THE 4TH INTERNATIONAL CONFERENCE ON ALUMINUM ALLOYS

SOFTENING CAUSED BY RECOVERY MECHANISMS

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Abstract

Recovery, defined as a coarsening of the mean subgrain size, has been studied theoretically. By assuming that the subgrains coarsen in a similar manner as the case of normal grain growth, a rate of coarsening equation can be formulated for sub-boundary migration. Another possible process resulting in a coarsening of the mean subgrain size is subgrain coalescence. Sub-boundaries are thus eliminated by a rotation of the subgrains until coalescence is obtained. A theory for two-dimensional subgrain coalescence is described and compared with a simple theoretical treatment of sub-boundary migration. Some recent experimental results from T. Furu et al. [1]-[2] are compared with the theoretical models.

Introduction

An Aluminium Alloy which has undergone cold deformation will have obtained a higher yield stress than an undeformed specimen due to the work hardening process. Heat treatment at elevated temperatures leads to recovery and often recrystallization, thus obtaining the yield stress of undeformed material. In the present work, the process of recovery defined as the coarsening of the mean subgrain size, $\overline{d}$, is studied. The following well known equation for the yield stress, σ, is based on empirical data [3]:

$$\sigma = \sigma_0 + K\,\overline{d}^{-m} \qquad (1)$$

where σ_0, K and m are constants, m>0. Rate functions of $\overline{d}$ can thus indicate the softening response, i.e. the reduction of the yield stress with time during recovery, if Eq. (1) is valid and the constants are known.
In the present work, two idealised processes for coarsening of the mean subgrain size has been studied: sub-boundary migration and subgrain coalescence. The two processes are described briefly and differences in microstructural evolution which have a potential of indicating in experiments which process is the dominating, will be discussed.

Sub-boundary migration

It has been suggested by Sandström[4] that sub-boundary migration can be treated as normal grain growth . The increase of the mean subgrain size with time can thus be written (cf. e.g. [5]-[6]):

$$\overline{d}^n - \overline{d}_0^n = c_1 t \tag{2}$$

where $\overline{d}_0$ is the initial mean subgrain size and c_1 and n are constants. In the case of statistical self-similarity which is often assumed, n=2. Basically, during normal grain growth, coarsening occurs by a growth of the larger grains at the expense of the smaller ones. Small grains will eventually disappear thus reducing the number of grains per unit volume. A coarsening of the mean subgrain size thus reduces the energy of the material. The determination of the energy of a sub-boundary is relatively complex in three dimensions (cf. [7]-[8]) and the present work will consider two dimensional models only. Furthermore, it is assumed that all boundaries are tilt boundaries governed by the Read and Shockley[9] equation for the specific sub-boundary energy, $\gamma^{(sb)}$:

$$\gamma^{(sb)} = \gamma_0 \theta \ln \frac{\theta_0}{\theta} \tag{3}$$

where γ_0 and θ_0 are constants and θ is the angle of misorientation. By sub-boundary migration, the energy of the material can be reduced by eliminating subgrains similarly to normal grain growth as pointed out above. The energy is also reduced, according to Eq. (3), if two sub-boundaries with angles of misorientations θ_1 and θ_2 are replaced by one boundary with misorientation $\theta_3 = \theta_1 + \theta_2$.

To accommodate the strain imposed on a deformed lattice and to ensure compatibility with the surrounding grains, an effect known as cumulative misorientation ("lattice curvature") can be found experimentally. The evolution of the mean angle of misorientation is thus of importance when studying recovery for indicating the mean specific energy and the cumulative misorientation. If it is assumed that there is a mean misorientation, $\overline{\theta}$, due to a global cumulative misorientation, θ_g, when comparing the end-points of a path, S, the following equation can be written:

$$\overline{\theta} = \frac{\theta_g}{N_s} \tag{4}$$

where N_s is the number of subgrains along the path. Combining $\overline{d} = \frac{S}{N_s}$, Eqs. (2) and (4) yields:

$$\overline{\theta} = \frac{\theta_g}{S}\left(c_1 t + \overline{d}_o^{\,n}\right)^{\frac{1}{n}} \tag{5}$$

By introducing the initial mean misorientation, $\overline{\theta}_0$, Eq. (5) can be written:

$$\frac{\overline{\theta}^n}{\overline{\theta}_o^{\,n}} = \frac{c_1}{\overline{d}_o^{\,n}} t + 1 \tag{6}$$

Hence, a plot of $\left(\overline{\theta} / \overline{\theta_o}\right)^n$ vs. time should yield a straight line with the slope determined by Eq. (2).

Subgrain coalescence

Ideally, if two subgrains with a common sub-boundary rotate towards a common orientation, the angle of misorientation will decrease until the boundary is eliminated, thus achieving coalescence between the two subgrains in question. Hence, subgrain coalescence is an alternative to sub-boundary migration for obtaining a coarsening of the mean subgrain size during recovery. Since subgrain coalescence is not curvature driven, a growth law similar to Eq. (2) is expected to have a different form.
Considering the rotation of one subgrain, for each sub-boundary the following equation can be written:

$$\theta_i = \psi_i^{(nb)} - \psi \tag{7}$$

where i is the sub-boundary identifier, θ is the angle of misorientation, $\psi^{(nb)}$ is the orientation angle of the neighbouring subgrain relative to a main direction and ψ is the orientation of the considered subgrain. By introducing the normalised angle of misorientation, φ, and taking all the N boundaries around the subgrain into account by summation, the following equation can be written:

$$N\psi = \sum_{i=1}^{N} \psi_i^{(nb)} - \theta_{\max} \sum_{i=1}^{N} \left(\vartheta_i \varphi_i\right) \tag{8}$$

where $\varphi=\theta/(\vartheta\theta_{max})$, θ_{max} is a constant and $\vartheta=sgn(\theta)$. A rate of rotation equation for one subgrain can thus be written:

$$\frac{d\psi}{dt} = \frac{1}{N} \sum_{i=1}^{N} \frac{d\psi_i^{(nb)}}{dt} - \frac{\theta_{\max}}{N} \sum_{i=1}^{N} \left(\vartheta_i \frac{d\varphi_i}{dt} \right) \tag{9}$$

It has previously been shown [10]-[12] that

$$\frac{d\varphi}{dt} = \frac{C_2}{\omega^3} \ln \varphi \qquad (10)$$

where c_2 is a constant and ω is the length of the sub-boundary. Computer simulations [10]-[12] have yielded the following growth equation for subgrain coalescence where there is no cumulative misorientation ("lattice curvature") but orientations determined by a pseudo-random number generator, and assuming $\bar{d} \approx \sqrt{\bar{A}}$ where $\bar{A}$ is the mean subgrain area:

$$\bar{d} = \bar{d}_0 e^{c_3 t} \qquad (11)$$

where c_3 is a constant.

Boundary Migration versus Coalescence

A discussion on differences in the microstructure which could give experimental hints of the governing mechanism will be based on recent experimental results by Furu et al. [1], [2], cf. Table I, and results from computer simulations of subgrain coalescence.

Table I. Experimental data [1], [2]. The alloy is an AlFeSi-alloy with 0.43% Fe and 0.09% Si. The material was cold rolled to ε=3 and then annealed at 325°C.

t [s]	0	2	4	6	8	12
$\bar{d}$ [μm]	0.3	0.4	0.45	0.48	0.52	0.59
$\bar{\theta}$ [deg]	3.0	4.9	5.6	-	6.1	6.9

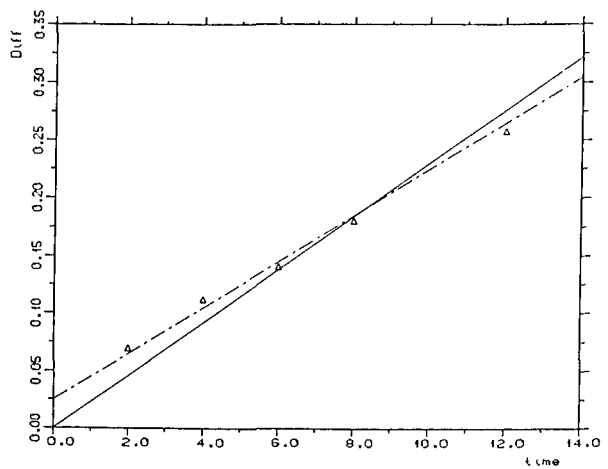


Figure 1. A plot of the data in Table I. $Diff = \bar{d}^2 - \bar{d}_0^2$

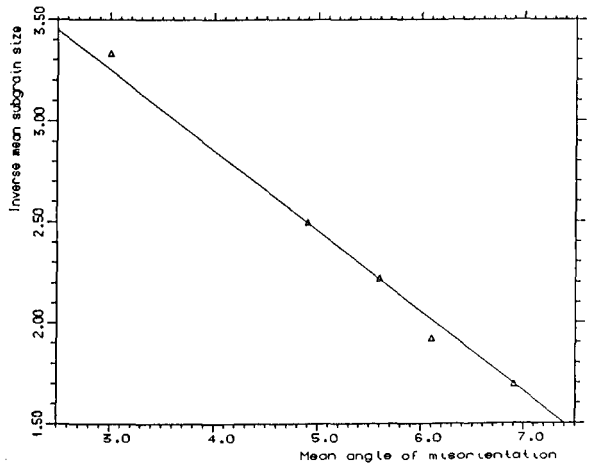


Figure 2. Correlation between the inverse mean subgrain size and mean angle of misorientation, cf. Table I. ($\overline{d}^{-1}$ vs. $\bar{\theta}$)

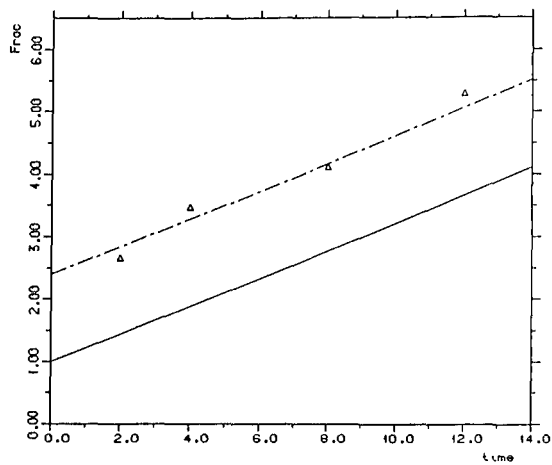
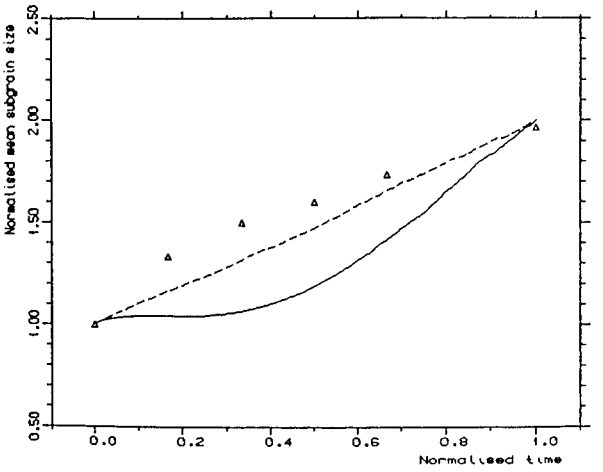
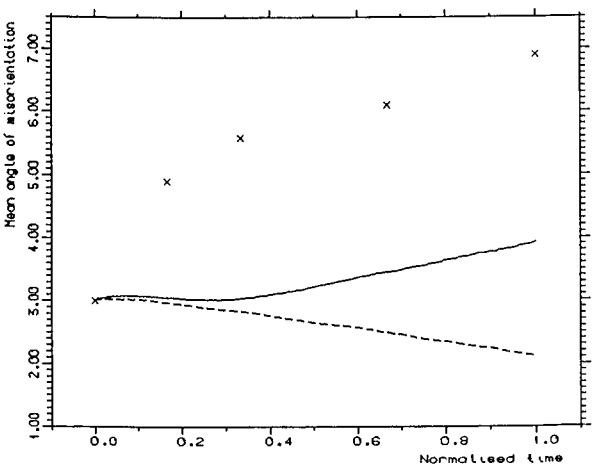


Figure 3. According to Eq. (6), the data should lie along the solid line if the process had been identical to the theoretical coarsening process. It is indicated by the broken line which is parallel to the solid line, that the slope fits the data fairly well. Frac= $\left(\overline{\theta}\,/\overline{\theta_o}\right)^n$.



(a)



(b)

Figure 4. Results from computer simulations of subgrain coalescence with periodic boundary conditions are compared to the experimental data of Table I. The mean angles of misorientation are compared directly, while the mean subgrain sizes are normalised to unity as the initial value and the processes are studied until the mean subgrain sizes obtain values of two. The time-axes are normalised in order to obtain unit time when the mean subgrain size is twice the initial value. It is seen that the simulated cases evolved differently as compared to the experimental data. Solid lines: A two-dimensional simulation with a cumulative misorientation. Dashed lines: A two-dimensional simulation without a cumulative misorientation. (a): Normalised mean subgrain size vs. normalised time. (b): Mean angle of misorientation vs. normalised time. The two simulated cases were initiated with the same mean angle of misorientation as the experimental data; i.e. 3 deg. (Note that the simulations are two-dimensional while the data are measured on three-dimensional specimens.)

A plot of $\overline{d}^{\,2} - \overline{d_o}^{2}$ vs. time is given in Fig. 1. It is seen that the broken line represents the data relatively well. However, this can give rise to a false conclusion since the line in question fails to meet the condition: $\overline{d}^{\,2} - \overline{d_o}^{2} = 0$ for t=0. The solid line meets this condition but does not represent the data points as well as the broken line. It is known from the literature, e.g. [3], that similar data show a proportionality between $\overline{d}^{-1}$ and $\bar{\theta}$. Fig. 2 confirms this proportionality for the present data. However, it could be of greater interest to plot $\left(\overline{\theta}/\overline{\theta_o}\right)^n$ vs. time, cf. Eq. (6). It is seen in Fig. 3 that the data-points yield nearly a straight line. However, the line given by Eq. (6) is well below the data-points as indicated by the solid line. The slope seems to give a good fit to the data points, indicated by the broken line which has identical slope as the solid line but is otherwise moved by changing the last constant of Eq. (6) in order to yield the best fit.

Results from computer simulations of two-dimensional subgrain coalescence and data-points from Table I can be seen in Fig. 4. As studied previously, the data-points can be modelled by a parabolic growth law whereas the dashed line seems nearly linear and the solid line resembles to some extent an exponential function, cf. 4(a). In 4(b), the initial mean angle of misorientation was 3 deg. for all cases. The evolution of the mean angle of misorientation is quite different for the experimental data as compared to the simulated cases. In the case of a cumulative misorientation (solid line), the mean angle of misorientation is increasing slowly, whereas the case without a cumulative misorientation obtained a decrease in the mean angle of misorientation. These effects could be indicators of whether or not subgrain coalescence is the predominant process of recovery in experimental cases. The data of Table I thus indicate sub-boundary migration as the main process for coarsening the subgrain size according to the present simplified models. It was concluded that subgrain coalescence, as modelled in the present work, cannot yield a rate of the angle of misorientation as indicated by the data. This is due to the fact that subgrain coalescence is most favourable for small angles of misorientations. The coalescence of sub-boundaries with large angles of misorientations, which yields the greatest effect of altering the mean angle of misorientation, is thus less likely to occur in the initial stage and will normally occur after a time lapse. This is indicated by the initial small decrease in the mean angle of misorientations until a relatively steady increase in the mean angle of misorientation takes place, cf. 4(b) solid line. If a deformation results in a heterogeneity as seen schematically in Fig. 5(a), where there is a large cumulative misorientation in the x-direction and a low or zero cumulative misorientation in the y-direction, the mean subgrain size, $\overline{d}$, will increase mainly in the y-direction resulting in only a modest increase of the mean angle of misorientation if subgrain coalescence takes place. However, it can be assumed that the mobility of the sub-boundaries increases with the angle of misorientation. Migration of the sub-boundaries with the highest angles of misorientation could lead to fusion of boundaries with the reduction of the energy as a result as discussed in the theory, cf. Eq. 3. This could also give rise to an increase in the mean angle of misorientation similar to the experimental data.

In conclusion, softening caused by recovery defined as the coarsening of the mean subgrain size has been discussed both in the context of subgrain boundary migration and subgrain

coalescence. Experimental data from Furu et al. have been compared with some simple theoretical models. None of the theoretical models predicted the data in a satisfactory manner. However, it can be stated that the data indicate processes similar to the sub-boundary migration cases discussed in the present paper. Computer simulations of subgrain coalescence indicate a very slow increase in the mean angle of misorientation despite an initiated cumulative misorientation.

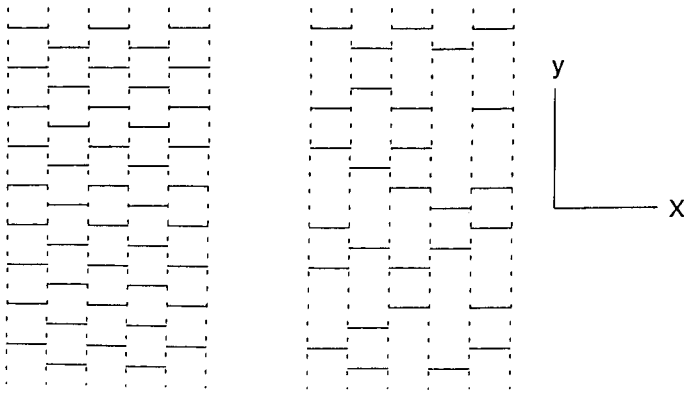


Figure 5. A schematic drawing of a deformation heterogeneity. **(a)**: The sub-boundaries parallel to the y-axis, broken lines, are of higher angles of misorientation due to a cumulative misorientation in the x-direction. The sub-boundaries parallel to the x-axis, solid lines, are of low angles of misorientations and there is no cumulative misorientation in the y-direction. **(b)**: Subgrain coalescence will result in the disappearance of the sub-boundaries with the lowest angles of misorientation. Hence, the mean angle of misorientation will change only moderately whilst the mean subgrain area increases with time. If sub-boundary migration can occur, it can be assumed that the boundaries parallel to the y-axis will be more likely to migrate than the boundaries parallel to the x-axis.

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