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Triple Junctions Effect on the Grain Growth in Nanostructured Materials

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Abstract. Microstructure evolution and grain growth in nanostructured aluminium films has been examined. The films were produced by vacuum evaporation on NaCl (100) substrate. Time dependences of mean grain area are presented. It has been revealed that the normal grain growth takes place in the films. The obtained data on the normal grain growth in 3-D films were compared with those for 2-D aluminium strips and foils. It was concluded that in the temperature range studied the grain growth kinetics is determined by triple junctions dragging force.

Keywords: nanostructured aluminium films, grain growth, grain boundary, triple junction

1. Introduction

Properties of polycrystalline materials are strongly influenced by their structure, namely by mean grain area, grain size distribution and the distribution of grain orientations [1, 2]. In turn these latter are determined by grain nucleation and grain growth. Grain growth proceeds by generation of new grains and migration of grain boundaries and triple junctions. Grain boundaries and triple junctions are not alike in their properties, especially in their kinetics. To control the microstructure during grain growth it is necessary to understand what determines the growth kinetics: grain boundaries or triple junctions. It is especially important in nanostructured materials, where grain boundaries and triple junctions make up a considerable part of the structure. In many studies concerning grain boundary migration and grain growth it was assumed that triple junctions do not have any influence on the motion of the grain boundaries, and their role in this process was reduced to establish the thermodynamic equilibrium angles at triple junction during boundary motion (e.g., see [1]).

Recently we carried out investigations on triple junction motion in Al tricrystals. The geometry of the tricrystals is shown in Table 1. The effect of triple junction on grain boundary motion is determined by the dimensionless criterion Λ [3]:

$$\Lambda = \frac{m_{\mathrm{TJ}} a}{m_{\mathrm{GB}}} = \frac{2\theta}{2\cos\theta - 1}, \qquad (1)$$

where m_{TJ} and m_{GB} are the mobilities of triple junction and grain boundaries correspondingly.

One can distinguish two limiting situations:

- Λ tends to infinity. In this case the angle θ tends to the thermodynamically equilibrium value, $\theta = 60^\circ$. The motion of grain boundary system does not depend on the triple junction mobility and is governed by the mobility of grain boundaries, i.e. there is *grain boundary kinetics*.
- Λ tends to zero. For this situation the angle θ tends to zero. In other words the motion of the system is governed by triple junction mobility, i.e. there is *triple junction kinetics*.

There is temperature at which a transition from triple junction kinetics to grain boundary kinetics is observed. This temperature will be called transition temperature (T_{tr}).

It can be seen from (1) that Λ also depends on grain size a: the smaller the grain size the smaller Λ value, and grain growth will be determined by triple junction kinetics. The presented paper concerns the influence of triple junctions on the normal grain growth in nanostructured aluminium films.

2. Experimental

Aluminium 99.999% nanostructured films were produced by vacuum evaporation on NaCl (100) substrate.

Table 1. Kinetic parameters of grain growth with different grain size (in aluminium rods, films, foils and strips) and grain boundary and triple junction motion at $T = 500^{\circ}$C.

Type of structure	Mean GB mobility $\bar{A}$ (m^2/s)	Mean grain growth velocity $d\bar{S}/dt$ (m^2/s)	Grain size, (m)	Schematic view of samples
Individual GB	10^{-9}–10^{-7} [4]		10^{-3}	
Individual TJ	TJ kinetic 10^{-10}–10^{-7} [5–7] GB kinetic 10^{-9}–10^{-8} [5–7]		10^{-3}	
1-D rods ("bamboo" structure)		10^{-10} [5]	10^{-3}	
2-D structure ("columnar" structure)	Strips 3.0×10^{-11} [5, 8]	7.5×10^{-11} [5, 8]	10^{-3}	
	Foils 5.4×10^{-13} [9]	9.2×10^{-13} [9]	10^{-4}	
3-D films	7.18×10^{-18}	1.5×10^{-17}	10^{-8}	

The film thickness was about 800 Å. In order to obtain non-textured nanocrystalline structure the substrate temperature was maintained at 100°C. The mean grain size $\bar{R}$ was 200–400 Å. The films were annealed in vacuum furnace at 200–400°C for 1, 4, 8 and 10 minutes; the temperature was maintained with an accuracy of 1°. The annealed films were investigated by transmission electron microscopy (TEM). The dark field TEM technique was used to determine the grain size R and grain area S. In order to obtain reliable data the measurements were made for more than 500 grains.

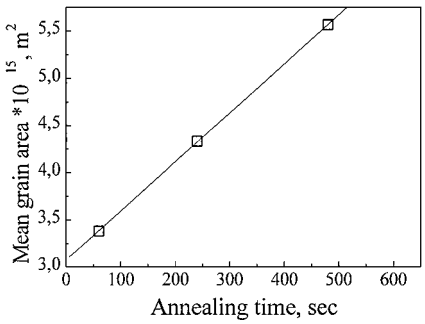

Figure 1. Time dependence of mean grain area increment at $T = 200^{\circ}$C.

3. Results

The term *normal grain growth* is used to describe the steady-state grain growth process with power growth law of the mean grain size $\bar{R}$, with monomodal and time self-similar grain size distribution and some other features. This kind of grain growth is observed both for two-dimensional (2D) and three-dimensional (3D) systems [1, 2]. Results of grain growth study in aluminium films are presented in Figs. 1 to 3 and Table 1. Figure 1 shows the time dependence of the mean grain area $\bar{S}$ for annealing at $T = 200^{\circ}$C. The grains size distribution vs. relative grain size $R/\bar{R}$ for various annealing times is presented in Fig. 2. Figure 3 shows the grain area distribution vs. relative grain area $S/\bar{S}$ for different annealing time. This dependence corresponds to the equation $f(\xi) = \exp(-\xi)$, where $\xi = S/\bar{S}$—is the

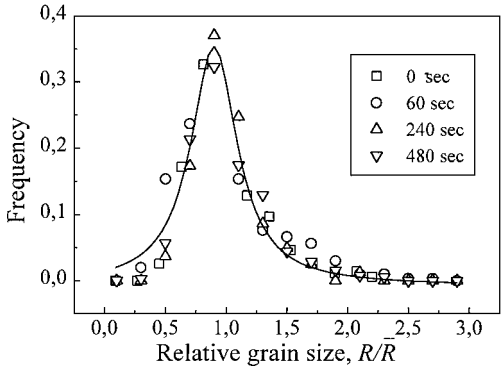

Figure 2. The grains distribution vs. relative grain size at $T = 200^{\circ}$C.

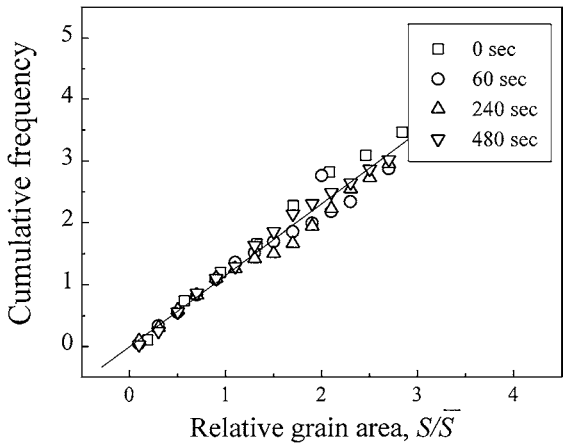

Figure 3. Grains area distribution (cumulative frequency).

relative grain area. The cumulative frequency is determined as—$\ln(1 - \int_0^{\xi} f(\xi)\, d\xi)$ [1]. All the results confirm that the process that we observe in aluminium films can be described as normal grain growth.

As it was mentioned above the most of the theoretical studies concerning grain growth supposed that at the stage of normal grain growth the triple junction have no influence on the grain boundary motion. However we received a great amount of experimental data on the triple junctions motion [5, 6] and on the 2D normal grain growth in polycrystals [5, 8, 9]. Results for individual grain boundary motion were taken from [4]. These data demonstrate that there is a dragging force of triple junctions that influences the grain boundary motion. The dimensionless criterion $\Lambda = m_{\mathrm{TJ}^*} a / m_{\mathrm{GB}}$ depends on grain size a and reflects the drag influence of the triple junction on the migration of the system.

It is interesting to compare the obtained data on grain growth in aluminium films with those for polycrystals: 2D structure in aluminium with different grain size (strips and foils); one-dimensional (1D) structure (rods); individual grain boundaries and individual triple junctions (Table 1). We extrapolated mean grain boundary mobility $\bar{A}$ and mean grain growth velocity $d\bar{S}/dt$ in films for $T = 500^{\circ}$C.[1] The data presented in Table 1 show that the values of mean grain growth velocity and mean grain boundary mobility decrease with decreasing of the grain size (and with corresponding increasing of the triple junctions number).

As it is known [6, 10] the kinetics of the system of grain boundaries with a triple junction depends on its temperature. For the most of the individual triple junctions in aluminium T_{tr} is higher then 500°C. The data obtained for individual triple junctions demonstrate that at $T < T_{\mathrm{tr}}$ the systems of grain boundaries with triple junction move by junction kinetics, i.e. the triple junctions drag the motion of these systems. Triple junctions that remain immobile at this temperature were also observed [7]. Since our experiments have been carried out at $T \leq 500^{\circ}$C it can be concluded that all the results for aluminium films, strips and foils are obtained at temperature lower than T_{tr}.

The temperature T_{tr} is not the same for the structures with different grain size a. For a very small grain size a, e.g. nanostructured material, the T_{tr} is comparatively high. At a given temperature T, as it is seen from Table 1, the mean grain boundary velocity is different for different grain size (strips, foils, films). The value of mean grain boundary mobility in investigated polycrystalline objects at a given temperature is distinctly lower for fine grained (films) than for coarse grained (strips and foils) microstructures. Hence the observed low value of grain growth velocity in films is the reason for the high thermal stability of nanostructured materials.

4. Conclusions

1. The normal grain growth was observed in 3D aluminium films.
2. Triple junctions have a dragging force on the normal grain growth in aluminium foils.
3. The smaller the grain size, the stronger the effect of triple junction on grain growth in polycrystalline materials.

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Note

1. We use the term "mean grain boundary mobility" for the description of grain growth in polycrystals as in [1]. However we imply that the process of grain growth in polycrystals is defined not only by grain boundary motion but also by the motion of triple junctions.

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