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Quantified Static Recovery Trend of Constricted Jogs of Aluminium Alloys During Annealing

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ABSTRACT

The static recovery of dislocations in aluminium alloys is known to observe during re-heating and inter-annealing of aluminium alloys, so that the fully recrystallised and partially recrystallised grain structures are deliberated respectively for a judicious control on their final tempering of strength, ductility, toughness and crystallographic texture to eliminate the earing related problems. An elaborate physical based static recovery simulator is required to address the trend of dislocation recovery during the time of industrial annealing to evaluate the extent of discontinuously and continuously developed recrystallised aluminium alloys. New industrial annealing practices to develop an extensively wide range of aluminium alloys with the medium to low stacking fault energy range, suitable for their plenty of use in defence vehicles, inevitably demand quantified dislocation density, the decisive element of flow strength. The formulated static recovery rate of the constricted dislocation jogs increases with the stacking fault energy and increases with the industrial annealing temperature. The formulated static recovery of dislocations is found to be very precise and concentric to address the process and materials characteristics, so that it would be liable to define the minute change in the processing temperature, i.e. 50K.

Keywords: Simulation; Annealing; Static recovery; Constricted jogs; Stacking fault energy; Aluminium alloys

1. INTRODUCTION

The re-heating and inter-annealing are generally used for industrial annealing of aluminium alloys for discontinuously and continuously developed recrystallised grain structure to address the final tempering of strength, ductility and toughness, to fabricate crucial shape forms. The re-heating is industrially performed for heat-treatable aluminium alloys before solution treatment to obtained discontinuously recrystallised structure, while inter-annealing is done for the aluminium alloys to obtain continuously developed recrystallised structure, used for the light weigh aircrafts, aerospace and military vehicles respectively [1]. As the precipitate free zones of the creep resistant aluminium alloys generally used for airspace vehicle, require grain-boundary pinning by precipitates in heat-treatable aluminium alloys and high dislocation density with random crystallographic texture is required for crucial shape forms made of non-heattreatable aluminium alloys, used for military vehicles, an elaborate knowledge on dislocation recovery kinetics during industrial annealing is required to be formulated. The usual practice to employ inter-annealing, with the continuous heating from 300 K to about 600K in slightly less than 10 h, is known to be allied with predominant static recovery, which is deliberated in the annealing of many aluminium alloys[1]. Practically it is known to stabilise the partially recrystallised structure and recovered deformed structure. That is exercised to control the balance of $\frac{\pi}{2}$ and $\frac{\pi}{4}$ ear forming crystallographic texture constituents for eliminating the forming related problems[2,3]. An elaborate physical based annealing simulator is required with the additional static recovery simulator to predict the extent of the partially recrystallised and statically recovered deformed microstructure to design and to optimise the new annealing processes for an extensively wide range of aluminium alloys form the medium to low stacking fault energy range. The basic theory postulated earlier is the non-conservative movement, climb of jogs, which is known to remain in equilibrium with the diffusive flux of atoms, driven by the self-diffusivity of aluminium alloys[4]. The effect of the elastic stress field of the stacking fault on unit jogs is liable to constrict the unit jogs[5]. The static recovery of the constricted unit jogs has been derived for the industrial annealing of aluminium alloys, generally used for the hull of the light weight military vehicles, military bridges, rockets, missile casings, fighter aircrafts and versatile marine structures with their judicious final tempering.

2. FORMULATED STATIC RECOVERY OF DISLOCATIONS

The jog velocity, υ, during non-conservative movement climb, to be recovered and to increase the dislocation spacings, L, of opposite signs by diffusive flux of atoms is

$$\upsilon = \frac{dL}{dt} = P_D D L^{-1} = P_D D_0 \exp\left(-\frac{Q_d}{kT}\right) L^{-1} \tag{1}$$

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where, the rare event probability of occurrence of concerned surface area per unit area of bulk is

$$P_D = \frac{1}{0.5\rho_0} \quad (2)$$

where, ρ_0 is the initial dislocation density, Q_d is the enthalpy for self-diffusion, D is the self-diffusivity at temperature T, D_0 is the diffusion co-efficient at 0 K, k is the Boltzmann constant, t is the time and T is the annealing temperature in Kelvin. An atomic stacking fault is known to create an elastic energy field in the lattice and therefore, jogs under non-conservative movement are constricted by the energy of the stacking fault. The stacking fault energy helps the diffusing atoms to cross the activation energy hill. Thus, the magnitude of the elastic energy of the stacking fault $Q_j\gamma_{SFE}$, which will reduce the enthalpy Q_d at an annealing temperature T, is contributed in the term, E_K, which is deliberated to derive the recovery velocity of constricted jogs.

$$E_K = \exp\left(\frac{Q_j\gamma_{SFE}}{kT}\right) \quad (3)$$

where, $Q_j = bl = b\lambda b = \lambda b^2$ is the activation area of jogs with burger vector b and length of jogs, λb.

Thus, the velocity of the non-conservative movement of constricted jogs under the elastic stress field of the stacking fault and diffusive flux is denoted as

$$\upsilon = \frac{dL}{dt} = P_D E_K D_0 \exp\left(-\frac{Q_d}{kT}\right)L^{-1} = P_D D_0 \exp\left(-\frac{Q_d - Q_j\gamma_{SFE}}{kT}\right)L^{-1} \quad (4)$$

Therefore,

$$LdL = P_D D_0 \exp\left(-\frac{Q_d - Q_j\gamma_{SFE}}{kT}\right)dt \quad (5)$$

When the L is integrated for the increase from L_0 to L_t with the increase in time from 0 to t

$$\int_{L_0}^{L_t} LdL = P_D D_0 \exp\left(-\frac{Q_d - Q_j\gamma_{SFE}}{kT}\right)\int_0^t dt \quad (6)$$

Therefore,

$$\left[\frac{L_t^2 - L_0^2}{2}\right] = P_D D_0 \exp\left(-\frac{Q_d - Q_j\gamma_{SFE}}{kT}\right)t \quad (7)$$

Since, the dislocation density is expressed as the total length of dislocations per unit volume, The L is defined by the dislocation density[6], ρ.

$$L^2 = \frac{1}{\rho} \quad (8)$$

and

$$\frac{1}{\rho_t} - \frac{1}{\rho_0} = 2P_D D_0 \exp\left(-\frac{Q_d - Q_j\gamma_{SFE}}{kT}\right)t \quad (9)$$

$$\frac{1}{\rho_t} - \frac{1}{\rho_0} = 2P_D D_0 \exp\left(-\frac{Q_d - \lambda b^2\gamma_{SFE}}{kT}\right)t \quad (10)$$

where, ρ_t and ρ_0 are dislocation densities at time t and 0 respectively. The rare event probability P_D is expressed as initial dislocation density term and therefore,

$$\frac{1}{\rho_t} = \frac{1}{\rho_0} + \frac{4}{\rho_0} D_0 \exp\left(-\frac{Q_d - \lambda b^2\gamma_{SFE}}{kT}\right)t \quad (11)$$

The probability from stacking fault energy is disintegrated from that of diffusivity and finally the static recovery kinetics of constricted jogs is addressed as

$$\frac{1}{\rho_t} = \frac{1}{\rho_0} + \frac{4}{\rho_0} D \exp\left(\frac{\lambda b^2\gamma_{SFE}}{kT}\right)t \quad (12)$$

3. RESULTS

The initial dislocation density of the cold worked aluminium alloys has been considered to be 10^{16} m^{-2}. The room temperature self-diffusivity of aluminium alloys is taken to be 0.0075 m^{2}s^{-1} from which self-diffusivities at 623 K, 573 K and 523 K have been derived to be 0.0598 m^{2}s^{-1}, 0.0506 m^{2}s^{-1} and 0.0429 m^{2}s^{-1} respectively, from

$$D_2 = D_1 \exp\left(\frac{T_2}{T_1}\right) \quad (13)$$

where D_2 and D_1 are the diffusivities at T_2 and T_1 temperature.

The constricted jog length of b has been used for simulation of dislocation recovery, where λ=1 for unit jogs and $b = \frac{d\sqrt{1^2+1^2+0^2}}{2} = 0.286$ nm, when the lattice parameter, d, of aluminium alloys is 0.405 nm. Pure aluminium is known to have the stacking fault energy 160 mJm^{-2}, while the alloying elements are used to decide the stacking fault energy based on their size and valence electron[7] and for the wide range of aluminium alloys the stacking fault energy is varied from 160 mJm^{-2} to 60 mJm^{-2} to derive the effect of constricted jogs on static recovery. An appreciable static recovery of dislocations has been found during simulated annealing at temperature only above 473K. The recovered dislocation density is simulated for the iso-thermal annealing temperature range 523-623K. The trend of static recovery for the higher bound at T=623K is depicted in Fig. 1 and for the lower bound of T=523K is delineated in Fig. 3, while the quantified static recovery at the intermediate T=573K, which is often the industrial practice, is displayed in Fig. 2 for the range of the stacking fault energy from 160 mJm^{-2} to 60 mJm^{-2}. The increase in the stacking fault energy from 60 mJm^{-2} to 160 mJm^{-2} is observed to increase the static recovery rate by an order of 3 after 10 hrs of simulated annealing at T=573K.

The predicted statically recovered dislocation density of an aluminium alloy with the stacking fault energy 110 mJm^{-2} after 10 h of iso-thermal simulated annealing at T=573 K is

Table 1. The simulation variables used for the static recovery of aluminium alloys

ρ_0 m^{-2}	D m^{2}s^{-1}	λ	b nm	γ_{SFE} mJm^{-2}			T K
10^{16}	0.0598	1	0.286	160	110	60	623
10^{16}	0.0506	1	0.286	160	110	60	573
10^{16}	0.0429	1	0.286	160	110	60	523

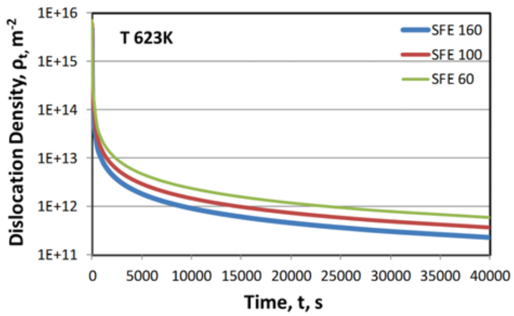

Figure 1. The static recovery kinetics at 623K for different stacking fault energies.

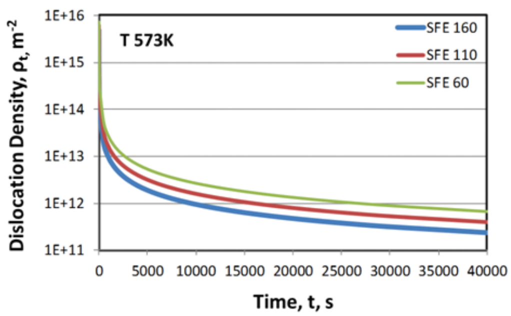

Figure 2. The static recovery kinetics at 573K for different stacking fault energies.

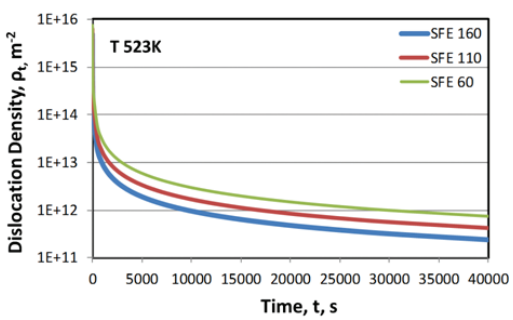

Figure 3. The static recovery kinetics at 523K for different stacking fault energies.

estimated to be $4.4x10^{11}$ m^{-2} but that recovery kinetics is liable to be adjusted by self-diffusivity and elastic energy of the atomic vacancy in the lattice, if traces of little difference in flow stress are found in recovered alloys after industrial annealing. The static recovery rate increases with the annealing temperature. The simulator has been found to address the recovery kinetics for the change T=50 K, even in the annealing temperature range from T=573 K to T=523 K. The change in the recovery kinetics in this range is found to be imperceptible for the highest stacking fault energy, which is 1.007 and for the lowest stacking fault, which is 1.11. An expected greater effect of the stacking fault energy is observed in static recovery kinetics at the lowest annealing temperature, T=523K, of an order of 3.

4. DISCUSSION

The usual industrial practice of heat-treatable aluminium alloys is to re-heat before solutionising treatment. The continuous annealing trend of re-heating at elevated temperature for comparatively less time is used to develop discontinuously recrystallised many smaller grain structure and re-precipitated particles at the high angle grain boundaries during cooling, alternatively it can render less precipitate free zones in creep resistant aluminium alloys, even after solutionising. The use of dislocation recovery simulator to predict dislocation density during heating is predominantly required for re-heating of T6 processed aluminium alloys. Cold rolling of aluminium alloys is known to increase the strength, while the annealing increases the ductility. The industrial practices used to employ H1, H2 and H3 tempering of formable wrought aluminium alloys to increase strength, ductility and recovery induced microstructural stability to meet the demand. H19 processing is observed to increase the strength at an imposed true strain of the order of 2.52, to an extent may not be expected. The batch annealing of H19 processed aluminium alloy is known to develop strong recrystallisation texture, which is not desirable for forming and therefore, the forming related problem is mitigated by inter-annealing [1,2]. The inter-annealing processed final gauge has been reported to have the random crystallographic texture, which is liable to eliminate the forming related problems. Since, the driving force for the recrystallisation is less for inter-annealing, profound dislocation recovery occurs and the partially recrystallised microstructure of aluminium alloys are fabricated with the combination of $\frac{\pi}{2}$ ear forming cube texture and $\frac{\pi}{4}$ ear forming rolling texture, with the resultant random crystallographic texture. The requirement of an elaborate annealing simulator with an additional recovery simulator, which will percept the stacking fault energy and the minute change in the annealing temperature to meet the demand of optimised new annealing processes, is justified for an extensively wide range of aluminium alloys.

The elastic energy of the stacking fault helps the diffusing atoms to cross the activation energy hill, reducing the requirements of the enthalpy. The increase in the stacking fault energy will naturally enhance the static recovery but within limit, where the highest stacking fault energy in Joule should be less than the enthalpy for self-diffusion in Joule, otherwise the hardening will occur with time. That is very crucial to identify the jog length, which is unit jogs for this simulator and for the used stacking fault energy range in Joule per unit area. This simulator does not imply the effect of the stacking fault area, which exerts very high energy to constrict the partial super-jogs, resulting in hardening, rather the length and width of used activation area of stacking fault is less than the usually reported and conceptualised long and wide stacking fault area between the partial super-jogs, which are believed to be produced in lower stacking fault energy alloys.

5. CONCLUSIONS

The re-heating and inter-annealing of wrought aluminium alloys used for the final tempering of strength, ductility, toughness and creep resistance for the crucial shape forms, are liable to require an elaborate physical based annealing simulator with an additional dislocation static recovery simulator to predict the extent of the discontinuously and continuously recrystallised aluminium alloys, to design and to optimise new annealing processes for an extensively wide range of aluminium alloys form the medium to low stacking fault energy range.

The increase in dislocation spacings, L, which increases with the annealing time due to the diffusive flux of atoms and the elastic energy of the stacking fault have been addressed and later the dislocations spacing has been expressed as the dislocation density. Unit jogs, liable to be constricted by elastic energy of the stacking fault, have been formulated.

The extent of the static recovery of dislocations has been quantified and observed to increase with the stacking fault energy as the stacking fault energy helps the diffusing atoms to cross the activation energy hill.

The recovery simulator has been cross verified to derive the temperature sensitivity in the range usual for industrial practices of the inter-annealing from 523 K to 623 K.

CONFLICT OF INTEREST

Author would like to declare that he do not have any personal, financial and other conflicts of interest, which have the importance for compromise or bias objectivity of professional judgment.

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