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An investigation into the phenomenon of macroscopic plastic deformation localization in metals

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Abstract. Experimental and theoretical studies are combined to investigate the phenomenon of macroscopic plastic deformation localization in metallic tensile specimens of AL6061, HSLA350 and Q235. The longitudinal strain and cross-section reduction of the specimens at different instant during testing are estimated through the measurement technique of three dimensional digital image correlation (3D-DIC). The Ling weighted-average method referred as WAM is used to compare the true stress-strain relation obtained from the experiment. A new mathematical model is suggested to estimate the localization zone length, which is a crucial parameter that can be used to anticipate the behaviour of metals past the peak load. The effect of material property on the necking zone length is examined. The experimental results show that the axial strain within the necking zone is non-uniform. It is also found that the WAM can precisely derive the true stress of steels Q235 and HSLA350 but not AL6061. The localization zone length of the round specimens Q235, HSLA350, and AL6061 equals six, five, and four times their initial diameter, respectively. Materials with a higher fracture strain ratio to the ultimate strain have a shorter necking zone length. This work provides insights into the physical mechanism of macroscopic plastic deformation localization.

1. Introduction

As an essential failure mechanism, plastic strain localization widely exists in a variety of engineering materials such as soil [1], rock [2], concrete [3, 4], and metal alloys [5, 6]. With the occurrence of strain localization, the uniform strain field changes rapidly to a discontinuous pattern resulting in an intense straining within a narrow region. The ability to characterize strain localization as a precursor to final material failure is important for engineering applications of, e.g., metallic materials. In ductile metals, there are three frequent forms of macroscopic inelastic deformation: (1) Lüder's bands [7] which occur in some metals as a plateau past the yield stress for a small percent of strain until strain hardening resumes; (2) necking [8] which is a precursor to fracture; and (3) Portevin-Le Châtelier effect [9] which represents a typical plastic instability in many metallic alloys. This paper investigates the phenomenon of local plastic strain in metals occurring in the form of necking.

Over the past decades, many experimental, analytical, and numerical studies have been conducted to characterize the behaviour of tensile metallic specimens following initiation of necking [10-13]. Assuming that within the narrowest cross-section of a tensile specimen longitudinal strain is uniform; Bridgman [14] determined the stress-strain relation based on the neck profile relying on two key parameters namely the specimen’s current minimum radius and the radius of curvature. However, as
shown in section 3, our experiments reveal that axial strain is not distributed uniformly on the neck section. The weighted-average method (WAM) proposed by Ling [15] is another widely used approach to determining true stress following initiation of necking. For a rod of mild carbon steel, the WAM predictions agree well with experimental results [15]. However, it remains unclear whether the WAM can characterise accurately the post-necking hardening behaviour of other metallic materials.

In addition, strain localization initiation and fracture of steels were qualitatively studied [16-19]. However, the attempts to quantify the localization zone are limited in literature [20]. Besides, existing studies predicted the necking zone length as a constant [16, 21]. In this work, it is shown that as soon as necking occurs, the necking region length varies with loading. Saif et al. [22] also found that the localization length of low carbon steels is not constant but changes with loading past the maximum load. The length of the plastic deformation zone is a crucial indicator of strain localization and is useful to anticipate the behaviour of metals beyond the peak load.

In this study, the strain evolution of three metals (Q235, HSLA350, and AL6061) is measured using 3D-DIC technique. The Ling weighted-average method referred as WAM is used to compare the true stress-strain relation obtained from the experiment. A new mathematical approach is suggested to estimate the localization zone length of the tested materials. The influence of material property on the necking zone length is examined. This work provides further insights into the phenomenon of macroscopic plastic deformation localization in metals.

2. Materials and methods
Metallic tested materials in this study include tensile coupons of AL6061 (aluminum alloy), HSLA350 (high strength low alloy steel) and Q235 (mild steel). The ASTM E8 standard [23] was taken as reference to prepare the round specimens. A description of the geometry of the specimens with dimensions (in mm) is outlined in figure 1.

![Figure 1. Geometry description of tested metallic round coupons.](image_url)

All the tensile tests were conducted at room temperature using a dual system comprising of a Material Testing System (MTS) tensile machine of 250 KN maximum loading capacity and a 3D-DIC measurement system. The crosshead displacement rate of the MTS was set at 2 mm/min. The surface of the coupons particularly the measurement area was prepared before testing with random speckle pattern. To capture digital images throughout the test under different loading, which are critical for deformation measurement, a pair of high-performance area scan cameras with a resolution of 2320 pixels × 1726 pixels was used. Due to its advantages in particular simplicity and non-contact, DIC has been widely used for direct deformation measurement [24-28].

Load data were acquired directly from the MTS tensile machine. The 3D-DIC software (Correlated Solutions) was utilized to process the captured digital images which enable calculation of displacement and strain. In figure 2, the measured load-extension curves of the materials are shown into the same plot to facilitate direct comparison. The deformation trend of both materials Q235 and HSLA350 can be divided into four main stages: (1) normal elastic extension up to the yield point; (2) Lüders band propagation (plateau) until hardening resumes; (3) strain hardening up to the maximum loading; and (4) necking past the maximum load until fracture of the specimen. A similar deformation
trend can be observed for the coupons of AL6061 but without the Lüders band propagation. As illustrated in figure 2, the specimens of Q235 and HSLA350 exhibit higher extensions than AL6061.

![Load–elongation curves of the three materials.](image)

**Figure 2.** Load–elongation curves of the three materials.

3. Results and discussions

3.1. Measured axial strain and cross-section reduction

When investigating the necking phenomenon, Bridgman [14] assumed that the longitudinal (axial) strain on the neck section is constant. As depicted in figure 3, two outside (A and B) and four inside (C to F) deformation regions are selected to further examine the Bridgman’s assumption. The principle to measure the axial true strain with 3D-DIC software can be found in [29]. The temporal evolutions of the axial true strain outside and inside the necking zone are illustrated in figure 3. After necking, the axial true strain outside the necking zone (Sections A and B) remains uniform. However, following initiation of necking, the axial true strain from sections C to F increases monotonically until fracture occurs and is therefore not constant. A similar conclusion from an analytical study has been drawn by Yamashita [28].

The estimation of the true cross-sectional area is important to evaluate the true stress. Therefore, in this study, the cross-sectional diameter of the specimens was estimated directly from the measured longitudinal strain, and is plotted in figure 4 versus the engineering strain. When necking just initiates, the specimen’s cross-section reduction is very small. But under well developed plastic strain localization condition, the cross-sectional diameter of the specimens reduces considerably with increasing engineering strain.

![Evolution of the axial true strain before and after the occurrence of necking.](image)

**Figure 3.** Evolution of the axial true strain before and after the occurrence of necking.
3.2. True stress-strain relations

Many mathematical models to extrapolate the true stress of ductile metals in the necking zone can be found in the literature. Due to their simplicity, extrapolation models such as the Hollomon equation and the linear law [30] are largely used. The main concern however is the accuracy of the results predicted by these two methods. To overcome this drawback, Ling [15] developed the weighted-average method (WAM) using a weight constant \( w \) to combine the Hollomon equation and the linear extrapolation as defined by Eq. (1).

\[
\sigma = \sigma_0 \left[ w (1 + \varepsilon - \varepsilon_0) + (1 - w) \left( \frac{\varepsilon_0 \varepsilon}{\varepsilon_0 \varepsilon} \right) \right] \quad (1)
\]

where \( w \in [0,1] \); \( \sigma_0 \) and \( \varepsilon_0 \) denote true stress and true strain when necking initiates, respectively; \( \sigma \) and \( \varepsilon \) true stress and true strain within the necking zone. At the onset of necking, the true stress and corresponding true strain can be estimated directly from engineering values measured with an extensometer assuming that volume before and after deformation is equal. However, a more sophisticated method is required (DIC for instance) to directly measure the strain distribution in the necking zone.

In this section, attention is focused on comparing the true stress extrapolated by the WAM (Eq. (1)) and measured with digital image correlation technique for materials Q235, HSLA350, and AL6061. The true strain \( \varepsilon \) was obtained directly from processing digital captured images. Ignoring the effects of stress triaxiality, the measured true stress is firstly obtained as \( P/A \) where \( P \) is the load applied to the specimen and \( A \) is the corresponding true cross-sectional area. Then, a stress correction factor is used to convert the average axial true stress to equivalent stress as follows

\[
\sigma_c = M_k \sigma \quad (2)
\]

where \( \sigma_c \) is the equivalent stress and \( M_k \) is a stress correction factor derived as a polynomial function of degree 4 [31].

\[
M_k = 1 - 0.6058(\varepsilon - \varepsilon_0)^2 + 0.6317(\varepsilon - \varepsilon_0)^3 - 0.2107(\varepsilon - \varepsilon_0)^4 \quad (3)
\]

For each material, the true stress-strain response measured using DIC technique and derived by the WAM is compared in figure 5. When the effects of stress triaxiality are not taken into consideration, the measured and extrapolated true stresses correspond at \( w = 1 \) for the steel coupons of Q235 and HSLA350 and at \( w = 0 \) for the coupons of AL6061 as depicted in figure 5(a, c, e). On the other hand, as illustrated in figure 5(b, d), when the experimental average axial true stress is corrected as defined by Eq. (2) and (3), a good correlation with the WAM can be observed when \( w = 1/2 \) for coupons of

**Figure 4. Cross-section reduction versus engineering strain of the tensile specimens.**
Q235 and HSLA350. However, for any weight constant \( w \) value, the WAM cannot accurately match up the measured corrected true stress for the coupons of AL6061 as shown in figure 5(f). Therefore, the suitability of the WAM to provide good results highly depends on material property.

![Figure 5](attachment:figure5.png)  

**Figure 5.** Comparison between experimental and extrapolated (WAM) true stress-strain curves.

3.3. Influence of material property on the localization length  
The necking zone length is a key indicator of the localization level reached by a material. It may provide opportunity to precisely estimate localization level forming limit diagram [20] and ductility of metal structures. It is therefore important to investigate how the necking zone length varies with material property. For cylindrical specimens, the necking zone length, \( L_w \), can be expressed as

\[
L_w = \beta d_0
\]  \hspace{1cm} (4)

where \( d_0 \) is the original diameter of a specimen’s reduced section and \( \beta \) is a dimensionless parameter that may vary depending on specimen size and material property. In this study, considering
that the ratio of the original gage length, $L_0$, to the original diameter, $d_0$, ($L_0 / d_0 = 5$) is similar for all tested specimens, the dependency of the parameter $\beta$ is thus checked against material property considering the ratio of the average engineering strain at fracture, $e_L$, to the average engineering ultimate strain, $e_u$. Based on the evolution of necking observed during the tests, the parameter $\beta$ of a specimen is derived with respect to deformation regions before and after necking initiation.

$$\beta = \begin{cases} 
0, & \omega < 1.0 \\
\zeta \ln(\omega) + m, & \omega \geq 1.0 
\end{cases} \tag{5}$$

In Eq. (5), $\omega$ denotes displacement level and is expressed as the ratio of $\delta_i$ to $\delta_u$ in which $\delta_i$ is the average axial displacement within the gauge length of a specimen for a load $P_i$ and $\delta_u$ is the ultimate displacement at the maximum load $P_u$ [28]. The variation of $\beta$ with respect to displacement level $\omega$ observed from the tests is shown by discrete data points in figure 6 for each material. Data regression using a natural logarithmic function was conducted to estimate the constants $\zeta$ and $m$. The material parameters including the constants $\zeta$ and $m$, the average engineering ultimate strain, the average engineering strain at fracture and the average value of $\beta$ ($\omega = 1.4$) are summarized in Table 1.

In region I which is outside the necking zone (figure 6), regardless of the material property, $\beta = 0$ ($\omega < 1.0$), i.e., strain localization does not occur. However, in region II where necking occurs ($\omega \geq 1.0$), as shown in figure 6, as the displacement level $\omega$ increases, $\beta$ increases for each material. Parameter $\beta$ at any displacement level ($\omega \geq 1.0$), is higher for Q235 than both HSLA350 and AL6061. Overall, the lower the value of $e_L / e_u$ of a material (Table 1), the higher the value of $\beta$ and thus the larger the necking zone length, $L_w$.

![Figure 6. Variation of the parameter $\beta$ with respect to the displacement level $\omega$.](image)

### Table 1. Parameters of the three metallic materials.

| Material   | $\zeta$ | $m$ | $e_u$ (%) | $e_L$ (%) | $e_L / e_u$ | $\beta$ |
|------------|---------|-----|-----------|-----------|-------------|---------|
| Q235       | 12.75   | 2.3 | 32.86     | 47.86     | 1.46        | 6.0     |
| HSLA350    | 10.66   | 1.3 | 23.67     | 36.8      | 1.55        | 5.0     |
| AL6061     | 8.55    | 1.1 | 11.93     | 19.71     | 1.65        | 4.0     |

#### 4. Conclusions

Experimental investigation using 3D-DIC was carried out into the phenomenon of macroscopic plastic deformation localization in metallic coupons of AL6061, Q235, and HSLA350 subjected to uniaxial loading. The following key findings can be drawn from this study:

- It is demonstrated that the axial strain in the necking region is not constant, indicating that Bridgman’s assumption is not correct for the tested materials.
• The average true stress-strain curves measured directly with DIC and extrapolated by the weighted-average method (WAM) correlate perfectly. However, when the measured true stress is converted to equivalent stress, the Ling weighted-average method fails to accurately predict the true stress of AL601 tensile coupons.
• Materials with a higher fracture strain ratio to the ultimate strain have a shorter necking zone length.

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References
[1] Desrues J and Viggiani G 2004 Strain localization in sand: an overview of the experimental results obtained in Grenoble using stereophotogrammetry Int. J. Numer. Anal. Met. 28 279-321
[2] Zhang H, Huang G, Song H and Kang Y 2013 Experimental characterization of strain localization in rock Geophys. 194 1554-8
[3] Wei Y and Wu Y F 2016 Experimental study of concrete columns with localized failure J. Compos. 20 04016032
[4] Wu YF and Wei Y 2016 Stress–strain modeling of concrete columns with localized failure: an analytical study J. Compos. 20 04015071
[5] Antolovich SD and Armstrong RW 2014 Plastic strain localization in metals: origins and consequences Prog. Mater. Sci. 59 1-160
[6] Gruben G, Morin D, Langseth M and Hopperstad OS 2017 Strain localization and ductile fracture in advanced high-strength steel sheets Eur. J. Mech. A-Solid. 61 315-29
[7] Hallai JF and Kyriakides S 2013 Underlying material response for Lüders-like instabilities Int. Mech. 47 1-12
[8] Bouktir Y, Chalal H and Abed-Merai F 2018 Prediction of necking in thin sheet metals using an elastic–plastic model coupled with ductile damage and bifurcation criteria Int. J. Damage Mech. 27 801-39
[9] Renard K, Ryelandt S and Jacques P 2010 Characterisation of the Portevin-Le Châtelier effect affecting an austenitic TWIP steel based on digital image correlation Mater. Sci. Eng. A. 527 2969-77
[10] Kamaya M and Kawakubo M 2011 A procedure for determining the true stress–strain curve over a large range of strains using digital image correlation and finite element analysis Mech. Mater. 43 243-53
[11] Zhang Z, Hauge M, Ødegård J and Thaulew C 1999 Determining material true stress–strain curve from tensile specimens with rectangular cross-section Int. J. Solids Struct. 36 3497-516
[12] Zhao K, Wang L., Chang Y and Yan J 2016 Identification of post-necking stress–strain curve for sheet metals by inverse method Mech. Mater. 92 107-18
[13] Zhu F, Bai P, Zhang J, Lei D and He X 2015 Measurement of true stress–strain curves and evolution of plastic zone of low carbon steel under uniaxial tension using digital image correlation Opt. Lasers Eng. 65 81-8
[14] Bridgman PW 1952 Studies in Large Plastic Flow and Fracture (New York: McGraw-Hill)
[15] Ling Y 1996 Uniaxial true stress-strain after necking AMP J. Tech. 5 37-48
[16] Ding L, Lin J, Min J, Pang Z and Ye Y 2013 Necking of Q&P steel during uniaxial tensile test with the aid of DIC technique Chin. J. Mech. Eng-En. 26 448-53
[17] Guelorget B, François M, Vial-Edwards C, Montay G, Daniel L and Lu J 2006 Strain rate measurement by electronic speckle pattern interferometry: a new look at the strain localization onset Mater. Sci. Eng. A. 415 234-41
[18] Labergere C, Guelorget B and Francois M 2014 Strain rate distribution and localization band width evolution during tensile test Int. J. Solids Struct. 51 3944-61
[19] Petit J, Montay G and François M 2014 Strain rate measurements by speckle interferometry for necking investigation in stainless steel *Int. J. Solids Struct.* **51** 540-50

[20] Hora P, Berisha B, Gorji M and Manopulo N 2012 A generalized approach for the prediction of necking and rupture phenomena in the sheet metal forming *IDDRG12* pp 79-93

[21] Paul SK, Roy S, Bar HN and Tarafder S 2018 Identification of post-necking tensile stress-strain behaviour of steel sheet: an experimental investigation using Digital Image Correlation technique *J. Mater. Eng. Perfom.* **27** 5736-43

[22] Altai S, Orton S, and Chen Z 2020 Evolution of localization length during postpeak response of steel in tension: experimental study *J. Eng. Mech.* **146** 04020069

[23] ASTM International 2011 ASTM E8/E8M-09 standard test methods for tension testing of metallic materials (USA: ASTM International)

[24] Ma S, Zhao ZL and Wang X 2012 Mesh-based digital image correlation method using higher order isoparametric elements *J. Strain Anal. Eng.* **47** 163-75

[25] McNeill S, Sutton M, Miao Z and Ma J 1997 Measurement of surface profile using digital image correlation *Exp. Mech.* **37** 13-20

[26] Wu YF and He L 2019 Width effect of interfacial bond characteristics *Constr. Build. Mater.* **220** 712-26

[27] Wu YF and Jiang C 2013 Quantification of bond-slip relationship for externally bonded FRP-to-concrete joints *J. Compos.* **17** 673-86

[28] Yamashita N 1966 The stress and strain distribution at the neck of a tensile specimen *Bulletin of JSME.* **9** 637-43

[29] Versaillot PD, Wu YF, and Zhao ZL 2021 Experimental study on the evolution of necking zones of metallic materials *Int. J. Mech. Sci.* **189** 106002

[30] Ho H, Chung K, Liu X, Xiao M and Nethercot D 2019 Modelling tensile tests on high strength S690 steel materials undergoing large deformations *Eng. Struct.* **192** 305-22

[31] Mirone G 2004 A new model for the elastoplastic characterization and the stress–strain determination on the necking section of a tensile specimen *Int. J. Solids Struct.* **41** 3545-64