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An Optical Interferometric Band of an Indicator of Plastic Deformation Front

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The Lüders' front and a previously discovered optical interferometric band structure were observed simultaneously in steel specimens under tensile loading. The observed Lüders' front and optical band structure show the same propagation characteristics, confirming our previous interpretation that the optical band structure represents the plastic deformation front. Analysis shows that the stress at which the optical band structure begins to appear is approximately 10% lower than the corresponding Lüders' front, indicating that the optical band structure reveals the plastic deformation front with higher sensitivity than the Lüders' front.

1 Introduction

Previously, Yoshida et al. [1] discovered an optical interferometric band-structure whose appearance is quite similar to that of the plastic deformation front. This band structure, called the white band (WB) hereafter [2], can be observed in an interferometric fringe pattern formed by a technique known as the in-plane sensitive, electronic spackle-pattern interferometry (ESPI) [3]. Near the yield point, the WB propagates in a way similar to the plastic deformation front known as the Lüders' front [4], and in later

stages, it resembles a more developed deformation front which eventually stays at the location of fracture [1]. These observations indicate that the WB can be used as an indicator of the plastic deformation front, and will be useful for various studies including quantitative analysis of plastic deformation. In fact, a previous study [5] indicates that the stress is getting concentrated at the banded region where the WB is about to form. To further continue this line of research, it is important to confirm that the WB indeed represents the plastic deformation front.

In this study, we simultaneously monitored Lüders' fronts and WBs on the front and rear surfaces, respectively, of the same specimen under tensile loading. Consequently, pairs of Lüders' fronts and WBs were observed to appear concurrently and propagate synchronously at locations close to each other, indicating that they certainly represents the same phenomenon. Also of interest is that the WB begins to appear at about 10% lower stress than the Lüders' front, showing that it indicates the plastic deformation front with higher sensitivity than the Lüders' front.

2 Experimental Setup

The material used in this study was commercially available structural steel SS400. Prior to the machining, the material was annealed at 900 °C, and its grain size was measured to be 15 μm . The material was then machined to be two types of specimens; the first type was a bone shape with a parallel part of 50 mm long, 10 mm wide, and 5 mm thick, and the second type was a rectangle of 80 mm long (the grip-to-grip length), 15 mm wide and 3 mm thick. To visualize the Lüders' front to the naked eye, we polished the rear surface of the specimen with an abrasive paper of grit number 2000. [6]. The front surface was first polished with an abrasive paper of grit number 100 and then painted white to visualize WBs at a high contrast.

We illuminated the rear surface of the specimen with a fluorescent lamp, and recorded the image with a video recorder. The ESPI setup used for the front surface of the specimen was a typical dual-beam configuration [3]. We took specklegrams of the specimen with a CCD (Charged Coupled Device) camera at a sampling rate of 1 frame/s, and stored the image data into computer memory at the same rate. The tensile load was applied at constant crosshead speeds. The applied load and the stroke of the dynamic grip were recorded at a rate of 10 sample/s. Rulers were attached to the lower grip of the test machine on both sides, so that the locations of the Lüders' line and WB could be read directly on the respective images. We formed interferometric fringe patterns by subtracting the specklegram taken at one time step from the specklegram taken several time steps before, which corresponded to the total elongation of 10–30 μm .

3 Results and Discussions

Figure 1 shows the Lüders' front and WB observed in the first type of specimen at the crosshead speed of 2.5 $\mu\text{m/s}$. In this particular run, a pair of Lüders' front and WB appeared near the lower end of the specimen and propagated upward. Except that the Lüders' front and the corresponding WB are slanting in mutually opposite orientations because they are observed from the

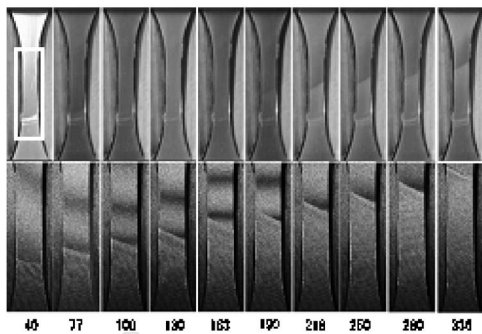


Fig. 1 Lüders' front (upper) and WB (lower) observed simultaneously at the crosshead speed of $2.5 \mu\text{m/s}$. Numbers represent the elapsed time in s from a reference time set before the yield point. The window inserted in the leftmost image of the upper row indicates the view of the lower images approximately.

opposite sides of the specimen, they propagate in a very similar fashion. Figure 2 plots the locations of the centers of the Lüders' front and WB measured from a reference point near the lower grip as a function of time. The solid lines are the best fits to the data points. From the slopes of these lines, the propagation velocities of the Lüders' front and the WB are found to be $1.11 \times 10^{-4} \text{ m/s}$ and $1.13 \times 10^{-4} \text{ m/s}$, respectively. Considering that the error associated with the reading of the locations of the Lüders' line and WBs is estimated to be $\pm 2\%$, it is fair to say that the Lüders' front and the WB propagate at the same velocity.

Figure 3 shows the stress-strain diagram in the plastic regime along with its expanded view near the yield point. This diagram was recorded at the same time as Fig. 1. The extents where the Lüders' fronts and WB appear are marked, respectively. From the observed yield elongation (region between points A and B) and the specimen length of 50 mm, the yield strain ϵ_L can be estimated to be 0.0197. Using this yield strain, the crosshead speed $V_c = 2.5 \times 10^{-6} \text{ m/s}$ and the relationship $V_L = V_c / \epsilon_L$ derived by Sylwestrowicz and Hall [7], the theoretical velocity of the Lüders' front can be estimated to be $V_L = 1.27 \times 10^{-4} \text{ m/s}$. This value shows a good agreement with the measurement, as the dashed line in Fig. 2 indicates.

While the theoretical velocity of the Lüders' front based on the yield strain agrees with experiment, Fig. 3 indicates that the Lüders' front or WB does not extend the whole span of the yield elongation. A possible explanation of this observation is that while the plastic deformation front begins to propagate at the lower end of the specimen at the yield stress and completes the propagation at the upper end of the specimen at the end of the yield elongation,

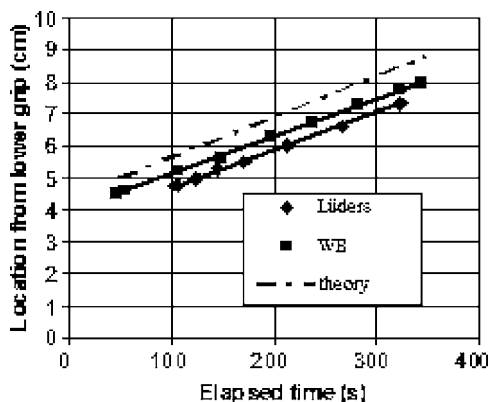


Fig. 2 Locations of Lüders' front and WB as a function of time. The crosshead speed is $2.5 \mu\text{m/s}$.

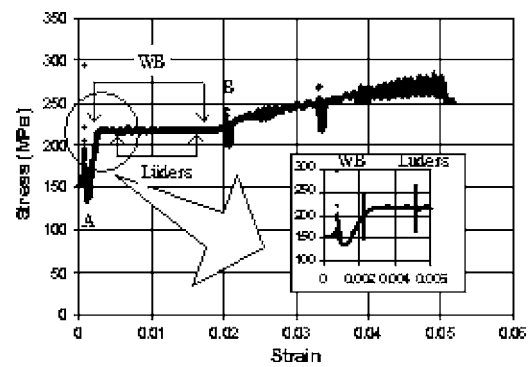


Fig. 3 The stress-strain diagram in the plastic regime recorded at the same time as Fig. 1. The expanded view indicates the stress values when the Lüders' front and WB begin to appear.

the initial and final parts of the propagation are not manifested as the Lüders' front or WB. The fact that the WB appears earlier and disappears later than the Lüders' front indicates that the former has higher sensitivity as an indicator of the plastic deformation front. The expanded view in Fig. 3 shows that the WB begins to appear at 8% lower stress than the Lüders' front [8]. This observation is consistent with the previous finding by Funamoto [9] for the same material that the WB begins to appear near a circular hole at a stress value 11% lower than the corresponding stretcher-strain.

At the crosshead speed of $25 \mu\text{m/s}$, a similar relationship between the Lüders' front and WB was observed. Figure 4 shows the Lüders' front and WB observed in the second type of specimen at this crosshead speed. In this run, two pairs of Lüders' front and WB began to appear at the upper and lower end of the specimen, respectively, within a time lag less than 30 s. At this crosshead speed, the Lüders' fronts show less sharp edges, as is normally the case. The two pairs of Lüders' front and WB propagated along the length of the specimen in mutually opposite directions. Figure 5 shows the locations of the pairs as a function of time. Like Fig. 2, the Lüders' front and WB of the same pair propagate at the same velocity, which is reasonably close to the theoretical Lüders' front velocity (dashed lines) estimated in the same fashion as Fig. 2. (The lower Lüders' front and WB show somewhat higher velocity than the theoretical value, and its reason is not clear.) Unlike Fig. 2, however, both the Lüders' front and the WB fluctuate around the fitted straight lines, indicating that when the Lüders' front forms a less sharp edge, it does not propagate at a constant velocity but somewhat fluctuates around a mean value. The WB observed under this condition follows a similar, fluctuating trend, indicating that it still represents the same phenomenon as the

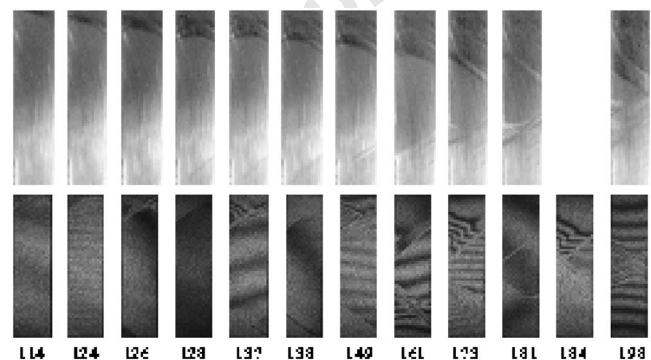


Fig. 4 Lüders' front (upper) and WB (lower) observed simultaneously at the crosshead speed of $25 \mu\text{m/s}$. The Lüders' front taken at time step 184 is not shown because of poor quality.

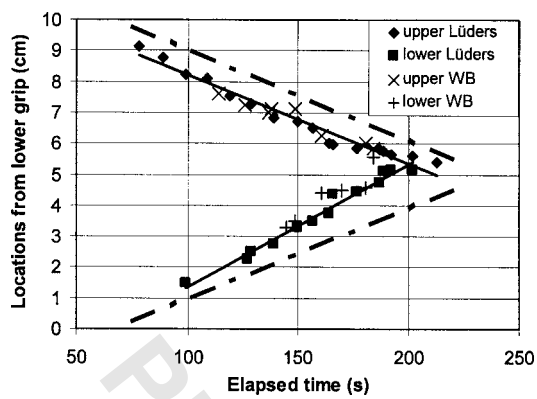


Fig. 5 Locations of Lüders' front and WB as a function of time. The crosshead speed is $25 \mu\text{m/s}$.

Lüders' front. We examined the second type of specimen at the crosshead speed of $2.5 \mu\text{s/s}$ and observed a straight trend similar to Fig. 2. Judging from this result, the fluctuating trend observed in Fig. 5 is not caused by the difference in the shape of the specimen but the difference in the crosshead speed.

The fringe patterns observed in the regions divided by the WBs can be characterized as consisting of nearly equidistant and horizontally parallel fringes (see Figs. 1, 4, and 6). A system of perfectly equidistant and horizontally parallel fringes observed in a horizontally sensitive ESPI setup represents a rigid body rotation of the object [10]. This observation, therefore, indicates that the deformation is concentrated at the Lüders' front in such a way that the regions divided by the front experience rigid body like rotations [5]; i.e., there is a stress concentration at the Lüders' front.

Figure 6 shows fringe patterns formed by subtracting several specklegrams from a common specklegram (frame #180) varying the time-step increment. The number shown underneath each fringe pattern denotes the number of the frames involved in the subtraction. The fringe systems seen in these patterns have the following features. The region above the WB (region 1) shows nearly the equidistant, horizontally parallel system representing a rigid body like rotation. The region inside the WB (region 2) shows a dense fringes parallel to the WB, representing a concentrated strain normal to the WB. The region below the WB (region 3) does not show a clear fringe structure. As the number of the time-step increment increases in going from (a) to (f), the number

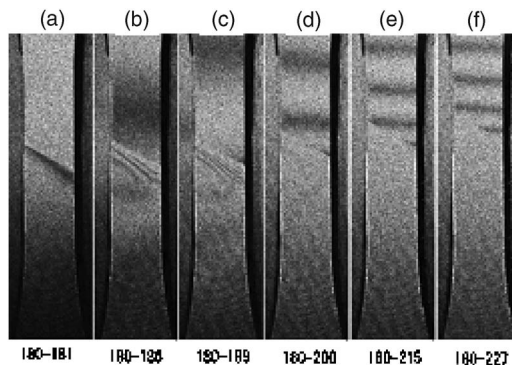


Fig. 6 WB obtained for a common specklegram with various subtraction increments

of fringes in region 1 increases rather constantly. The number of fringes in region 2 also increases, at a rate much higher than region 1. In going from (a) to (c), the fringe density in region 2 becomes four or five times higher, while the number of fringes in region 1 increases by one. The fringe pattern in region 3 remains more or less the same in (a) through (f). These features can be interpreted as follows. When the Lüders' front was formed, the material in the vicinity of the front experienced a localized deformation. As the time went by, the part of the specimen held by the dynamic grip (region 3) displaced in the vertical direction as a rigid body (without substantial deformation), forming no clear fringe structure. This motion sustained the localized deformation in region 2. While this happened, the localized deformation moved up by some mechanism as the other side of the material (region 1) rotated as nearly a rigid body at an approximately constant rate.

4 Conclusion

The result of this study confirms that the WB represents the same phenomenon as the Lüders' front, supporting our previous interpretation. Now that this has been confirmed, further investigation on the plastic deformation front can be pursued through analysis on the WB. It is observed that the WB appears at about 10% lower stress than the Lüders' front, indicating that the WB has higher sensitivity than the Lüders' front as an indicator of the plastic deformation front.

Acknowledgments

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