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Effect of strain on the microstructure and mechanical properties of multi-pass warm caliber rolled low carbon steel

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Abstract

Development of microstructure and mechanical properties during multi-pass warm caliber rolling of low carbon steel has been investigated as a function of strain. While tensile and lower yield strengths increased with strain monotonically, impact properties deteriorated up to a strain of 0.7 and then drastically improved beyond a strain of 1.5. Based on this study, it is concluded that severe plastic deformation is not essential for obtaining useful engineering products with a good combination of strength and impact properties for the present steel.

Keywords: Ferrite–pearlite steels; Bainitic steel; Severe plastic deformation; Ultrafine-grained microstructure; Caliber rolling

1. Introduction

In recent years, the process development for the manufacture of ultrafine-grained (UFG) steels has become an issue for researchers around the world. Extensive research has been conducted in this regard on techniques for refining the grain structure of steel to a submicron level. Various multi-pass, large strain deformation processing techniques have been developed such as equal channel angular pressing (ECAP) [1], accumulative roll bonding [2], multiple compression [3] and multi-axial and multi-stage deformation through multi-pass warm caliber rolling [4–6] for the production of UFG materials. In order to evolve a UFG structure, large plastic strain deformation exceeding a true strain in the range of 1 and 2 is generally required. The present authors have demonstrated [7,8] that a submicron ferrite structure can be formed by single pass warm deformation of ferrite phase when the strain exceeds approximately 3. However, considering the capacity limitations of practical rolling and processing equipment, this type of heavy single pass deformation is not realistic with large bulk materials, suggesting that study of a multi-pass deformation process is indispensable for industrial applications.

Shin et al. [9,10] have studied the UFG microstructures in low carbon steels by ECAP and evaluated their mechanical properties. Storojeva et al. [11] have studied heavy warm deformation of medium carbon steel resulting in ultrafine ferrite grains. Song et al. [12] have reported the large strain warm deformation of 0.2%C–Mn steel leading to the evolution of a UFG ferrite microstructure and studied their mechanical properties. However, all these studies were conducted on laboratory scale specimens and full scale impact properties of the resultant UFG microstructures were not reported. This is an important issue to be resolved because the strength–toughness combination of UFG materials has to be evaluated before any practical application of these materials can be attempted.

Ohmori et al. [4,13] and Hanamura et al. [14] have carried out multi-pass warm caliber rolling of 0.15C steel at various temperatures in the range 500–650 °C subjected to a nominal strain of about 3 and studied the

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microstructure development and evaluated the strength and Charpy impact properties of the caliber rolled bar. However, detailed mechanical properties as a function of cumulative strain are not reported anywhere in the literature.

Therefore, the aims of the present investigation were (i) to produce steel bars subjected to various strains by isothermal multi-pass warm caliber rolling; (ii) to investigate the mechanical properties as a function of cumulative plastic strain and (iii) probe the correlation between microstructure and mechanical properties.

2. Experimental

In the present study, vacuum melted steel of a composition equivalent to SM490 (composition in wt.% C-0.16, Si-0.29, Mn-1.53, P-0.011, S-0.0012, Al-0.029, N-0.0016 and Fe-balance) was used. In order to investigate the role of initial microstructure on the evolved UFG structure, two starting microstructures viz. (ferrite + pearlite) and bainite were studied. Square bars (□) with a diameter of 80 mm were produced by hot forging and were subjected to a pre-heat treatment such that two initial microstructures were produced. The first preparation consisted of heat treatment of the steel bar at 1080 °C for 2 h followed by water quenching so as to obtain a bainitic structure and the second involved heat treating the bar at 870 °C for 2 h followed by air cooling so as to obtain a normalized ferrite–pearlite microstructure. These two bars were then subjected to multi-pass isothermal caliber rolling at 500 °C. The caliber rolling was conducted in five stages to obtain specimens at different cumulative strains for microstructure and mechanical property evaluation. The cumulative reduction (R) and cumulative strain $\left(\varepsilon = -\ln\left(1 - \frac{R}{100}\right)\right)$ at each stage of rolling are shown in Fig. 1. Immediately following each stage, caliber rolled rods were water quenched. The caliber rolling temperature was selected based on the single pass large strain anvil compression test results [11] which results in a submicron ferrite grain structure. The reduction direction was changed in increments of 90° by rotating the material one quarter turn in each pass. The surface temperature of the bars was measured with a contact type thermocouple and controlled within a range of ±25 K by adjusting the time interval between the passes.

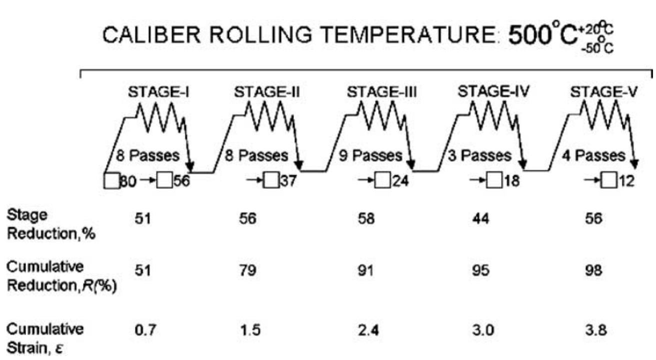

Fig. 1. Caliber rolling schedule followed in the present study. The cross-section of the caliber rolled bar is indicated by □ and the dimensions are indicated in mm following the symbol.

Round bar tensile test specimens with a parallel section length of 24.5 mm and a diameter of ϕ3.5 mm and full size 2 mm V-notch Charpy test specimens were taken from the center of the cross-section in the rolling direction (longitudinal direction of bars). Scanning electron microscopic observations were made after etching the specimens with 1.5% Nital to reveal the microstructure.

3. Results and discussion

3.1. Microstructure as a function of cumulative strain

Figs. 2 and 3 show the scanning electron micrographs of the cross-sections of the caliber rolled rods after different stages of rolling corresponding to various cumulative strains (viz. 0.7, 1.5, 2.4, 3.0 and 3.8) as well as undeformed microstructure ($\varepsilon = 0$) for the initial ferrite + pearlite and bainite microstructures respectively. All microstructural observations were carried out at the center of the rolled bar. This was to ensure a clear correlation of the microstructure and mechanical properties of the specimens, which were taken from the center of the rolled bars. Fig. 2(a) reveals the initial microstructure of the material consisting of clear ferrite grains and pearlite colonies. Fig. 2(b–f) shows the microstructures for the caliber rolled specimens subjected to various cumulative strains. At a low strain of 0.7 (Fig. 2(b)), faintly etched boundaries in ferrite grains can be clearly seen along with partial spheroidization of cementite at a few locations. At this stage no new grain formation is observed anywhere in the cross-section of the bar. Based on single pass compression results [7] of this material and detailed electron back scattered diffraction results of deformed specimens, it was noted that faintly etched boundaries are of low angles and darkly etched boundaries are of high angles. It may be noted that the formation of a large number of low angle (sub)boundaries is attributed to the multi-directional deformation processing which promotes rapid formation of intersecting sub-boundaries compared to uniaxial compressive deformation [7,8]. After the second deformation stage ($\varepsilon = 1.5$), the average ferrite grain size decreases (Fig. 2(c)) with the formation of clearly etched (indicating that they are of high angles) small equiaxed ferrite grains. No more pearlite colonies could be observed and spheroidization of cementite was complete at this stage. At the end of the third deformation stage ($\varepsilon = 2.4$), more and more clearly etched new ferrite grains were noticed (Fig. 2(d)). However, the cementite was still in the form of colonies of spheroidized particles. After the fourth stage of deformation ($\varepsilon = 3.0$), the microstructure has fine equiaxed ferrite grains (Fig. 2(e)). After a cumulative strain of 3.8 which is the last stage of caliber rolling, the microstructure is essentially same as that of fourth stage with cumulative strain of 3.0