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A State-Variable Approach for Predicting the Time required for 50%Recrystallization

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Abstract

It is important to be able to model the recrystallization kinetics in aluminum alloys during hot deformation. The industrial relevant process of hot rolling is an example of where the knowledge of whether or not a material recrystallizes is critical to making a product with the correct properties. Classically, the equations that describe the kinetics of recrystallization predict the time to 50% recrystallization. These equations are largely empirical; they are based on the free energy for recrystallization, a Zener-Holloman parameter, and have several adjustable exponents to fit the equation to engineering data. We have modified this form of classical theory replacing the Zener-Hollomon parameter with a deformation energy increment, a free energy available to drive recrystallization. The advantage of this formulation is that the deformation energy increment is calculated based on the previously determined temperature and strain-rate sensitivity of the constitutive response. We modeled the constitutive response of the AA5182 aluminum using a state variable approach; the value of the state variable is a function of the temperature and strain-rate history of deformation. Thus, the recrystallization kinetics is a function of only the state variable and free energy for recrystallization. There are no adjustable exponents as in classical theory. Using this approach combined with engineering recrystallization data we have been able to predict the kinetics of recrystallization in AA5182 as a function of deformation strain rate and temperature.

keywords: recrystallization; AA5182 aluminum; state variable; constitutive relation

Introduction

We will discuss a physical based approach for predicting the time required for 50% recrystallization. The model that we are proposing will be very similar to and in the spirit of the classical models.[1] A model of the classical form has been proposed by Wells et al.[2] for AA5182. Our model is similar to that of Wells in concept, but we replace many of her empirical parameters with a single state variable, $\hat{\sigma}_T$, to reflect the energy of the final increment of plastic strain. Wells employs a Zener-Hollomon type parameter while our state variable, $\hat{\sigma}_T$, will be derived from the MTS (mechanical threshold strength) model[3], a temperature and strain-rate dependent constitutive relation, and its two state variables: the mechanical threshold strength, $\hat{\sigma}_i$, and the deformation-history dependence of structure, $\hat{\sigma}_e$.

The model proposed by Wells has the following form:

$$t_{0.5} = A(d_0)^b \left(\exp\left(\frac{\dot{\varepsilon} Q_{def.}}{RT_{def.}} \right) \right)^c (\varepsilon)^d \left(\exp\left(\frac{Q_{Rxtal.}}{RT_{Rxtal.}} \right) \right). \quad (1)$$

The parameters in Eq. 1 have their classical definitions: d_0 is the initial grain size (μm), $\dot{\varepsilon}$ strain rate (s^{-1}), ε maximum deformation strain, $Q_{def.}$ the free energy available from deformation (Joule/Mole), $Q_{Rxtal.}$ the activation energy for recrystallization (Joule/Mole), R is the universal gas constant (Joule/(Mole-K)) and the temperatures, $T_{def.}$ and $T_{Rxtal.}$ (K), are the temperature of deformation and recrystallization respectively. The coefficients *A, b, c,* and *d* were all determined from a curve fit to a series of recrystallization experiments. In these experiments AA5182 transfer gauge was deformed in plane strain at different temperatures and strain rates to several deformation levels and immediately quenched. Subsequent to deformation and quenching the samples were recrystallized at 400°C to determine the time for 50% recrystallization. This approach suffers from several difficulties. First we should *not* expect $Q_{def.}$ to be a constant, rather it should be a function of the deformation history. Secondly, there are too many degrees of freedom in Eq. 1. One must specify four individual fitting parameters: *A*, *b*, *c*, and *d*. This becomes a process of turning knobs to please ones eye rather than explicitly fitting a series of experimental data.

A physical approach to the prediction of 50% recrystallization times is to think in terms of an energy balance. Some energy terms do appear in Eq. 1, for example the free energy required for recrystallization. However, we believe that aspects of the complete energy balance are missing. Our idea is that one needs to pose the problem in terms of three particular energies. First, and most obvious, is the free energy required for recrystallization. This is balanced by the free energy supplied by the final increment of plastic deformation, at a particular strain rate and temperature. Classically, researchers have tried to describe this quantity with a single term, for example the Zener-Hollomon parameter in Wells's equation. We, however, are proposing that one should think in terms of two quantities, in the manner of Kocks, Argon, and Ashby[4]: a reference energy for plastic deformation, an equivalent of a mechanical threshold if you will, and the amount of energy "lost" by the reference dislocation structure through the process of thermally activated dynamic recovery. This energy, lost through recovery, will be a function of strain rate and temperature. We can convert these energies to a 50% recrystallization time through the following rate formulation:

$$t_{0.5} = \frac{A \exp\left(\frac{Q_{rec.}(\dot{\varepsilon}, T)}{RT_{def.}} \right) \exp\left(\frac{Q_{Rxtal.}}{RT_{Rxtal.}} \right)}{\exp\left(\frac{Q_{ref.}}{RT_{def.}} \right)}. \quad (2)$$

Analysis and Results

Kocks, Argon, and Ashby[4] chose the following phenomenological form for the free energy, in the final plastic strain increment, associated with the process of dynamic recovery:

$$Q_{rec.} = g_0 \mu b^3 \left[1 - \left(\frac{\sigma_T / \mu}{\hat{\sigma}_T / \mu_0} \right)^{p_T} \right]^{q_T}. \tag{3}$$

Terms have their classical meanings, as in the MTS equations: μ is the shear modulus, μ_0 the shear modulus at 0K, b the Burger's vector, g_0 an activation area, σ_T the current flow stress, $\hat{\sigma}_T(\dot{\varepsilon}, T)$ is the mechanical threshold, which is a reference flow stress, proportional to the square root of the statistically random dislocation density, not including the effects of thermal activation, and p_T and q_T are exponents assigned one of four values, 1/2, 2/3, 1, or 3/2. One should note that in Eq. 3 both the yield and plastic flow stresses have been combined into a single flow stress, σ_T, and single state variable, $\hat{\sigma}_T$. This is different than classical MTS. In Eq.3 the exponents p_T and q_T will also have values independent of the p's and q's from the MTS fit for AA5182. To evaluate Eq. 3 for different strain rate and temperature histories, we will calculate the total flow stress, σ_T, by summing all terms of the classical MTS constitutive equation, using the coefficients determined for AA5182 by Chen et al.[5] This model will also be used to determine the state variable reference stress $\hat{\sigma}_T$. It will be taken as the sum of the two state variables in Chen's MTS equation: $\hat{\sigma}_T = \hat{\sigma}_i + \hat{\sigma}_e$.

One should note that the reference incremental energy of deformation (Q_{ref}), no thermal activation, can be deduced from Eq. 3. At very high temperatures and low strain rates (but not so high a temperature or low a rate that diffusion creep deformation mechanisms become active) $\hat{\sigma}_T$ becomes much greater than the flow stress, σ_T, or $\left(\frac{\sigma_T / \mu}{\hat{\sigma}_T / \mu_0} \right) \to 0$. In other words, all of the stored energy from deformation is lost to the recovery process: $Q_{ref.} \to Q_{rec.}$. In terms of Eq. 3, this defines the reference energy of deformation as: $Q_{ref.} = g_0 \mu b^3$.

By substituting into Eq. 2, taking the natural logarithm, and arranging terms we can obtain a linear form for the time required for 50% recrystallization:

$$\ln t_{0.5} = \left(\ln A + \left(\frac{Q_{Rxtal.}}{RT_{Rxtal.}} \right) \right) + g_0 \frac{N \mu b^3}{RT_{def.}} \left[\left[1 - \left(\frac{\sigma_T / \mu}{\hat{\sigma}_T / \mu_0} \right)^{p_T} \right]^{q_T} - 1 \right]. \tag{4}$$

We have sufficient information to calculate A and g_0 in Eq. 4, by coupling the recrystallization data published by Wells et al. with the MTS fit and the MTS coefficients determined by Chen et al. (note that N is Avagadro's number). This will be done with a linear regression analysis. The values of p_T and q_T cannot be solved for explicitly in this analysis. To determine the best combination of values for these terms we will assume that they can be equal to 1/2, 2/3, 1, or 3/2 only. This results in 16 possible combinations. The regression analysis can be done for each one of the combinations and the coefficient of determination calculated. The highest coefficient of determination will tell us the proper values to assign p_T and q_T.

The recrystallization data we used were presented by Wells et al. in their Table VI. From these data we know the time for 50% recrystallization: after a particular deformation history, strain rate to a level of strain at a known temperature, and a recrystallization treatment at 400°C. Chen's

coefficients for AA5182 and the MTS law were used to evaluate the stress ratio, $\left(\frac{\sigma_T/\mu}{\hat{\sigma}_T/\mu_0}\right)$, for Wells's deformation histories. This was done using each of the different values of p_T and q_T. In all cases the recrystallization treatment was at 400°C, $T_{Rxtal.}$ = 673K. We used the same value for $Q_{Rxtal.}$ as Wells, $Q_{Rxtal.} = 2\times10^6$Joules/Mole.

We first performed the regression analysis including all of the data listed by Wells. However, two particular data points appeared unreliable, one quoting a very short 50% recrystallization time (deformation at 520°C recrystallization in 3.4s) and the other a very long time (deformation at 427°C 50% recrystallization in 17.3s). These data clearly deviated from the others and were eliminated from the analysis leaving the data set shown in Table I for evaluation of A and g_0.

Table I: Data of Wells et al.[2] that were used in our current analysis

T_{def} (°C)	$\dot{\varepsilon}$ (s^{-1})	ε	$t_{0.5}$
377	1.0	1.0	5.3
387	9.1	0.5	2.8
411	10.2	1.0	2.5
498	48.9	0.9	8.5
461	44.6	1.5	6.4
470	43.0	1.9	5.2
413	0.5	1.0	53.1
420	1.0	1.0	37.9
443	10.5	1.0	11.4
448	89.6	1.0	4.2
508	1.1	1.0	250.6
511	10.4	0.5	168.9
530	10.5	1.5	34.5

We found that the fit of the regression analysis, as specified by the coefficient of determination, was relatively insensitive to the combinations of p_T and q_T. The values of $p_T = 3/2$ and $q_T = 1/2$ gave the best fit to Wells's data. For $p_T = 3/2$ and $q_T = 1/2$ the regression analysis found values of $\ln A + \left(\frac{Q_{Rxtal.}}{RT_{Rxtal.}}\right) = 7.82349$ and $g_0 = 0.625491$. Noting, $Q_{Rxtal.} = 2\times10^6$Joules/Mole, R = 8.314Joules/Mole-K, and $T_{Rxtal.}$ = 673K we calculated $A = 7.48538\times10^{-13}$s. By plotting the Wells data, $\ln t_{0.5}$, versus $\frac{N\mu b^3}{RT_{def.}}\left[\left[1-\left(\frac{\sigma_T/\mu}{\hat{\sigma}_T/\mu_0}\right)^{3/2}\right]^{1/2}-1\right]$ together with the linear fit we can get an idea of the validity of Eq. 2 and isolate whether or not particular datum points might be questioned. It was from this plot that the deviant data points were identified. The data listed in Table I are plotted in this manner, together with the linear fit, in Figure 1. One can see, in Figure 1, that the data appear to show a linear form, and they are completely consistent with one another. Figure 2 is the same kind of plot for these data except that Wells's expression describing the time to 50% recrystallization, Eq. 1, has been linearized and her values for the coefficients A, b, c, d and $Q_{def.}$

substituted. The same plot including the two inconsistent data points, which we have not shown, appears in Wells's paper.

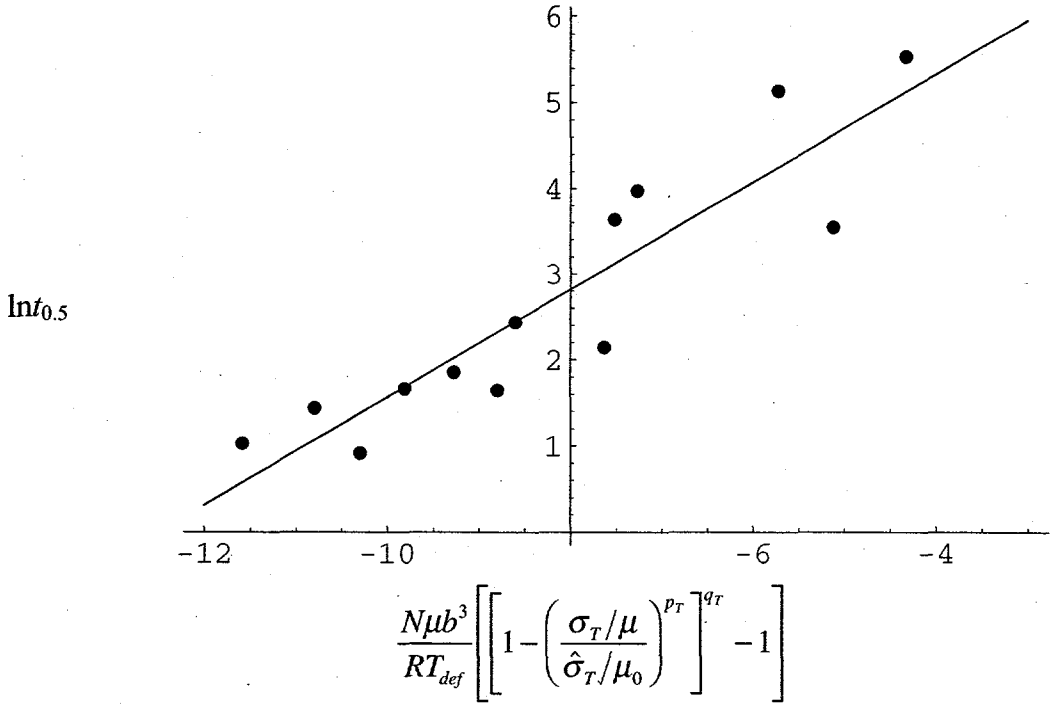

Figure 1. Plot of Wells's recrystallization data and our linear fit based on the MTS constitutive law.

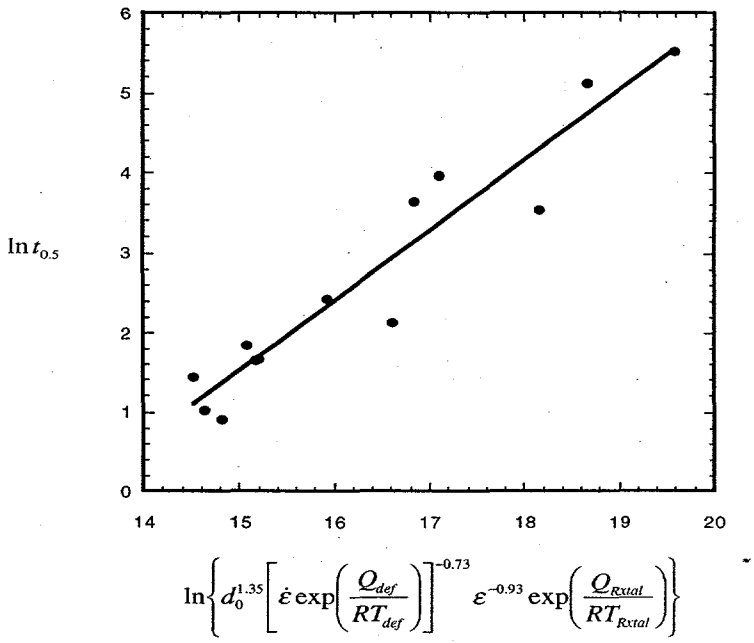

Figure 2. A plot of Wells's data and recrystallization law. With permission from *Metall. Trans. A*.

The interpretation of Wells et al's.[2] recrystallization data in Figures 1 and 2 is very satisfying. The data appear to follow a linear trend and there is only a reasonable random scatter from the fits. We are very pleased with how our approach to modeling the time to 50% recrystallization interprets the results. Our interpretation produces the same linear fit without an increase in the scatter of individual datum points. One also notes that the data collect, group, in much the same fashion in Figures 1 and 2. Thus, we believe that our approach based on an a priori independently-determined constitutive relation describes the recrystallization kinetics with equivalent accuracy as Wells et al's.[2] empirical, albeit classical, approach.

Summary and Conclusions

A new approach for modeling the kinetics of recrystallization has been presented. The approach has similarities to the classical approach, but is based on the constitutive response of the metal rather than an empirically determined collection of exponents. We found that our approach performed equivalently to the classical approach, for an extensive data set on an AA5182 aluminum alloy[2], giving us confidence in its validity.

The advantage of using a model such as ours is that the time for 50% static recrystallization can be predicted for deformations that are not at a constant strain rate or temperature, as required by the classical approach. Thus, our approach can be used without approximation in a finite element method, FEM, simulation of an engineering process. The flow stress σ_T and state variable $\hat{\sigma}_T$ are calculated incrementally at each element in the process of performing the finite element simulation; thus, few additional calculations are required to test whether the criterion for 50% recrystallization has been reached. This is particularly well suited for FEM simulation of hot rolling where there is the possibility for static recrystallization on the stands between rolling passes.

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