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Observing non-uniform, non-Lüders yielding in a cold-rolled medium manganese steel with digital image correlation

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Abstract

Digital image correlation (DIC) techniques were used to evaluate strain distributions along tensile gage lengths immediately after yielding of a medium manganese steel (7 wt% Mn) in samples cold rolled in the range of 1–6 pct. With an increase in cold work, DIC confirmed that the yielding behavior transitioned from nucleation and propagation of a single localized deformation zone (Lüders band) to uniform deformation, that is, no evidence of strain localization. At intermediate amounts of cold work, a unique yielding behavior was evident where the initially-low positive strain hardening rate increased with tensile strain until conventional strain hardening (i.e., decrease in strain hardening rate with strain). The intermediate yielding behavior was associated with the development of multiple non-propagating regions of strain localization, an observation not previously evident without the use of DIC.

Keywords: digital image correlation; incipient yielding behavior; medium manganese steel; non-uniform deformation

Introduction

In tensile testing of metals and alloys, multiple different strengthening-mechanism dependent characteristics are observed at strains associated with the transition from elastic to plastic deformation (Hall, 1970). The transition region is typically characterized by “yielding behavior”: continuous yielding where the strain hardening rate decreases with an increase in strain associated with uniform deformation; discontinuous yielding where distinct upper and lower yield points are followed by non-uniform deformation due to propagation of a localized band (i.e., Lüders band) at essentially a constant macroscopic stress leading to a strain increment referred to as yield point elongation (YPE); or an intermediate behavior, where on yielding the strain hardening rate is initially low and continuously increases with strain prior to transitioning to continuous yielding. This intermediate behavior has been interpreted to reflect inhomogeneous deformation and propagation of an incipient Lüders band (Matlock et al., 1979) and is referred to here as “incipient yielding.” For selected steels, orderly variations in yielding behavior from continuous to discontinuous or vice versa can result from systematic modifications in processing. Increasing the amount of cold reduction during temper rolling of initially hot rolled or annealed low carbon steels changes the discontinuous yielding behavior to continuous yielding, a change attributed to the introduction of mobile dislocations by cold work (Lake, 1985). Low-temperature aging of dual-phase steels initially quenched to produce ferrite–martensite microstructures with continuous yielding behavior, leads to discontinuous yielding, by pinning mobile dislocations introduced in ferrite to accommodate the volume expansion of martensite on quenching (Matlock et al., 1984). Thermal processing of precipitation-hardenable aluminum alloys (Dieter, 1986) and variations in test temperature of metastable austenitic stainless steels (Huang et al., 1989) also produce systematic variations in yielding behavior. Forming of materials that exhibit discontinuous yielding and non-uniform deformation usually results in unacceptable parts with poor geometries and surfaces (e.g., stretcher strains in formed sheets) and temper rolling is one approach to eliminate the undesirable characteristics (Lake, 1985). Understanding how deformation uniformity evolves for the different yielding behaviors is essential to design processing histories to eliminate unacceptable forming response due to non-uniform deformation. In this study, digital image correlation (DIC) techniques were used to map strain variations along tensile sample gage lengths of a batch annealed 0.15C-7.33Mn-0.24Si (wt%) steel (Glover, 2020) (one of the candidate materials for new third-generation advanced high strength steels) processed with different degrees of cold rolling to induce variations in yielding behavior. Unique strain distributions, not evident using alternate techniques (e.g., a series of strain gages mounted along a tensile gage length (Matlock et al., 1979)), were revealed.

Methods

Longitudinal ASTM E8 subsized tensile samples (reduced gage length of 32 mm, width of 6 mm, and as-received 1.4 mm sheet thickness) were produced using wire electrical discharge machining. Tensile samples were cold rolled on a laboratory mill with 133 mm diameter work rolls. Rolls were unlubricated and sample orientations were reversed with each pass to minimize out-of-plane bending. The amount of cold work was based on sheet thickness measurements; levels of cold work ranged from 0.8–5.5 pct, with reductions of 2.5–3.5 pct targeted for analyses of the unique strain distributions observed within the incipient yielding region.

Prior to testing, DIC speckled patterns were applied over a white spray-painted background using a commercial stamp roller (Correlated Solutions, 2022) moved across the sample surface in multiple different directions (creating a “star” array of application paths), a procedure found to produce the best level of contrast. During testing, sample surfaces were illuminated with two polarized light sources, one on either side of a Basler ACA3800-14 µm camera. Image data were captured at 2 Hz, a rate that produced good temporal strain evolution resolution at the imposed tensile strain rates while minimizing computational processing times. ARAMIS 3D DIC software (Trilion, 2022) was used to produce local strain maps as well as provide bulk strain data used for generating stress strain curves. Room temperature tensile data were obtained at a crosshead displacement rate of 0.01143 mm/s on a commercial electromechanical test system. Samples were preloaded to 650 N (equivalent to 75 MPa, a value significantly less than the macroscopic yield stress) to ensure proper seating within the grips. Load data were captured at 2 Hz to match the camera acquisition rate.

Results and conclusions

Figure 1 shows portions of stress–strain curves selected to highlight the effects of cold work on yielding characteristics resulting in the three different yield regimes described in the introduction. Figure 1a shows the behavior for the as-received batch annealed steel which exhibited well-defined upper and lower yield points followed by YPE with the following properties: yield strength (YS) of 790 MPa, ultimate tensile strength (UTS) of 850 MPa, total elongation to fracture (TE) of 32.2 pct, and YPE of 7.70 pct. Despite 1.5 pct cold work, Figure 1b shows the presence of 6.38 pct YPE with a defined upper and lower yield point, followed by uniform deformation until the point of necking, observations similar to those for the as-batch annealed steel (Glover, 2020). After 4.0 pct cold work, Figure 1c shows the absence of YPE and continuous uniform deformation. After 2.6 pct cold work, Figure 1d, illustrates the unique incipient yielding behavior. From Figure 1, it is apparent that changing the level of cold work has strong influence on the yielding behavior. The 2.5-3.5 pct cold work range was shown to produce the incipient yielding behavior while lower levels resulted in Lüders band behavior and higher levels produced uniform

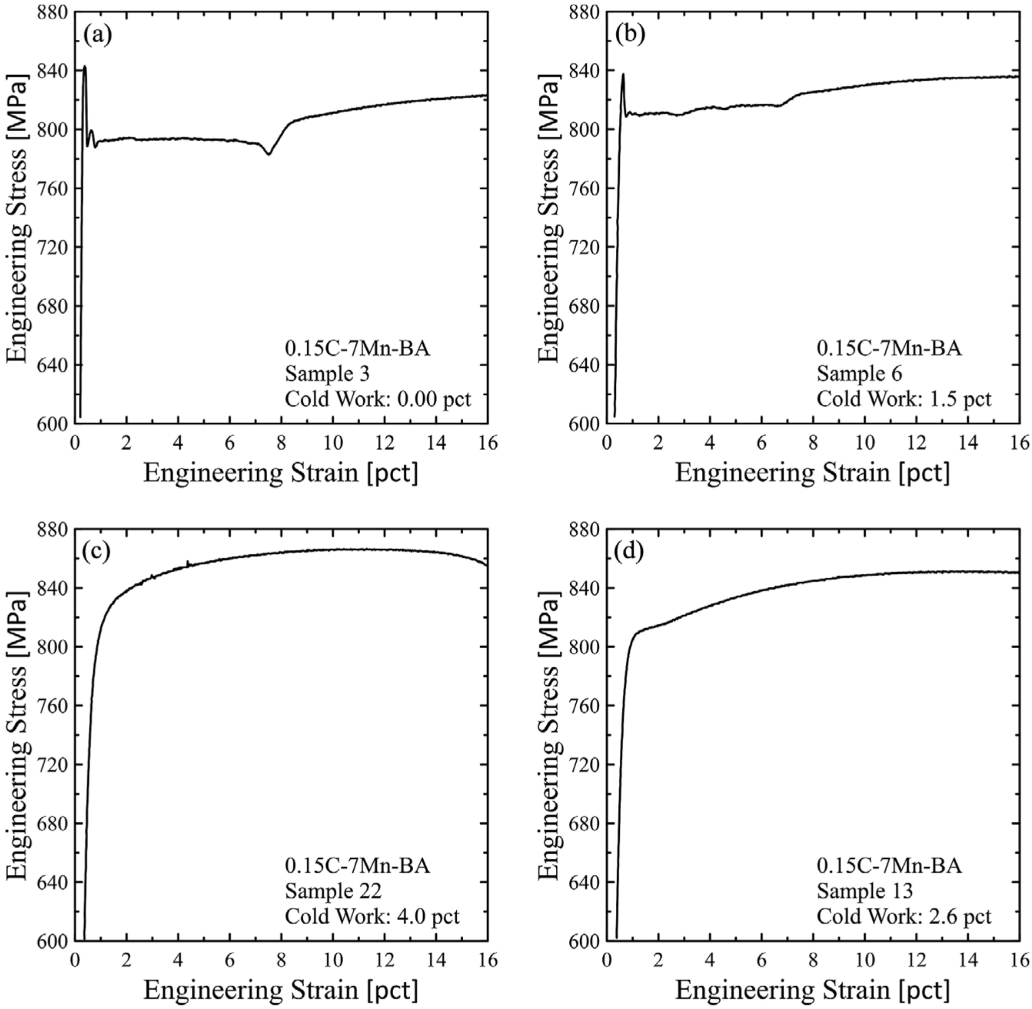

Figure 1. Yielding portions of the room temperature engineering stress–strain curves for the 0.15C-7Mn (wt%) steel were selected to illustrate the yielding behavior in the as-received condition in (a) and after cold rolling of 1.5 pct (b), 4.0 pct (c); and 2.6 pct (d).

deformation. To provide a basis for comparison of the effects of cold work on the overall tensile properties of the four samples shown in Figure 1 and the additional tensile results discussed in the following paragraphs, Table 1 summarizes the effects of cold work on the UTS and TE for each sample and indicates the corresponding figure for each. The tabulated results are grouped by nominal amount of cold work by rolling (i.e., as-received (0.0 pct); 1.5 pct; 2.6 pct; and 4 pct or greater) and show that with an increase in cold work the UTS increased slightly, TE decreased, and excellent reproducibility was obtained within each group.

Figures 2–4 correlate DIC-determined strain distributions along the tensile gage lengths to selected macroscopic strains identified on the associated stress–strain curves for the three types of yielding behavior shown in Figure 1. It should be noted that the cold work amounts and specific stress–strain data in Figures 2–4 differ slightly from the data shown in Figure 1; additional sample data were selected to illustrate the reproducibility of the different types of yielding phenomena. Also, in each strain distribution figure, five curves are shown with each curve corresponding to the strain distribution along equally spaced DIC reference lines parallel to the tensile axis along with a horizontal red line to illustrate the

Table 1. Summary of the effects of cold work by rolling on the UTS and TE values for all tensile results

Cold work (pct)	UTS (MPa)	TE (pct)	Figures
0	840	34.4	1a
1.5	840	25.0	1b
1.5	840	23.5	2a
2.6	850	22.1	1d
2.6	860	22.9	4a
4.0	870	18.2	1c
4.9	870	19.2	3a

Note. Data are grouped by four nominal levels of cold work and the relevant figure for each data set is also indicated.
Abbreviations: TE, total elongation; UTS, ultimate tensile strength.

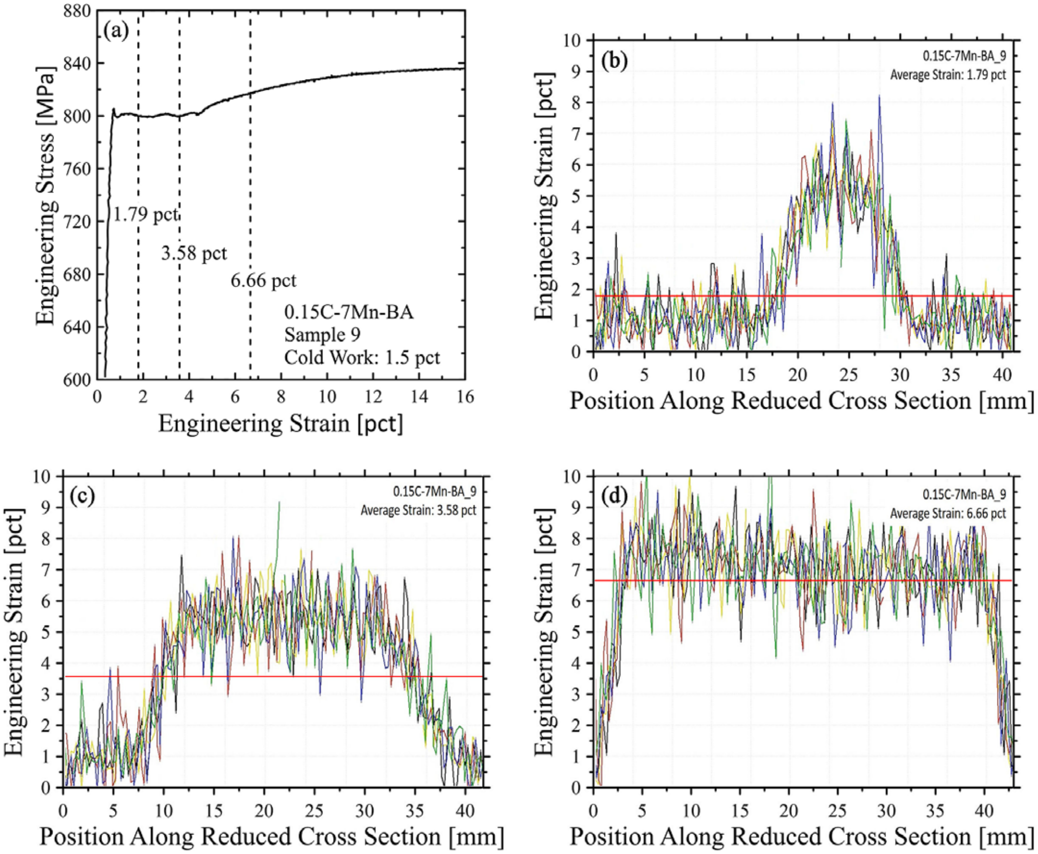

Figure 2. Stress–strain data for a sample of the 0.15C-7Mn (wt%) steel cold worked 1.5 pct resulting in the discontinuous yielding behavior (i.e., Lüders band propagation) shown in (a) along with the strain locations for the DIC strain distributions shown for tensile strains (indicated by horizontal red lines) of (b) 1.79 pct, (c) 3.58 pct, and (d) 6.66 pct.

average imposed macroscopic tensile strain. Observed fluctuations within a given profile are a consequence of interactions between the selected DIC pattern and the software and are viewed here as background noise. Supplementary material includes Figure S1, a photograph of a tensile sample prior to testing selected to illustrate a typical DIC pattern and Supplementary Figures S2–S4, videos which

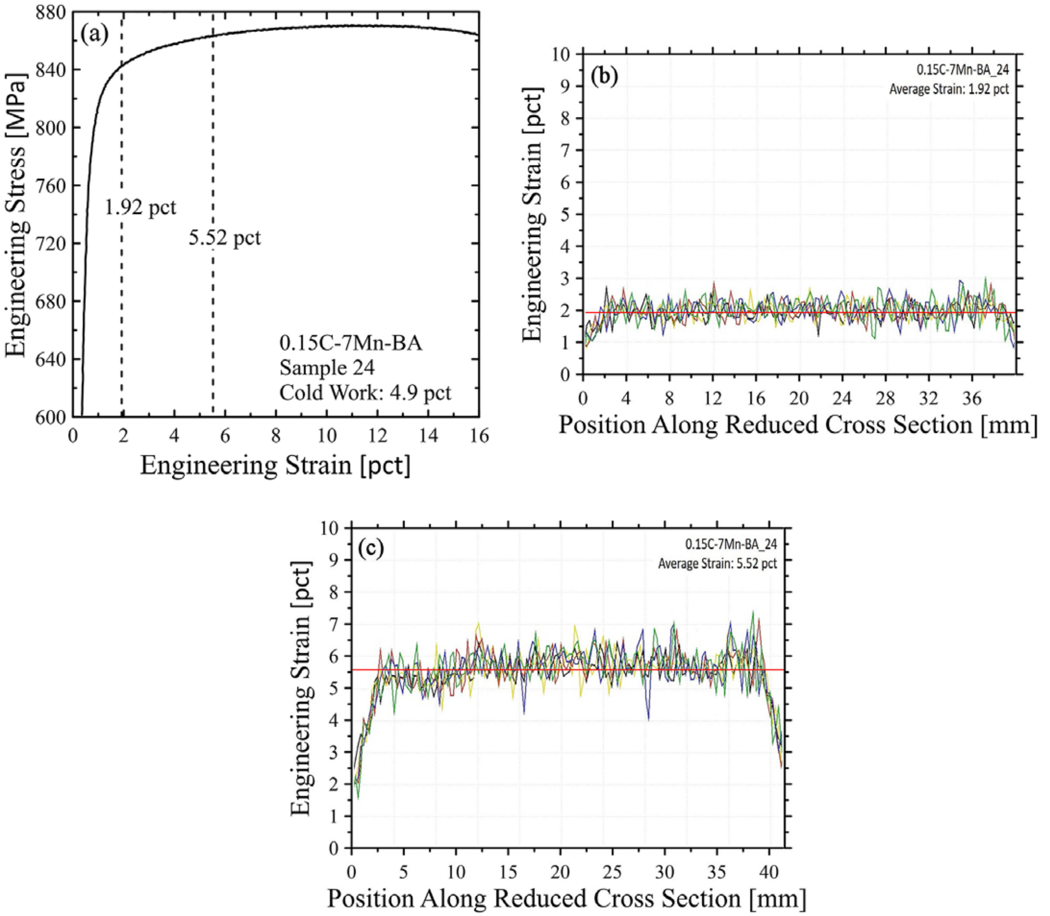

Figure 3. Stress–strain data for a sample of the 0.15C-7Mn (wt%) steel cold worked 4.9 pct resulting in the continuous yielding behavior shown in (a) along with the strain locations for the DIC strain distributions shown for tensile strains (indicated by the horizontal red lines) of (b) 1.92 pct and (c) 5.52 pct.

show time-dependent changes in the strain distributions corresponding to the selected strain distributions discussed in Figures 2–4.

Figure 2a shows data for a tensile sample cold worked 1.5 pct which displayed distinct upper and lower yield points followed by Lüders band behavior at yielding similar to Figure 1b and includes specific strain locations for the strain distributions shown in Figure 2b–d. Figure 2b is the strain distribution at an average macroscopic strain of 1.79 pct, a value early within the YPE region. The DIC data clearly show a region of strain localization with a peak strain of approximately 6 pct after the Lüders band nucleated and initiated propagation through the reduced cross-section. The strain at either extreme of the horizontal axis remains near zero since these correspond to strains approaching the wider sample grip sections. Figure 2c shows the strain distribution at an average macroscopic average strain of 3.58 pct after the Lüders band propagated though the YPE region. Note that the peak localized strain values evident in Figure 2b,c remain unchanged at about 6 pct. Figure 2d shows essentially uniform strain along the gage length at a macroscope strain of 6.66 pct, that is, beyond the YPE region.

Figure 3a shows tensile data for a sample cold worked 4.9 pct which illustrates uniform deformation comparable to the sample shown in Figure 1c. The sample in Figure 3a exhibited continuous yielding without the presence of distinct upper and lower yield points. Figure 3b,c shows strain distributions at macroscopic average strains of 1.92 and 5.52 pct, respectively. For both average strains, the strain

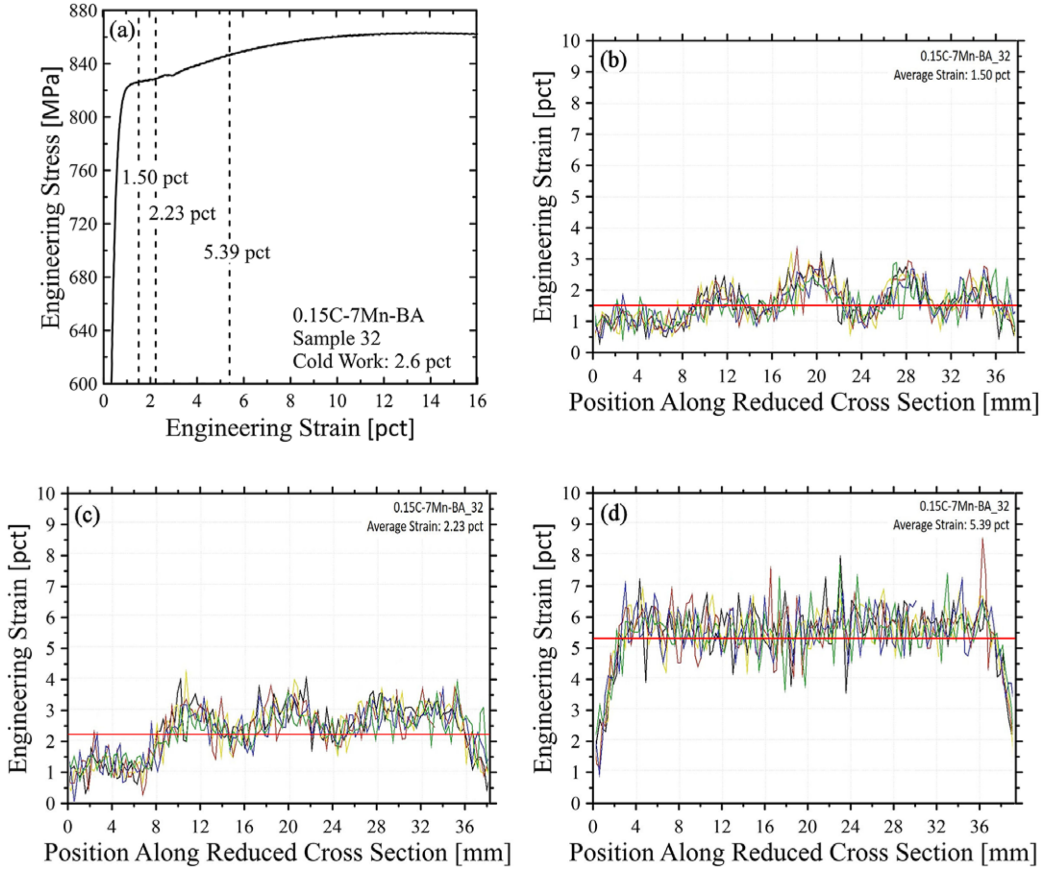

Figure 4. Stress–strain data for a sample of the 0.15C-7Mn (wt%) steel cold worked 2.6 pct resulting in the intermediate yielding behavior shown in (a) along with the strain locations for the DIC strain distributions shown for tensile strains (indicated by the horizontal red lines) of (b) 1.50 pct, (c) 2.23 pct, and (d) 5.39 pct.

distributions are essentially constant without any evidence of strain localization and remain constant with an increase in macroscopic strain consistent with the uniform deformation behavior evident in the stress–strain data.

Figure 4 displays unique incipient yielding behavior for a sample cold worked 2.6 pct. After yielding and throughout the initial deformation region the strain hardening rate remained positive but exhibited the distinct incipient behavior consistent with Figure 1d. At an imposed macroscopic average strain of 1.50 pct, Figure 4b shows that multiple strain localization zones developed as evidenced by the multiple peaks and valleys. This behavior was completely unanticipated and differs significantly from the behavior exhibited in Figures 2 and 3. The features shown in Figure 4b were not evident at lower macroscopic strains where the DIC data showed uniform deformation immediately after the onset of plastic deformation. As a consequence of this short initial uniform deformation, the lower strain valleys have a strain level above 1 pct while for Lüders band behavior shown in Figure 2b the regions beyond the band had nominally no deformation. With continued macroscopic deformation, the bands did not propagate, but as shown in Figure 4c, the peak and valley strains both increased with the strain in the valleys increasing at a greater rate. Following further bulk deformation, uniform strain along the gage length evolved as shown in Figure 4d. Observing the transition between localized and uniform deformation was difficult since localization occurred over a few pct strain. However, the strain evolution video included as Supplementary Material clarifies the behavior. Once a uniform strain level was achieved, deformation remained uniform as shown in Figure 4d (average strain 5.39 pct) and consistent with the uniform strain distributions shown in Figures 2d and 3b,c. In contrast to the distinct Lüders band shown in Figure 2b where the strain difference between the peak and background was about 5 pct, the peak to valley strain separation shown in Figure 4b is much smaller, approximately 1–2 pct. DIC data were essential for capturing the unique deformation, that is, the simultaneous development of multiple strain localization zones along the gage length, characteristics not evident by assessment of only stress–strain data. Future research will be required to identify the microstructural variables and deformation mechanisms responsible for the uniquely observed multiple strain localization zones associated with the incipient yielding phenomena.

Acknowledgments. The authors gratefully acknowledge input from the corporate sponsors of the Advanced Steel Processing and Products Research Center, an industry/university cooperative research center at the Colorado School of Mines. Technical discussions on DIC applications with Drs. Adam Creuziger and Mark Iadicola of the National Institute of Standards and Technology, Gaithersburg, MD were greatly appreciated.

Supplementary Materials. To view supplementary material for this article, please visit http://doi.org/10.1017/exp.2022.22.

Data Availability Statement. Readers can contact the authors if they want access to information beyond that included here and in the Supplementary Material.

Authorship Contributions. B.R. and D.K.M. conceived and designed the study. B.R. conducted the experimental work and data analyses. B.R. and D.K.M. wrote and edited the article.

Funding Statement. The research was funded as a special undergraduate research project by the Advanced Steel Processing and Products Research Center at the Colorado School of Mines.

Conflict of Interest. The authors declare none.

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Peer Reviews

Reviewing editor: Dr. Mert Celikin

University College Dublin, Mechanical and Materials Engineering, Dublin, Ireland, 4

Minor revisions requested.

doi:10.1017/exp.2022.22.pr1

Review 1: Observing Non-Uniform, Non-Lüders Yielding in a Cold-Rolled Medium Manganese Steel with Digital Image Correlation

Reviewer: Dr. A. Abedini

Univ Waterloo, Canada

Date of review: 27 June 2022

Conflict of interest statement. Reviewer declares none.

Comment

Comments to the Author: This study investigates the formation of Lüders bands in uniaxial tensile tests on a 0.15C-7.33Mn-0.24Si steel grade subjected to cold rolling with different reduction levels. Using digital image correlation (DIC), it is demonstrated that the magnitude and severity of Lüders bands depend on the amount of cold work. Please see the remarks below to improve the quality of the paper:

- The paper reads like a “test report” and does not include critical discussions and evaluations expected to see in scientific published studies. The authors should investigate the underlying reasons for the observed experimental trends, or at least discuss these in more detail. This can be done with microstructural studies of the material before and after cold-rolling, for example. The authors should better discuss why the increase of the cold work eliminates the localized bands.

- The introduction section covers studies in the 1980s and can benefit from inclusion of more recent studies. Please provide a more updated literature survey on Lüders bands for steel grades. See the study by Kozlowska et al. (2019, doi:10.3390/ma12244175). For the application of DIC for revealing non-uniform yielding and PLC effects, see the studies published by the research group of Prof. Worswick and Prof. Butcher of the University of Waterloo (like the study by Rahmaan et al. 2015, https://doi.org/10.1016/j.ijimpeng.2015.09.006) as well as the studies by the group of Prof. Korkolis (Ohio State University) on aluminum alloys.

- Include images showing DIC strain contours of major strain for the snapshots in time associated with the data shown in Figures 2-4.

- Include tensile results of the as-received material besides the results of the material after cold rolling.

- Please present values or numbers in the form of tables rather than within the text. This will make reading the article much easier.

Score Card

Presentation

2.6 /5

Is the article written in clear and proper English? (30%)	4/5
Is the data presented in the most useful manner? (40%)	2/5
Does the paper cite relevant and related articles appropriately? (30%)	2/5

Context

2.8 /5

Does the title suitably represent the article? (25%)	3/5
Does the abstract correctly embody the content of the article? (25%)	3/5
Does the introduction give appropriate context? (25%)	2/5
Is the objective of the experiment clearly defined? (25%)	3/5

Analysis

2.2 /5

Does the discussion adequately interpret the results presented? (40%)	2/5
Is the conclusion consistent with the results and discussion? (40%)	2/5
Are the limitations of the experiment as well as the contributions of the experiment clearly outlined? (20%)	3/5

doi:10.1017/exp.2022.22.pr2

Review 2: Observing Non-Uniform, Non-Lüders Yielding in a Cold-Rolled Medium Manganese Steel with Digital Image Correlation

Reviewer: Dr. Shengci Li

Date of review: 15 August 2022

Conflict of interest statement. Reviewer declares none.

Comment

Comments to the Author: Some novel result were obtained in this paper by observing Non-Uniform, Non-Lüders Yielding in a Cold Rolled Medium Manganese Steel with DIC. The overall quality of the paper is good. Please consider the following comments.

1. The experimental details should be described more clearly, and some important photos, such as photos of dic patterns, should be provided.
2. It is recommended to provide strain distribution maps for analysis and understanding of strain evolution.

Score Card

Presentation

5.0 /5

Is the article written in clear and proper English? (30%)	5/5
Is the data presented in the most useful manner? (40%)	5/5
Does the paper cite relevant and related articles appropriately? (30%)	5/5

Context

5.0 /5

Does the title suitably represent the article? (25%)	5/5
Does the abstract correctly embody the content of the article? (25%)	5/5
Does the introduction give appropriate context? (25%)	5/5
Is the objective of the experiment clearly defined? (25%)	5/5

Analysis

5.0 /5

Does the discussion adequately interpret the results presented? (40%)	5/5
Is the conclusion consistent with the results and discussion? (40%)	5/5
Are the limitations of the experiment as well as the contributions of the experiment clearly outlined? (20%)	5/5

doi:10.1017/exp.2022.22.pr3

Review 3: Observing Non-Uniform, Non-Lüders Yielding in a Cold-Rolled Medium Manganese Steel with Digital Image Correlation

Reviewer: Dr. Muxin Yang

Date of review: 18 August 2022

Conflict of interest statement. Reviewer declares none.

Comment

Comments to the Author: Comments:

a) The main finding of this paper is the observation of the incipient yielding behavior of the 2.6% pre-deformed sample, in which the multiple strain localization regions have been generated in the early plastic strain stage, but not propagated in the subsequent tensile deformation. The possible microscopic mechanisms for the formation of such non-propagating strain regions should be discussed accordingly in this paper.

b) It is suggested that the applied macroscopic strains should be marked with a red horizontal lines in Figs. 2/3/4b-d, in order to more clearly show the variation of the non-uniform local strain. After doing this, it is not difficult to compare Figs. 4b and 4c to find that at applied strain of 1.5%, there are 4 local strain peaks exceeding the applied strain, and when the strain reaches 2.23%, the number of local strain peaks reduces to 3, i.e., the prior strain-valley at the position of 32 mm is disappeared gradually. This indicates that the strain-concentrated region in the moderately pre-deformed sample also undergo axial propagation during the tensile deformation.

c) The author claim in their Abstract that "… a unique yielding behavior was evident where the initially-low positive strain hardening rate INCREASED with tensile strain …". The authors should plot the corresponding strain hardening rate-true strain curve to prove that. The authors are also encouraged to continue in-depth research to clarify the quantitative relationship between non-uniform local deformation and macroscopic strain hardening behavior, as well as its influence on macroscopic ductility.

Score Card

Presentation

4.1 /5

Is the article written in clear and proper English? (30%)	4/5
Is the data presented in the most useful manner? (40%)	5/5
Does the paper cite relevant and related articles appropriately? (30%)	3/5

Context

4.8 /5

Does the title suitably represent the article? (25%)	4/5
Does the abstract correctly embody the content of the article? (25%)	5/5
Does the introduction give appropriate context? (25%)	5/5
Is the objective of the experiment clearly defined? (25%)	5/5

Analysis

4.2 /5

Does the discussion adequately interpret the results presented? (40%)	4/5
Is the conclusion consistent with the results and discussion? (40%)	4/5
Are the limitations of the experiment as well as the contributions of the experiment clearly outlined? (20%)	5/5

doi:10.1017/exp.2022.22.pr4

Review 4: Observing Non-Uniform, Non-Lüders Yielding in a Cold-Rolled Medium Manganese Steel with Digital Image Correlation

Reviewer: Dr. Huseyin Aydin

Tubitak Marmara Arastirma Merkezi, Gebze, Turkey, 41470

Date of review: 24 August 2022

Conflict of interest statement. Reviewer declares none

Comment

Comments to the Author: This work provides an interesting study about discontinuous yielding phenomena in a Cold- Rolled Medium Manganese Steel with Digital Image Correlation. Basic tensile testing experiment were used to systematically carry out the results, which are described clearly with acceptable supplemental data. The conclusion sounds reasonable since the characteristic feature of discontinuous yielding in this material is that at the yield point the specimen goes from a condition where the availability of mobile dislocations is limited to one where they are in abundance which increase in mobile density largely arising from dislocation multiplication at the high stress level. Although, paper provides significant technical importance for the experimental process, more test results and DIC data should be presented for the proper data acquisition of the results. The reviewer recommends for publication of the article on Experimental Results after the authors presenting few more repeatable results.

Score Card

Presentation

3.9 /5

Is the article written in clear and proper English? (30%)	5/5
Is the data presented in the most useful manner? (40%)	3/5
Does the paper cite relevant and related articles appropriately? (30%)	4/5

Context

4.8 /5

Does the title suitably represent the article? (25%)	5/5
Does the abstract correctly embody the content of the article? (25%)	5/5
Does the introduction give appropriate context? (25%)	5/5
Is the objective of the experiment clearly defined? (25%)	4/5

Analysis

3.8 /5

Does the discussion adequately interpret the results presented? (40%)	4/5
Is the conclusion consistent with the results and discussion? (40%)	4/5
Are the limitations of the experiment as well as the contributions of the experiment clearly outlined? (20%)	3/5