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PREDICTION OF THE STRESS-STRAIN RESPONSE OF THE ULTRAFINE-GRAINED MATERIALS USING MULTI-SCALE ANALYSIS

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ABSTRACT

There are several severe plastic deformation processes that transform the material from microsized grains to the nanosized grains under large deformations. The grain size of a macrostructure is generally 300 μm. Following severe plastic deformation it can be reached a grain size of 200 nm and even less up to 50 nm. These structures are called ultrafine grained materials with nanostructured organization of the grains. There are severe plastic deformation processes like equal angular channel, high pressure torsion which lead to a 200 nm grain size, respectively 100 nm grain size. Basically, these processes have a common point namely to act on the original sized material so that an extreme deformation to be produced. The severe plastic deformation processes developed until now are empirically-based and the modeling of them requires more understanding of how the materials deform. The macrostructural material models do not fit the behavior of the nanostructured materials exhibiting simultaneously high strength and ductility. The existent material laws need developments which consider multi-scale analysis. In this context, the present paper presents a laboratory method to obtain ultrafine grains of an aluminum alloy (Al-Mg) that allows the microstructure observations and furthermore the identification of the stress – strain response under loadings. The work is divided into (i) processing of the ultrafine-grained aluminum alloy using a laboratory-scale process named in-plane controlled multidirectional shearing process, (ii) crystallographic analysis of the obtained material structure, (iii) tensile testing of the ultrafine-grained aluminum specimens for obtaining the true stress-strain behavior. Thus, the microscale phenomena are explained with respect to the external loads applied to the aluminum alloy. The proposed multi-scale analysis gives an accurate prediction of the mechanical behavior of the ultrafine-grained materials that can be further applied to finite element modeling of the microforming processes.

1. INTRODUCTION

Ultrafine grained (UFG) materials with grain sizes below 200 nm are of a great interest due to unusual combination of mechanical behavior such high strength and good ductility comparing to the coarse grain size. These materials are nowadays requested by the applications such as medical implants and microelectronics. To achieve UFG, there are several processes namely severe plastic deformation (SPD) processes (table 1). SPD are manufacturing processes that can lead to ultrafine grain formation and even nanostructures in high pressure condition and large deformation paths. To control the properties resulted during manufacturing of the metallic materials, a fundamental description of their mechanical behaviour according to the material structure is required. The relation between mechanical behaviour and material structure is the deformation mechanism that involves subdividing the original coarse grains into much smaller domains (subgrains) by various systems of shear bands followed by subgrain rotations [1]. To be effective, this description must be based on a solid understanding of operative deformation mechanisms [7,8].

Table 1 Some of the severe plastic deformation processes classified on the basis of the speed of the deformation

Category	SPD method		
Nonsteady-state deformation processes	High-pressure torsion (HPT), Valiev, 1997	Multiaxial forging (MF), Ghosh, 1988	
Steady-state deformation processes	Equal channel angular pressing (ECAP), Segal, 1977	Cyclic extrusion-compression (CEC), Richert, at al., 1979	Accumulative roll-bonding (ARB), Saito, at al., 1998
Incremental deformation processes	Incremental equal channel angular pressing (I-ECAP), Rosochowski, 2006		

Because of the lack of explanations concerning the deformation mechanisms of the nanostructured materials, prediction of the stress-strain relation is difficult to be done. Macroscale finite element simulation of the nanostructuring process cannot take into account the nanoscale transformations. The existent material laws like Swift and Voce describes the internal transformations of the microstructures under large deformations but doesn't consider the activation of the slip systems associated to decreasing the grain size under 200 nm. That is why there are needed further developments of the materials laws in order to consider internal variables which describe these phenomena. Multi-scale analysis is one of the method which model the macroscale structure taking into account nanolevel transformations. The present paper present a laboratory method to ultrafine grains of an aluminum alloy (Al-Mg) that allows the microstructure observations and furthermore the identification of the stress – strain response under loadings. The work is divided into (i) processing of the ultrafine-grained aluminum alloy using a laboratory-scale process named in-plane controlled multidirectional shearing process, (ii) crystallographic analysis of the obtained material structure, (iii) tensile testing of the ultrafine-grained aluminum specimens for obtaining the true stress-strain behavior. Thus, the microscale phenomena are explained in relation to the external loads applied to the aluminum alloy. The proposed multi-scale analysis gives an accurate prediction of the mechanical behavior of the ultrafine-grained materials that can be further applied to finite element modeling of the microforming processes.

2. PROCESSING OF THE ULTRAFINE-GRAINED ALUMINUM ALLOY

2.1. Experimental details

A controlled multidirectional shearing test was used for generating the ultrafine grained aluminium alloy. The specimen is square shaped of 15 mm x 15 mm, 3 mm thickness, made of aluminium alloy Al-Mg. The shearing is applied in multiple directions following composed cycles of deformation. The shearing is applied to the specimen which is rotated at each step of the deformation to cumulate the large amount of strain and to avoid ultimate strength. The phenomenon that appears across the thickness represents the effect of the nanostructuring by multidirectional shearing.

The experimental tests of controlled multidirectional shearing with different paths of the deformation has underligned the effect of cumulating strain which potentially breaks the coarse grains into ultrafine grains. The amount of the strain is done by progressively rotating of the specimen during shearing, so that the material is not deformed in only one direction. Based on this principle of the deformation, two methods of obtaining ultrafine grains are composed, namely Nanotest 1D and Nanotest 2D. The methods are designed to generate an equivalent amount of strain corresponding to the severe plastic deformation processes by different combinations of the deformation patterns.

Two loading methods were designed and implemented on the MTS20 machine named Nanotest 1D (figure 1) and Nanotest 2D (figure 2).

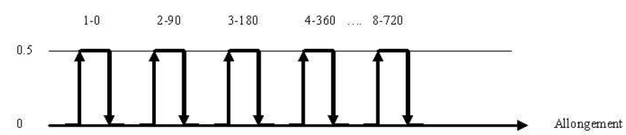


Fig. 1 Shearing with one branch (Nanotest 1D): first direction with the displacement between 0 - 0.5 mm, second direction with the displacement between 0.5 - 0 mm.

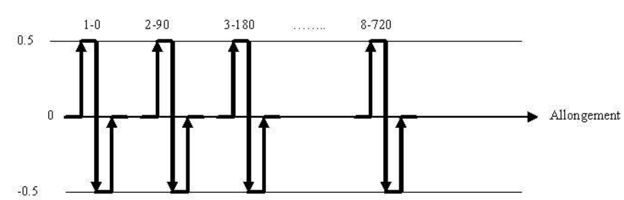


Fig. 2 Shearing with two branches (Nanotest 2D): the first direction with the displacement between 0 - 0.5 mm, the second direction with the displacement between 0.5 - -0.5 mm and the third direction with the displacement between 0.5-0 mm, loading speed: 0.38 mm/min, elongation +0.5/-0.5 mm.

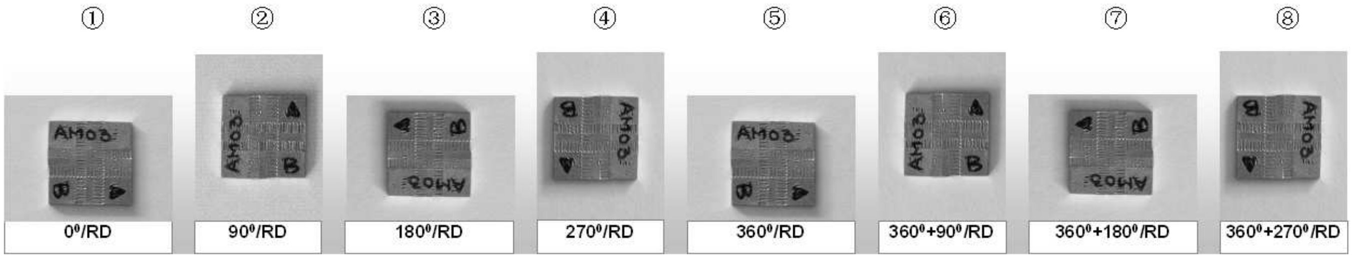


Fig. 3 A complete cycle of the controlled multidirectional shearing applied to the square specimen. The cycle has eigth steps that represents a rotation to the initial position corresponding to the rolling direction (RD 0^0)

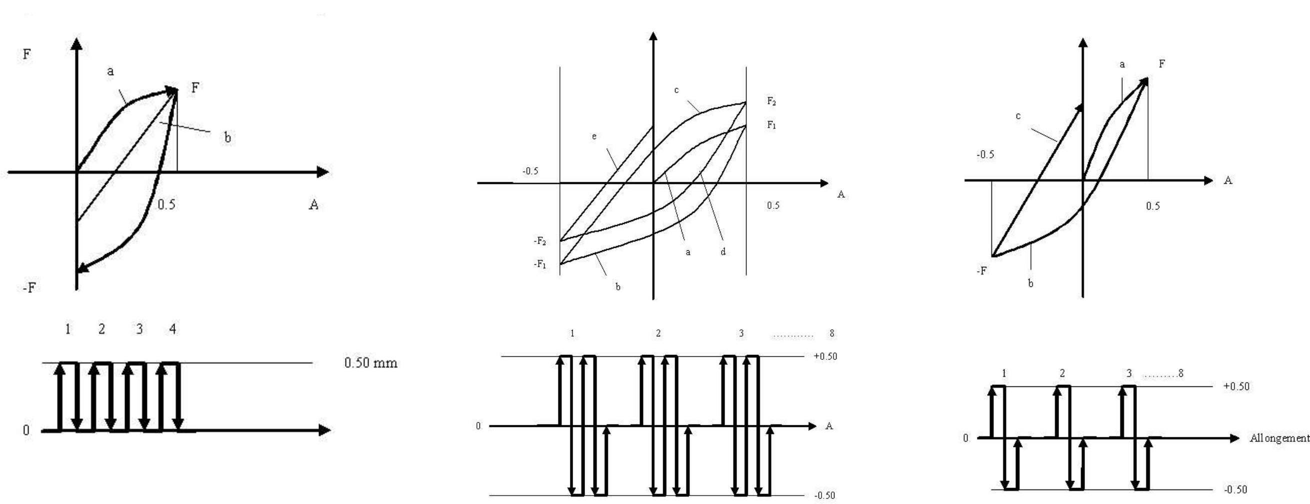
2.2. Experimental paths of the deformation

First path of the deformation is loading – unloading with the stroke of 0.5 mm applied to the squared specimen. The direction of loading-unloading is progressively changed by rotating the specimen and fixing it in the shearing clamping device. For example, a stroke of 0.5 mm is applied on the rolling direction (a force F is generated). After reaching this stroke, the unloading starts on the same RD until a new stroke of 0.5 mm is achieved. The next step is to turn the specimen with 90^0/RD and repeat the loading – unloading cycle with the 0.5 mm stroke, respectively -0.5 mm. By rotating the specimen relative to the RD, an increased amount of shearing is achieved avoiding the ultimate strength. This is Nanotest 1D and the force displacement curves are presented in figure 4.
The other method to cumulate the strain is to apply loading with 0.5 mm, unloading with 0.5 mm and to continue in the same direction with loading in a reverse direction as in the case of Bauschinger test. Loading in the reversed direction is followed by a loading with 0.5 mm until it is reached the initial position. After one cycle, the next step is to turn the specimen with 90^0/RD and to apply again the loading cycles above described (figure 6).

3. MICROSTRUCTURAL AND CRYSTALLOGRAPHIC ANALYSIS

3.1. Microstructural analysis

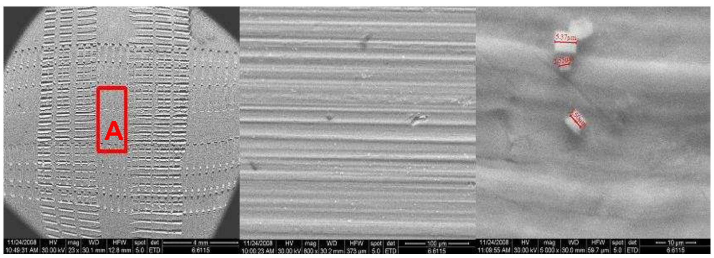
The microstructures obtained following the experimental tests presented in the previous paragraph have been investigated macroscopically and nanoscopically aided by Quanta Scanning Electronic Microscopy (SEM) and AFM (Nanosurf EasyScan2). In figure 5 and figure 6 there are presented the SEM respectively AFM images of the deformed volume of the initial specimen. The expected nanostructured grains are obtained only in the central volume of the specimen where the value of the cumulated strain is 20%. This volume corresponds to the area between the clamps of the testing machine; A in figure 5.



(a) (b) (c)

Fig. 4 Multidirectional hearing cycles: (a) Nanotest 1D method., (b) Nanotest 2D method, (c) Nanotest 2D method variant

SEM image shows a very organized structure of the grains that means the in-plane controlled multidirectional shearing lead to nanostructuring of the grains. Nanostructuring itself means organising the grains in raws. In the present case, this nanostructuring comes from the extreme solicitations of the coarse grained material that produces severe plastic deformation.
Moreover, AFM qualitative analysis gives information about the size of the grains. Using ISO5436 Step Height method for AFM measurements, the grain sizes were measured. The average size of the grains is 202 nm that means the experimental method provide an ultrafine grained material that pass the frontier of the nanostructures.



(a) (b) (c)

Fig. 5 SEM image of the deformed area (a) x 4, (b) x 200 evidence the nanostrctured microstructure with the grains aligned, (c) x 1000

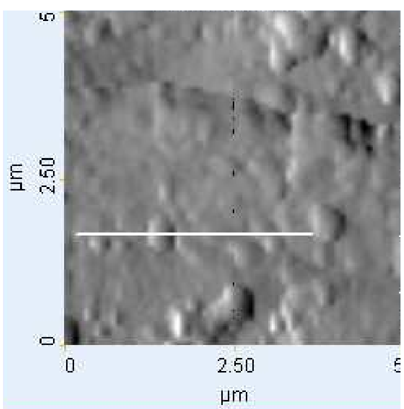


Fig. 6 Scanned image of the deformed area using AFM Nanosurf Easy Scan by software SPIP, ISO5436 Step Height method. Average grain size of 202 nm.

To proof the SEM observations, a MEBD analysis was carried out which gives the size and the orientation of the grains across the thickness.

3.2. Crystallographic analysis

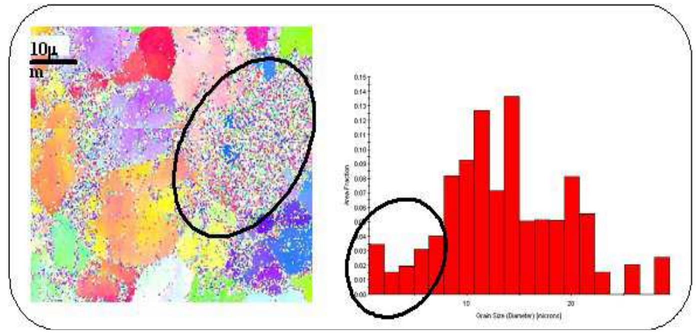


Fig. 7 Hystogram of the grain size distribution in zone A. The grains have dimensions from 200 nm to 100µm

Orientation imagining microscopy is used to measure the distributions of grain boundary misorientations in ultrafine-grained nickel processed by controlled multidirectional shearing process. The crystallographic analysis shown a distribution of the grain sizes heterogeneous but the smallest size of the grain is 200 nm. The grains with the smallest dimensions appear near to the central point of the specimen, where the cumulated strain is maximum. Shearing of the coarse grain that lead to diminishing the grain size is not simultaneously in all the volume. A possible explanation is that the dislocation density is not uniform. It is known that the dislocations play an important role in deformation of the polycrystalline materials. To verify such hypothesis, a molecular dynamic simulation was done for the same deformation conditions like in the experimental one having only 4 dislocations. The external load of the structure lead to the movement of the dislocations that means changing the map of the densities.
The results show that it exist a strong relation between the stress – the dislocation pattern – the grain size and the strain as a consequence of the material properties modification.

4. CONCLUSIONS

A new laboratory scale method of processing ultrafine grained materials which lead to 200 nm grain sizes is proposed. This is applied to aluminum alloy (Al-Mg) and the method is based on the controlled multidirectional shearing.

The cumulated strain applied by shearing induces in a polycrystalline material an effect of grain size decreasing. Frank Read dislocation mechanisms act until the granulation of 100 µm. There are effects generated by the grains boundaries (sliding, diffusion) at the level of 200nm. These effects cause decreasing the size of the grains until 50 µm, only if the compresion stress state exists.

Premises of the microscale modelling: A multiscale model of the ultrafine grained materials must consider as internal variables the densities of statistically stored dislocations and geometrically necessary dislocations. The evolution of the densities is based on a balance between dislocation accumulation and annihilation rates depending on the slip rates. The densities on the other hand result from the incompatibilities in the crystal lattice due to gradient of the dislocation slip. All densities are taken into account for the isotropic hardening of the material. A part of the densities naturally induce a physically based kinematic hardening through the internal stresses that they generate.

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