New possibilities of intense plastic deformation of aluminium alloys using a special CEC press

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ABSTRACT: A new 600 kN capacity press was designed and built to deform metals and alloys by Cyclic Extrusion Compression (CEC). The press was equipped with a microprocessor system for controlling the hydraulic actuators and measuring the forces exerted by the tools. The microstructure of the AlMgSi (6082) samples deformed during 24 cycles ($\varphi = 16$) of CEC using the new press showed the nanometric features such as the average grain size below 100 nm and large misorientation between nanograins. The simulation of plastic flow in the CEC process was performed using a DEFORM software. It was found that a certain minimal value of the counterforce was required to ensure the geometrical consistency of the process. Further increment of the level of hydrostatic pressure prevented the development of tensile stresses, which might lead to material fracture. Based on the results of the numerical simulation of CEC, a special diagram has been obtained, which can be used to facilitate the choice of a suitable counterforce.

Key words: Severe plastic deformation, Cyclic Extrusion Compression, ultrafine grained metals

1 INTRODUCTION

The process of Cyclic Extrusion Compression (CEC) is one of the special methods of Severe Plastic Deformations (SPD) that enable production of bulk nanocrystalline (NC) materials and ultrafine grained (UFG) materials with the unusual features and properties [1 - 6]. The achieved grain size depends on the kind of the material subjected to SPD and details of the SPD process used. It is reported that the grain size commonly ranges from 70 nm to 200 nm, which means that the microstructure of the materials deformed by SPD processes consists partly of the NC structure, with the grain size below 100 nm, and partly of the UFG structure, with grain size above 100 nm. The most important properties related to the grain size are the high level of hardening accompanied by relatively good ductility [2, 7].

As all SPD methods, CEC retains the initial shape of the sample after each deformation cycle [1, 2]. The deformation in CEC is exerted cyclically by forcing a sample from one chamber of the die to the other; as the sample is forward extruded in one chamber, it is compressed back to its initial shape in the other chamber. In this way the deformation can be carried out unlimitedly provided the level of hydrostatic pressure is high enough to prevent fracture of the sample.

The main tendency in the development of SPD processes is to achieve a high volume of highly deformed material resulting in the minimal grain size and high misorientation angles. In the context of CEC, the performed investigations have shown that, in order to achieve the highest possible deformation without fracture, the value of hydrostatic pressure should increase with the increase of the accumulated deformation and the level of sample hardening [3]. The new CEC press, developed at the AGH University of Science and Technology, ensures a proper control of the value of hydrostatic pressure. This considerably improves the conditions of material deformation in the CEC process.

The aim of this paper is to present the improved possibilities of material deformation provided by the new CEC press, present the grain structure in an

AlMgSi alloy obtained by performing CEC up to a strain of $\varphi = 16$ and demonstrate some results of the finite element (FE) simulation of CEC which help understand the process mechanics.

2 EXPERIMENTAL TECHNIQUE

2.1 The CEC technique of deformation

The improvement of control over material deformation in the CEC process has been achieved by building a new unique press with the 600 kN capacity [1, 3] (Fig. 1a). The extrusion force F_e and the counterforce F_c in this press (Fig. 1b) are applied by two horizontal hydraulic actuators. The most important feature of the new press is the possibility of controlling the counterforce F_c. The counterforce F_c has to be high enough to plastically deform the material entering the compression chamber and to provide a high hydrostatic pressure during this deformation, which prevents material fracture. On the other hand it should not be too high because of the increased tool contact pressure and friction, which are detrimental to the tool life. The new CEC press is furnished with servo valve and control software to automatically select the optimal level of the counterforce F_c. It was experimentally found that if the level of the forces in each cycle of the CEC process is the same ($F_e = \text{const}$) the sample cohesion is preserved. For preservation this condition the special software was work up for press steering. The lowest decrease of the force, in comparison to the maximal force of the process, which appears at the beginning of the process, is instantly detected by the control software procedures and quickly levelled by an increase of the counterforce F_c.

2.2 The investigation procedures

Using the new CEC press, an AlMgSi alloy (Al-1.0Mg-1.18Si-0.66Mn-0.04Cu-0.04Zn-0.03Cr-0.03Ti in wt.%) was deformed in the range of strains $\varphi = 0.65\text{-}16$, by exerting the strain of $\varphi = 0.65$ in each cycle (by changing the sample diameter from 10 mm to 8.5 mm and back to 10 mm). The value of strain was calculated from equation: $\varphi = 4n\ln(d_o/d_m)$ (where n – number of CEC cycles, d_o – chamber diameter, d_m – die diameter). The deformation has been applied at the strain rate $\dot{\varepsilon} = 10^{-3}$ (v = 0.1 mm/s). The microstructure of AlMgSi alloy was investigated by the optical microscopy and transmission electron microscopy techniques. The mean size of grains was determined by the mean chord parameter. The PMT3 tester was used for the microhardness measurement of samples. The DEFORM - 2D v.8.1 software was applied for the simulation of plastic flow in the CEC process.

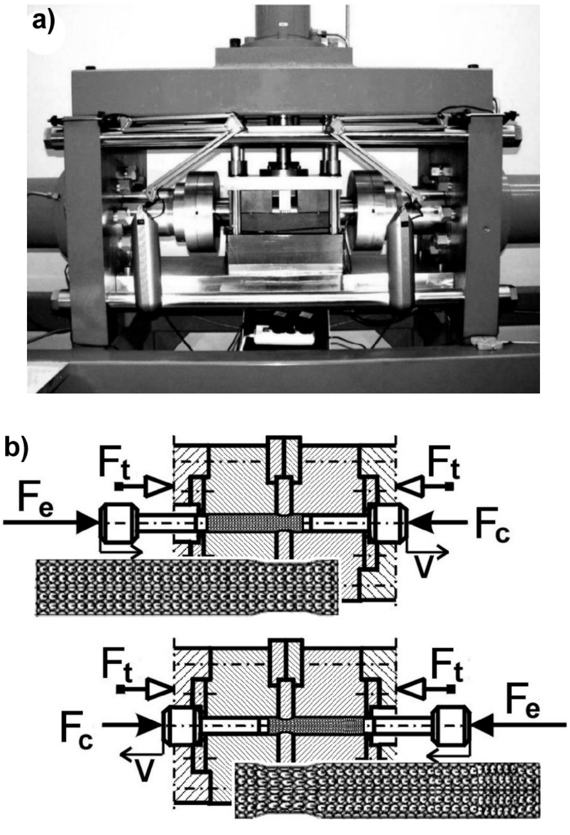

Fig.1. The new CEC press: a) view of the tool module, b) conditions of deformation in CEC processes; forces in CEC process: F_e - extrusion force, F_c - counterforce, F_t - tool clamping force, v – punch velocity

3 RESULTS OF INVESTIGATIONS AND DISCUSSION

The performed investigations have shown that, with the increase of strain, the mean grain size of the AlMgSi alloy deformed by CEC is gradually diminished (Fig. 2). After 25 cycles of CEC ($\varphi = 16$), the mean grain size was reduced to 75 nm. This result proves the possibility of generating the NC structure in the investigated alloy. The observations indicated that the NC structure appeared in about 75% of the sample volume. The samples deformed to a lower strain than $\varphi = 16$ showed a larger volume fraction of the UFG material, with grains larger than 100 nm. The characteristic feature of the nanograins produced by CEC was high misorientation angles (Fig. 3a). Also very significant was high misorientation between microbands and the surrounding material (Fig. 3b). The mechanism of the formation of nanograins was presented in the works concerning the CEC deformation and showed that nanograins were mostly formed in the areas of the mutual crossing of microbands [2, 8].

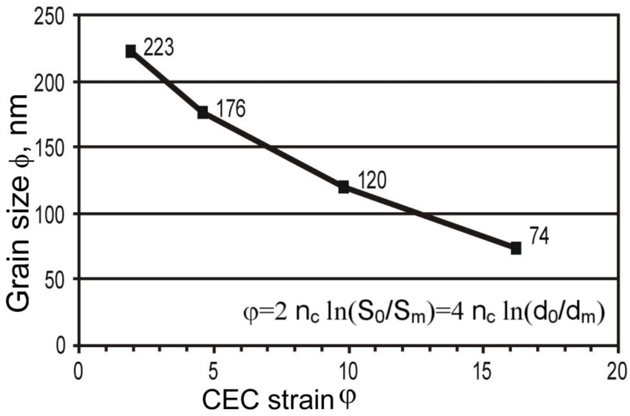

Fig.2. The mean size of NC/UFG grains in an AlMgSi alloy

The simulation of plastic flow in the CEC process was performed using the DEFORM software. The process has been modelled in relation to the technically pure aluminium and a 6082 aluminium alloy. The different CEC deformation conditions were applied. The most interesting results were obtained from the simulation of deformation of an imaginative circular lattice. During extrusion from a chamber, the circular lattice changes into the elliptical lattice. This, in turn, should be converted back into a circular lattice as a result of compression in the opposite chamber. It was found that a suitably selected value of the minimal counterforce F_c could restore the circular shape of the lattice. The proper conditions of the CEC process require that such a minimal force is present to help the material fill the entire compression chamber.

Another important factor is the level of hydrostatic pressure, which prevents an increase of the dangerous tensile stresses (Fig. 4a). Based on the results of the numerical simulation of the CEC processes, a special diagram has been prepared, which facilitates a suitable choice of the counterforce F_c (Fig. 4b). Fig. 4b illustrates that with the increase of the number of CEC cycles, the hardening of material increases while the hydrostatic stress $p_h=-\sigma_m$ decreases. This may lead to the material not fully filling the compression chamber, development of tensile stresses and eventually fracture of the material. Fig.4b indicates a threshold hydrostatic stress p_{min} at which material fracture begins; the boundary hydrostatic stress that preserves material cohesion is denoted p_{st}. From the presented data, the proper deformation conditions can be derived. The crucial information is that the level of σ_m should not fall below p_{st}.

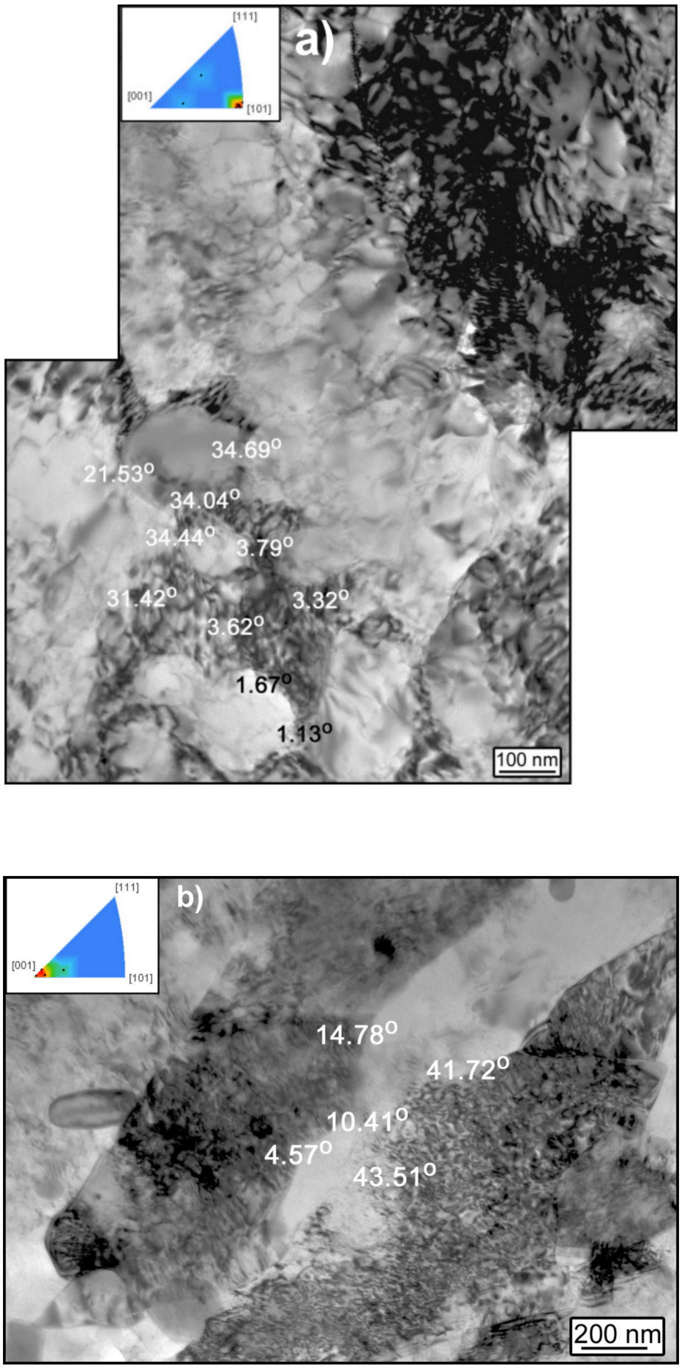

Fig.3. The microstructure of an AlMgSi alloy strained to φ = 16: a) area of nanograins, b) microbands with high misorientation

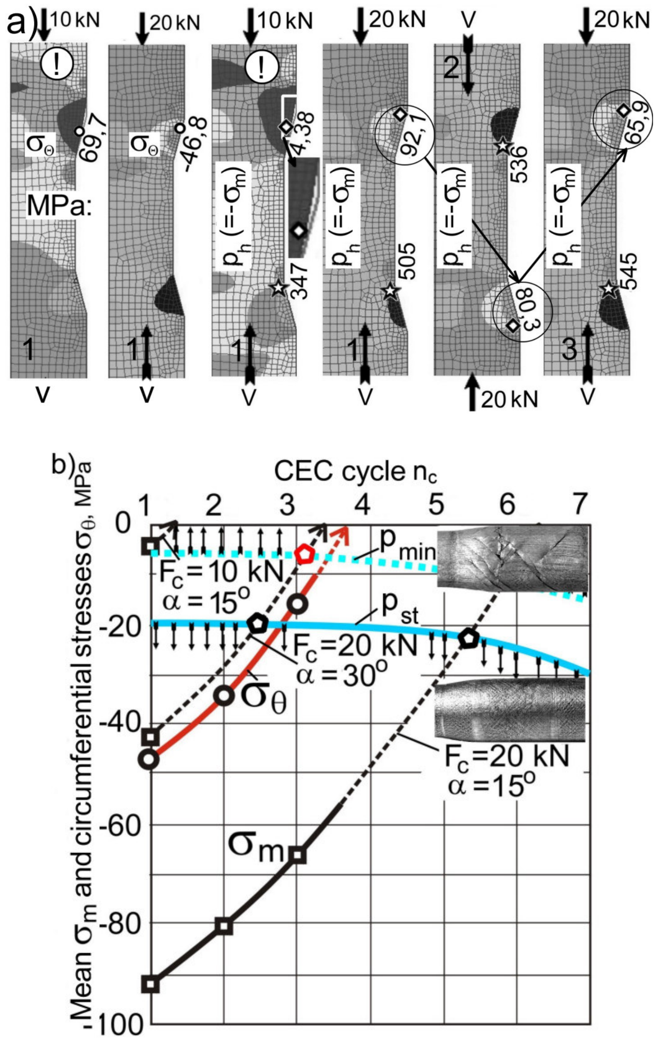

Fig. 4. The method of determination of optimal conditions of CEC: a) simulation results for different levels of counterforce, b) diagram summarising the simulation results (p_{st} – boundary hydrostatic stress preserving material cohesion, p_{min} – hydrostatic stress at which material fracture starts)

4 CONCLUSIONS

The obtained results show that:

1. Using the CEC process enables generating special materials with nanocrystalline or ultrafine grained structure and unusual properties.
2. The deterioration of CEC conditions with the increase of the number of CEC cycles is related with the increase of the material yield strength and can be improved by a controllable increase of the counterforce during the deformation process.
3. The simulation of the CEC process using a DEFORM software allows detail determination of the stress state, especially the hydrostatic conditions of the material plastic flow, which enables carrying out CEC on the new press in a controllable way.

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