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# Influence of asymmetric hot rolling on through-thickness microstructure gradient of Fe–20Mn–4Al–0.3C non-magnetic steel

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ABSTRACT

Through-thickness microstructure gradient as a function of asymmetric hot rolling (ASHR) process parameters was investigated for a high manganese non-magnetic steel. Shear strain distribution was calculated using a two-dimensional finite element method. According to the simulation results, the surface layer of ASHR plate undergoes the highest total shear deformation which leads to the formation of a fine-grained surface layer under conditions of large rolling reduction and relatively high temperature. In the central layer is still the partially recrystallized microstructure. With velocity ratio increasing, the depth of fine-grained surface layer approaches 1/4 plate thickness, while the recrystallization proportion for the central layer is also enhanced due to the reinforced extra shear deformation. By appropriate parameter optimization, the austenitic grain size is finally refined to $\sim$5 μm for the surface layer and $\sim$9 μm for the center, such that the tensile property is improved.



## 1. Introduction

High-Mn non-magnetic steels are one kind of functional steel materials widely used in many engineering fields and situations such as cryogenic superconducting, nuclear fusion reactor, electronic measuring instrument and the concrete reinforcing bars for radar installations. The so-called non-magnetism originates essentially from the low permeability of paramagnetic austenite matrix [1–3]. Nevertheless, hot rolled non-magnetic steels usually consist of coarse austenitic grains that have a relatively low yield strength, thereby limiting their industrial application to some degree.

For improving both the strength and ductility of high-Mn non-magnetic steels by further grain refinement, asymmetric rolling (ASR) method is reportedly one of the most feasible candidates for the large-scaled steel sheet production [4], compared with equal channel angular pressing (ECAP), high pressure torsion (HPT) and other severe plastic deformation (SPD) methods [5,6]. ASR can be easily achieved by the different circumferential velocities of two working rolls with different diameters or rotational speeds, which introduce an extra shear deformation throughout the plate thickness. The extra shear deformation can increase the equivalent strain for asymmetric hot rolling (ASHR) process, and give rise to an effective grain refinement by promoting the recrystallization nucleation in comparison with conventional symmetric hot rolling (SHR) process. The refined austenitic grains not only exhibit a higher strength but also can enhance the phase stability. Furthermore, the superior austenitic stability always plays a critical role in remaining low permeability and resisting the ferromagnetic martensite transformation during room- and cryogenic-temperature deformation [3,7].

Both the stress and strain field of deformation region related to the sheet flatness have been extensively investigated under asymmetric cold rolling (ASCR) condition [8,9]. Undoubtedly the asymmetric shear stress distribution induced by ASR will exert a certain but distinguishable influence on the microstructural state variables (grain size, dislocation density, orientation, *etc*) for different deformation layers along the thickness direction [10]. Such microstructure gradient, especially in terms of ASCR followed by an annealing, greatly affects the nucleation homogeneity and grain size for the subsequent recrystallization event on annealing. Analogous microstructural inhomogeneity is most likely to be enlarged during ASHR process, because the extra shear deformation becomes harder to penetrate from the surface to the central layer for a larger thickness of hot rolled plates than that of cold rolled sheets. Accordingly, ASHR method, on the one hand, can promote the further grain refinement for hot rolled plates, on the other hand, it may also cause a microstructure gradient through-thickness in the case of inappropriate processing parameters. This disadvantage of inhomogeneous microstructural distribution probably will influence the final mechanical properties of non-magnetic steel products, and hence should be evaluated in more detail.

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However, most of the published literatures focus on comparing the individual effect of SHR and ASHR on the microstructure and texture evolution for metallic materials, including magnesium and aluminum alloys, carbon steels, electrical steels and stainless steels [11–13]. Chen et al. [14] reported the toughness improvement in a hot rolled HSLA steel plate using ASHR method. Liu and Kawalla [15] investigated the grain refinement effect caused by ASHR process for AISI304 steel. The results showed that the austenitic grains in the central layer could be refined from ~67 μm to ~20 μm at a relatively high temperature and large thickness reduction. Nevertheless, the likely appearance of microstructure gradient extending from top surface to the bottom was hardly implicated in both works.

In this paper, the emphasis was laid primarily on the through-thickness microstructure gradient as a function of ASHR processing variables for a high-Mn non-magnetic steel. Extra shear deformation at different depths was quantitatively calculated according to a two-dimensional finite element method (FEM). The influence of such inhomogeneous distribution of microstructure on the microhardness and tensile properties was also evaluated for the ASHR plates. By appropriate process optimization, the through-thickness microstructure gradient can be largely avoided, and an improved mechanical property arising from significant grain refinement can be expected for the ASHR plates of high-Mn non-magnetic steels.

## 2. Experimental

The material used in present study is Fe–20Mn–4Al–0.3C non-magnetic steel. Steel making was performed in a vacuum induction furnace. The cast ingots were forged and cut into several billets, followed by seven passes conventional hot rolling within the temperature range of 920–1050 °C. The hot rolled plate with a final thickness of 5.5 mm was subsequently used as the billets for ASHR experiments. The single-pass ASHR procedure was conducted on a Φ400 two-roll reversible rolling mill in the laboratory. The asymmetric rolling condition was implemented via the different circumferential velocities of two working rolls with the same diameters but different rotational speeds. Three velocity ratios were selected, corresponding to 1.0 (i.e. SHR used for comparison), 1.1 and 1.2, respectively. The velocity of lower roll always remained constant and was slower than that of the upper roll. The workpiece was held for 20 min at a certain temperature before ASHR and water-quenched immediately after a finished ASHR procedure. A portable infrared thermometer was used for the temperature measurement. A more detailed schedule has been given in Table 1. Compared with the ASCR process in which workpiece can be easily reversed, the interference from both the complex strain path and inconstant temperature drop between two rolling passes can be greatly diminished in present single-pass ASHR experiment. As a consequence, the experimental accuracy and feasibility for investigation on the influence of ASHR processing variables were both increased.

A two-dimensional rigid-plastic finite element method (FEM) was utilized to obtain the shear stress and strain fields of deformation region in the roll gap during ASHR, based on the flow stress model for experimental steel regressed from the data of uniaxial compression on a thermomechanical simulator [16]. The frictional condition and heat transfer between steel plate and rolls were also taken into account. The metallographic microstructure of single-pass ASHR plates was etched by 5 vol% Nital. Recrystallized fraction and refined grain size for both surface and central layers were measured using electron backscattered diffraction (EBSD) techniques on a Zeiss Ultra 55 field emission scanning electron microscope (SEM). In addition, tensile properties of single-pass ASHR plates were tested on an INSTRON 4206 universal tensile testing machine at a cross-head displacement rate of 2 mm/min. The tensile samples were cut off along the rolling direction (RD) and have a gauge length of 25 mm. Microhardness distribution across the plate thickness was also examined using a FUTURE-TECH FM-700 microhardness tester. The values at five various locations of the same depth were measured and then averaged.

**Table 1**
Single-pass ASHR schedule including circumferential velocity of lower roll ($\upsilon$), velocity ratio ($R_v$), Heating Temperature (HT), start rolling temperature (SRT), finish rolling temperature (FRT) and reduction.

| Process | $\upsilon$ (m/s) | $R_v$ | HT (°C) | SRT (°C) | FRT (°C) | Reduction (%) |
|---|---|---|---|---|---|---|
| ASHR-1 | 1 | 1.0/1.1/1.2 | 1100 | 1050 | 1010 | 60 |
| ASHR-2 | 1 | 1.0/1.1/1.2 | 1100 | 1000 | 940 | 60 |
| ASHR-3 | 0.5 | 1.0/1.1/1.2 | 1100 | 1000 | 940 | 60 |
| ASHR-4 | 1 | 1.2 | 970 | 930 | 830 | 60/40/20 |
| ASHR-5 | 1 | 1.0/1.1/1.2 | 970 | 860 | 750 | 60 |

## 3. Results

### 3.1. Microstructure gradient of ASHR plate

#### 3.1.1. Effects of velocity ratio and thickness reduction

Fig. 1 shows the microstructural evolution both on upper surface (contacting fast roll) and in the central layer with varying velocity ratio under ASHR-3 process. It is seen that a noticeable microstructure gradient exists in the 2.2 mm thick plates along normal direction (ND). At $R_v$=1.0 (i.e. SHR) a fine-grained layer with the thickness of ~150 μm is produced near the upper surface due to the intense frictional action from the rotating rolls. As the velocity ratio is raised to 1.1 and 1.2, the depth of fine-grained surface layer is increased up to ~300 μm and ~400 μm, respectively. The average grain size of fine-grained layer approximates 5 μm. If the annealing twins are excluded, the average grain size recalculated by EBSD analysis is around 9 μm (See Fig. 3a). With the microstructure gradient extending from surfaces to the center, the recrystallization fraction is gradually reduced because of the diminished shear deformation. The heavily deformed austenitic grains still remain predominant in the partially recrystallized microstructure for the central layer. With the increasing velocity ratio, its recrystallization fraction is also improved.

It is worth noting that the microstructural evolution in either the lower surface or subsurface layer behaves almost as the same as that of the upper half. The fine recrystallized grains, whether in surface layer or at the center, are all nucleated and grow through the static recrystallization after a finished rolling pass immediately. The possibility of the occurrence of dynamic recrystallization can be ruled out, because the strain rate of workpiece is estimated as ~40 $s^{-1}$ and ~20 $s^{-1}$, respectively, for ASHR-2 and ASHR-3 processes, at which dynamic recrystallization can hardly be activated for the experimental high-Mn non-magnetic steel [17]. Fig. 2 shows the variation of surface microstructure with different thickness reductions in Process ASHR-4. At this rolling temperature the static recrystallization can hardly be activated until the thickness reduction up to 60%. Under such a reduction level, only a few partially recrystallized grains are present both on the surface and in central layer for the ASHR plate.

#### 3.1.2. Effects of rolling temperature and roll speed

Fig. 3 shows EBSD image quality (IQ) maps of the microstructure on top surface for ASHR-2, ASHR-4 and ASHR-5 plates with different SRT at $R_v$=1.2 and reduction of 60%. The dominant