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Deformation analysis of ferrite/pearlite banded structure under uniaxial tension using digital image correlation

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ABSTRACT

The ferrite/pearlite banded structure causes the anisotropic behavior of steel. In this paper, digital image correlation (DIC) was used to analyze the micro deformation of this microstructure under uniaxial tension. The reliability of DIC for this application was verified by a zero-deformation experiment. The results show that the performance of DIC can satisfy the requirements of the tensile deformation measurement. Then, two uniaxial tensile tests in different directions (longitudinal direction and transverse direction) were carried out and DIC was used to measure the micro deformation of the ferrite/pearlite banded structure. The measured results show that the ferrite bands undergo the main deformation in the transverse tension, which results in the relatively weaker tensile properties in the transverse direction than in the longitudinal direction. This work is useful to guide the modification of the bands morphology and extend the application scope of DIC.

1. Introduction

A banded structure occurs commonly in steel, due to the micro-segregation caused by substitutional alloying elements [1–3]. The banded structure is usually detrimental to the quality of steel. Processing and heat treatment methods designed to prevent or erase the banded structure are expensive or thermodynamically impossible [4–6]. Thus, in order to remove the detrimental effects of the banded structure, an economical solution of modifying the band morphology is essential for steel industry.

A common form of the banded structure comprises alternating parallel bands of ferrite and pearlite. It can result in anisotropic mechanical properties (e.g. tensile properties and impact properties) of steel [7,8] and affect the mechanism of micro-crack formation and growth [9–11]. The relationship between the morphology of the band and the mechanical behavior of steel has become the interest of research in recent years [12]. However, despite many studies about the ferrite/pearlite banded structure, the effect of banded structure on the mechanical properties of steel is not well understood. For example, while banded structure is generally considered as a defect in steel, but some test results show that banded structure can increase the fatigue life of steel [10]. The inconsistent results are caused by the neglect of the directions of bands and the deformation characteristics of bands. In order to understand the deformation characteristics of the banded structure in different directions, a technique for measuring full-field deformation is in urgent need.

Digital image correlation (DIC) method is a non-destructive deformation measurement method with the advantages of sufficient sensitivity, simple experimental setup, multi-scale view and widespread application [13–15]. It has been successfully used for the deformation analysis of steel [16,17]. With a microscope and an in-situ tester, DIC can be used to measure the micro deformation field with high accuracy. Thus, DIC is an effective approach to investigate the deformation behavior of the ferrite/pearlite banded structure. The influence of the banded structure on the tensile behavior for two limit cases has been investigated by DIC [18]. However, the reliability of DIC for this particular application has not been verified, and the tensile properties in the transverse direction were not considered in Ref. [18].

In this paper, DIC is used to analyze the micro deformation of the ferrite/pearlite banded structure in two directions (longitudinal direction and transverse direction) under tensile load. Firstly, the performance of DIC in this application is verified by a zero-deformation experiment. Then, two tensile tests are carried out and DIC is used to measure the micro deformation of the ferrite/pearlite bands. Finally, further analysis of the results contributes to a better understanding of the relationship between the ferrite/pearlite banded structure and the tensile properties of steel.

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2. Zero-deformation experiment

2.1. Specimen preparation

Dumbbell-shaped specimens for tensile tests were made of WB36 steel. Their surfaces were metallographically prepared using successive grinding and chemical polishing. The polishing solution was prepared as follows: firstly, 30 wt% hydrogen peroxide, glycerol and distilled water were mixed together with the volume proportion 13%:0.2%:86.8%; then, 75 g oxalic acid and 20 g urea were added into per liter of solution and stirred evenly. The duration of chemical polishing was 3–6 min. Although there exist some techniques of micro-scale speckle pattern fabrication to enhance the accuracy of DIC in the micro deformation measurement [19,20], the artificial speckle may affect the microstructure of the specimen in this application. Thus, the morphology of the banded structure was considered as the speckle pattern used for DIC. Fig. 1(a) shows the shape and size of the specimens. Four holes were made in each specimen to connect with a micro-tensile stage. Fig. 1(b) shows the banded structure morphology of the specimen used for the longitudinal direction, i. e. rolling direction (RD) tensile test, and Fig. 1(c) shows the banded structure morphology of the specimen used for the transverse direction (TD) tensile test. Fig. 1(b) and (c) are the secondary electron images taken using ZEISS EVOMA15 scanning electron microscope (SEM). The bands with deep color are ferrite bands and the bands with light color are pearlite bands. For all tests in this work, the main parameters of SEM were maintained the same as: the extra high tension was 20 kV; the detector was secondary electron detector; the work distance was 15 mm; the magnification was 892 × ; and the cycle time was 9.4 s.

2.2. Experimental work

The specimen was installed on a GATAN MTEST 5000W in-situ micro-tensile stage, Then, the stage was placed into SEM to conduct the zero-deformation experiment. Six images of a region of the specimen were captured by SEM at different times without loading. The images were numbered in a chronological order. The first image was selected as the reference image. DIC (Vic-2D 2009, Correlated Solutions, Columbia, SC, USA) was used to measure the relative displacements of the successive images with respect to the reference image. The main parameters of DIC were set as follows: the size of the region of interest (ROI) was 610 × 460 pixels; the calculation step was 5 pixels; and the size of the subset was 41 × 41 pixels.

2.3. Results and discussion

The theoretical displacement of ROI should be zero, because there was no load in the experiment. However, the system errors of DIC resulted in non-zero measured displacements. The reference image and the measured results are shown in Fig. 2. In the figure, u and v represent the mean value of the measured horizontal and vertical displacements of ROI, respectively. The mean value of the measured displacements reflects the accuracy of DIC, and the standard deviation indicates the robustness of DIC. Fig. 2(b) shows that both the mean values and standard deviations of measured displacements are smaller than 0.1 pixels. Generally, the displacement of the ferrite/pearlite banded structure extends to several or dozens pixels in the uniaxial tensile test. Thus, the performance of DIC is proven to satisfy the requirements of a tensile deformation measurement experiment. In addition, Fig. 2(b) shows that the accuracy and the robustness of DIC reduce with an increase in time. This suggests that the reduction in the image acquisition time interval may be helpful to improve the measured results by DIC. Sutton et al. have investigated the drift and spatial distortion of SEM image and proposed a correction method, which can improve the accuracy of displacement measurement by DIC to ± 0.02 pixels [21,22]. It should however be noted that since there was no artificial micro-scale speckle pattern on the specimen, the measured displacement accuracy in this work is relatively lower. In addition, their test results show that the magnitude of the relative drift within each image changes with time, which is consistent with the present test results in this section.

Pan et al. have proposed a parameter called mean intensity gradient to evaluate the speckle pattern quality [23]. A so-called good speckle pattern should be of large mean intensity gradient. The mean intensity gradient of Fig. 2(a) was calculated, which is equal to 10.01. This value shows that the banded structure morphology is not a good speckle pattern. However, when DIC was used for this kind of pattern, the mean bias error is smaller than 0.05 pixels in a simulated experiment of Ref. [23]. Based on this observation, the banded structure morphology in this study was considered as the speckle pattern to be used for DIC, which can still satisfy the requirements of the tensile deformation measurement.

3. Tensile tests

3.1. Tests and measurement

Uniaxial tensile tests in RD and TD were carried out using the GATAN MTEST 5000W in-situ micro-tensile stage. The stage with a specimen installed is shown in Fig. 3. The loading rate was 0.5 mm/min. After each 0.2 kN increment of the load, the tensile test was paused to acquire an image of the specimen surface by SEM. Out-of-plane displacement is inevitable in the tensile test, which can result in the image defocus and affect the measurement accuracy of two-dimensional DIC. Many studies have investigated the effect of out-of-plane motion on two-dimensional DIC

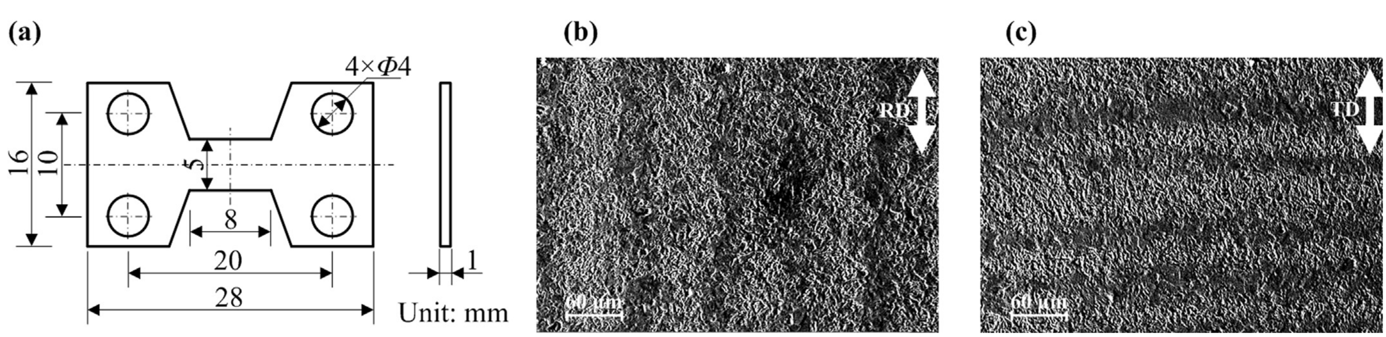

Fig. 1. Dimensions and microstructure of the specimen: (a) the size and shape of the specimen. (b) The banded structure of the RD specimen. (c) The band structure of the TD specimen.