STATIC RECOVERY PROCESS MODELLING OF ENGINEERING METALLIC ALLOYS

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ABSTRACT

Static recovery annealing of cold worked metallic alloys will change mechanical properties without major changes in the elongated grains structure. A series of experiments have been carried out to investigate the effect of pre-strain, annealing time and annealing temperature on static recovery kinetics of aluminium-based alloys and copper-based alloys. The static recovery kinetics is then modelled using an empirical static recovery kinetic model. Analysis of activation energies of the above mentioned metallic alloys also suggests that static recovery process could be model using isochronal experimental data.

Keywords: static recovery, activation energy, aluminium alloy, copper alloy

INTRODUCTION

Recovery is a thermally activated process of restoring microstructure after cold deformation. The term refers to the changes in the properties of a deformed material, which occur prior to recrystallisation. Recovery changes the dislocation microstructure of the deformed material. The process consists of a series of micro-mechanisms evolution, i.e. cell formation, dislocation annihilation, sub-grain formation and sub-grain growth [1]. The extent by which these mechanisms occur during annealing of a specimen depends on a number of parameters, like material, purity, strain, strain rate, deformation temperature, annealing time and annealing temperature.

Static recovery of cold-worked pure metals and alloys is specifically attributed to annealing stage at recovery temperature range that is just below the recrystallisation temperature without accompanying deformation. Scientific investigation of static recovery was pioneered by the work of Kuhlmann et al. [2], Masing and Raffelspier [3] and Friedel [4]. Unlike recrystallisation and grain growth which received extensive treatment, recent work on recovery has been sparse. One notable seminal paper is by Nes [5] and more recently on internal stress model [6] and static recovered strain model [7]. All of these past works have been concerned in modelling isothermal static recovery kinetics based on experiments of either tensile or compressive strain path and quantification of activation energy.

The present paper focuses on investigating the effect of different strain path and modelling the static recovery kinetics. Based on the developed model, activation energy of different strain will be compared and discussed.

EMPIRICAL STATIC RECOVERY MODEL

Static recovery could be measured by changes in a single mechanical property such as hardness or yield stress. Fraction of static recovery X_R is defined in terms of the yield stress after static recovery annealing ($(_r$), yield stress of the as-deformed state ($(_m$) and the yield stress of fully recrystallised state ($(_o$).

(Equation 1)

An example of recovery kinetics measurement by Michalak and Paxton [8] on high purity iron deformed 5% prior to annealing and by Martinez-de-Guerenu [6] on an extra low carbon steel (0.03 wt% C) after 84% cold rolling reduction is shown in Figure 1(a). If ($1-X_R$**)** represents a single parameter, the data fit a general logarithmic expression ($1\text{-}Xr) = c_2 – c_1 lnt$, where t is the static recovery annealing time. This relationship follows the type 1 recovery kinetics identified by Humphreys and Hatherly [1]. It is further shown [1] that a recovery kinetic relationship which relate the amount of annealing time (t), annealing temperature (T), gas constant (R) and activation energy (Q) was found to be:

(Equation 2)

Equation 2 follows that of straight line equation, $y = mx - c$. If the annealing time, t were to take the natural logarithmic form, then the term Q/RT is equivalent to the y intercept (Figure 1 (b))

Figure 1: (a) Fraction of recovery as function of annealing time. (b) According to Equation 2, activation energy, Q could be determined by equating the interception of the straight line with the term Q/RT.

EXPERIMENTAL PROCEDURES

Two engineering alloys have been investigated in this paper for their value of activation energy. The first one is a copper-zinc alloy (70 wt% Cu - 30 wt% Zn). The second material is aluminium-manganese alloy (AA 3003, 1.2wt% Mn). Both materials were received as 25 mm diameter rod in a wrought form. The Cu-Zn alloy rod was annealed for 6 hours at 1073K and the Al-Mn alloy was annealed for 6 hours at 773K. According to the dimensions set by ASTM E8M-94a, tensile test specimens were machined and prepared. In order to characterise the static recovery softening, interrupted double tension tests were carried out. Sequence and characteristic of stress values obtained in the interrupted double tension can be found in Figure 2.

Two groups of experiments were carried out using the interrupted double tension test. The first one is an isothermal static recovery annealing experiments which were carried out at 503K for copper-zinc alloy and 423K for aluminium-manganese alloy. The second group is an isochronal static recovery annealing experiments which were carried out for fixed duration of one hour for both types of alloys.

Figure 2: $(_o$, the yield stress of fully recrystallised state; $(_m$, maximum flow stress during the first step of deformation and $(_r$, the yield stress after static recovery annealing. These values are used in determining fraction of recovery, X_R (see Equation 1).

RESULTS AND DISCUSSION

Isothermal static recovery annealing results were plotted as X_r versus ln(t). Using Equation (2) and the method describe in preceding section, activation energy Q, were determined (see Figure 3(a)). The activation energy, Q value of both materials is shown in Table 1 below.

Figure 3: (a) Plot of X_r versus Ln(t). Straight lines fitted to the data and their slope and interception values are shown and label. (b) Equation 2 is fitted to the isochronal experimental data. The slope of the straight line is equal to Q/R.

In addition, the kinetic recovery model presented in Equation 2 was fitted with the isochronal data as shown in Figure 3 (b). The experimental data is fitted to X_r versus $1/T$. This led to the slope of the straight line to be equal to the term Q/R. Thus activation energy, Q could be determined. The activation energy, Q for both alloy determine from the isochronal experiments are shown in Table 1.

TABLE 1: Activation energy determine from static recovery process.

Isothermal Experiments		Isochronal Experiments	
Al-Mn	Cu-Zn	Al-Mn	Cu-Zn

300 kJ/mol	220 kJ/Mol	608 kJ/Mol	515 kJ/Mol

The value of activation energy determine from the isothermal experiments can be compared with the self-diffusion activation energy of pure metal. For pure aluminium the self-diffusion activation energy is 165 kJ/mol and for pure copper it is 196 kJ/mol [9]. The activation energy for both alloys is in the same order of magnitude of their respective self-diffusion values. The higher value for both alloys could be attributed to the alloying elements impeding the dislocations rearrangement during static recovery.

The isochronal experiments produce higher values of activation energy than the isothermal experiments. However the values are of the same magnitude as their self-diffusion values. So far in the literature there have not been any attempts to carry out isochronal static recovery annealing [1-8].

CONCLUSIONS

The kinetics of static recovery of Al-Mn and Cu-Zn alloy has been model by means of a simple empirical static recovery model. The empirical model was tested using isothermal and isochronal experimental data. Activation energy values from both experiments did not agree. However the magnitude of the values is of the same order of magnitude.

NOTATIONS

X_r	Fraction of static recovery	(dimensionless)
($_r$	Yield stress after static recovery annealing	MPa
($_r$	Yield stress of the as-deformed state	MPa
($_o$	Yield stress of fully recrystallised state	MPa
t	Annealing time	s
Q	Activation energy	kJ/mol
T	Annealing temperature	Kelvin
R	Molar gas constant	J/(mol.K)

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