Improving Ductility in Dual-Phase Steel by Cold Rolling and Intercritical Annealing

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Abstract. Dual-phase steels offer huge potential to provide a cost-effective solution in the automobile industry to fulfill the demand for high strength with formability. The desirable strength is achieved by increasing geometrical necessary boundaries and ferrite grain refinement but not by increasing martensite fraction. The major challenge is to improve the ductility and formability, without compromising its strength. In this work, cold rolling reductions to \( \sim 84\% \) was given to hot rolled annealed steel, followed by intercritical annealing and water quenching. Tensile tests, Optical microscopy, Electron Back Scattered Diffraction and X-Ray characterizations were carried out. The improvement in strength and ductility were correlated with microstructure and texture.

Keywords: Dual-phase steel; Cold rolling; Intercritical annealing; Microstructure; Texture; Ductility

1. Introduction

Dual-phase (DP) steels are one of the most important members of the advanced high strength steel (AHSS) family, widely used as automobile structural components [1,2]. These steels are low carbon alloyed steels with Mn, Si, Cr, Nb, Ti, Mo, and B additions up to 4\% [2,3]. The low alloying in DP steels leads to lower the production cost, ease of casting due to less segregation effect, better weldability and simple thermomechanical treatments in comparisons to other steels in the AHSS family [2,3]. These steels are industrially produced using a combination of hot/cold rolling and intercritical heat treatments [2,4–6]. The microstructure of DP steels mainly consists of ferrite and martensite phases, with some bainite and retained austenite [1,7]. This composite microstructure provides continuous yielding, high tensile strength with limited ductility and formability [7–10]. The reason for limited ductility and formability is the low damage tolerance in DP steels due to martensite cracking and martensite-ferrite interface decohesion [7,9]. Damage tolerant DP steels could be produced by engineering the microstructure and texture. Ultrafine ferrite grains with finely dispersed martensitic islands \( \sim 30\% \) volume fraction are the most desirable microstructural features in DP steels for better endurance limit and formability [2,11]. It is important to carry out a fundamental study to develop a deeper understanding of microstructure, texture and deformation mechanisms to guide novel strategies to develop ductile, formable, and damage-tolerant DP steels. In this work, cold rolling (CR) studies of an annealed DP steel has been carried out in conjunction with intercritical heat treatment (IHT). The evolution of the microstructure and texture in correlation with ductility and formability is investigated.

2. Experiments and Methodologies

A DP steel (chemical composition: C < 0.10\%, Mn < 2.0\%, Si < 0.5\%, and Cr < 1.0\%) was used in this study. Hot rolled steel sheets were annealed at 1163K (890\degree C) for 60 mins to obtain a full ferrite microstructure as the initial material for this study (figure 1a,d). The initial steel sheets were subjected to CR up to \( \sim 84\% \) (\( \varepsilon_{VM} = 2.1 \)) rolling reductions, followed by intercritical annealing at 1113K (840\degree C) for 60 min and water quenching. These intercritically annealed samples were further annealed at 873K (600\degree C) for 15 min and water quenched. Tensile tests were performed as per ASTM E-8 on a miniature sample geometry. Optical and EBSD analysis were carried out on the ND-RD plane.
EBSD data were analyzed using TSL-OIM software. Crystallite size and dislocation density were determined by X-ray line profile analysis [12,13].

3. Results

3.1 Microstructural Features
The optical micrographs, inverse pole figure (IPF) maps and grain size distributions for the initial, CR and CR+IHT steels are shown in figure 1. The IPF maps (figure 1d-f) represent the orientation of the grains by different colors as per the crystallographic triangle code. The initial steel had a unimodal grain size distribution that ranges from ~1 − 25μm (figure 1g) with an average grain size of 8.2 ± 3.2μm. After CR (figure 1b) thin elongated grains could be observed (figure 1b,e). A bimodal grain size distribution ranging from ~0.20 − 20μm (figure 1h), with an average grain size of 8.2 ± 8μm was observed. The first peak lies at the start of distribution around ~0.2μm in small grains range, and these small grains have formed due to the phenomena of dynamic recrystallization (DRX) during deformation. The other peak lies at the end of distribution around ~21μm which indicate elongated deformed grains, where DRX did not take place. The CR +IHT processed steel sheet possesses island type ferrite ~34% martensite morphology (figure 1c,f) with equiaxed grains, size ranging from ~0.40 − 16μm and average grain size, 5.5 ± 3.5μm.

Figure 1. (a-c) Optical microstructures, (d-f) Inverse pole figure (IPF) maps, and (g-i) Grain size distributions for the Initial, CR and CR+IHT processed steel sheets.
Further, the density of geometrically necessary boundaries (GNB) with $2^\circ - 15^\circ$ misorientation angles, random high angle boundaries (RHAGB) with $15^\circ - 65^\circ$ misorientation angles and coincidence site lattice (CSL) boundaries (a subset of $15^\circ - 65^\circ$ boundaries) were determined from the EBSD data (figure 2a). The GNB are defined as curvature type dislocations arising during deformation due to dislocation activity inside the grains [14]. They are subgrain feature with $2^\circ - 15^\circ$ misorientation angles and usually captured during EBSD analysis using a fine step size. The GNB and RHAGB density increases from the initial state ($\sim 0.05 \times 10^{12} m^{-2}$ and $\sim 0.04 \times 10^{12} m^{-2}$) to after CR ($\sim 0.6 \times 10^{12} m^{-2}$ and $\sim 1.39 \times 10^{12} m^{-2}$), respectively. It reduces after the IHT to ($\sim 0.5 \times 10^{12} m^{-2}$ and $\sim 0.42 \times 10^{12} m^{-2}$). The CSL density remains the same and negligible $\sim 0.05 \times 10^{12} m^{-2}$ for all the samples. The $(110)$ X-ray diffraction peak was used to obtain the crystallite size and statistically stored dislocation (SSD) density [12,13]. The SSD density showed a similar trend, as the GNB density obtained from EBSD (figure 2b). Corroborating the observation the crystallite size decreases from 56nm to 48 nm after CR followed by an increase to 63nm after IHT (figure 2b).

![Figure 2](image-url). (a) GNB, RHAGB, CSL boundary density; and (b) Crystallite size, dislocation density; for the the initial, CR and CR+IHT steel sheets.

### 3.2. Crystallographic Texture
The $\varphi_2 = 0^\circ$ and $\varphi_2 = 45^\circ$, sections of the orientation distribution functions (ODF) sections were utilized to represent the texture in figure 3a-c for the initial, CR and CR+IHT steel sheets. The ideal orientations for rolling of BCC materials are shown in figure 3d. The initial material possesses a weak $\alpha$-fiber, $\beta$-fiber as well as partial $\gamma$-fiber with $\sim 2.6$ multiples of random distribution (MRD). After CR $\gamma$-fiber with the intensity of $\sim 5$ MRD, and a partial but strong $\theta$-fiber, with intensity of $\sim 10$ MRD at the rotated cube positions could be observed. The texture spreaded as well as diffused after IHT with the presence of faint $\theta$, $\beta$ and $\gamma$- fibers.

### 3.3 Mechanical Properties
Table 1 compares the yield strength (YS), ultimate tensile strength (UTS), ductility ($\varepsilon_f$), and uniform elongation ($n$) of the initial, CR, and CR+IHT steel sheets. The YS and UTS increase substantially after CR, but ductility decreases from $\sim 0.58$ to $\sim 0.15$. The ductility is restored to 0.51 after IHT with a reasonable compromise in YS and UTS to $\sim 396$MPa and $\sim 544$MPa, respectively. The uniform elongation, which is equivalent to strain hardening exponent and is an index to show formability, reduces after CR. However, it regains and become quite high, $\sim 0.35$ after IHT. After CR+IHT, DP steel with desirable ferrite-martensite morphology, strength and formability was obtained.
Figure 3. $\phi_2 = 0^\circ$ and $45^\circ$ ODF sections for steel samples (a) Initial, (b) CR and (c) CR+IHT and (d) Ideal end orientations of BCC texture fibers.

Table 1. Mechanical properties of the initial, CR, and CR+IHT steel sheets.

| Sample Name | YS (MPa) | UTS (MPa) | $\varepsilon_f$ | n   |
|-------------|----------|-----------|----------------|-----|
| Initial     | 220      | 438       | 0.58           | 0.40|
| CR          | 650      | 790       | 0.15           | 0.07|
| CR+IHT      | 396      | 544       | 0.51           | 0.35|

4. Discussions
CR of the initial hot rolled and annealed ferritic steel sheet led to the breakdown of the microstructure into elongated laminar type grains with heterogenous bimodal grain size distribution (figure 1). After CR a large strain hardening took place in the material which leads to the increase in YS and UTS to $\sim$650 MPa and $\sim$790 MPa with reduced ductility (table 1). This strengthening is reflected in terms of the increase in SSD, GNB, RHAGB density with the decrease in crystallite size in figure 2. The Hall-Petch as well as dislocation hardening both took place during the CR process [2,8]. Dislocation hardening consists of both GNB ($\rho_{\text{GNB}}$) and SSD ($\rho_{\text{SSD}}$) present in the microstructure and their contribution in strength is given by the relation: $\sigma = \sigma_0 M \alpha G b (\rho_{\text{SSD}} + \rho_{\text{GNB}})^{-0.5}$, where $\sigma_0$ is the frictional stress, $\alpha$ is a constant coefficient (between 0 to 1), M is the Taylor factor, G is the shear modulus and b is the Burgers vector [14,15].

Further, the IHT treatment of CR steel by intercritical annealing at 1113K(840°C) and quenching, with secondary annealing at 873K(600°C) and quenching led to the formation of desirable microstructure with ferrite-martensite island type structure. The martensite fraction was $\sim$34%, which is desirable for the higher formability and endurance limit [2,11]. High strength of $\sim$544MPa, ductility of 0.51, and $n = 0.35$ could be obtained in this inexpensive grade steel. The improvement in strength and ductility could also be associated with (i) equiaxed grains with a lower average grain size of 5.5 $\pm$ 3.5um, (ii) low SSD, GNB, RHAGB density, large crystallite size; and (iii) diffused crystallographic texture with the low intensity that improves the isotropy.
5. Conclusions
Hot-rolled and annealed ferritic steel sheets were cold rolled up to ~84% reduction. Thereafter, intercritical annealing at 1113K (840°C) for 60min and water quenching, followed by secondary annealing at 873K (600°C) for 15min and water quenching was carried out. DP steel with ~34% volume fraction martensitic structure in island type ferrite morphology was obtained, which is desirable. The DP steel possesses a high strength of ~544MPa, ductility of 0.51, and n=0.35, and is attributed to equiaxed grains, recovered microstructure and weak texture.

Acknowledgement
The authors would like to acknowledge the facilities availed in ‘Light Metals and Alloys Research Lab’ at the Department of Metallurgical and Materials Engineering and Central Research Facility in Indian Institute of Technology, Kharagpur, India.

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