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Model to determine recrystallization temperature of tungsten based dilute solid solution alloys

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Abstract A new model is developed and used to predict the effect of the deformation history and the chemical purity on the recrystallization temperature of tungsten based dilute solid solution alloys.

Experience shows that incomplete recrystallization often proves to be of better use to achieve the desired balance in material properties [1]. If the recrystallization temperatures (T_{re}) of materials, especially high temperature materials, are well known, the material properties can be well improved by controlling recrystallization during application. T_{re} of materials depends mainly on the deformation history and the chemical purity. However, the most researches are at qualitative stage at present, especially for metal alloys. In this paper, a model is developed by the thermal fluctuation model of nucleation to describe the effect of the deformation history and the chemical purity on T_{re} of dilute solid solution tungsten alloys.

The nucleation and growth process of recrystallization can be described by the nucleation theory. Time for 50% static recrystallization ($t_{0.5}$) is temperature dependent and is often found to obey an Arrhenius type relationship of the form [2–4]:

$$t_{0.5}^{-1} = A \exp\left(\frac{Q}{RT_{\mathrm{re}}}\right) \tag{1}$$

where Q is the activation energy (J/mol); R is a gas constant (J/mol K); T_{re} is the recrystallization temperature (K); A is a constant related to the initial gain size.

The time ($t_{0.5}$) for static recrystallization is also commonly described by strain dependent and obeys the following form [4–7]:

$$t_{0.5} \propto \varepsilon^{n} \tag{2}$$

where n is a constant.

Therefore, T_{re} can be expressed as

$$\frac{1}{T_{\mathrm{re}}} = \frac{R}{Q} n \ln \varepsilon + \frac{R}{Q} \ln B \tag{3}$$

In order to describe the relationship between the T_{re} and solute content, Gao and Zee [8] conclusions about the creep activation energy for tungsten and molybdenum based solid solution alloys were referred. The static recrystalliztion activation energy is assumed to be a function of atomic mismatch (e) and solute content (x):

$$Q = f(e,x) = Cex^{1/2} + Q_o \tag{4}$$

$$e = |r_{\mathrm{W}} - r_{\mathrm{solute}}|/r_{\mathrm{W}} \tag{5}$$

where e is the atomic mismatch; x is the molar fraction of solute atoms; C is a constant (J/mol); Q_o is the activation energy of pure tungsten; r_{W} and r_{solute} are the atomic radius of tungsten and solute atoms, respectively.

The relationship between strain and T_{re} of pure tungsten (the experimental data come from [9]) is shown in Fig. 1. T_{re} decreases with increasing strain. The value of the activation energy of pure tungsten is computed to be about Q_o=362.5 kJ/mol.

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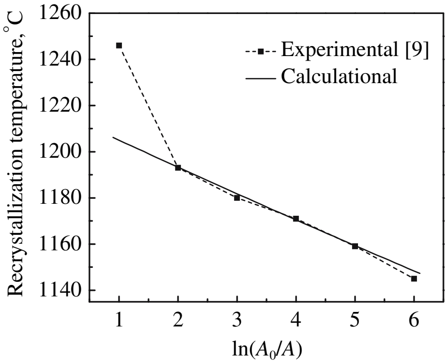

Fig. 1 Relationship between T_{re} and strain

The elements of solid solution strengthened tungsten are mainly Re (Mo), Nb, Ta, Hf, Zr. The values of the atomic size mismatch between tungsten and solute atoms are given in Table 1.

As well known, recrystallization process in the metals or alloys after large deformation (generally, ε>0.7) has completed more than 95% within a specified time (1~3 h) at an approximate minimum temperature, and the lowest temperature is defined as T_{re} [10]. The effect of solute content on T_{re} of tungsten alloys (the experimental data come from [11]) is shown in Fig. 2. T_{re} increases with increasing solute content. The calculated results compare well with the experimental results for W–Re alloys. The model predicts well when the solute content is less than 5 at.% for W–Nb alloys and less than 1.5 at.% for W–Zr alloys. However, the calculated results are much higher than the experimental results with increasing solute content.

The vast majority of structural transformations in materials take place by the mechanism of "nucleation and growth". The nucleation and growth for recrystallization is completed by the movement of the thermally activated atoms. The addition of the solute hinders the movement thus imposing an extra energy barrier in these tungsten based solid solution alloys, and the larger the atomic size mismatch is, the stronger the barrier is, indicating that the additional energy is required. Therefore, T_{re} and activation energy increase with increasing solute content and the atomic size mismatch. The effect of solute content on the activation energy is shown in Fig. 3. The activation energy is between 360~390 kJ/mol for W–Re alloys, which is a little lower than the creep activation energy for W–Re alloys [12], indicating that the recrystallization process is a thermally activated process and a part energy was reserved after cold working. However, no data for W–Zr and W–Nb alloys are available.

Table 1 Atomic size mismatch between tungsten and some types of solutes [8]

Elements	Atomic radius r (nm)	Atomic size mismatch e
W	0.138	0.000
Re(Mo)	0.134	0.029
Nb(Ta)	0.144	0.043
Hf(Zr)	0.155	0.123

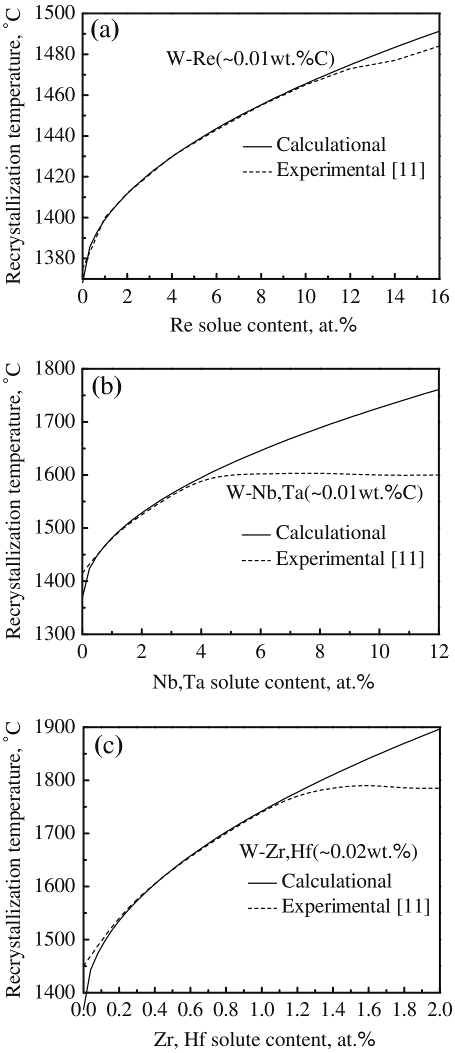

Fig. 2 Effect of solute content on T_{re} of tungsten Alloys (ε=0.7). (**a**) Re; (**b**) Nb (Ta); (**c**) Zr (Hf)

With increasing solute content, the barriers to recrystallization nucleation and growth are increased, and the recrystallization temperature of tungsten alloys should also increase. However, the calculated results gradually deviate from the experiment results at high solute levels. Firstly, the melting point of tungsten alloys are abruptly decreased as the solute contents (especially for Zr, Hf, Nb, Ta) reach to certain level [11], and the solubility of the solid solute atoms in tungsten is decreased, in other words, the effect of solid

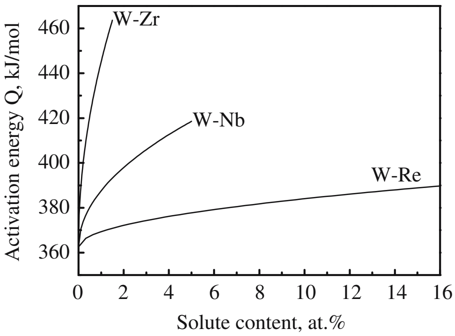

Fig. 3 Relationship between the activation energy and solute content

solution strengthening on tungsten alloys is weakened at high solute levels; on the other hand, the higher flow stress levels occur as solute levels are raised, which tend to counteract increases in barriers to recrystallization nucleation and growth, and the stored energy in tungsten alloys is increased. Therefore, there occurs a leveling off at high solute levels in the plots of the recrystallization temperature against the solute contents, and the calculated results by the model are higher than the experimental results.

In conclusion, we describe here a new model which has proved to provide very reasonable predictions for the effect of solute content and strain on the recrystallization temperature of dilute solid solution tungsten alloys. The model successfully explains the available data in tungsten based dilute solid solution alloys.

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