International Journal of Mechanical Sciences 80 (2014) 109–121

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Two-scale finite element analyses for bendability and springback evaluation based on crystallographic homogenization method

Eiji Nakamachi [a], Takeshi Honda [a], Hiroyuki Kuramae [b,*], Yusuke Morita [a], Tomiso Ohata [c], Hideo Morimoto [d]

[a] Department of Biomedical Engineering, Doshisha University, 1-3 Tatara-Miyakodani, Kyotanabe, Kyoto 610-0394, Japan
[b] Department of Technology Management, Osaka Institute of Technology, 5-16-1 Omiya, Asahi-ku, Osaka 535-8585, Japan
[c] Department of Mechanical Engineering, Osaka Sangyo University, 3-1-1 Nakagaito, Daito, Osaka 574-8530, Japan
[d] Furukawa Electric Co. Ltd., 2-4-3 Okano, Nishi-ku, Yokohama 220-0073, Japan

ARTICLE INFO

Article history:
Received 11 September 2013
Received in revised form
25 December 2013
Accepted 13 January 2014
Available online 22 January 2014

Keywords:
Crystallographic homogenization method
Finite element method
Two-scale
Bendability
Springback
V-bending test

ABSTRACT

In this study, a relationship between the sheet metal formability, such as the bendability and springback property, and the crystal texture was investigated by using our two-scale finite element (FE) analysis code based on the crystallographic homogenization method (Nakamachi et al., 2010 [1]). Our code employed a two-scale finite element model, such as the microscopic polycrystal structure and the macroscopic elastic plastic continuum, which can predict the anisotropic 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, punch and sheet metal. The die and punch were modeled as the rigid bodies for "V-bending" process analyses. The measured crystal orientation distribution was adopted as the initial texture in the microscopic polycrystal FE model, which corresponded to the three-dimensional representative volume element (RVE). RVE model was featured as $3 \times 3 \times 3$ equi-divided solid finite elements, totally 27 FEs with 216 crystal orientations assigned at the integration points of micro-finite elements. The bendability was evaluated by the surface wrinkle growth index and the strain localization – the shear band formation – by using two-scale FE results. On the other hand, the springback property was defined by the angular difference between before and after the punch and die removing process – the post-process. At first, we investigated the bendability of single crystal sheets, which have typical preferred orientations of the copper alloy sheet, to elucidate the fundamental mechanism of shear band formation and wrinkle growth in the V-bending process. Next, we analyzed V-bending processes of four copper alloy polycrystal sheets to evaluate the bendability and springback property. The Cube-dominant texture sheet of the Corson series copper alloy and the $\{001\}\langle 110\rangle$-dominant texture sheet of the phosphor-bronze alloy show a high-bendability. On the other hand, the S-dominant texture sheet of the Corson series copper alloy and the Brass-dominant texture sheet of the phosphor-bronze alloy show a low-bendability. By contraries, the Cube-dominant and $\{001\}\langle 110\rangle$-dominant texture sheets have a low-springback property, and the S-dominant and Brass-dominant textures sheets have a high-springback property. Our two-scale FE results of four copper alloy sheets in the V-bending and the post-process were compared with experimental results, and finally the validity of our two-scale FE code was confirmed.

1. Introduction

Recently, the electronic components, such as the connector and switch, became miniaturized, because of narrow pitch packaging of electric components. Therefore, the copper alloy sheet used mainly for the electro-mechanical devices, such as the Corson series copper alloy (Cu–Ni–Si) and the phosphor-bronze (Cu–Sn–P), required better bendability and accurate forming property – a very low-springback. In this study, we develop bendability and springback prediction code, such as the two-scale finite element analysis code. The sheet metal formability strongly depends on the microscopic polycrystal structure and hardening at the initial, in-process and post-process of the forming. The crystallographic texture evolution and hardening occur in various stages of forming process, such as the casting, the sheet rolling and the heat treatment. Recently, an optimum texture of aluminum sheet for a high-formability is designed through a process-metallurgy simulation [1,2], which can be categorized as a new technology of "process metallurgy." Recently, in the bending process, it has been revealed by experimental studies that Cube orientation $\{100\}\langle 001\rangle$ of sheet has an extremely high

* Corresponding author. Tel.: +81 6 6954 4692; fax: +81 6 6952 6197.
E-mail address: kuramae@dim.oit.ac.jp (H. Kuramae).

0020-7403/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijmecsci.2014.01.011

Nomenclature

C^e_{ijkl}	forth 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
$M^0_{\alpha\beta}, C^0_{\alpha\beta}, P^0_{j\alpha}, F^0_{j\alpha}$	the mass, the viscous, the external force and the internal force in the macro-continuum region, respectively
$M^1_{\alpha\beta}, C^1_{\alpha\beta}, F^1_{j\alpha}$	the mass, the viscous, the internal force in the micro-crystal structure region, respectively
N	total number of slip systems
$N^0_\alpha\ N^{1[p,q]}_\alpha$	shape functions of the eight-node iso-parametric solid element for macro- and micro-finite element
q_{ab}	latent hardening matrix
r	Lankford value (r-value)
T	total parallel processing time
$\dot{U}_i$	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

resistance to the shear band formation and then a high-bendability [3,4]. Further, the asymmetric rolled material, which has shear texture, shows a high-bendability [5,6]. But, an optimum texture design tool to satisfy both high-bendability and high-springback property in the bending process has not been developed. Therefore, it is required to develop a two-scale finite element analysis technique [7–14] to evaluate both the sheet bendability and the springback property.

In this study, the dynamic explicit crystallographic homogenized finite element (FE) code [7–9,15,16] is applied to analyze the V-bending and springback processes of copper alloy sheet metals. At first, we studied the bendability of single crystal sheets, which have typical preferred orientations of the sheet, to elucidate the fundamental mechanism of shear band formation and wrinkle growth. Next, the V-bending and springback processes of four copper alloy sheet metals, such as annealed and rolled Corson series copper alloy sheet metals, and symmetric and asymmetric rolled phosphor-bronze sheet metals, are analyzed by employing the crystal orientation distribution measured by scanning electron microscope electron backscatter diffraction (SEM-EBSD) apparatus. We evaluate (1) the bendability and (2) the springback property of four copper alloy sheets, which have typical textures of rolled and heat treated sheets, by using our two-scale FE analysis code.

2. Two-scale elastic/plastic finite element procedure

2.1. Crystallographic homogenization procedure

Recently, the multi-scale finite element 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 [17–20]. We have already developed the two-scale dynamic-explicit type finite element code and applied to several industrial forming processes and confirmed its validation. In our two-scale finite element code, we introduce both microscopic and macroscopic coordinate systems so the physical quantities are represented by two different length scales; one is $\boldsymbol{x}$ in the macroscopic region Ω and the other is $\boldsymbol{y}(=\boldsymbol{x}/\lambda{:}\lambda$ means the scale factor) in the microscopic region Y as shown in Fig. 1. The equations in the microscopic and macroscopic levels are derived by employing defined velocities, $\dot{U}_i$ and $\dot{u}_i$ [7].

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

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

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

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:

$$\sigma^H_{ij} = \langle\sigma_{ij}\rangle = \sum_{e=1}^{N_e}\left(\sum_{G=1}^{N_G} |J_G|\sigma^G_{ij}\right) \Big/ \sum_{e=1}^{N_e} |J_e|, \quad (3)$$

where σ^G_{ij} and $|J_G|$ are Cauchy stress and the Jacobian calculated at Gaussian integration point G of a finite element in the microscopic

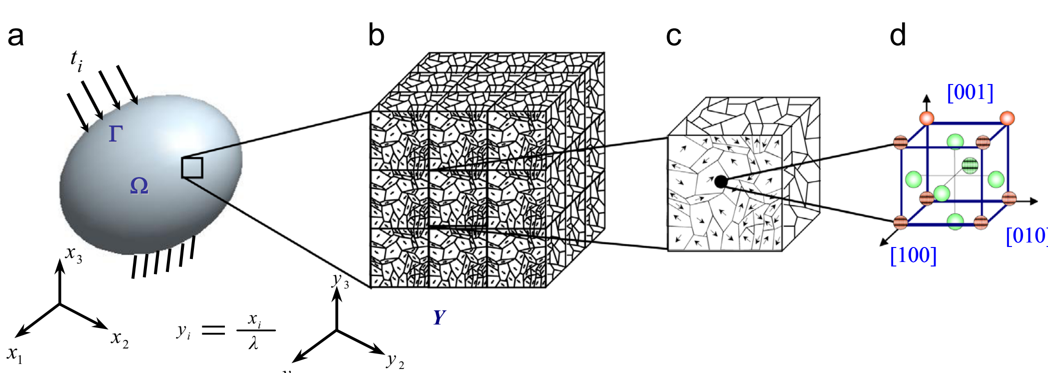

Fig. 1. Macroscopic continuum and micro-polycrystal structure: (a) macro-continuum, (b) micro-polycrystal structure, (c) RVE and (d) crystal lattice.