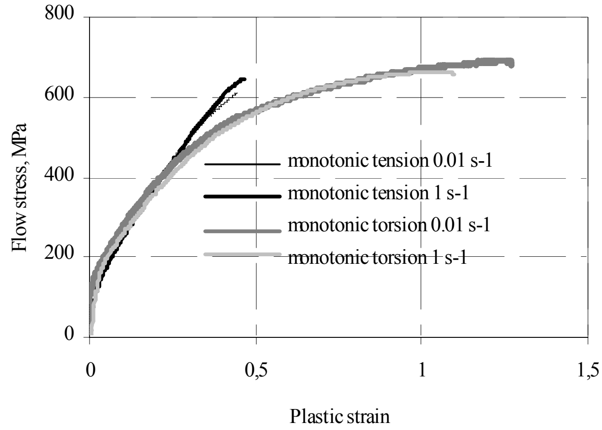

Fig. 7. The flow stress– plastic strain relationships achieved in separate monotonic torsion and tension of CuSi3.5 silicon bronze at ambient temperature and different strain rates

In the range of deformation lower than 0.25 the course of flow stress–plastic strain relationships obtained in monotonic torsion and monotonic tension are very similar. For lager deformation, the work hardening of material is greater in tension than in torsion. The limit strain in torsion is about 2.5 time greater than in tension. At ambient temperature silicon bronze CuSi3.5 is characterised by great hardening, but did not obtain saturated state, because it achieves limit strain earlier. In torsion as well as in tension at applied different strain rates the structure of bronze is highly deformed. In torsion, the great difference in degree of deformation between outer and inner layers is visible, such difference is caused by large deformation gradient along specimen radius. It is the reason, that in this work the degree of deformation at 2/3 radius from sample axis is taken as representative for average deformation of sample.

In torsion and tension tests at ambient temperature in the range of strain rate 0.01–1 s^{-1} there is no distinct influence of strain rate on the maximum values of flow stress (Fig. 7).

The twinning is the base mechanism of deformation of silicon bronze CuSi3.5 at ambient temperature. The structure of silicon bronze CuSi3.5 deformed in monotonic torsion contains the twinning planes almost parallel to each other and to direction of maximum shear stress (Fig. 8).

Fig. 8. Structure of silicon bronze CuSi3.5 after monotonic torsion at ambient temperature to ε_{pm} = 0.5 with strain rate of 0.1 s^{-1}

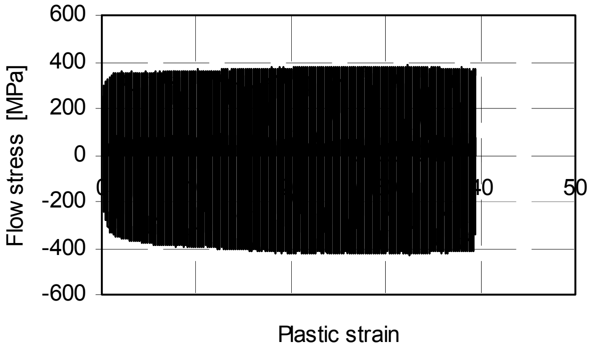

Fig. 9. Flow stress courses for CuSi3.5 bronze during cyclic deformation at ambient temperature with strain rate of 0.1s^{-1} and amplitude of 0.11

Flow stress courses of CuSi3.5 bronze during cyclic deformation at ambient temperature with strain rate of 0.1s^{-1} and amplitude of 0,11 is shown in Fig. 9. Maximum values of flow stress slowly increases with deformation until about 20 and at further straining is constant. Comparing the level of flow stress in cyclic deformation with that of monotonic torsion and tension it can be stated that cyclic deformation causes large decrease of flow stress. The opposite effect is observed in the case of limit strain, in torsion the limit strain is in comparison with limit strain in tension for about 80 times larger, and in the case of torsion test for about 25 times.

At temperature of 600°C in monotonic torsion and tension the flow stress grew up to maximum values and then decreases, in case of torsion test, to steady state flow. In case of tension flow stress doesn't obtain steady state, because it achieves limit strain earlier. The limit strain in torsion especially for lowest strain rate is much higher than in tension.

For monotonic tests the decrease in flow stress and limit strain in case of torsion is connected with dynamic recrystallization. In torsion the steady state flow is usually obtained and structure is fully recrystallized (Fig. 10), but structure obtained in tension is only partially recrystallized (Fig. 11), because before steady state flow the fracture takes place.

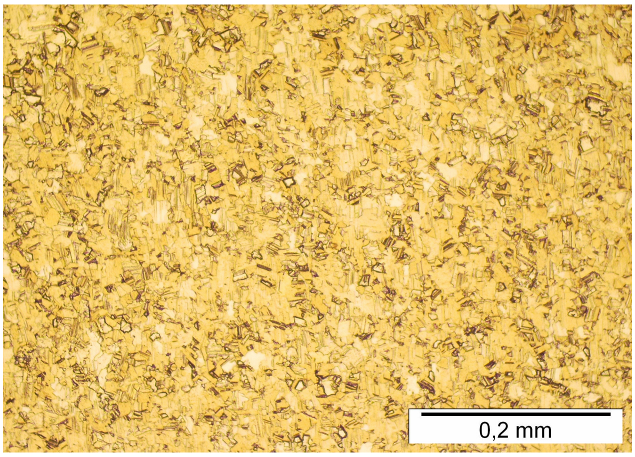

Fig. 10. Structures of silicon bronze CuSi3.5 after monotonic torsion at temperature of 600°C to ε_{pm} = 3 with strain rate of 0.1 s^{-1}

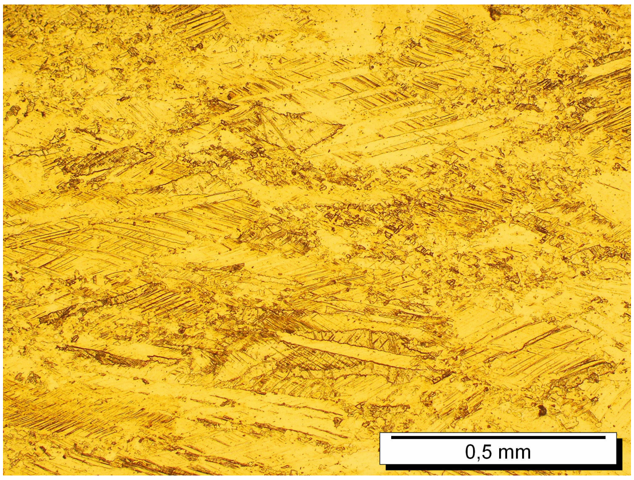

Fig. 11. Structures of silicon bronze CuSi3.5 after monotonic tension at temperature of 600 °C to ε_{pm} = 0.3 with strain rate of 0.1 s^{-1}

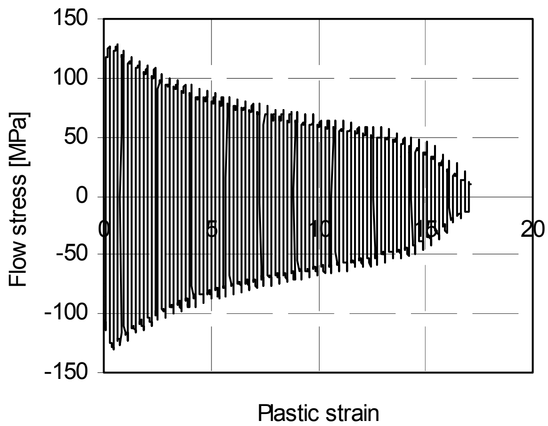

Fig. 12. Flow stress courses for CuSi3.5 bronze during cyclic deformation at temperature of 600 ^{0}C with strain rate of 0.1s^{-1} and amplitude of 0,11

Flow stress courses of CuSi3.5 bronze during cyclic deformation at temperature of 600 °C with strain rate of 0.1s^{-1} and amplitude of 0,11 is quite different than the flow stress course obtained in monotonic torsion and tension and cyclic deformation at ambient temperature (Fig. 12). The highest values of flow stress was obtained at the beginning of deformation and with increase in deformation the continuous decrease in flow stress is observed until the flow stress obtains very low values. The increase of limit strain at high temperature caused by cyclic deformation is not so big as at ambient temperature, for torsion is only 5 times greater.

4. Sequence of deformation of low cyclic torsion, monotonic tension and monotonic torsion

For determination of the effect of low cyclic torsion on the work hardening of initially deformed silicon bronze CuSi3.5 the following experiments were performed:

- initial monotonic torsion to strain of 0.5, then low cyclic deformation with amplitude of 0.11 until strain of 5.1 and repeated monotonic torsion in the same direction as before with strain rate of 0,1s^{-1} until fracture at ambient temperature (Fig. 13),
- initial monotonic tension to plastic strain of 0.2, then low cyclic deformation with amplitude of 0.11 until strain of 5.6 and repeated monotonic tension until fracture at ambient temperature (Fig. 15),
- initial monotonic tension to plastic strain of 0.12, then low cyclic deformation with amplitude of 0.11 until strain of 2.6 and repeated monotonic tension until fracture at temperature of 600°C (Fig. 16).

In the first experiment the initial monotonic torsion followed by cyclic deformation with 180°C change of direction of strain rate vector shows distinct Bauchingera effect and decrease in flow stress in successive cycles of deformation. The flow stress decreases from 550 MPa at the change of deformation direction to 459 MPa after 25 deformation cycles and at further straining is constant (Fig. 13). The level of flow stress is the same as flow stress during low cyclic deformation with the same amplitude of 0.11 in the whole range of deformation. In Fig. 13 the horizontal line describes highest values of flow stress in low cyclic torsion with amplitude of 0.11.

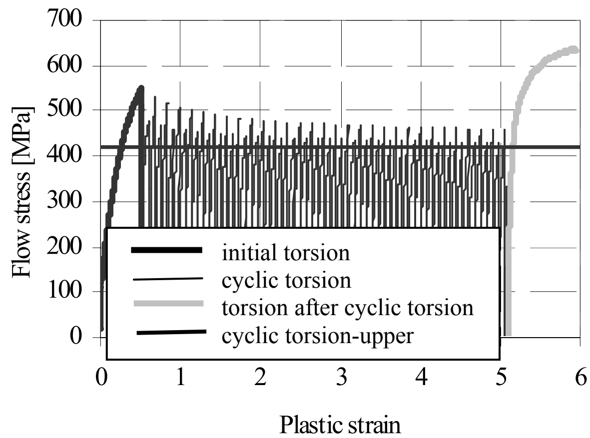

Fig. 13. Flow stress courses for CuSi3.5 bronze during deformation sequence at ambient temperature with strain rate of 0.1s^{-1}

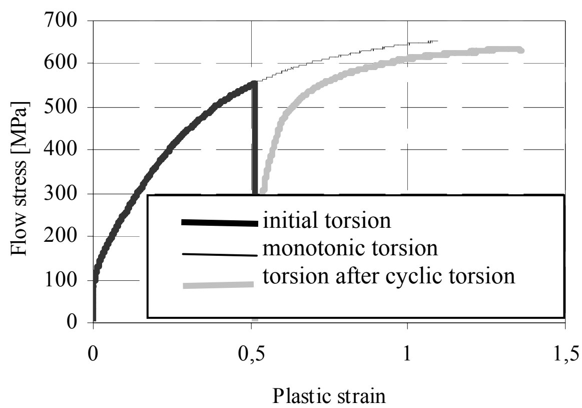

Fig. 14. The course of flow stress after removal from Fig. 11 the low cyclic deformation on the background of flow stress in monotonic torsion

The course of flow stress after removal from Fig. 13 the low cyclic deformation on the background of flow stress in monotonic torsion is shown in Fig. 14. Flow stress after low cyclic deformation is lower than flow stress obtained in monotonic torsion in the whole range of deformation. That confirms early observation that low cyclic deformation increases softening of material.

In the second experiment at the moment of transformation from initial tension to low cyclic deformation at ambient temperature the quick increase in flow stress for about 180 MPa is observed. It testifies that during tension the large work hardening of material takes place (Fig.15). During low cyclic strain in successive cycles, the decrease in flow stress takes place, but the decrease is not so big to obtain the level of flow stress equal to flow stress in the cyclic deformation with the same amplitude applied in the whole range of deformation (horizontal line). Repeated tensile plastic deformation starts from the flow stress level obtained in the final step of low cyclic deformation. Similar as in the first experiment the Bauschinger effect exists but not as distinct as before.

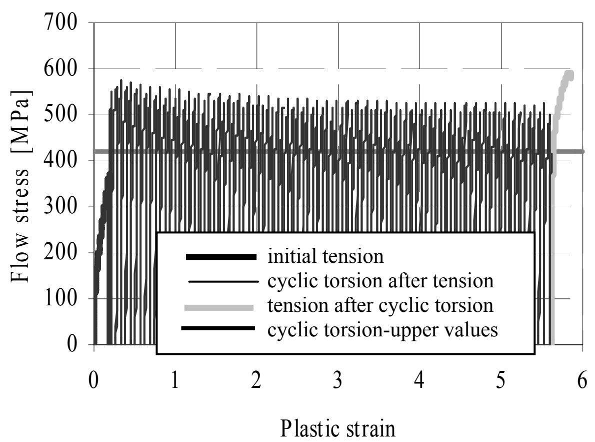

Fig. 15. Flow stress courses for CuSi3.5 bronze during deformation sequence at ambient temperature with strain rate of $0.1s^{-1}$

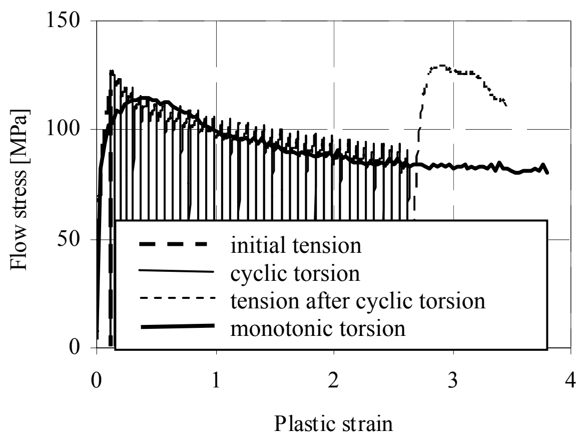

Fig. 16. Flow stress courses for CuSi3.5 bronze during deformation sequence at temperature of 600 °C with strain rate of $0.1s^{-1}$

In the last experiment at the moment of transformation from initial tension to low cyclic deformation at temperature of 600 °C the quick small increase in flow stress for about 10 MPa is observed (Fig.16). It testifies that during tension the work hardening of material take place but no as big as at room temperature (Fig. 15). In the Fig. 16 the course of flow stress in monotonic torsion in the whole range of deformation is also shown. Similar to sequence of deformation at ambient temperature (Fig. 15), at high temperature, during low cyclic strain in successive cycles, the decrease of flow stress takes place until the level of flow stress equals the flow stress in monotonic torsion. Repeated tensile starts from the very low value of flow stress, as the whole work hardening was removed by low cyclic deformation at high temperature of 600 °C.

On the above-described experiments it can be stated that in sequence deformation the low cyclic torsion causes softening of initially work hardened CuSi3.5 silicon bronze. The softening of work hardening distinctly increases with rise of temperature and nearly is independent on the way of deformation.

5. Conclusions

The courses of flow stress in monotonic torsion, monotonic tension and cyclic deformation by torsion are different. Besides, at high temperature the investigated silicon bronze has large strain rate sensitivity that make difficult to transform torque on the shear stress. Because the precise stabilization of temperature at high temperature is difficult, therefore at high strain rate the local increase in heterogeneity of deformation in torsion and cyclic deformation caused by no uniform distribution of temperature was observed. That is the reason that interpretation of results obtained in sequence deformation processes at high temperature is difficult.

For hot deformation condition the cyclic torsion stress-strain curves did not show the distinct peak stress typical for dynamic recrystallization, it suggests the absence of this phenomenon.

The rule that the level of the flow stress during the deformation at high temperature is function of actual conditions of deformation and is not affected by deformation history was confirmed by obtained results. In all cases, the initial torsion decreases the flow stress in secondary tension in comparison with monotonic tension, but especially great softening effect can be obtained if after monotonic torsion the cyclic deformation is applied.

The limit strain of samples if initial torsion reaches the critical strain and steady state flow is much larger than the limit strain of samples initially torsion to small deformation below critical strain or initially tension. The very great increase in limit strain in comparison with different sequences of deformation was observed in cyclic deformation.

Obtained results shown that by change of direction of displacement velocity vector for about 90° it is possible to increase or decrease in the flow stress. Without such changes of this vector the dislocation structure is not enough disturbed and strain localization in shear bands is absent, so there is no softening of materials caused by increase of free distance of dislocation movement.

References

[1] J. Gronostajski, Z. Gronostajski, A. Matuszak, A. Niechajowicz, Z. Zimniak, Proc. of 9th Int. Sci. Conf. "Achievements in Mechanical and Materials Engineering, AMME`2000", 231-234.

[2] S. Kocańda and A. Kocańda, Niskocyklowa wytrzymałość zmęczeniowa metali, PWN, Warszawa 1989.

[3] J.P. Pinheiro, R.A.N.M. Barbosa, P.R. Cetlin, J. Mater. Proc. Tecnol., 125-126 (2002) 125-129.
[4] J.P. Pinheiro, R.A.N.M. Barbosa, P.R. Cetlin, Scripta Mater., 38 (1998) 53-57.
[5] J.P. Pinheiro, R.A.N.M. Barbosa, P.R. Cetlin, Scripta Mater., 44 (2001) 187-193.
[6] J.P. Pinheiro, R.A.N.M. Barbosa, P.R. Cetlin, Proc. of Symposium of Thermomechanical Processing of Steel, Ottawa, the Metallurgical Society of the Canadian Institute of Metallurgy, Ottawa, 2000, 221-233.
[7] Z. Gronostajski, N. Misiołek, K. Jaśkiewicz, Materiały Konf. Forming'2002, Luhacovice, (2002) 93-98.
[8] Z. Gronostajski, K. Jaśkiewicz, Proc. of Int. Sc. Conf. Achievements in Materials and Mechancal Engineering, AMME'2002, Zakopane, (2002), 215-218.
[9] Z. Gronostajski, N. Misiołek, Proc. of Int. Sc. Conf. Achievements in Materials and Mechancal Engineering, AMME'2002, Zakopane, (2002) 219-222.
[10] Z. Gronostajski, N. Misiołek.: Proc. of 6th Int. ESAFORM Conference on Material Forming, Salerno, (2003) 807-810.
[11] Z. Gronostajski, K. Jaśkiewicz, Proc. of the Int. Conf on Advanced in Materials and Processing Technologies (AMPT'2003), (2003) 1404-1407.
[12] Z. Gronostajski, N. Misiołek, Proc. of the Int. Conf on Advanced in Materials and Processing Technologies (AMPT'2003), Dublin, (2003) 1408-1411.
[13] Z. Gronostajski, K. Jaśkiewicz,, Forming 2003. Materiały X Jubileuszowej Konferencji Forming'2003, Podlesice, (2003) 27-32.
[14] Z. Gronostajski, K. Jaśkiewicz: Proc. of the Int. Conf on Advanced in Materials and Processing Technologies AMME'2005, Gliwice, 220-223.
[15] Z. Gronostajski, K. Jaśkiewicz, Proc. of 20th Int. Manufac. Conf. "Knowledge Driven Manufacturing", IMC20, Cork, Ireland, (2003) 666-671.
[16] Z. Gronostajski, K. Jaśkiewicz, Arch. of Metallurgy, 48 (2003) 435-453.
[17] Z. Gronostajski, K. Jaśkiewicz, Arch. of Civil and Mechanical Engineering, 4 (2004) 17-30.
[18] Z. Gronostajski, K. Jaśkiewicz, N. Misiołek, Proc.of 7th Esaform Conference on Materials Forming ESAFORM 2004, Trondheim, Norwegia, (2004) 683-686.
[19] Z. Gronostajski, N. Misiołek, J. of Steel and Related Materials, Steel Grips 2, 2004, Suppl. Metal Forming (2004) 547-553.
[20] Z. Gronostajski, K. Jaśkiewicz, J. Mat. Proc. Technol, 155-156 (2004) 1144-1149.
[21] Z. Gronostajski, N. Misiołek, J. Mat. Proc. Technol, 155-156 (2004) 1138-1143.
[22] J. Pawlicki, F. Grosman, Medznarodna Vedecka Konferencia FORMING'2001, Plasticita Materiałov, Stara Lesna, 2001, 155-162.
[23] J. Pawlicki, F. Grosman, Materiały Międzynarodowej Konf. FORMING'99, Ustroń, (1999) 208-213.
[24] J. Pawlicki, F. Grosman, Rudy i Metale Nieżelazne, 42 (1997) 501-503.
[25] J. Pawlicki, F. Grosman Rudy i Met. Nieżelazne, 10 (1999) 565-568.
[26] J. Pawlicki, F. Grosman, Proc. of Int. Conf. Forming'99, Ustroń (1999) 208-213.
[27] Z. Gronostajski, Informatyka w Technologii Materiałów, 2 (2002) 46-54.
[28] P.J. Hurley, P.D. Hodgson, B.C. Muddle, Scripta Materialia, 40 (1999) 433-438.
[29] P.E. Armstrong and J. E. Hockett, J. Mech. Phys. Solids, 30 (1982) 37-58.
[30] Z. Garczyński, Materiały Konferencji Obróbka Plastyczna Metali'98, Poznań-Kierz, (1998) 29-34.
[31] Z. Gronostajski, Proc. of 4th Int. Scien. Conf. Achievements in Mechanical and Materials Engineering AMME'95, Gliwice, 1995, 129-132.
[32] Z. Gronostajski, Proc of 5th Int. Sc. Conf. „Achievements in Mechanical and Materials Engineering, AMME'96", Wisła, 1996, 131-134.
[33] Z. Gronostajski, Proc. of 9th Int. Sci. Conf. "Achievements in Mechanical and Materials Engineering, AMME`2000", 235-238.
[34] Z. Gronostajski, Proc. of 10th Jubilee Int. Conf. Achievements in Mechanical and Materials Engineering, AMME'2001, Gliwice-Cracow-Zakopane, 2001, 225-228.