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Grain refinement in Al-Si-Cu alloy during cyclic extrusion

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Abstract

The effect of severe plastic deformation (SPD) during cyclic extrusion (CE) on grain refinement and strain hardening in AlSiCu alloy is studied quantitatively. New experimental results are presented showing that the average of grain size decrease below 130 nm, i.e. a nanocrystalline material is obtained. In the modelling part, the decrease in size of dislocation cells and micro bands is expressed in terms of the effective plastic strain defined such that strain rate reversals slow down its accumulation. Examples of microstructure of tested alloy severely deformed by cyclic extrusion are given as experimental results.

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1. Introduction

Cyclic extrusion (CE) [1] is one of the methods of applying severe plastic deformation (SPD) to polycrystalline materials in order to refine the grain size up to the sub micrometer or nanometre level and, in consequence, to obtain extreme mechanical properties of the material. Other widely applied SPD methods include equal-channel angular pressing (ECAP) [2], high-pressure torsion (HPT) [3], multi-axis compression, and others. Unlike traditional cold rolling or drawing processes of large plastic deformation, the SPD techniques that employ cyclic strain paths lead to an essentially unchanged shape of the specimen after processing. The resulting microstructural and mechanical properties, for instance, the sub grain size, disorientation angle across boundaries, the fraction of the high angle grain boundary (HAGB) area and the flow stress or micro hardness, have been measured in a number of papers, cf. [4, 5, 6].

Based on those extensive investigations, and also on certain ideas presented earlier in the literature, cf. [7, 8, 9], a constitutive model of large-strain plasticity has recently been developed and used to simulate numerically the effect of applying different SPD routes for pure aluminum. In the present paper, the model is applied to simulate the behaviour of AlMgSi aluminum alloy, and the results are compared to new experimental data.

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2. Experimental results

Cyclic extrusion (CE) as the method of applying severe plastic deformation originated in 1979 [1]. The investigations started using a laboratory version of the CE equipment. A schematic illustration of the CEC process is shown in Fig. 1. During plastic flow between two chambers of diameter d_0 through the connecting channel of diameter d_m , compression occurs simultaneously with extrusion, so that the sample is restored to its initial shape.

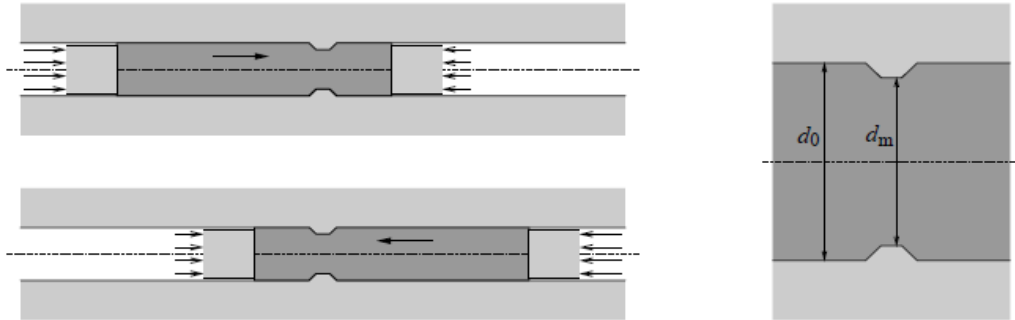


Figure 1. Schematic illustration of the cyclic extrusion process

In the work reported on here, AlSiCu samples were deformed using a hydraulic press up to the accumulated equivalent von Mises strain $\varepsilon_{VM} = 16$. The samples were 10 mm in diameter and approximately 40 mm long. The channel diameter was $d_m = 8$ mm, which corresponds to a strain increment $\varepsilon_{VM} = 4 \ln(d_0/d_m) = 0.65$ exerted in a single CE cycle.

ATSi5Cu1 is an alloy from the 6000 series. The alloy belongs to the easy deformable materials which could be hardened by artificial ageing. The CEC deformation was performed at supersaturated state.

The microstructural investigations were performed on the longitudinal sections. The microstructure was investigated on thin foils using transmission electron microscopy.

The investigations of microstructure revealed the characteristic evolution from the ultrafine grained material at lower deformation to a nanomaterial at the deformation of $\varepsilon_{VM} = 16$. The average intercept distance was measured in the direction orthogonal to micro band boundaries, and in two orthogonal directions for grains. In Table 1, the decrease of the average micro band thickness (D_b) in ATSi5Cu1 alloy with the increase of deformation is compared with the reduction of the mean size of grains (D_g). At the strain $\varepsilon_{VM} = 16$ about 70% of the sample volume was occupied by the grains with the dimension below 130 nm.

Table 1. Measured average microband thickness D_b and average grain size D_g in ATSi5Cu1 after processing by CE.

No. of cycles	ε_{VM}	D_b [nm]	D_g [nm]
2	1.83	203.2	234.6
4	3.71	176.8	218.7
10	8.17	116.5	178.8
15	12.78	87.9	126.4

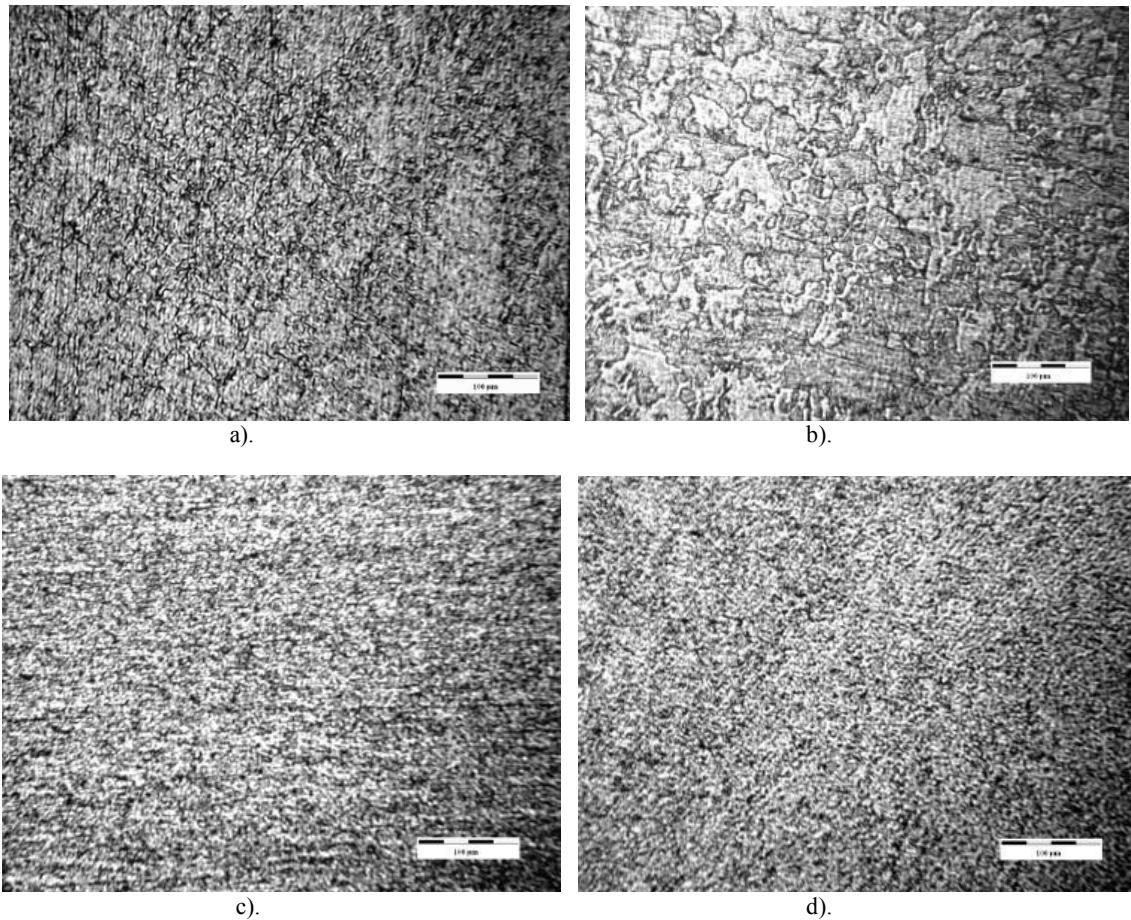


Figure 2. Microstructures after 2, 4, 10 and 15 cycles - respectively a);b);c);d).

3. Discussion and conclusions

The experimental results presented above show that CE as a method of applying severe plastic deformation without affecting the initial shape of the material sample is capable of refining the grain size in ATSi5Cu1 alloy below 130 nm. A geometrical mechanism of creation of nanograins by mutual crossing of micro bands is inferred.

A quantitative description of grain subdivision and strain hardening during CE has been obtained by applying a new, physically motivated constitutive model. The effective plastic strain ε_{eff} is introduced whose growth is suspended for a transitory period after a strain rate reversal. Dislocation cell size and cell-block thickness are modelled as functions of ε_{eff} .

Since CE is a cyclic process with relatively small amplitude, a slower grain refinement than during ECAP is predicted for comparable values of the equivalent strain ε_{VM} , at least when nominal deformation paths (without shear banding) are only properties.

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