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SUBSTRUCTURAL STRENGTHENING OF ALUMINIUM ALLOYS AFTER THERMAL CYCLING TREATMENT

The paper estimates the dislocation structure parameters and characteristics of the internal friction amplitude dependence in aluminium alloys, which are determined according to damping curves.

Key words: *thermal cycling, substructure, composite materials, point effects, dislocation structure, impurity atoms, substructural strengthening.*

Introduction

In the conditions of scientific and technological progress there is a constant need in the creation of materials with properties, which are not inherent to natural materials. These include composite materials (CM). Aluminium alloys, where the components are atoms of copper and zinc, are used in such materials as a matrix much more often than pure aluminium. The presence of these additives in pure aluminium effects the substructure formation. Therefore, it would be expedient to investigate the influence of these additives on strengthening of the aluminium alloys during their thermal cycling process.

Problem statement

Amplitude dependence of internal friction (ADIF) is explained by interaction of dislocations with point defects. Under small variable stresses, vibrations of the dislocation segments occur in accordance with the model of Granato – Lücke (GL) [1, 6]. Dislocation segment separation from the impurity atoms causes appearance of the amplitude-dependent decrement, which occurs under definite amplitude value that is referred to as critical. The second critical amplitude corresponds to the dislocation loop separation from the dislocation nodes in accordance with the model of Frank – Read. Respectively, there is a direct relationship between the measured characteristics of the internal friction (IF) amplitude dependence and the dislocation structure parameters: energy of the dislocation line cohesion with point defects and dislocation nodes, the length of sections, segments and dislocation density. Therefore, this work attempts at estimation of said dislocation structure parameters by the curves of internal friction amplitude dependence.

Research results

Amplitude dependence of internal friction (ADIF) makes it possible not only to evaluate the entire complex of the dislocation structure characteristics, but also to follow their development under the influence of time-temperature and power factors. Among various ADIF models, GL model is the most universal one [1]. Analytical substantiation of ADIF theory and of its modifications is given in [1, 2, 3, 4].

Aluminium alloys Al-2%Cu-2%Zn (alloy 1), Al-2%Cu (alloy 2) were selected for the research. In selecting the materials, it was taken into account that additional strengthening could be achieved in these alloys through substructure creation and its stabilization by the dispersion phase precipitation.

In order to create a developed substructure in the materials under study, thermal cycling was performed in the temperature interval of 510 – 20 ^{0}C with heating and cooling rates of 50 $^0C \cdot c^{-1}$. External tensile load was $0,2 – 0,4\sigma_{0,2}$. Internal friction was measured using a low-frequency device (~1Hz) of the inverse-torque pendulum type [2, 3].

Fig. 1, 2, 3, 4 present ADIF results after 20 ordinary TC cycles (curve 1) and 20 TC cycles in the field of external load (curve 2) for the alloy Al-2%Cu-2%Zn and the alloy Al-2%Cu.

The value of the second critical strain amplitude $\gamma_{cr.2}$ after 20 TC cycles in field of external load, which characterizes the process of dislocations multiplication and motion in a solid solution according to the Frank – Read mechanism, is by 1.29 – 1.74 times higher for alloy 1 and by 1.26 – 1.62 times higher for alloy 2, than that after ordinary TC process (Fig. 1, 2, 3, 4).

If vibration amplitudes are small ($\gamma<\gamma_{cr.1}$), vibrations of dislocation segments (L_s), pinned by the admixture atoms, make the main contribution to damping under small deformations. In this case, the expression for logarithmic decrement can be written in the form of

$$\delta_1 = \frac{120\Omega B_o \omega \Lambda L^4}{\pi^4 C}, \tag{1}$$

where B_o – damping constant; C – force per unit dislocation length, which is determined by tension of a bent dislocation, ω – vibration frequency, Λ - density of dislocations, L – effective length of dislocation.

In the next region, corresponding to deformations $\gamma_{cr.1}<\gamma<\gamma_{cr.2}$, separation of dislocations from the impurity atoms occurs and they remain pinned only in the nodes of the dislocation network L_n (L_n – length of dislocations between strong pinning points). According to the theory, mechanical energy of dissipation in materials is described by the expression

$$\delta_2 = \frac{C_1}{\gamma} \cdot \exp\left(-\frac{C_2}{\gamma}\right), \tag{2}$$

where C_1 *i* C_2 – coefficients, determined from the data of ADIF in GL coordinates as $L_n(Q^{-1}\ \gamma\pi)=f(1/\gamma)$. Relationship between constant C_1 and dislocation density Λ is given by:

$$C_1 = A_1 \Lambda L_n^3 / L_c^2, \tag{3}$$

while constant C_2 is determined by the dislocation segment length:

$$C_2 = k\eta a / L_c, \tag{4}$$

where $A_1=(\Omega/\pi\theta)(P_p/4aM)$; P_p – force of the dislocation separation from the pinning point; θ – factor, which depends on the stress on sliding plane; Ω – orientation factor; a – parameter of the grid; η – dimensionality factor; $k = 0{,}2 – 0{,}3$ – dimensionality coefficient.

The second critical amplitude deformation $\gamma_{cr.2}$ corresponds to the stress, which causes generation of dislocations by the sources of the length L_n according to the Frank – Read mechanism. From this amplitude, background internal friction Q_0^{-1} starts to increase. Relationship between the values $\gamma_{cr.2}$ and L_n (dislocation length between strong pinning points) is given by

$$L_n = b/\gamma_{cr.2}. \tag{5}$$

where b – Burgers vector.

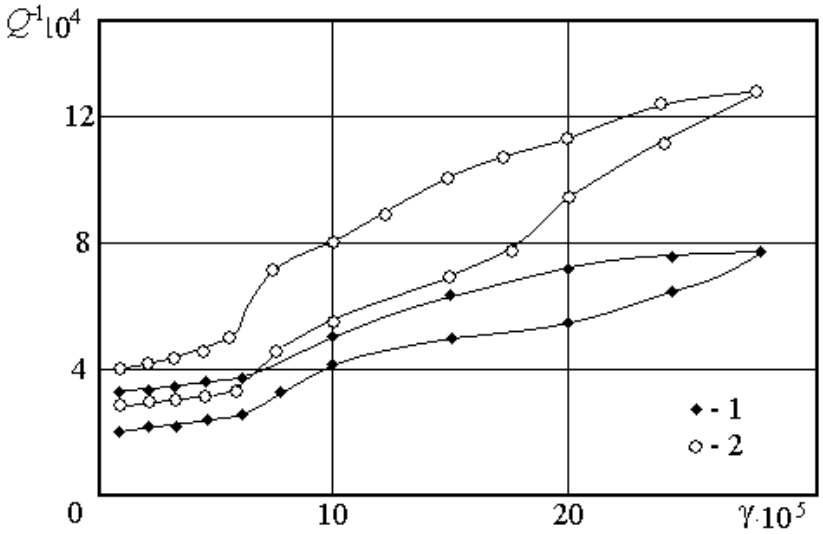

Fig. 1. Amplitude dependence of internal friction of the alloy Al-2%Cu –2% Zn after 20 TC cycles in field of external load (1) and 20 ordinary TC cycles (2)

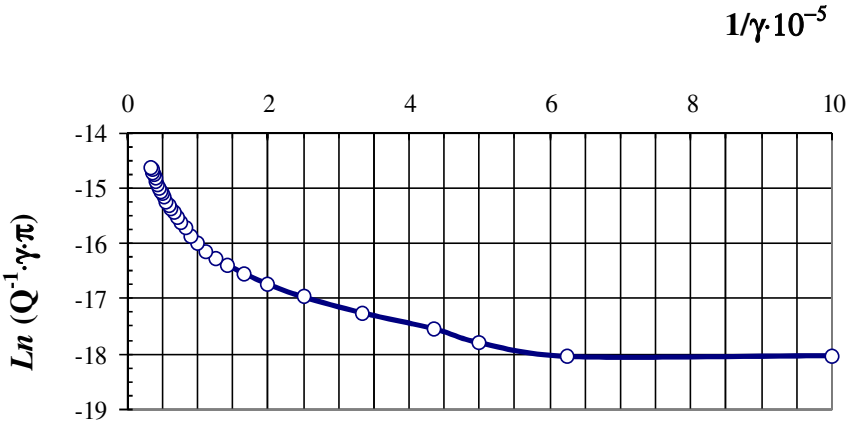

Fig. 2. Amplitude dependence of internal friction of the alloy Al-2%Cu –2% Zn after 20 TC cycles in field of external load in $ln(Q^{-1}\gamma\pi)=f(1/\gamma)$ coordinates

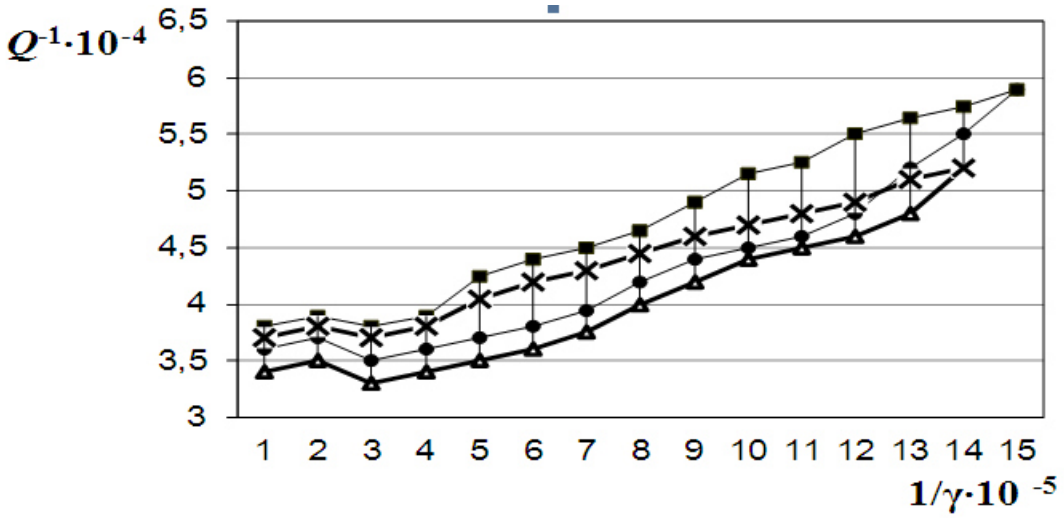

Fig. 3. Amplitude dependence of internal friction of the alloy Al-2%Cu after 20 TC cycles in field of external load (Δ, ×) and 20 ordinary TC cycles (•, ■)

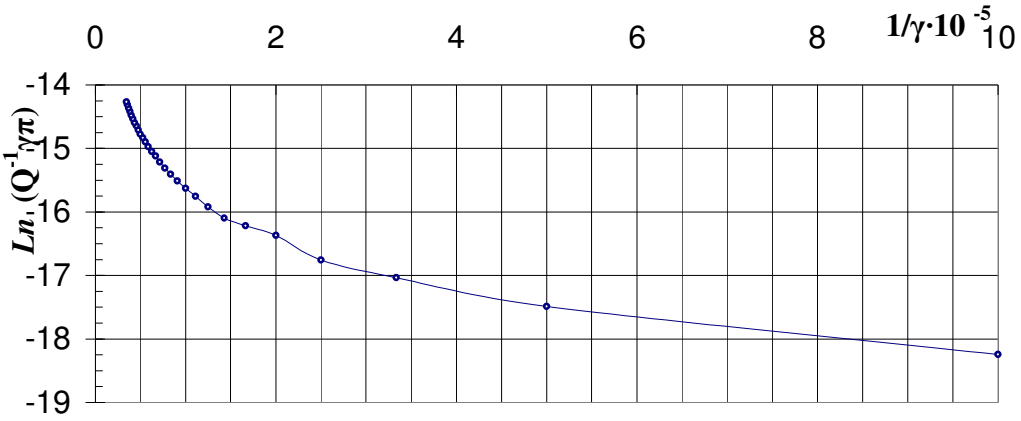

Fig. 4. Amplitude dependence of internal friction of the alloy Al-2%Cu after 20 TC cycles in field of external load in Ln($Q^{-1}\gamma\pi$)=f(1/γ) coordinates

Equations (3), (4) and (5) make it possible to find the parameters of dislocation structure L_s, L_n and Λ. Besides, ADIF method enables determining binding energy of dislocation H_d with the blocking atom according to the value of $\gamma_{cr.1}$ and module defect $\Delta M/M$:

$$\gamma_{\text{ф.п.1}} = \frac{H_B - B}{Mb^3}, \tag{6}$$

$$\frac{\Delta M}{M} = \frac{6\Omega L^2}{\pi^2}, \tag{7}$$

where c_{im} – concentration of the impurity atoms on dislocation ($c_{im} = L_n/L_s$).

Computation of the dislocation structure parameters, performed on the basis of the theory of GL, correspond to the experimental results for deformations $\gamma_{cr.1} < \gamma < \gamma_{pcr.2}$. However, this method has an essential disadvantage: the constants C_1 and C_2, determined in this way, directly describe the experimental dependence only in the narrow spectrum region of IF amplitude dependence. Therefore, the authors [5] propose ADIF description in all the regions by the method of regressive analysis, based on the theory of Granato – Lücke. Experimental dependence is well described by the formula:

$$\delta = \sum_{i=1}^{\Lambda} \delta_i, \tag{8}$$

where δ_i is calculated on the basis of GL theory [1], using the formulas (2), (8).

Using this method, a linear equation system of the following form is solved:

$$\frac{\partial \delta}{\partial (\ln C_1)} = \sum_{i=1}^{\Lambda} \left[\ln \delta_i - \left(\ln C_1 - \ln \gamma_i - \frac{C_2}{\gamma_i} \right) \right]^2 = 0, \tag{9}$$

$$\frac{\partial \delta}{\partial C_2} = \sum_{i=1}^{\Lambda}\left[ln\,\delta_i - \left(ln\,C_1 - ln\,\gamma_i - \frac{C_2}{\gamma_i} \right) \right]^2 = 0,$$

The system is solved by the equations:

$$C_2 = \frac{\Lambda \sum_{i=1}^{\Lambda}\left[(ln\,\delta_i + ln\,\gamma_i)\frac{1}{\gamma_i} \right] - \sum_{i=1}^{\Lambda}\left[ln\,\delta_i + ln\,\gamma_i \right] \sum_{i=1}^{\Lambda}\frac{1}{\gamma_i}}{\left(\sum_{i=1}^{\Lambda}\frac{1}{\gamma_i} \right)^2 - \Lambda \sum_{i=1}^{\Lambda}\frac{1}{\gamma_i^2}},$$

(10)

$$C_1 = exp\left[\frac{1}{\Lambda}\left(\sum_{i=1}^{\Lambda}(ln\,\delta_i + ln\,\gamma_i) + C_2 \sum_{i=1}^{\Lambda}\frac{1}{\gamma_i} \right) \right].$$

Constants C_1 and C_2 in expressions (9, 10) are best to be calculated using PC. This makes it possible to exclude random experimental values through performing experimental data smoothing by the method of parabolas before starting computations and to avoid a cumbersome procedure.

According to the theory of GL, after obtaining the values for C_1 and C_2 and using the expressions for C_1 and C_2, it is possible to calculate parameters L_s and L_n between weak and strong pinning points, bulk density of dislocations Λ, concentration of point defects in dislocation c_d as well as the energy of a dislocation binding with the atoms and the module defect.

In Tables 1, 2 the computation results for the alloys Al-2%Cu-2%Zn and Al-2%Cu are compared using the procedures described in [1, 5]. It should be noted that the latter correlate well with the experimental data. The disagreement does not exceed 3 – 5%.

When deformation amplitudes are sufficiently small, microplasticity is observed, which is caused by the motion of dislocations in the field of variable stresses. In this regard, VT method is the most informative one: as the deformation amplitude increases, new dislocation sources contribute to the energy dissipation in the material, their contribution to the total absorption of the mechanical oscillation energy being different.

Table 1

Dislocation structure parameters for the alloy Al-2%Cu-2%Zn

N	$L_n \cdot 10^6$, m		$L_s \cdot 10^8$, m			$\Lambda \cdot 10^{-12}$, m^{-2}			C_d		
TC	A, B		A	B	GL	A	B	GL	A	B	ГЛ
0	2.4	5.1	10	1.4	10.8	25	8.0	21.5	21	38	28
5	2.2	2.4	12	1.6	12.4	30	5.7	22.7	20	21	17
10	1.8	1.8	11	1.3	10.2	45	9.8	38.0	19	18	16
25	1.4	2.1	9	0.9	8.5	60	18.0	45.0	16	19	26
50	1.8	0.9	9.4	0.8	7.3	62	14.5	60.0	20	26	16

Table 2

Dislocation structure parameters for the alloy Al-2%Cu

N	$L_n \cdot 10^6$, m		$L_c \cdot 10^8$, m			$\Lambda \cdot 10^{-12}$, m^{-2}			c_d		
TC	A, B	GL	A	B	GL	A	B	GL	A	B	GL
0	2.15	2.90	11.1	10.4	11.5	17.1	5.5	1.5	19	20	25
5	2.02	2.35	10.3	9.1	11.2	15.5	6.4	7.9	19	22	21
10	1.65	2.10	10.1	7.3	9.3	21.5	8.9	10.1	16	22	22
25	1.48	2.04	9.5	6.8	7.6	25.9	23.6	26.6	15	22	27
50	1.58	1.50	8.2	6.2	5.3	36.8	21.9	22.1	19	25	28

Notes*:1. *A* ($\gamma_{cr.1}<\gamma<\gamma_{cr.2}$), *B* ($\gamma>_{кcr.2}$) – computation of the dislocation structure parameters was performed, using the procedure described in [5]. 2. GL ($\gamma_{cr.1}<\gamma<\gamma_{cr.2}$), – using the procedure from [1].

Conclusions

Substructural strengthening is characterized by an intensive growth of dislocations density, which is blocked by the impurities during dispersion hardening. For equal number of thermal cycles, dislocation density in the conditions of TC in field of external load increases by 1.2 – 1.8 times more intensive than during ordinary thermal cycling (Tables 1, 2).

Dislocation structure development in thermocycling process is accompanied by a sharp reduction of the length of dislocation segments between the pinning points on dislocation lines (L_s) and between the nodes of dislocation network (L_n). These data were obtained from the results of measuring IF amplitude dependence and further processed in accordance with the models [1, 5] (Tables 1, 2).

Reduction of parameters L_s and L_n after TC in field of external load indicates significant refinement of the dislocation network. This structural state of metals is characterized by high energy intensity and their ability to distribute external stresses uniformly throughout the entire volume of the materials or technical structures, made of them. This, in combination with the increased thermal stability level of the locked subboundaries, results in sharp increase of the resistance to plastic deformation at room temperature and at the temperatures exceeding it.

Therefore, measuring IF amplitude dependencies at different stages of substructural strengthening of metals makes it possible to reveal general regularities of formation, stabilization and breaking of the networks of polygonal boundaries, the state of which directly determines the level and stability of high-temperature properties.

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