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Process metallurgy analyses to design a high-bendability and high-springback property sheet by using two-scale finite element method

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ABSTRACT

In this study, we develop bendability and springback prediction analysis code for an optimum crystal texture design to generate an ideal aluminum alloy sheet through the sheet rolling and heat treatment processes. To elucidate the relationships between the sheet metal formability and the crystal texture, we applied our two-scale finite element (FE) procedure based on the crystallographic homogenization method to analyze the bending and springback process. Our code employed two-scale FE model, such as the microscopic polycrystal structure and the macroscopic elastic plastic continuum by introducing the crystal orientation distribution, such as the texture characteristics. It means that our code can predict the plastic deformation of sheet metal in the macro-scale, and the crystal texture and hardening evolutions in the micro-scale. The macro-FE model consisted of the die, the punch and the sheet metal. The die and the punch were modelled as the rigid bodies in "V-bend" test problem. The crystal orientation distribution was employed in the microscopic polycrystal FE model, which was assigned by a three-dimensional representative volume element (RVE). This FE model was used as the initial textures for "V-bend" process analyses. The RVE model was featured as $3 \times 3 \times 3$ equi-divided iso-parametric solid elements, totally 27 FEs with 216 crystal orientations. Bendability was evaluated by the coefficient of shear strain concentration index using two-scale FE results. On the other hand, the springback characteristics were evaluated by springback angle defined by the angular difference between before and after springback, which occurred in the punch and die removing process. We studied two relationships between (1) the bendability and (2) the springback. Furthermore, we designed the polycrystal texture through the asymmetric rolling and annealing heat treatment process to generate a high-bendability and high-springback property polycrystal material. Annealing heat treatment was modeled as the growth of Cube $\{0\,0\,1\}\langle 1\,0\,0\rangle$ orientation by using the Johnson–Mehl–Avrami's equation. In the process optimization, we adopted the asymmetric rolling ratio and the annealing heat treatment time for the design parameters, and the bendability factor and the springback angle as the objective functions. The response surface algorithm was used to optimize the design parameter for maximizing the bendability and minimizing the springback angle. As an optimized result, the asymmetric ratio 1.13 and the annealing heat treatment time 13.5 min were obtained.

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1. Introduction

Recently, the high demands for high-formability sheet has grown in the automotive industry, because of quite severe bending has been introduced, such as the hem forming, for the complicated shaped parts of lightweight metal. Therefore, the aluminum alloy sheet, which is mainly used for automotive parts, is required to have better bendability and accurate forming property.

The crystallographic texture evolves at various stages in the mechanical processes and heat treatment of polycrystalline metals, such as the sheet rolling process and annealing, and has significant influence on the mechanical and metallurgical characteristics of the products. In particular, the texture evolution during plastic deformation is of great concern in sheet metal forming, because the evolving texture can lead to changes in the plastic anisotropy. Until now, there were several studies which aimed an improvement of sheet formability by optimization of material process by using optimization tool [1–6], and numerical tool was applied to analyze ASR sheet deformation and the optimized ASR process to concentrate toward $\{1\,1\,1\}$ plane by

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Nomenclature

C^{e}_{ijkl}	fourth order tensor of elastic modules
D_{kl}	rate of deformation tensor
$g^{(a)}$	reference shear stress on the slip system a
h_{ab}	coefficient of hardening evolution
h_0, τ_0	parameters of crystal plasticity constitutive law (initial hardening, critical resolved shear stress (CRSS))
m	coefficient of strain rate sensitivity
$\mathbf{M}^0$, $\mathbf{C}^0$, $\mathbf{P}$, $\mathbf{F}^0$	the mass, the viscous, the external force and the internal force in the macro-continuum region
$\mathbf{M}^1$, $\mathbf{C}^1$, $\mathbf{F}^1$	the mass, the viscous, the internal force in the micro crystal structure region
N	total number of slip systems
q_{ab}	latent hardening matrix
r	Lankford value (r-value)
$\dot{U}_i$	macroscopic velocity
$\dot{u}_i$	microscopic velocity
γ	accumulated shear strain
$\dot{\gamma}^{(a)}$	shear strain rate on the slip system a
$\dot{\gamma}^{(a)}_0$	reference shear strain rate
σ^{H}_{ij}	homogenized Cauchy stress tensor
σ_{ij}	Cauchy stress
$\hat{\sigma}^{*}_{ij}$	objective rate of Cauchy stress
$\tau^{(a)}$	resolved shear stress on the slip system a
λ	macro–micro scale factor

employing the response surface method for aiming to improve r-values to generate a high-formability sheet [5–10]. This means the concept of "process metallurgy." In the study field of bendability, Kuroda's shear band formation results show that Cube texture {0 0 1}⟨1 0 0⟩ which evolves in annealing process significantly enhances the resistance to shear localization [11,12] and there are several research which Cube component show high bendability [13–15]. Further, the asymmetric rolled material, which has shear texture, shows a high bendability [16–18]. But an optimum process design tool by aiming crystal texture control by using two-scale finite element (FE) analysis technique [19–28] to satisfy both high-bendability and high-springback property has not been developed successfully in the industrial application.

In this study, we develop the process metallurgy method combined by the optimization method, such as the response surface method, our crystallographic homogenized elasto/visco-plastic FE code [24–28], which applies to analyze the asymmetrical rolling (ASR) process. Further, the Cube texture evolution prediction algorithm by using Johnson–Mehl–Avrami's equation is adopted in the annealing process [29–31]. We apply our process metallurgy analysis method to search an optimum condition of asymmetric rolling (ASR) process and annealing process to generate a high-bendability and high-springback sheet.

2. Two-scale elastic/polycrystal plasticity FE procedure

2.1. Crystallographic homogenization procedure

Recently, the multi-scale FE codes based on Taylor's assumption, the homogenization algorithm and the self-consistent theory using the discrete Fourier transform algorithm, were proposed. These adopted the crystal plasticity theory and EBSD measured or random orientation models, and analyzed the texture evolutions [32–35]. We have already developed the two-scale dynamic-explicit type FE code, applied to several industrial forming processes, and confirmed its validation. We introduce both microscopic and macroscopic coordinate systems so that physical quantities are represented by two different length scales; one is $\mathbf{x}$ in the macroscopic region Ω and the other is $\mathbf{y}$ $(=\mathbf{x}/\lambda$: λ means the scale factor) in the microscopic region Y as shown in Fig. 1. Equations in the microscopic and macroscopic levels are derived by employing defined velocities, $\dot{U}_i$ and $\dot{u}_i$ [24].

The equation of virtual power principle for the micro polycrystalline structure is expressed as:

$$\int_V \rho\, \ddot{u}_i(\mathbf{x},\mathbf{y})\delta\dot{u}_i(\mathbf{x},\mathbf{y})dV + \int_V \nu\, \dot{u}_i(\mathbf{x},\mathbf{y})\delta\, \dot{u}_i(\mathbf{x},\mathbf{y})dV = -\int_V \sigma_{ij}\delta\, \dot{u}_{i,j}(\mathbf{x},\mathbf{y})dV, \tag{1}$$

$$\delta\dot{u}_i(\mathbf{x},\mathbf{y}) = 0: \text{ on the boundary of region } Y, \tag{2}$$

where ρ and ν mean the mass density and the viscosity coefficient, respectively. By solving the governing equation, Eq. (1), we obtain the Cauchy stresses σ_{ij}. The macroscopic Cauchy stress tensor, which means the homogenized stress tensor, σ^{H}_{ij} is obtained by averaging Cauchy stresses in microstructure as follows:

$$\sigma^{H}_{ij}\langle\sigma_{ij}\rangle = \sum_{e=1}^{N_e}\left(\sum_{G=1}^{N_G}|J_G|\sigma^{G}_{ij}\right)\Bigg/\sum_{e=1}^{N_e}|J_e| \tag{3}$$

where σ^{G}_{ij} is Cauchy stress at Gaussian integration point G of an FE in the microscopic region, $|J_G|$ is the Jacobian at the integration point, N_G is the total number of integration points.

We introduced the homogenized stress σ^{H}_{ij} and then formulate the virtual power equation of the macro-continuum as follow;

$$\int_\Omega \rho\ddot{U}_i(\mathbf{x})\delta\dot{U}_i(\mathbf{x})d\Omega + \int_\Omega \nu\dot{U}_i(\mathbf{x})\delta\dot{U}_i(\mathbf{x})d\Omega = \int_\Omega \bar{f}_i\delta\dot{U}_i(\mathbf{x})d\Omega + \int_{\Gamma_\sigma}\bar{T}_i\delta\dot{U}_i(\mathbf{x})d\Gamma - \int_\Omega \sigma^{H}_{ij}(\mathbf{x})\frac{\partial\delta\dot{U}_i(\mathbf{x})}{\partial\mathbf{x_j}}d\Omega \tag{4}$$

where Ω, Γ_σ, $\bar{f}_i$, and $\bar{T}_i$ are the volume, force boundary surface, the body force and the external surface force, respectively.

2.2. FE analysis based on dynamic explicit method

To solve equations of motion without solving simultaneous equations, the central difference method is applied to both microstructure and macro-continuum as follows:

$$\mathbf{u}^{t+\Delta t'} = \left(\frac{1}{\Delta t'^2}\mathbf{M}^1 + \frac{1}{2\Delta t'^2}\mathbf{C}^1\right)^{-1}\left\{-\mathbf{F}^1 + \mathbf{M}^1\frac{1}{\Delta t'^2}(2\mathbf{u}^t - \mathbf{u}^{t-\Delta t'}) + \mathbf{C}^1\frac{1}{2\Delta t'}\mathbf{u}^{t-\Delta t'}\right\} \quad : \text{for microstructure,} \tag{5}$$

$$\mathbf{U}^{t+\Delta t} = \left(\frac{1}{\Delta t^2}\mathbf{M}^0 + \frac{1}{2\Delta t^2}\mathbf{C}^0\right)^{-1}\left\{\mathbf{P} - \mathbf{F}^0 + \mathbf{M}^0\frac{1}{\Delta t^2}(2\mathbf{U}^t - \mathbf{U}^{t-\Delta t}) + \mathbf{C}^0\frac{1}{2\Delta t}\mathbf{U}^{t-\Delta t}\right\} \quad : \text{for macro-continuum,} \tag{6}$$

where $\mathbf{M}$ and $\mathbf{C}$ are the mass and damping matrices, $\mathbf{F}$ and $\mathbf{P}$ are the internal and external force vectors, $\mathbf{u}$ and $\mathbf{U}$ are the micro and macro displacement vectors, in which superscripts 0 and 1 mean macro-continuum and microstructure, respectively. At time t, microscopic equation of motion is solved by Eq. (5) under periodic boundary condition, which is based on macroscopic displacement $\mathbf{U}^t$, as shown in Fig. 2 [24]. When time is reached to $t+\Delta t$, the homogenized stress σ^{H}_{ij} is computed and is returned to Gaussian integration point on macro-continuum. After that, the macroscopic displacement is updated to $\mathbf{U}^{t+\Delta t}$ by Eq. (6). These incremental calculation processes are repeated during analysis. The time increments for macro-continuum and microstructure, Δt and $\Delta t'$ respectively, are determined as

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