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The Role of the Triple Junctions During Grain Growth

V.G. Sursaeva, S.G. Protasova and A.Yu. Tuflin

Institute of Solid State Physics, Russian Academy of Sciences, Chernogolovka, RU-142432, Moscow, Russia

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Abstract
Experimental data on triple junction (TJ) motion in Al and Zn are presented. There is experimental evidence that during TJ motion the pre-exponential factor changes linearly with activation enthalpy. The TJs impact on the kinetics of microstructure evolution during grain growth is outlined.

Introduction.

Grain growth studies in polycrystals provide only an average grain boundary (GB) mobility, i.e. a mobility averaged over a large number of GBs. If all GBs and TJs were alike, this would be correct. As will be shown below, this is far from reality. GBs and TJs movement is strongly affected by crystallography and temperature interval of motion. Such dependencies cannot be obtained from experiments on polycrystals, but only from systems with individual GBs and TJs.

Theories on grain growth and microstructure evolution assume the existence of free GBs whose motions don't interact with each other. This implies that TJs that are a main part of a grain boundary network, do not affect the kinetics of microstructure evolution.

Experimental.

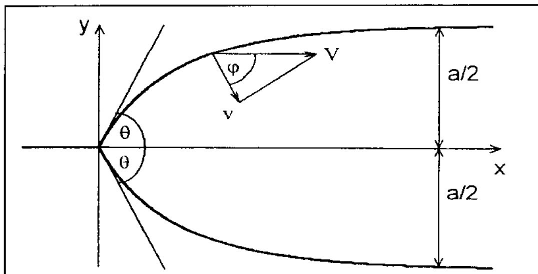

Fig.1. The scheme of the GB system with TJ.

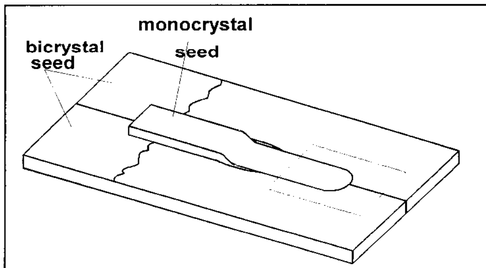

Fig.2. Tricrystal geometry for TJ measurements under a constant driving force.

Investigations conducted under reproducible experimental conditions. The major requirements for a proper experiment on system with individual TJ are a controlled driving force, a continuous monitoring of TJ displacement and a good reproducibility of TJ crystallography.

We used a continuous method to determine the successive boundary positions with time. It has the advantage to provide a real time TJ monitoring without forcing the grain boundary to stop. For Zn samples, the contrast difference under polarized light due the discontinuity in crystal orientation at the TJ was used [1]. Al samples required a special dark field set up including a large aperture inclined beam connected to an optical microscope. During experiment boundary displacement and angles at triple junction are recorded. Zn experiments were carried out in the temperature range (0.87÷1) T_m K, Al experiments were carried out in the temperature range

(0.7÷0.8) T_m K. Tricrystals Zn (99,999 at %) and Al (99,999 at %) were grown by a directional crystallization technique [1,7]. TJ motion under a constant driving force **p** was investigated in aluminium and zinc tricrystals. The driving force was provided by the surface tension of a curved GB. **p** per unit volume is given by **p=σ/2a**, where σ is the GB surface tension, and **a** - the width of the grain to be consumed. (Fig.1). (Fig.2) Pure <111> tilt TJs with different tip misorientation were studied in Al.. Crystal seeds and fabricated tricrystals orientations were measured using Selected Area Channeling Pattern technique based Scanning Electron Microscopy. Owing to the constant driving force, the TJ was expected to displace at a constant rate, and this was actually observed. Velocity was determined from displacement and time measurement. During isothermal experiments temperature remained constant within 0.3°C. To avoid thermal grooving and oxidation, the sample was set under argon atmosphere during measurement.

Results and discussion.

The main structural elements of polycrystals-grain boundaries and triple junctions. Grain boundaries motion has been widely studied, whereas no experimental literature on triple junctions migration is available so far. A theoretical consideration of triple junction motion was reported in [2]. The steady-state motion of a system with an individual triple junction can be precisely measured for a given configuration as shown in Fig.1.System behavior is discussed in terms of the parameter Λ, which describes the drag influence of the triple junction on the grain boundary system migration:

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

where m_{TJ} and m_{GB} are respectively triple junction and grain boundary mobility; 2θ the vertex angle and a the width of the consumed grain. (Fig 1). For Λ>>1 the triple junction does not drag the migration, and the angle θ tends to π/3. In this case the velocity V of the system (with an individual triple junction) motion is independent of the triple junction mobility. V is determined by the driving force and the grain boundary mobility [2].

$$V = \frac{2\pi m_{GB}\sigma}{3a} \qquad (2).$$

When Λ<<1, the steady state velocity V is controlled by the triple junction mobility, θ tends to zero.

$$V = \sigma m_{TJ} \qquad (3).$$

The value of the criterion parameter Λ, which defines by which kinetics - grain boundary or triple junction - the motion of the system is controlled, was derived using Eqs.(1). The current observations in Zn demonstrate that triple junction does not always act as pinning center. In some cases, the transition from triple junction to grain boundary kinetics occurs (Table 1). System motion is then controlled by grain boundaries mobility only.

Compensation effect.

So-called compensation effect was repeatedly observed in various thermally activated processes but most distinctly in processes related to interfaces and grain boundaries

$$H = \alpha \ln A_0 + \beta \qquad (4),$$

where α and β are constants, H the activation enthalpy, A_0 the pre-exponential factor.

The consequence of linear dependence between the activation enthalpy and the logarithm of the pre-exponential factor in the mobility equation $A = A_o \exp(-H/kT)$ is the existence of the so-called compensation temperature

$$T_c = \alpha/k \qquad (5).$$

In concept of [3] the compensation temperature is the equilibrium temperature for a virtual phase transformation. Above a compensation temperature the process with the highest activation enthalpy has the highest rate, while for $T<T_c$ the process with the lowest value of H proceeds fastest.

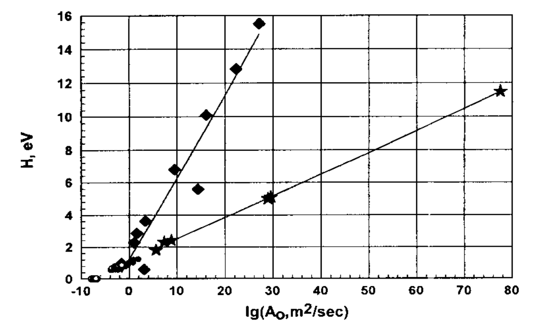

Fig 3.The dependence of migration activation enthalpy on the preexponential mobility factor for the investigated GBs[1,4] and TJs (Table 1). ●-GB[1,4], o-GB[1,4],★- TJ1-TJ6 (Table 1). ◆- TJ7-TJ16 (Table 1).

The compensation lines $\lg A_o$ for the mobility $<11\bar{2}0>$ individual tilt grain boundaries in Zn, $<01\bar{1}0>$ individual tilt boundaries in Zn [4] and mobility for individual triple junctions in Zn [5] are given on Fig. 3.

The corresponding temperature of compensation for tilt grain boundaries [4] and triple junctions TJ1 - TJ6 (Table 1) is 350°C. The corresponding temperature of compensation for triple junctions TJ7-TJ16 (Table 1) above melting point T_m. Compensation effect controls the kinetics of the processes. We suppose that the compensation temperature divides the temperature range into two regimes. Below T_c triple junction drag the system motion, vice verse, above T_c triple junction do not drag and grain boundary kinetics defines the processes.

For triple junctions TJ1 - TJ6 (Table 1) there are two regimes, above 350°C grain boundaries determine the system motion, below T_c=350°C triple junction determine the system motion. For triple junction TJ7-TJ16 (Table 1) $T_c >> T_m$,, there is one kinetics regime: triple junctions drag system motion. There is not transition from one regime to another.

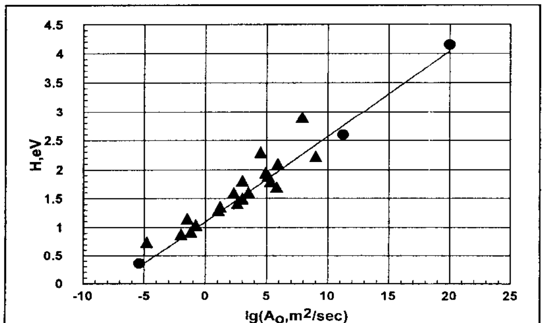

Fig.4. The dependence of migration activation enthalpy on the pre-exponential mobility factor for the investigated▲-<111> tilt GBs [7,8] and ●- <111> tilt TJs.

The dependence of migration activation enthalpy a pre-exponential mobility factor for the investigated <111> tilt GBs [7,8] and currently investigated <111> TJs (Table 1) is shown in Fig.4. There is the linear dependence for GBs and TJs. T_c(for GB) = 450°C. T_c(for TJ) = 380°C. We suppose that at high temperatures (T > 380°C) i.e. above the compensation temperature T_c., TJs exhibit highest mobility, then GBs and do not drag GBs motion, so TJs show highest activation enthalpy, while at low temperatures ($T<380$°C.), GBs with the lowest activation enthalpy can exhibit the highest mobility, but TJs drag the GBs.

At last, the compensation effect opens up possibilities to look at the grain growth from two point view (quite different perspective): grain boundary and triple junction.

Table.1.Kinetic parameters of the system with individual triple junction.

Probe	$T/T_{MELTING}$	Grain Boundary		Triple Junction		Ref.	Λ
		H_{GB} [eV]	$LogA_{0_{GB}}$	H_{TJ} [eV]	$LogA_{0TJ}$		
TJ1	0,87	0,6	-5,0	1,8	5,6	[6]	1-100
TJ2	0,91	2,3	7,3	4,0	22,0	[6]	
TJ3	0,93	5,0	28,9	10,1	69,3	[6]	1-1000
TJ4	0,94	5,1	29,6	5,1	29,8	[6]	
TJ5	0,90	2,4	8,6	3,2	15,6	[6]	1-100
TJ6	0,96	11,5	77,5	14,4	109,5	[6]	1-100
TJ7	0,93	5,6	14,3			Current	~1
TJ8	0,94	15,5	27,1			Current	~1
TJ9	0.94	12.8	22.3			Current	~1
TJ10	0.92	2.9	1.6			Current	~1
TJ11	0.94	101.0	16.1			Current	~1
TJ12	0.88	1.0	-1.6			Current	~1
TJ13	0.88	2.3	1.0			Current	~1
TJ14	0.93	3.6	3.4			Current	~1
TJ15	0.87	0.6	3.1			Current	~1
TJ16	0.96	6.8	9.5			Current	~1

Conclusions.

1. A linear relation between the activation enthalpy and the logarithm of pre-exponential factor was observed for all system with the individual triple junctions in Al and Zn. This is referred to as compensation effect.
2. Compensation effect controls the kinetics of grain growth in polycrystals.

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Corresponding author: Dr.V.Sursaeva,e-mail sursaeva@issp.ac.ru, Fax 096 576 41 11