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Application of Dynamic Recrystallization Model for the Prediction of Microstructure During Hot Working

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During hot working operation, the work-piece deforms to the shape of the die geometry at the imposed deformation rates and temperatures. Deformation processing maps, obtained based on the concepts of Dynamic Materials Modeling, can be used to identify optimum deformation conditions. Dynamic Recrystallization (DRX) is shown to be the operating softening mechanism at these optimum deformation conditions, and results in predictable microstructures. The model proposed for explaining the microstructural evolution during DRX is extended to predict the resulting microstructure based on the information about the deformation loads and work-piece temperatures. The model predictions are validated on Al and Cu. This model can be applied for on-line process control, provided the metal forming equipment is appropriately instrumented.

Keywords dynamic recrystallization model, grain size evolution, hot deformation, strain rate

1. Introduction

Proper selection of deformation rates and temperatures is essential to obtain large strains with appropriate microstructures. Deformation processing maps developed on the basis of Dynamic Materials Modeling[1] principles provide guidelines for selecting such suitable parameters. The occurrence of dynamic recrystallization (DRX) during hot deformation results in best workability as has been shown for a number of materials.[2,3] The characteristics of DRX process have been studied in a number of metals[4] and alloys.[5] The influence of Stacking Fault Energy (SFE) on the characteristics of DRX and its manifestation on the flow behavior has been investigated in pure fcc metals having different SFE values (ranging from high SFE metal Al to low SFE metal Pb).[4,6] The microstructural evolution during DRX has been modeled using the rates of interface formation and migration. This model is extended for predicting microstructures based on the deformation loads. Such a prediction can be useful for deciding the downstream process control parameters enabling predictable quality levels.

2. Experimental Procedure

Hot compressions tests were conducted on pure fcc metals. The material compositions and purity levels are given in Table 1. Cylindrical specimens of 10 mm diameter and 15 mm height were machined with parallel faces. Concentric grooves of about 0.5 mm depth were engraved on the specimen faces to facilitate retention of lubricant. Molten glass was used as the lubricant. A 1 mm 45° chamfer was machined along the edges of the face to avoid fold over during compression. A 0.5 mm diameter hole was drilled at half the height of the specimen for the insertion of a thermocouple. The specimens were all annealed at appropriate temperature with proper protective atmosphere. Hot compression tests were conducted on a servo-hydraulic machine (DARTEC, Stourbridge, UK), with a temperature control of ±2°. The flow stress values as a function of strain were calculated from the load-displacement data. All the samples were compressed to a true strain of 0.5, and quenched immediately after the tests; grain size measurements were then conducted on selected samples. The flow stress data and the measured grain sizes (at a strain of 0.5) were reported in Ref. 7 for Al of different purity levels and Ref. 8 and 9 for Cu with different initial grain sizes.

3. Discussion

3.1 DRX Model

During DRX, there is a certain energy input per second depending upon the strain rate and temperature and certain rate of energy dissipation due to softening processes. The behavior represents a dynamic balance between the rates of nucleation and growth under given boundary conditions. Thus, dynamic rates of recrystallization may consist of two competing processes: formation of interfaces (nucleation) and migration of interfaces (growth). An interface may be defined as a boundary formed as a result of dislocation generation, recovery, and rearrangement, and will migrate (nucleus) when it attains a configuration of a large angle boundary. As the material under hot working conditions acts essentially as a dissipater of power (no significant energy storage), the driving force for migration of interfaces is dislocations forming subgrains. Under constant true strain rate conditions, the rate of formation of interfaces will compete with the rate of migration to maintain the strain rate constant with strain. The relative values of these two rates will decide the shape of the stress-strain curve. For example, if these two rates lead to comparable changes in the interface area, steady state curves result. If the rate of formation is slower than the rate of migration, certain strain will have to

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Table 1 Chemical Composition, Starting Grain Sizes, Test Temperature Details of Al and Cu Used for the Study (the Employed Strain Rate was 0.001-100 1/s)

Material Identification	Chemical Composition, ppm						Initial Grain Size, µm	Temperature Range, °C
	Cu							
	Fe	**Sn**	**Zn**	**O**	**Cu**			
OFHC1	40	Tr	30	11	Bal.		280	650-900
OFHC2	300	Tr	60	30	Bal.		208	650-900
ETP	40	Tr	30	180	Bal.		160	650-900
	Al							
	Fe	**Mn**	**Si**	**Zn**	**Cu**	**Al**		
5-9 P	…	…	…	…	…	…	320	300-500
4-9 P	20	…	10	…	20	Bal.	750	250-500
3-9 P	100	…	400	600	200	Bal.	63	300-550

elapse before the critical configuration for the migration (of interface) is achieved and at the critical strain a large number of interfaces migrate leading to flow softening. On the basis of the above description, the model that explains the characteristics of DRX is presented below.

The rate of interface formation R_F depends on the rate of generation of recovered dislocations:

$$R_F = \beta \cdot \dot{\varepsilon} \cdot P_R/(bl) \qquad \text{(Eq 1)}$$

Where β is the constant, $\dot{\varepsilon}$ is the strain rate, P_R is the probability of recovery of dislocations, b is Burger's vector, and l is the link length. For mechanical recovery involving cross slip of screw dislocations.[10]

$$P_R = \exp - \{[\alpha G b^2 d \sqrt{(ln d/b)}]/(kT)\} \qquad \text{(Eq 2)}$$

where α is a constant, G is a shear modulus, d is stacking fault width, k is Boltzmann constant, and T is the absolute temperature. For thermal recovery involving climb of edge dislocations,[10]

$$P_R = \exp[-Q_{SD}/(RT)] \qquad \text{(Eq 3)}$$

where Q_{SD} is the activation energy for self-diffusion and R is the gas constant.

The rate of annihilation of recovered groups of dislocations (subgrains) caused by migration of interfaces,[11] R_M, is given by

$$R_M = c\dot{M}(\rho_{rec}/d_s) \qquad \text{(Eq 4)}$$

where c is a constant, ρ_{rec} is recovered dislocation density, and $\dot{M}$ is the interface (grain boundary) mobility, and d_s is subgrain size

$$\dot{M} = (D\Omega/kT\,r)(\Gamma/d_s) \qquad \text{(Eq 5)}$$

where D is the diffusion co-efficient, Ω is the atomic volume, r is the jump distance, and Γ is the grain boundary energy. During steady state flow (a) a linear relationship can be assumed between the recrystallized grain size D_s and the subgrain size d_s, and (b) the rates of interface formation and migration are equal.

3.2 Correlation Between Grain Size and the Deformation Parameters

When the interface formation and migration rates are equal, combining Eq 1 and 4, a relationship can be established between deformation strain rates, stresses, and grain sizes.

These rates balance to sustain the imposed strain rates, then $R_F = R_M$. Hence by rearranging Eq 1 and 4 the following predictions can be made:

The DRX grain size D_s,

$$D_s \propto 1/\dot{\varepsilon} \qquad \text{(Eq 6a)}$$

$$\propto 1/\sigma^n \qquad \text{(Eq 6b)}$$

To verify the model predictions the range of temperature and strain rate conditions under which DRX is active has been identified using processing maps.[7-9] The grain sizes were obtained from the corresponding samples. The measured grain sizes and flow stress data (both corresponding to a strain of 0.5) are plotted in Fig. 1 and 2 for Al and Cu, respectively. The figures indicate good conformance between the predictions and experimental data. The calculated m (= n/2) values were 1.1 for Al and 0.9 for Cu. These predictions are in accordance with that of the relationship between mean grain size and applied stress obtained by Derby and Ashby[12] (i.e., $\sigma \propto D_{mean}^{-m}$, with m in the range of 0.4-0.7).

During the progress of the DRX process the competing interface formation and migration rates balance such that the resulting flow stress either remains constant or shows a small drop as a function of strain. Therefore, for a given strain value, the resulting microstructure has a stronger correlation with flow stress or imposed strain rate than that of strain.

In industrial bulk forming, predetermined strains and strain rates are imposed and the forming loads are monitored through appropriate instrumentation. The model presented above provides a means for predicting the product microstructure based on the fundamental recovery mechanisms.

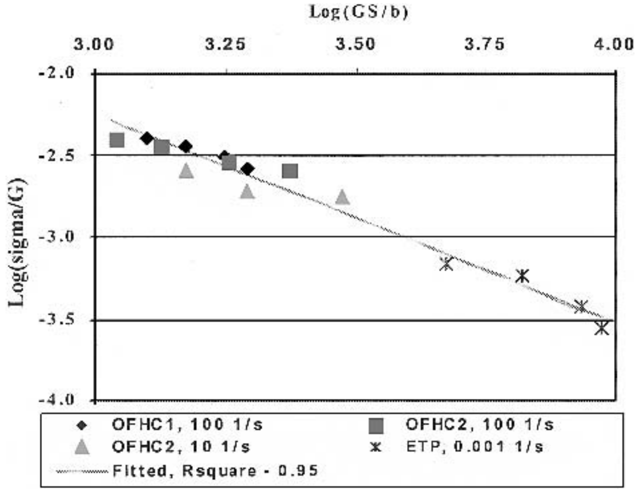

Fig. 1 Variation of normalized flow stress with grain size in Cu

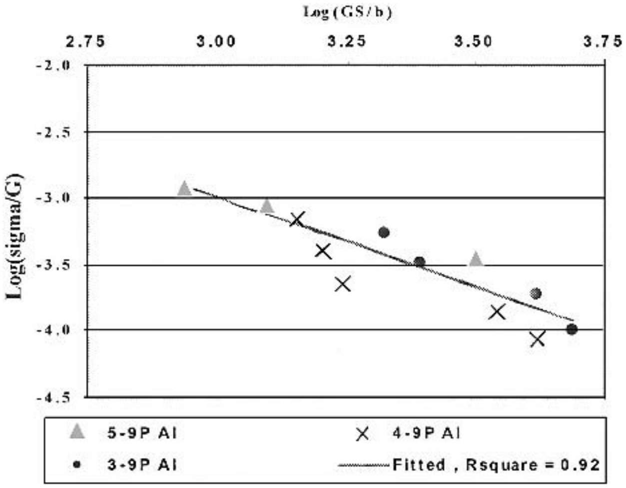

Fig. 2 Variation of normalized flow stress with grain size in Al

4. Conclusion

The DRX model presented has been extended to predict the relationship between the flow stress and the grain size. The correlation indicates that the measured hot working loads can be used for predicting the product microstructure. The predictions are also in line with the predictions by Derby and Ashby[12] for DRX microstructural evolution based on nucleation and growth model.

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