

INFLUENCE OF THE REPETITIVE CORRUGATION ON THE MECHANISM OCCURRING DURING PLASTIC DEFORMATION OF CuSn6 ALLOY

This paper presents the research results of CuSn6 alloy strip at semi-hard state, plastically deformed in the process of repetitive corrugation. The influence of process parameters on the mechanical properties and structure of examined alloy were investigated. Examination in high-resolution transmission electron microscopy (HRTEM) confirmed the impact of the repetitive corrugation to obtain the nano-scale structures. It has been found, that the application of repetitive corrugation increases the tensile strength (R_m), yield strength ($R_{p0.2}$) and elastic limit ($R_{p0.05}$) of CuSn6 alloy strips. In the present work it has been confirmed that the repetitive corrugation process is a more efficient method for structure and mechanical properties modification of commercial CuSn6 alloy strip (semi-hard) as compared with the classic rolling process.

Keywords: CuSn6 alloy, severe plastic deformation, repetitive corrugation, structure analysis, high-resolution transmission electron microscopy.

1. Introduction

The growing requirements of modern engineering materials, which are required for better properties with optimum cost of production, cause an increase in innovative processing methods. Nanocrystalline materials exhibit superior mechanical and physical properties in comparison with conventional polycrystalline materials. Nanograins have size of less than 100 nm, submicrograins have size from 100 to 1000 nm and the ultra-fine grains – UFG, incorporates both the nano and submicro ranges [1, 2]. A lot of methods have been used to produce bulk UFG materials [2-4]. One of recently developed methods of plastic working is the Repetitive Corrugation and Straightening process belongs to the group of Severe Plastic Deformation methods (SPD) [4, 5], whose aim is not to form shape, but to develop of the desired physical and mechanical properties of processed material, by fragmentation of the microstructure. The Repetitive Corrugation and Straightening process consists on cyclic bending and straightening metal strips to obtain a strong accumulation of plastic deformation strain for structures fragmentation in the metal under investigation [6]. During the processes with accumulation of strong plastic deformation, structures can be refinement by generate a large number of dislocations, which results in generation of grains with low-angle boundaries. Continued accumulation of strain create a homogeneous grain high-angle boundaries [7-9]. The paper presents results of studies on the effects of Repetitive Corrugation process on the structure and mechanical properties of commercial CuSn6 alloy at semi-hard state. The effect of process parameters on the structure and mechanical properties were investigated.

2. Experimental procedure

X-ray diffraction studies of analysed CuSn6 strips were performed on the PANalytical X'Pert diffractometer, using filtered radiation of the copper anode ($\lambda_{K\alpha} = 1.79 \text{ \AA}$). The measurements were performed in the Bragg - Brentano geometry using PIXcell 3D detector in two-dimensional area mode at range of $20 \div 120^\circ [2\theta]$ (step = 0.03° , counting time at step = 10s). Phase analysis was conducted by the PANalytical High Score Plus software with PAN-ICSD database. The microstructure of the samples was observed using the light microscope Zeiss Axio Observer, with the polarized light observation technique and Nomarski differential interference contrast (DIC). Structure studies were carried out on the high-resolution transmission electron microscopy S/TEM TITAN 80-300 (FEI Company) with field-emission gun (FEG) and high-angle annular dark-field detector (HAADF). Static tensile test of analysed strips CuSn6 were carried on Instron testing machine 4505/5500 K, using measuring head force carrying capacity 10kN and the stretching speed equal 2 mm/min.

3. Material for investigations

The studied material consisted on non-annealed commercial CuSn6 alloy (table 1) strips, at semi-hard strengthening state, which size is 0,75x20x130mm. To produce a series of samples a Repetitive Corrugation and Straightening plastic working station was used. The procedure consists of the set of bending and straightening rollers. The bending roller includes a pair of toothed wheels for deformation of strip in

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CuSn6 alloy elemental composition (PN-EN 1652:1999)

| Material | | mass concentration [% wt] | | | | | | | | |
|----------|--------|---------------------------|------|-----|-----|------|------|-----|-----|-------|
| Symbol | Number | Element | Cu | Fe | Ni | P | Pb | Sn | Zn | Other |
| CuSn6 | CW452K | min. | rest | - | - | 0,01 | - | 5,5 | - | - |
| | | max. | - | 0,1 | 0,2 | 0,4 | 0,02 | 7,0 | 0,2 | 0,2 |

a direction transverse to the rolling direction and a pair of bending rolls for deformation of strip in the direction of rolling (Fig. 1)

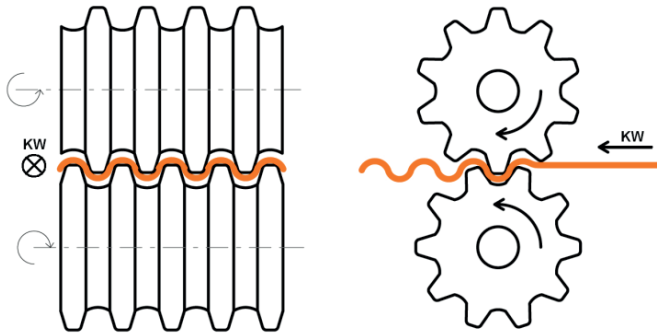


Fig. 1. Layout of bending rolls

The strips were processed on an alternating forming of repetitive corrugation in the rolling direction and cross direction. Tapes was rotating an 180° after each cycles. Distinct settings of bending rolls pressure were applied for each direction of corrugation, to perform as much as possible corrugation cycles. Selected pressure parameters allowed for performing a 35 cycles. The alloy strips, after the last corrugation cycle, were subjected to straightening by classic rolling. Repetitive corrugation processes were performed at room temperature.

4. Results and discussion

The X-ray diffraction analysis carried out using the two-dimensional detector mode (Pixel 3D), allowed to obtain information about the structure and extent of plastic deformation of the crystal lattice of investigated CuSn6 strips. The diffraction lines of crystal planes with Miller indices (111), (200), (220) and (311), characteristic for the structure of the CuSn- α solid solution, were observed on recorded two-dimensional diffraction pattern (Fig. 2). For the strongest diffraction line (220), spots with a distinct blurring was observed the. This is the result of structure deformation consisting in the bending or twisting of the lattice of individual crystallites.

In order to determine the effect of plastic deformation on the structure of the examined CuSn6 alloy strips, Zeiss Axio Observer optical microscope with polarized light was applied. As a result of analysis of the CuSn6 strips, performed by the optical microscope at a magnification of 500x there was found that the strips regardless of the method of plastic working, have a surface devoid of cracks, for which non annealed CuSn6 alloy strips were exposed during processing.

The microstructure of CuSn6 strip after repetitive corrugation, observed in polarized light technique and Nomarski differential interference contrast (DIC) is shown in Fig. 3 and 4. It was found that the structure of analyzed strip consists of grains of the solid solution α with annealing twins. Analyzed structures of CuSn6 strips after plastic deformation by using repetitive corrugation process are characterized by larger number of crossing slippage systems lines visible within the interior of grains. It can be assumed that unprivileged distribution of slip bands in the structure of the strip after repetitive corrugation, are the result of strengthening and block slip systems most privileged relative to the rolling direction and the gradual launching new slip systems. Another possible factor causing the increase in the number of active crystal planes involved in the mechanism of slip is critical shear stress in different directions, being the result of a complex deformation process.

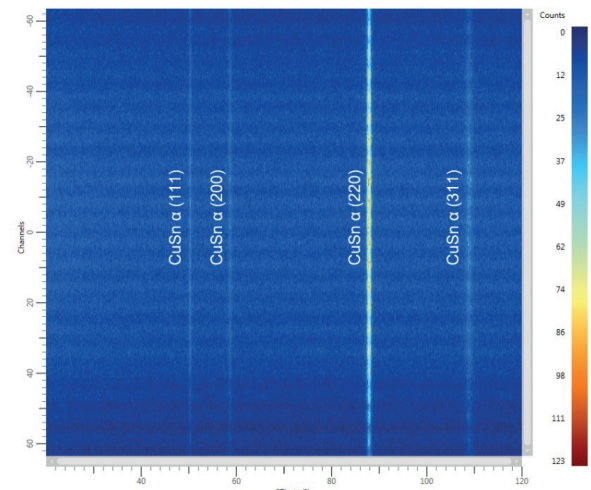


Fig. 2. Two-dimensional X-ray diffraction pattern of CuSn6 strip after repetitive corrugation process (detector PIXcel 3D)

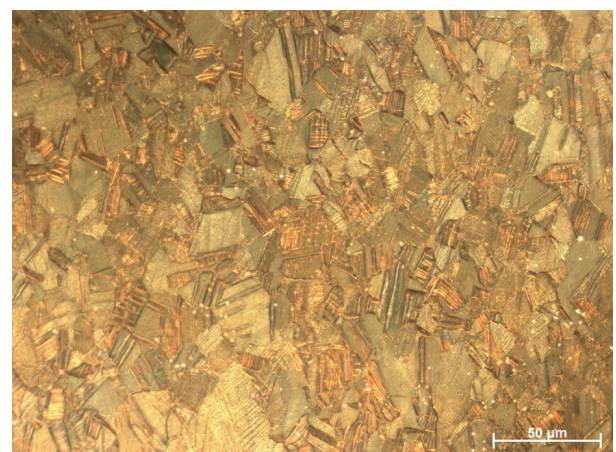


Fig. 3. Structure of CuSn6 alloy after repetitive corrugation process (magnification 500x, polarized light, optical microscope)

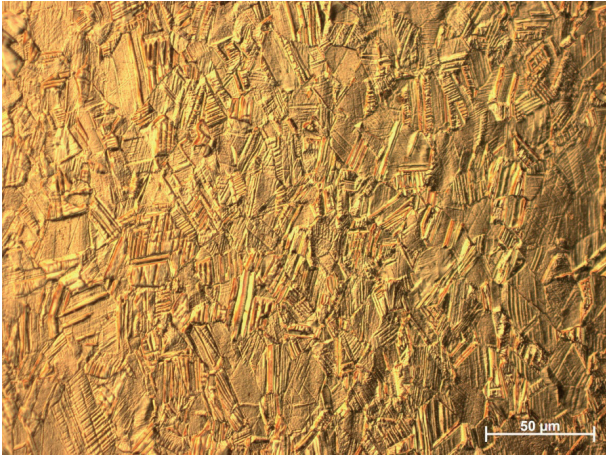


Fig. 4. Structure of CuSn6 alloy after repetitive corrugation process (magnification 500x, Nomarski differential interference contrast, optical microscope)

The results of the high-resolution transmission electron microscope are shown in Figures 5 ÷ 9. The structure of the strip after repetitive corrugation process (Fig. 5 and 6), consists of a well-developed dislocation sub-structure. The dislocation cells are characterized in size from 10 to 100 nm, and low-angle boundaries, which in some case they evolve, by interacting with the moving dislocations and increasing of disorientation angle. This can be observe (Fig. 7) as a higher contrast of the boundaries, which is the result of accumulation and decreasing the distance between dislocations with the increasing of disorientation angle. The high-energy grain boundaries, formed in this way, are an obstacle to moving dislocations, and are a source of new dislocations. In the analysed structure of the CuSn- α solid solution, there are numerous nanometric deformation twins (Fig. 8), and the slip lines in several independent slip systems (Fig. 9).

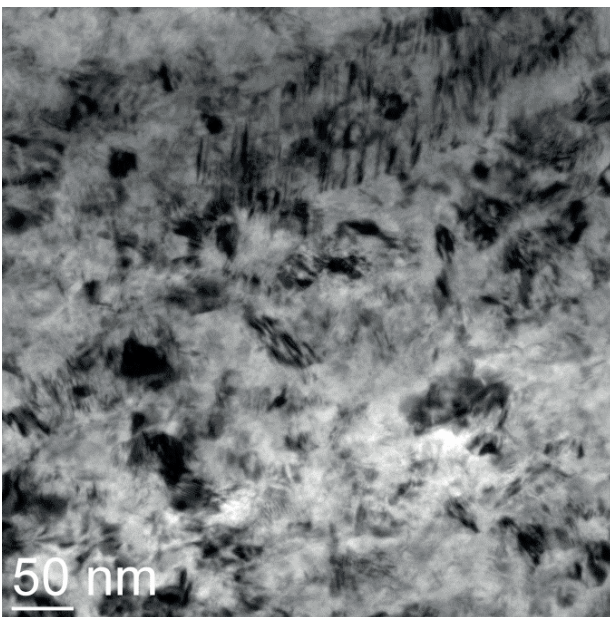


Fig. 5. Structure of CuSn6 alloy after repetitive corrugation process (TEM bright field mode, high-resolution transmission electron microscopy) [10]

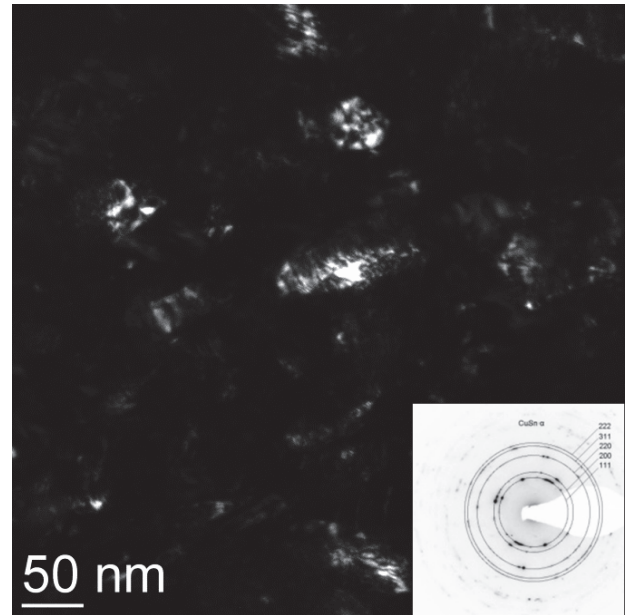


Fig. 6. Structure of CuSn6 alloy after repetitive corrugation process (TEM dark field mode, high-resolution transmission electron microscopy) [10]

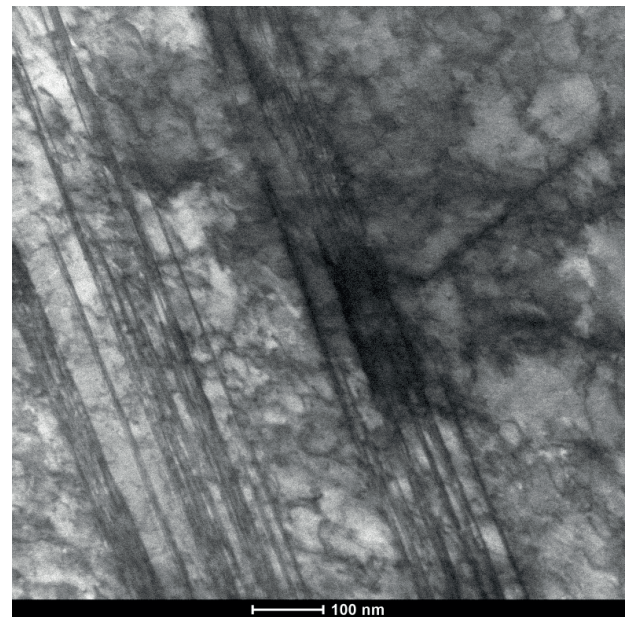


Fig. 7. Structure of CuSn6 alloy after repetitive corrugation process (STEM mode, high-resolution transmission electron microscopy) [10]

Mechanical properties of CuSn6 strip, determined in the static tensile test

| Strip | $F_{m_{max}}$ [N] | $R_{m_{max}}$ [MPa] | $F_{p_{0.2}}$ [N] | $R_{p_{0.2}}$ [MPa] | $F_{p_{0.05}}$ [N] | $R_{p_{0.05}}$ [MPa] | Elongation A 20% |
|------------------------|-------------------|---------------------|-------------------|---------------------|--------------------|----------------------|------------------|
| classic rolled | 1414 | 485 | 1211 | 415 | 1101 | 378 | 21,5 |
| repetitive corrugation | 1594 | 552 | 1514 | 525 | 1420 | 492 | 7,5 |

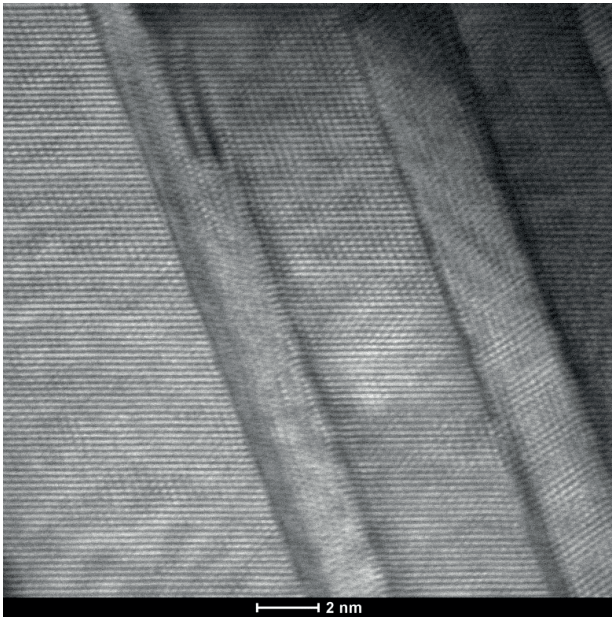


Fig. 8. Structure of CuSn6 alloy after repetitive corrugation process (STEM mode, high-resolution transmission electron microscopy) [10]

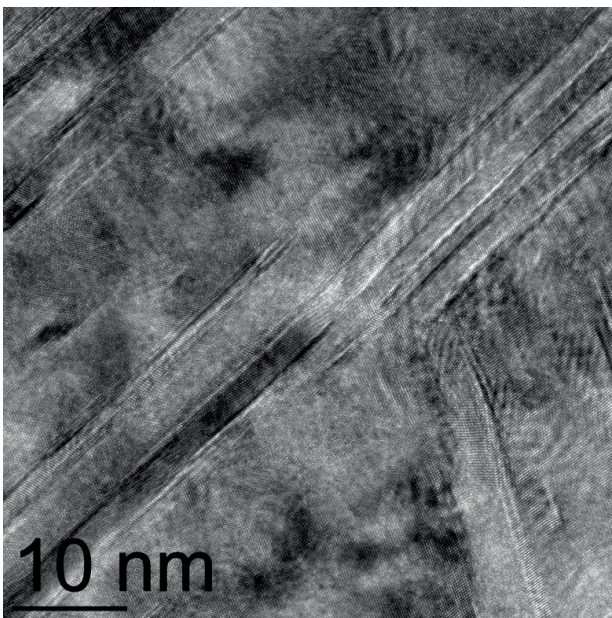


Fig. 9. Structure of CuSn6 alloy after repetitive corrugation process (HRTEM mode, high-resolution transmission electron microscopy) [10]

To determine mechanical properties of the analysed strips, the static tensile test was conducted and the obtained results are shown in Table 2. The test was conducted at room temperature. It has been found, that the application of repetitive corrugation

increases the tensile strength – R_m (552 MPa), yield strength – $R_{p_{0.2}}$ (525 MPa), elastic limit – $R_{p_{0.05}}$ (492 MPa) of CuSn6 alloy strips, in comparison to the classic rolled strip: 485 Mpa, 415 MPa, 378 MPa, respectively.

5. Conclusions

Accomplished studies have shown that the use of alternating bending process can effectively improve structure and mechanical properties of commercial CuSn6 alloy at semi-hard state, compared to the classic rolled strip. The high-resolution transmission electron microscopy confirmed that repetitive corrugation process allows to obtain nanostructure as the result of deformation twins and dislocation cells. Strips after deformation in repetitive corrugation process are characterized by the increase of the maximum tensile strength (R_m), yield strength ($R_{p_{0.2}}$), elastic limit ($R_{p_{0.05}}$), in relation to the classically rolled strips.

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