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EFFECT OF SEVERE PLASTIC DEFORMATION ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF Al AND Cu

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Abstract. The aim of the present study was to examine how various severe plastic deformation processes, in particular hydrostatic extrusion (HE), alter the microstructure and properties of metals with different stacking fault energies, such as copper and aluminum.
The mechanical properties of HE processed materials were examined in static tensile test and by microhardness measurements. The results show that the tensile strength and the yield stress increased significantly, especially in Cu. This decrease in strength is due to formation of intersecting deformation bands containing ultra-fine subgrains (Cu) and grains (Al).

1. INTRODUCTION

Plastic deformation strongly affects the microstructure and strengthens the material usually at the expense of their ductility. However severe plastic deformation (SPD) leads to the formation of submicron and nano-grained structures that show high strength at room temperature and significant ductility [1-6]. One of the methods which can be used for SPD is hydrostatic extrusion, HE [7,8]. Compared to the other SPD methods, this technique has advantage high deformation rates at low deformation temperatures and high homogeneity of the plastic strain over the volume of processed samples.

The microstructure evolution and the changes of the mechanical properties induced by SPD depend not only on the deformation process but also on the properties of the material subjected to extrusion, in particular on its crystalline structure, stacking fault energy and the value of the self-diffusion coefficient. These effects have been investigated in the past for different methods such as equal channel angular pressing (ECAP) and high pressure torsion (HPT).

The aim of the present study is to examine how HE extrusion alters the microstructure and properties of various metals with different stacking fault energies, such as copper and aluminum.

2. EXPERIMENTAL

Commercially pure copper and aluminum rods were subjected to two hydrostatic extrusion processes. The reduction coefficients and the values of the true strain are given in Table 1. The experiments were conducted at the High Pressure Research Center in Warsaw , Polish Academy of Sciences.

Thin foils of HE processed materials were investigated by TEM (JEM 2010 ARP). The mean grain size and the volume fraction of the ultra-fine grains were determined by a computer-aided image analysis.

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Table 1. The hydrostatic extrusion parameters with used symbol (fi) which represent diameters of samples.

Materials	Parameters of the HE			
	Initial diameter (fi) [mm]	Final diameter (fi) [mm]	Reduction coefficient (*R*)	True strain
Al	fi 9.5	fi5	*R* = 3.61	j = 1.28
	fi 9.5	fi 3	*R* = 10.03	j = 2.31
Cu	fi 8.8	fi 5	*R* = 3.1	j = 1.13
	fi 8.8	fi 3	*R* = 8.6	j = 2.15

The mechanical properties of the materials in the initial state and after hydrostatic extrusion were characterized by HV0.2 microhardness measurements, and tensile tests. The microhardness distributions were determined on the cross-sections of the extruded rods. The tensile tests were conducted at room temperature at a rate of $8.3 \cdot 10^{-4}$ s^{-1}.

3. RESULTS

The results obtained in the present study indicate that hydrostatic extrusion profoundly changes the microstructure and mechanical properties of Al and Cu as shown in Figs.1 and 2. TEM observations indicate that, the process of hydrostatic extrusion leads to a refinement of the structure of both aluminum and copper. In the microstructure of the HE processed aluminum, the average grain size is reduced down to 200 nm from 60 μm. However the grain size distributions in Al shown in Fig. 3 is relatively wide. On the other hand the ultra-fine grains formed at more severe deformations exhibit high disorientation with respect to the surroundings (Fig. 2).

In the HE processed copper, the microstructure contained equiaxial sub-grains with an average size of about 200 nm (Fig. 4). Locally, such subgrains were also observed in the extruded copper at lower reduction in banded structure (Fig.1c).

The influence of the hydrostatic extrusion, carried out to various true strains, on the mechanical properties of the materials was examined by measuring microhardness and tensile strength. The microhardness results obtained for the un-deformed materials and after the HE are shown in Fig. 5. It can be noted that the microhardness increases with the total strain accumulated during the HE processes. This can be attributed to the refinement of the structures of the deformed metals.

The typical strain-stress curves obtained for the two metals in the initial state and in HE processed are shown in Fig. 6. An analysis of the results shows that the extrusion process has increased the mechanical strength of the materials. In both metals, Al and Cu, the yield stress increases more than four times, and the tensile strength – two times. These changes in yield stress are accompanied by reduction of uniform elongation (Fig. 7). It can be

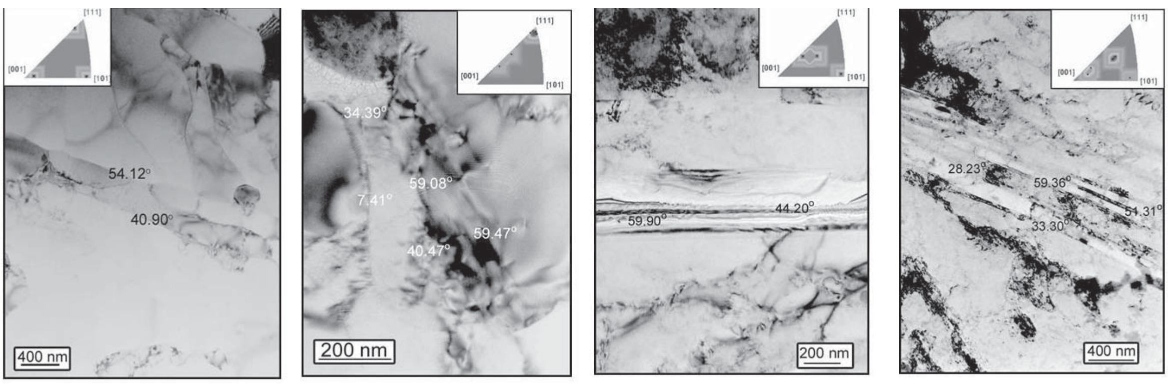


Fig. 1. Band type microstructure in investigated metals: a) Al-fi5, b) Al-fi3, c) Cu-fi5, d) Cu-fi3.

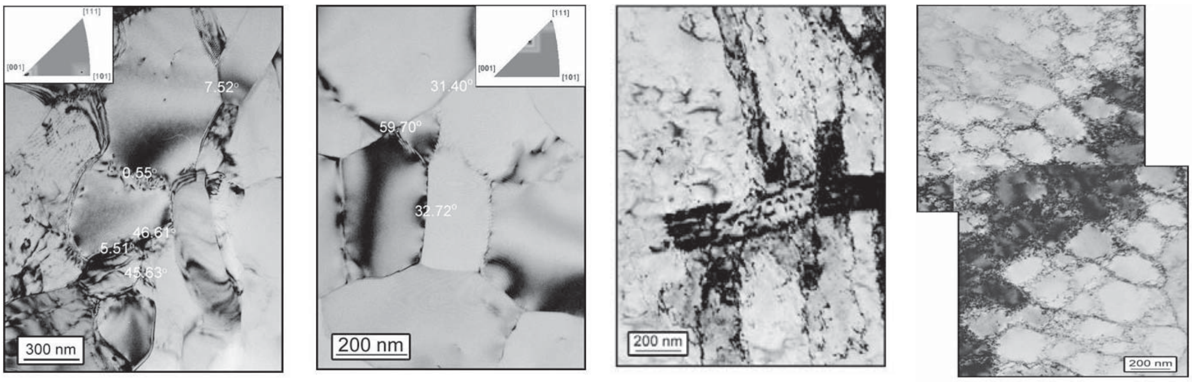


Fig. 2. TEM micrograph of investigated metals after HE: a) Al-fi5, b) Al-fi3, c) Cu-fi5, d) Cu-fi3.

also noted that the tensile strength rapidly increases already at small reduction coefficients *R*.

4. DISCUSSION

As it is known, the stacking fault energy (SFE) determines the deformation process of metal. In particular it affects the character of the strain induced dislocation structure [10]. A high SFE value favours transverse slips and dynamic recovery.

The metals examined in the present study have RSC structures and different SFE values. According to the literature data, SFE of aluminum is the range 135-280 mJ/m^2 [11], whereas copper has a low SFE in the range 65-74 mJ/m^2 [12].

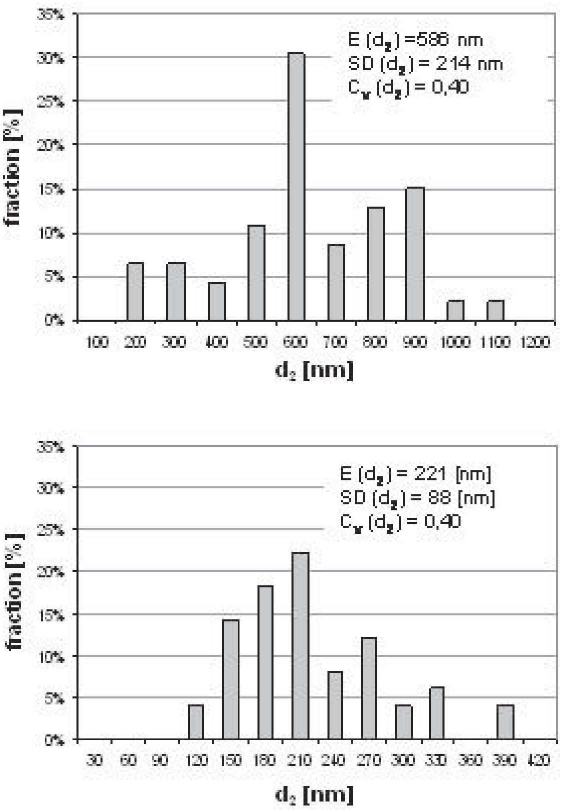


Fig. 3. Grain size distribution in aluminum after HE (*d*2- equivalent diameter of grain size, *E*(*d*2)- mean equivalent diameter of grain size, *SD*(*d*2)-standard deviation, C_v(*d*2)-variation coefficient): a) fi5, b) fi3.

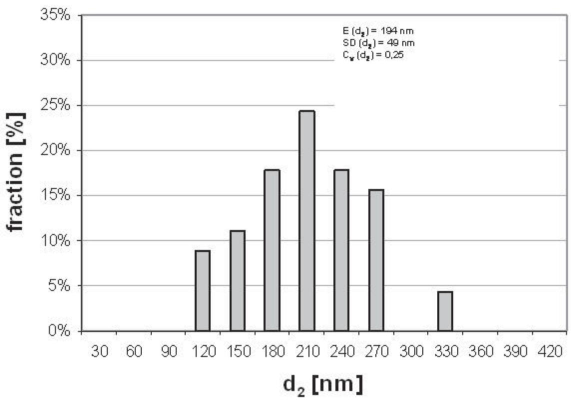


Fig. 4. Grain size distribution in copper after HE (fi3), the parameters *d*2, *E*(*d*2), *SD*(*d*2), C_v(*d*2) like Fig. 3.

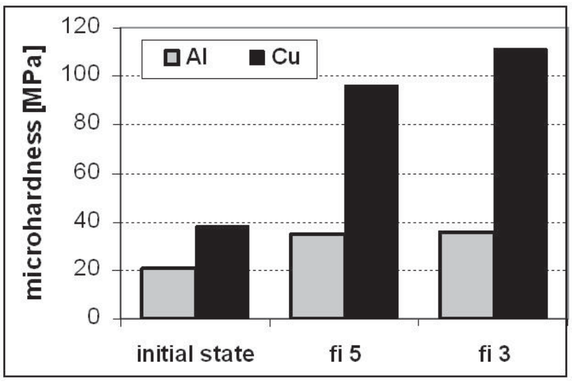


Fig. 5. Microhardness before and after hydrostatic extrusion.

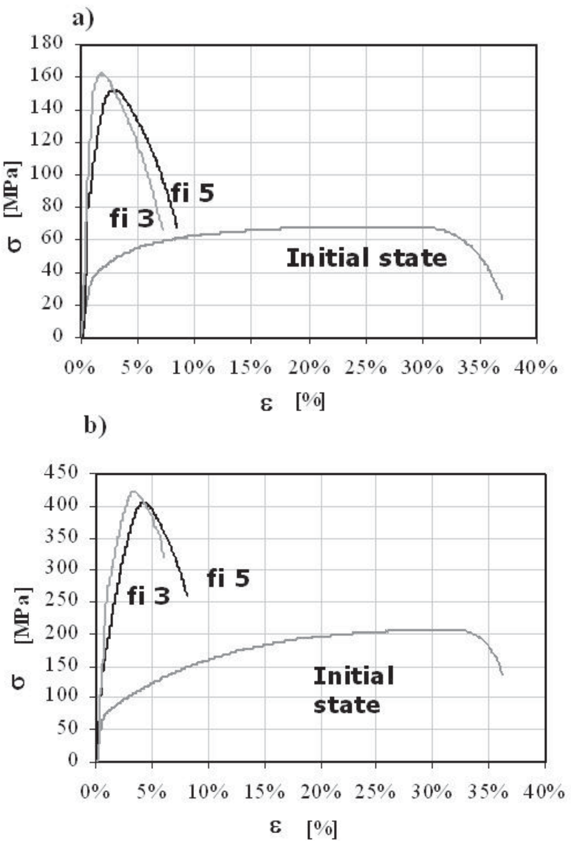


Fig. 6. Tensile curves of the investigated metals: a) aluminum, b) copper.

As seen from TEM examinations, the materials extruded hydrostatically show a strong tendency to strain localization within bands and micro-bands (Fig. 1). It has been found that the micro-bands are highly disoriented with respect to the surrounding microstructure both in aluminum and in copper. Characteristically, in Cu the micro-bands are highly planar rectilinearly (Figs. 1c and 1d), whereas in aluminum their boundaries are wavy (Figs. 1a and 1b). This suggests that the changes observed in aluminum are due probably to the easiness of the dislocation movements.

The fact that the microbands intersect each other explains to the formation of sub-grains and nano-grains with the sizes determined by the width of the micro-bands (Fig. 2c). In the aluminum structure, no dislocations can be seen within the grains; this suggests that intensive recovery processes have proceeded within this structure. In copper, the sub-grains formed as a result of the micro-bands intersecting have characteristic regular shapes and an average size of about 200 nm.

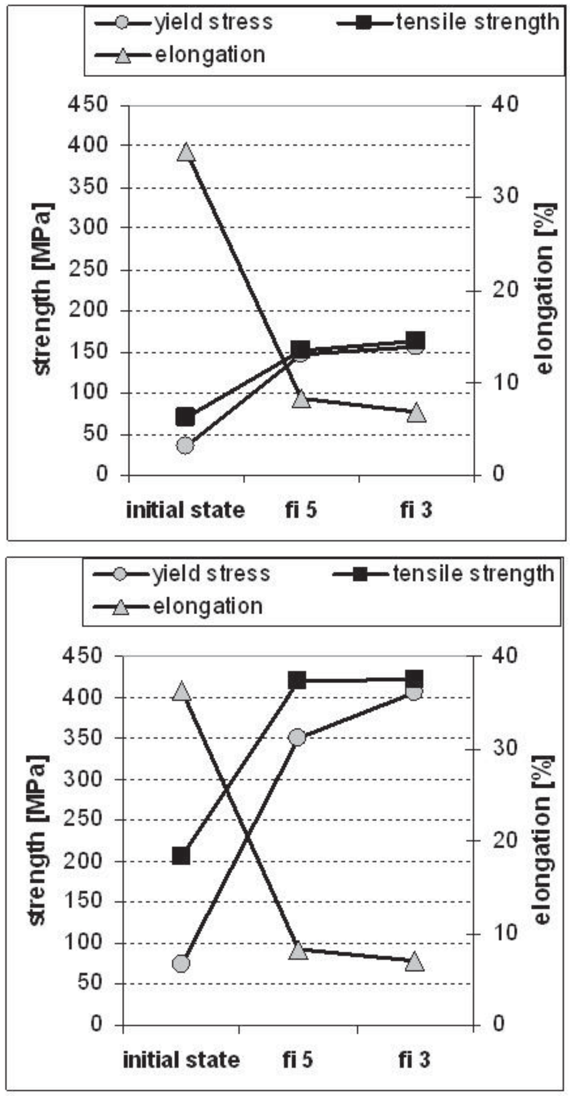


Fig. 7. The influence of the HE on the mechanical properties of a) aluminum, b) copper.

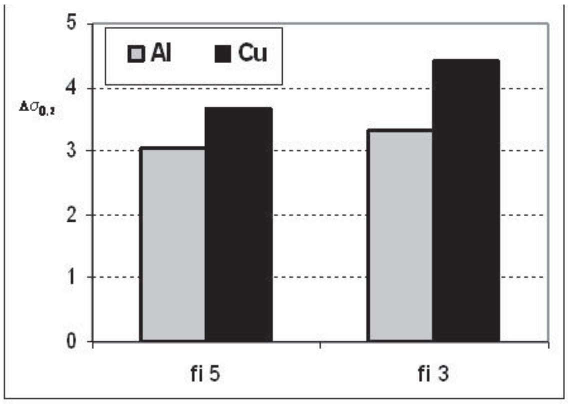
The extrusion process affects not only the strength of the materials but also the shape of the strain-stress curves. The increase of the reduction coefficient *R* results in these curves being shifted towards higher flow stress values, and in addition decreases the difference between the yield stress and the tensile strength. This term results in the uniform elongation being reduced.

In order to compare the reactions of the two materials examined to the plastic deformation, we introduced certain additional parameters that represented the relative changes of the yield stress (Fig. 8). As shown by our experiments, the changes of the strength parameters brought about by hydrostatic extrusion are similar in both materials, except that in copper the hardening is slightly stronger.

5. CONCLUSIONS

The following conclusions can be drawn in the present study.

1. A characteristic feature of hydrostatically extruded materials is the tendency to strain localization within bands and micro-bands highly disoriented with respect to the surroundings.
2. In aluminum, hydrostatic extrusion produces an ultra-finegrained structure, while in copper, hydrostatic extrusion (within the deformation range examined) yields a structure composed of equiaxial ultra-fine subgrains.
3. Hydrostatic extrusion brings about a considerably increase in the mechanical strength of Al and Cu.



$$\Delta\sigma_{0.2} = \frac{\sigma_{0.2\,\mathrm{final}} - \sigma_{0.2\,\mathrm{initial}}}{\sigma_{0.2\,\mathrm{initial}}}$$

Fig. 8. Relative changes of the yield stress.

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