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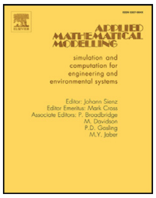

Simulation of softening kinetics and microstructural events in aluminum alloy subjected to single and multi-pass rolling operations

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ABSTRACT

In this study, a multi-scale model is proposed to assess softening kinetics and microstructural changes during isothermal annealing within an aluminum alloy. In the first stage, an elastic-plastic finite element analysis is performed for computing the distributions of effective plastic strain and stress while the stored energy after cold rolling is defined based on the predicted data and then utilized for generation of the initial conditions in the microstructural analysis. In the next stage, an algorithm based on cellular automata coupled with a first order rate equation is used to determine the progress of softening behavior at elevated temperatures while both recrystallization and recovery processes are taken into account. The model is examined on single and multi-pass rolling of AA1050 during which the softening progress is measured at temperature varying between 160 °C and 360 °C. The changes in microstructures and mechanical properties are determined by means of microstructural observations, tensile testing and hardness measurements. Finally, the experimental and the predicted results are compared and a reasonable consistency is observed between the two sets of data indicating the validity of the developed algorithm.

1. Introduction

The cold deformation of metallic materials leads to an unstable structure owing to introducing the imperfections and thus, subsequent restoration phenomena such as static recovery and recrystallization can be operative to reduce the internal stored energy. On the other hand, the softening processes may lead to considerable changes in final microstructure and mechanical properties of the deformed materials [1]. Accordingly, the required properties might be achieved by means of a proper combination of cold forming and subsequent annealing treatment. There have been several works for predicting material responses during annealing treatments using different methods including cellular automata. For instance, Ghosh et al. [2] estimated recrystallization kinetics of cold rolled copper by two-dimensional cellular automata under isothermal annealing conditions. Dewri and Chakraborti [3] developed a combined cellular automata and generic algorithm to define recrystallization progress and to predict grain size distribution in cold worked materials. Raabe [4] developed a coupled crystal plasticity finite element-cellular automata model to assess the yielding behavior of aluminum during partial static recrystallization. In the other work conducted by Raabe and Hantcherli [5], two-dimensional cellular automaton model was utilized for predicting the progress of recrystallization in deformed IF steels with regard to Zener pinning effect. Svyetlichny

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[6] developed a frontal cellular automata (FCA) approach for modeling of the microstructural changes while both deformation pattern and metallurgical events were considered. Xiao et al. [7] predicted the microstructural evolution during dynamic recrystallization using the uniform topology deformation technique. This method made it possible to determine the effects of topology deformation on the kinetics recrystallization and the final grain size. Kugler and Turk [8] considered a model to predict kinetics of isothermal recrystallization within metallic materials using a two-dimensional cellular automata approach while the effect of plastic strain on nucleation stage was also taken into account. Mark et al. [9] developed a three-dimensional cellular automata simulation for estimating the rate of static recrystallization in metallic materials.

It should be mentioned that aluminum and its alloys show considerable rate of recovery because of their high stacking fault energy [10] and thus, during annealing treatment both static recovery and recrystallization may occur at the same time. Therefore, in order to properly evaluate annealing behavior of the alloy, both processes should be considered simultaneously. In this work, softening behavior under isothermal annealing of cold-rolled AA1050 i.e. as a single-phase alloy, is carried out regarding simultaneous occurrence of recovery and recrystallization. Furthermore, the influence of deformation path i.e. rolling pass design, on the subsequent softening behavior is evaluated. Two-dimensional finite element analysis is first performed under various rolling schedules including single- and multi-pass rolling programs to assess the stored energy distributions within the plastically deformed plates and then, a probabilistic two-dimensional cellular automata coupled with a first order rate equation is employed for predicting the microstructural changes and progress of static softening during isothermal annealing treatments.

2. Mathematical modeling

The finite element software, ABAQUS/Explicit was used to predict the distributions of effective plastic strain and equivalent stress during cold rolling of AA1050 plates under plane strain condition. In the modeling a total reduction of 50% was applied but different roll-pass designs were considered as listed in Table 1. Moreover, the mechanical properties used in the deformation model are listed in Table 2 regarding the data reported in Ref. [11]. In the mechanical model, the displacement field for an elastic-plastic material was defined regarding the minimization given in Eq. (1) in which dynamic-explicit formulation was employed [12].

$$\int \sigma_{ij}\delta\varepsilon_{ij}\, dV + \int \rho\ddot{u}_i\, \delta u_i dV - \int q_i^0 \delta u_i ds = 0, \tag{1}$$

here, σ_{ij} is stress tensor, ε_{ij} is strain tensor, ρ is density, u_i is the displacement tensor, and $q_i{}^0$ denotes the stress tensor acting on the roll/metal interface [12]. The finite element form of the dynamic analysis can be written as [13]:

$$M\ddot{U} + f^{\text{int}} = f^{\text{ext}}, \tag{2}$$

here, U is nodal displacement vector, and M represents mass matrix that remains unchanged during deformation and might be derived as a diagonal matrix. It should be noted that the work-rolls were taken as rigid bodies and the Coulomb friction model was assumed to be operative on the roll/metal interface with a constant friction coefficient of 0.1. The upper half of the strip and the top work-roll were taken into account due to the existing symmetry. The material was taken to obey Von Misses yield function together with the isotropic hardening rule. The meshing system was generated using four-node bilinear elements while it contained 480 elements in length and 8 elements along thickness directions, respectively. Note that a mesh sensitivity analysis was first carried out to obtain the optimum mesh size which gives the accurate results with reasonable computation time. The geometry of deformation zone for the single-pass rolling condition are shown in Fig. 1. The developed analysis was also capable of considering multi-pass rolling layouts in which direct-forward rolling design was employed in the modeling as the plate passes through successive stands. All the work-rolls were set in the successive positions i.e. a single model was built and the successive passes were not considered in separate steps. In this way, the strain history in each point could be easily transferred to the following rolling stage.

The results of the mechanical modeling were then employed for estimating the stored internal energy within the cold-rolled plate. The determination of the stored energy after deformation is an important task because of non-uniform distribution of plastic strains during rolling. This directly affects the rate of recovery, the nucleation rate for static recrystallization

Table 1
Employed layouts in the cold rolling modeling.

Sample	1 pass	2 pass	3 pass
Reduction	50%	25%+25%	17%+17%+16 %

Table 2
Material properties of the examined aluminum alloy.

Material	Elastic modulus (GPa)	Poisson's ratio	Density (kg/m^3)
AA1050	70	0.33	2700

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