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Asymmetric rolling of interstitial free steel sheets: Microstructural evolution and mechanical properties

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ABSTRACT

Asymmetric rolling (ASR) is a promising method for introducing shear deformation throughout the thickness of sheets. The induced shear deformation in ASR will result in texture evolution and which could also affect microstructural features controlling mechanical properties (such as the tensile strength). The main objective of this work consists of the investigation of the influence of ASR process on microstructure and texture evolution and their induced mechanical properties in interstitial free (IF) steel sheets. Both reverse and continuous asymmetric rolling were carried out to deform IF steel sheets. The results of optical microscopy observations showed no significant differences between the grain morphology of asymmetric and conventionally rolled (CR) samples. However, the obtained results of transmission electron microscopy (TEM) and electron backscatter diffraction (EBSD) indicated that fine and equiaxed microstructure was formed through the asymmetric rolling process. Texture evolution through plastic deformation has also been analyzed using X-ray diffraction. In addition, polycrystalline plasticity simulations were used to predict the texture evolution and the induced mechanical properties. The effect of the induced amount of pre-straining on the mechanical response of the samples through uniaxial tensile test has been studied. Results showed that at low thickness reductions (18%) the asymmetric rolled sample presents higher stress than that of the conventionally rolled sheet; while for higher thickness reductions (60%) the trend is reversed.

1. Introduction

Improving the mechanical properties is desirable for reducing the weight of engineering materials used in components. This can directly translate into significant economic gains. Such a challenge can be partially met by reducing the grain size and controlling texture evolution. This has been has demonstrated by experiments that were performed with equal channel angular pressing [1], accumulative roll bonding [2] and high pressure torsion [3]. These previous works showed that shear plastic deformation applied through the methods, has a key role in grain refinement that allows for the production of the preferred texture in metallic materials. However, a weakness of these processes is the fact that they are conducted on samples with limited dimensions. This is a key factor that greatly affects their potential for industrial applications.

Recently, the Asymmetric rolling (ASR) process has been introduced. This process is able to produce ultrafine grain materials as well as develop desirable crystallographic texture with enhanced performance in metallic sheets for particular applications [4]. The principal base of ASR is the elimination of symmetries of conventional rolling (CR) process which causes shear deformation throughout the thickness of the metallic sheet. Kim and Lee indicated that various configurations can be used including different circumferential velocities of the two working rolls due to their different diameters or rotation speeds [5]. Also, Utsunomiya et al. introduced shear plastic deformation throughout the thickness of metallic sheets by applying different lubrication conditions [6]. In our previous study, the effect of ASR and heat treatment on texture modification of an aluminium alloy and subsequently on their mechanical response has been taken into consideration [7]. Furthermore, it was indicated that optimizing the process parameters,

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Table 1
Chemical composition of as received IF steel.

C	Ti	V	Ni	Mn	Co	Mo
0.004%	0.040%	0.001%	0.017%	0.061%	0.002%	0.002%

Table 2
Material constants for the IF steel sample in Eq. (2).

τ_0	θ_0	θ_1	τ_1
187 MPa	985 MPa	17 MPa	43 MPa

e.g. thickness reduction per pass, velocity ratios and contact conditions between the rolls and sample surface, can increase the shear plastic deformation through the sheet thickness [8]. The shear plastic deformation produced the desired texture, which resulted in enhanced mechanical properties in aluminium-magnesium alloy sheets. There have been a number of publications in recent years on the ASR process being used on steel sheets. Lee and Lee [9] employed the ASR at high temperatures on IF steel sheets and observed the impact of extra shear strain on texture evolution of IF steel during warm-ASR process whereas in the work of Wauthier et al. [10], the influence of ASR on the texture evolution during post annealing of recrystallization in the same material has been taken into account. In addition, Ding et al. used ASR process to produce an ultrafine structure in commercially available iron sheets, with the goal of increasing the strength of metallic sheets [11]. Cai et al. took the advantage of ASR and dynamic transformation to produce a gradient-distributed ultrafine grain ferrite and martensite duplex structure in micro-alloyed steel sheets [12]. In spite of previous studies regarding the ASR of steels, the impact of shear plastic deformation introduced in ASR and the effect of strain path changing in multi pass ASR process on microstructure of steels and their induced mechanical properties have not been systematically investigated. In the present study, IF steel sheets were asymmetrically rolled and the influence of shear deformation and strain path changing on the micro- and macro- properties of the specimens is investigated.

2. Experimental procedures and modelling

The material used in the present study was 1.2 mm thick IF steel sheet. The annealed sheet had an average grain size of about 25 μm. The chemical composition is given in Table 1.

The as-received samples were subjected to four ASR (and CR) passes leading to 60% of total reduction. The ASR process was carried out using a velocity ratio equal to 1.5 of upper to lower working-rolls (4 and 6 rotates per minutes as absolute speeds for the working-rolls) and without lubrication. We designated these plastic deformation routes as CR for conventional rolling and two types of ASR:

- Reverse asymmetric rolling (R-ASR) in which the rolling direction was reversed after each step.
- Continuous asymmetric rolling (C-ASR) in which the samples were not reversed with respect to rolling direction.

Schematics of these processes are shown in Fig. 1.

The resulting microstructure was investigated by optical microscopy and TEM. In addition, crystallographic texture measurement was performed using an X-ray diffractometer; with an X-ray texture goniometer, at the mid-thickness locations of the sheets. With the aim of studying the effect of using different strain paths on the microstructure and mechanical behaviors, heat treatment of recovery have also been carried out. For that end, the rolled samples were placed in an electrical furnace at 550 °C for 60 min. Subsequently, the influence of the heat treatment on the microstructure evolution was studied using EBSD analyses. Furthermore, tensile test specimens were prepared along the rolling direction (RD) from CR and C-ASR sheets and the tensile tests were conducted at ambient room condition and an engineering strain rate of $10^{-4}s^{-1}$ was used. In the last round of experiments, the influence of the total reduction of rolling (*i.e.* CR *vs.* C-ASR) on their mechanical behavior was investigated by imposing total thickness reductions of 18%, 36% and 60% followed by a recovery annealing as described previously.

The viscoplastic self-consistent (VPSC) model was employed in order to study the texture evolution through different types of rolling as described before. The VPSC model was firstly proposed by Molinari et al. [13] and was later developed by Lebensohn and Tome [14]. In this modeling, plasticity of the BCC single crystals of IF steel occurs by crystallographic slip on {110} <111>, {112}<111>, {123}<111> slip systems. The initial critical resolved shear stress is assumed the same for all slip systems.

The initial sample texture that was obtained from the X-ray data were used as input files for the VPSC code. The macroscopically imposed velocity gradient for the sheets under CR and ASR processes is approximated by plane strain compression for CR and combined plane strain compression and shear for ASR (Eq. (1)):

$$L_{CR} = \begin{bmatrix} \dot{e}_{11} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \dot{e}_{33} \end{bmatrix}, \; L_{ASR} = \begin{bmatrix} \dot{e}_{11} & 0 & \dot{e}_{13} \\ 0 & 0 & 0 \\ 0 & 0 & \dot{e}_{33} \end{bmatrix} \tag{1}$$

Here, $\dot{e}_{11}$, $\dot{e}_{33}$ and $\frac{1}{2}\dot{e}_{13}$ are strain rate components with indices 1–3 representing the normal, transvers and rolling directions, respectively. The tensor L presents the macroscopic velocity gradient. The through thickness shear strain under each pass of ASR was measured. To this end, a number of lines were scratched on the side (TD plane) of the sheet samples perpendicular to the ND plane using a metallic pen. During the ASR process, the lines become inclined by an angle with respect to the ND axis due to the shear plastic deformation as shown in Fig. 2. The measured inclination of the lines represents the additional shear deformation induced by ASR allowing us to evaluate the shear component of the velocity gradient tensor of ASR process.

Furthermore, the VPSC model was used to simulate the tensile stress-strain curves of different samples and the predicted results were compared to the experimental ones. For that, the threshold resolved shear stress-accumulated shear strain relationship of a single crystal ($\tau - \Gamma$)proposed by Tome et al. [15] was used:

$$\tau = \tau_0 + (\tau_1 + \theta_1 \Gamma)(1 - exp\left(-\Gamma \left|\frac{\theta_0}{\tau_1}\right|\right)) \tag{2}$$

Here, τ_0, θ_0, θ_1 and $(\tau_0 + \tau_1)$ are the initial critical resolved shear stress (CRSS), the initial strain hardening rate, the asymptotic hardening rate and the back-extrapolated CRSS, respectively. To determine these coefficients, we used tensile stress-strain curve of the CR sample as a reference and the values are therefore obtained by fitting, as presented in Table 2.

3. Results and discussion

3.1. Texture development under plastic deformation

In this section, the crystallographic textures are shown by ODFs in the Euler space represented by Phi_1, Phi and Phi_2 angles (Bunge's notation) [16]. Usually, the Euler space section at $Phi_2 = 45°$is only presented since the most important texture components of BCC materials are in this section. Fig. 3 shows the $Phi_2 = 45°$ section of the ODF presentation of the sheets deformed using CR and C-ASR. In order to facilitate the interpretation of the developed texture