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Finite element simulation of accumulative roll-bonding process

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A B S T R A C T

The accumulative roll-bonding (ARB) process, which is a severe plastic deformation process, was simulated using finite element analysis, including the influence of friction, stress–strain relations, and roll diameter. The complicated distributions of equivalent strain through the thickness of ARB-processed sheets were quantified. These quantitative strain analyses would be useful for analyzing the evolution of ultrafine-grained structures in the ARB process.

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1. Introduction

Bulk ultrafine-grained (UFG) materials with grain sizes of tens to hundreds of nanometers, which show improved mechanical properties without the addition of alloying elements, have attracted the attention of researchers in materials science. Since the microstructural evolution of plastically deformed materials is directly related to the magnitude of the plastic strain, understanding of the phenomenon associated with the strain development is very important. In accumulative roll-bonding (ARB), which is a severe plastic deformation (SPD) process for realizing UFG microstructures in metals and alloys, the microstructure and texture in a sheet processed by one ARB cycle without a lubricant dramatically changed depending on the thickness location of the sheet [1–3]. The embedded-pin method is often employed to measure the strain through thickness experimentally [4,5], but magnitude of the strain obtained by this method does not exhibit an exact value [6]. To control the microstructures, it is essential to understand the deformation behavior in the ARB-processed sheets accurately and quantitatively. Although some studies have used finite element analysis (FEA) for other SPD processes, such as equal-channel angular pressing (ECAP) [7], high-pressure torsion [8], and warm caliber rolling [9,10], there have been no reports for the ARB process. This study aims to quantify the equivalent strain in ARB-processed sheets using FEA, including the influence of friction, stress–strain relations and roll diameter.

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2. Modeling of ARB process

The two sheets were set in order to analyze three ARB cycles, as shown in Fig. 1a. The sheet is composed of two sheets with dimensions of 1 mm $t \times 12$ mm L. The finite element mesh in each sheet with dimensions of 2 mm $t \times 12$ mm L shown in Fig. 1b included 4141 nodes and 4000 elements. The mesh size in the thickness direction, t_{el}, is constant, $t_{el}=0.05$ mm. The mesh size in the longitudinal direction, L_{el}, gradually decreases toward the center from front and back, and the minimum L_{el} is 0.025 mm at mid-length (center element). In the present study, the condition of a commercial 1100 Al sheet rolled at ambient temperature, as reported by Lee et al. [1], was referred to as the rolling condition: initial thickness, $t_0=2$ mm; nominal reduction per pass, $r=50\%$; roll diameter, $d^{\Phi}=255$ mm; and rolling speed, 170 mm s^{-1}. In addition, the case of a small roll diameter, $d^{\Phi}=118$ mm, was also examined because the strain depends strongly on the roll diameter as well as the friction [11]. Young's modulus of 70 GPa and Poisson's ratio of 0.35 were used as the elastic modulus. The stress σ–strain ε relationships of 1100 Al at 301 K employed in the analysis were described by $\sigma=28+105.67\varepsilon^{0.32}\dot{\varepsilon}^{0.017}$ MPa, but the flow stresses were assumed to remain constant at $\varepsilon=4.0$ because hardness does not vary at equivalent strain of over 4.0 on the basis of the ECAP studies [12]. In order to investigate the effect of the σ–ε relations, the simulation for the 1100 Al at 473 K was also conducted using $\sigma=\sigma_0+K\varepsilon^n\dot{\varepsilon}^m$, where $\sigma_0=20$ MPa, $K=58.40$ MPa, $n=0.24$ and $m=0.0405$ with Young's modulus of 60 GPa and Poisson's ratio of 0.35. The Coulomb condition was used as the frictional condition between the rolls and the sheet. Assuming the Coulomb law, the minimum friction coefficient, μ, is 0.13 for $d^{\Phi}=118$ mm and 0.09 for $d^{\Phi}=255$ mm. Here, as the lubricated

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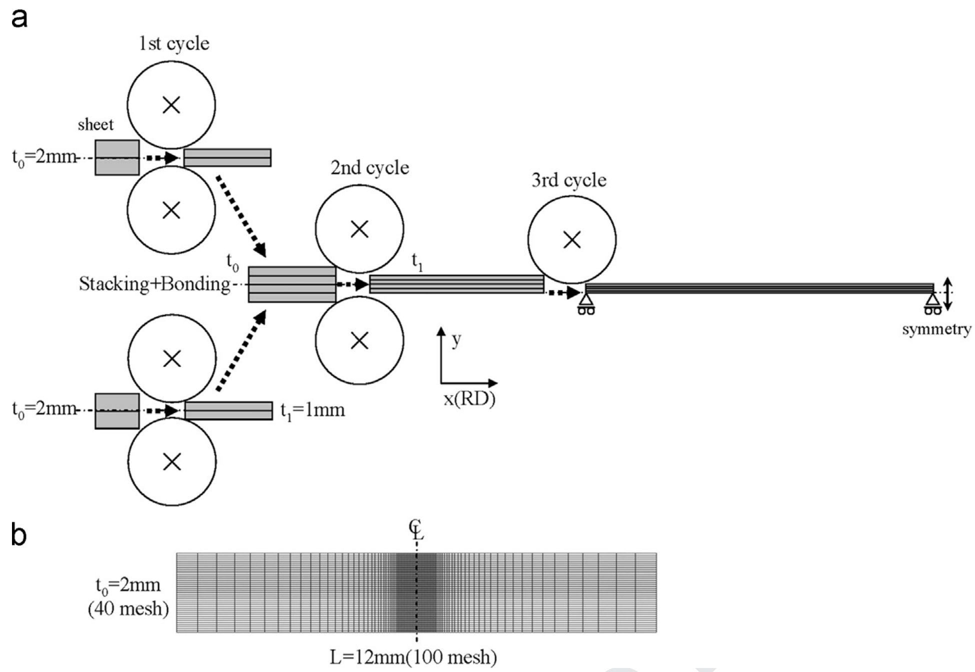

Fig. 1. Schematic illustration of three ARB cycles and finite element mesh used.

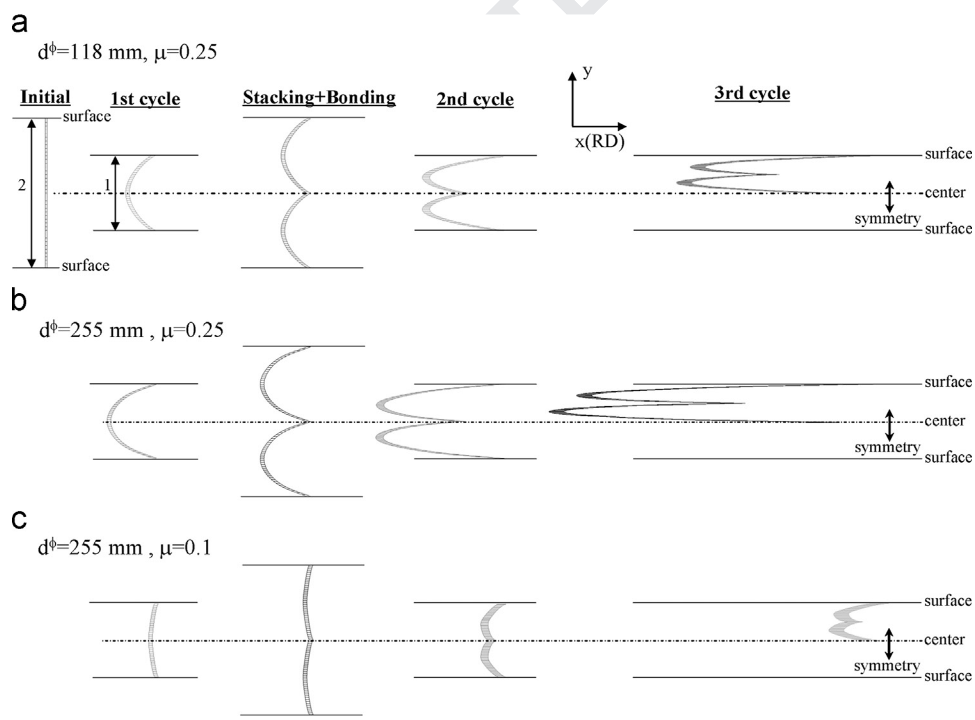

Fig. 2. Deformation histories of the center part of the FE mesh in the ARB process against roll diameter d^{ϕ} and friction coefficient μ.

conditions, $\mu=0.14$ for $d^{\phi}=118$ mm and $\mu=0.1$ for $d^{\phi}=255$ mm were adopted; furthermore, as the unlubricated condition, $\mu=0.25$ was adopted for both diameters.

In the analysis, the classical metal plasticity models with a von Mises yield surface, *PLASTIC, HARDENING=ISOTROPIC as keyword in ABAQUS, were employed. The equivalent strain, ε_{eq}, imposed by rolling is defined as follows:

$$\varepsilon_{eq} = \int_0^{t(\text{steady})} \frac{d\varepsilon_{eq}}{dt}\,dt \tag{1}$$

where $d\varepsilon_{eq}/dt$ denotes the incremental equivalent strain, and $t_{(\text{steady})}$ is the rolling time [11].

In the ARB simulation shown in Fig. 1a, first, a 2 mm-thick sheet was rolled to a thickness of 1 mm by 50% (1st ARB cycle). Subsequently, the two 1 mm-thick rolled sheets were stacked to be 2 mm in thickness and rolled again to a thickness of 1 mm (2nd ARB cycle). In order to repeat this procedure, a symmetry condition in the y-axis was set before the next rolling, and the sheet was rolled (3rd ARB cycle). Hence, for the 1st and 2nd ARB cycles, a 1/1 model was adopted, and, for the 3rd ARB cycle a 1/2 model was

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