Stress-strain dependence and the evolution of dislocation structure in Cu-Mn polycrystalline concentrated solid solutions

Nina Koneva[1,*], *Yuliya* Sentsova[2], *Lyudmila* Trishkina[1], and *Tatiana* Cherkasova[1,2]

[1]Tomsk State University of Architecture and Building, 634003 Tomsk, Russia
[2]National Research Tomsk Polytechnic University, 634034 Tomsk, Russia

Abstract. Deformation of metallic materials results in dislocations occurrence and accumulation, with establishment of their definite distribution (dislocation substructure). The type of dislocation substructure (DSS) defines largely resistance to deformation and fracture of materials. Quantitatively the interrelation of DSSs and resistance to deformation are studied on a limited number of alloys. Foreign literature lacks studies referring to those issues. The given paper investigates the stress-strain dependences in Cu-Mn polycrystalline solid solutions. Mn concentration in the alloys varied within the range of 10…25 at.%. Polycrystals with 10 and 240 µm mean grain size were investigated. Deformation was applied by means of tension at the velocity of $2{\cdot}10^{-2}$ s^{-1} and the temperature of 293 K. Using transmission electron microscope at the accelerating voltage of 125 kV, microstructure of the samples was investigated when they were deformed up to various deformation degrees. The types of DSSs were defined. The connection of the deformation stage under tension with the formed types of DSS was discussed. The sequence of transition of DSSs during the process of alloys deformation was defined. Appearance of the new stage of deformation hardening is attributed to the occurrence of the new type of substructure. The occurring "new" DSS develops during the deformation process, while "the old" DSS gradually disappears. Each of the stage of plastic deformation generally has two types of DSSs. The connection of the deformation stage and the strain hardening coefficient with the DSS was defined and it was shown to possess the definite dislocation density.

Introduction

The processes of plastic deformation are usually characterized by the clearly defined stages of strain hardening [1–4]. The staging of the dependency $\sigma = f(\varepsilon_{true})$ is identified from the mechanical testing. The number of stages of strain hardening and their duration depends on the type of polycrystalline aggregate, testing temperature and the deformation mechanisms.

[1] Corresponding author: koneva@tsuab.ru

The stages vary by the value of strain hardening coefficient $\theta = \frac{d\sigma}{d\varepsilon_{true}}$ (σ – stress, ε_{true} – strain), and by its dependence from ε_{true} [1]. A number of alloys enabled to establish that initiation of each of the stages was conditioned by appearance of the new substructure in local areas with the increased dislocation density and presence of the prior substructure in the material bulk [5]. The critical dislocation density [6] in the grain bulk cannot be reached yet, however it is realized in the grain boundary zone. The new substructure starts to form in that area, and the transition from one stage to another is dissolved at the dependence $\sigma = f(\varepsilon_{true})$. Broadening the number of alloys where the mentioned peculiarities are observed is the issue of the great relevance.

The present research is aimed to define the types of the formed substructures and their connection to the plastic deformation stages considering various grain sizes of Cu-Mn polycrystalline FCC alloys.

Materials and methods

Cu-Mn polycrystalline FCC solid solutions with the mean grain size <d>= 10 and 240 μm were investigated. Mn concentration in the alloys was varied within the range of 10…25 at.%. Flat samples (sized $100\times12\times2$ mm^3) were deformed by tension with the aid of Instron testing machine at the velocity of $2\cdot10^{-2}$ s^{-1} at the temperature of 293 K. Further, the dependences "σ – ε_{true}" were built and the value of the strain hardening coefficient $\Theta = d\sigma/d\varepsilon_{true}$ was defined. Samples microstructure deformed up to the various degree of deformation was investigated using Tesla–BS-540 electron microscope, equipped with the goniometer at the accelerating voltage of 125 kV. The obtained experimental data of polycrystalline alloys with the grain size 10 and 240 μm was used for establishing the connection between the strain hardening stages and the dislocation structure.

Results

The dependences σ – ε_{true} and θ – ε_{true} were built for the purpose of defining the deformation stages. For the dependencies $\sigma = f(\varepsilon_{true})$ the connection Θ was found with the type of DSS with various grain size.

Let us consider the dependences of the flow stress and the strain hardening coefficient on the deformation degree for Cu+10 at.% Mn samples with the grain size <*d*> = 10 and 240 μm. The dependences σ – ε_{true} and θ – ε_{true} for these grain sizes are given in Figure 1*a*. The analysis of dependence θ – ε_{true} demonstrated the presence of short transition stage π, stages II and IV with almost constant strain hardening coefficient and stage III with the decreasing strain hardening coefficient. Stage II is characterized by the higher value of θ. The values of θ and σ coefficients are higher in the alloy with the grain size of 10 μm. Figure 1*b* illustrates the dependences σ – ε_{true} and θ – ε_{true} for the alloys Cu+13 at.% Mn and Cu+25 at.% Mn with the grain size of 10 μm. It can be seen from the figure that the stress and strain hardening coefficient are higher in Cu+25 at.% Mn.

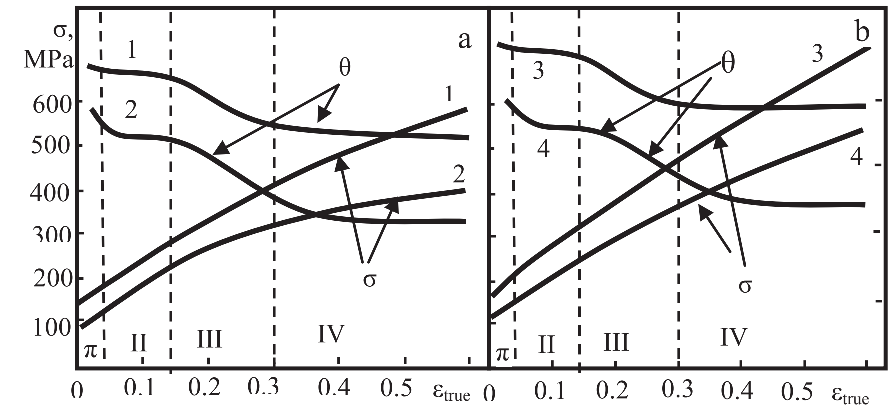

Fig. 1. The dependences of flow stress (σ) and the strain hardening coefficient (θ) on the deformation degree (ε_{true}): a – for Cu+10 at.% Mn alloy with the grain size of 10 µm (1) and 240 µm (2) and b – for Cu+13 at.% Mn (4) and Cu+25 at.% Mn (3) alloys with the grain size of 10 µm. Dashed lines and Roman numbers define the stage of the strain hardening.

Let us consider the evolution of dislocation structure with deformation for the alloys in the concentration range 10…25 at.% Mn. Figure 2 presents the sequence of transition of the DSSs types depending on their deformation degree.

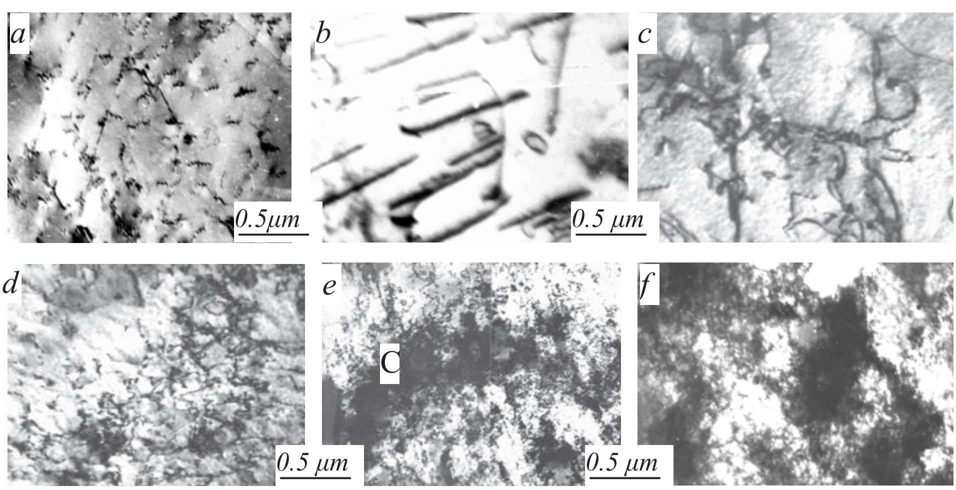

Fig. 2. The evolution of DSS in the alloys Cu+10 at.% Mn with deformation: a – dislocation accumulation, b – dislocation loops, c – cellular DSS, d – non-disoriented cellular-network DSS, e – disoriented cellular-network DSS, f – fragmented DSS. The grain size is 10 µm. C – bending extinction contour.

When the deformation degree is not high ($\varepsilon_{true} \approx 0.05$) chaotic distribution of dislocations and dislocation accumulation is observed (Fig. 2*a*). Dislocation loops given in Figure 2*b* can seldom be found. Increase in the deformation degree ($\varepsilon_{true} \approx 0.15$) is followed by occurrence of the rectilinear dislocations where thresholds and responses are observed. This will further lead to the formation of network DSS (Fig. 2*c*), and then cellular-network DSS (Fig. 2*d*). The increase in the deformation degree is followed by occurrence of disorientation in the substructure, which is characterized by the presence of bending extinction contours [7-10] (see e.g. Fig. 2*e*). Disoriented cellular-network DSS (Fig. 2*e*) and fragmented DSS (Fig. 2*f*) are observed.

It was established that the sequence of transitions of DSSs during the deformation process of Cu+10 at.% Mn – 25 at.% Mn alloys is as follows: chaotic dislocations distribution and dislocation accumulations → homogeneous network DSS→ non-disoriented cellular-network DSS → cellular-network DSS with disorientations → fragmented DSS. Result analysis revealed that occurrence of the new type of DSS corresponds to the occurrence of the new stage of strain hardening. The "new" DSS in the areas with increased dislocation density is evolving, and the previous "old one" disappears by the end of the stage. Redistribution of dislocations is followed by the reduction of the stored deformation energy [11, 12] and that is why it is energetically profitable. Thus, each of the stages generally has two types of dislocation substructure: "the new one" and "the old one". Stage II of the deformation is characterized by non-disoriented substructures: homogeneous network and cellular-network DSS. Disorientations start to form only at the end of stage II. The large bulk of the material at the stage III corresponds to the disoriented DSS. Stage IV is characterized by only disoriented DSS: cellular-network with disorientations and fragmented DSS are observed.

Conclusion

The stress-strain dependences and evolution of dislocation substructures were investigated in Cu-Mn polycrystalline solid solutions with the mean grain size $<d>=$ 10 and 240 μm. Mn concentration in the alloys varied within the range of 10…25 at.%. On the dependences $\sigma = f(\varepsilon_{true})$ four stages of strain hardening were observed, which varied by the value of the strain hardening coefficient: transition stage (π), stages II, III and the final longstanding stage IV.

The grain size does not influence the amount of the formed stages of plastic deformation; however the values σ and Θ depend on the grain size. Occurrence of the new stage of deformation hardening is connected to the formation of the new substructure type, where the dislocation density is higher than in the prior DSS. Dislocations redistribution resulting in the formation of the new type of DSS is attributed to the dislocation subsystem tendency to reduction of the stored deformation energy.

The studies were carried out within the support of the Government Task for research, project No. 3.8320.2017/БЧ.

References

1. N.A. Koneva, E.V. Kozlov, Russian Physics Journal, **8**, 90-98 (2004)
2. S.A. Firstov, G.F. Sarzhan, Russian Physics Journal, **34**(3), 23-34 (1991)
3. E. Nes, Progr. Mater. Sci., **41**, 129–193 (1998)
4. X.F. Fang, W. Dahl, Mater. Sci. Eng, **A203**, 14–25 (1995)
5. N.A. Koneva, E.V. Kozlov, Russian Physics Journal, **2**, 89-106 (1990)
6. N.A. Koneva, E.V. Kozlov, L.I. Trishkina, T.B. Cherkasova, Fundamental'nye problemy sovremennogo materialovedenia [Basic Problems of Material Science (BPMS)], **13**(2), 162-167 (2016) (in Russian)
7. P.B. Hirsch, *Electron Microscopy of Thin Crystals* (Mir, Moscow, 1968) (in Russian)
8. N.A. Koneva, L.I. Trishkina, E.V. Kozlov, Mater. Sci. and Eng. A, **319-321**, 156-159 (2001)

9. T.E. Konstantinova, *Mezostruktura deformirovannyh splavov* [Mesostructure of deformed alloys] (Don FTI NAN Ukrainy, Donetsk, 1997) (in Russian)
10. A.N. Tyumentcev, A.I. Ditenberg, A.D. Korotaev, K.I. Denisov, Physical Mesomechanics, **16**, 3, 63-79 (2013) (in Russian)
11. V.L. Indenbom, *Nekotorye voprosy fiziki plastichnosti kristallov* [Issues of the physics of the crystals plasticity] (Izd-vo AN SSSR, Mosscow, 1960)
12. W.A. Backofen, *Deformation processing* (Mir, Moscow, 1977)