Evolution of strain field in an over-matching welded joint under tension estimated using digital image correlation*

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Two-dimensional digital image correlation (2D-DIC) is a computer-based, non-contacting, surface deformation measurement. Using this method, the strain field was measured in the welded joint under tension. Due to the different mechanical properties, the strains are inhomogeneous in the different parts of the welded joint. Their differences were revealed, and the strain evolution in each part of the welded joint was estimated.

Key Words: Welded joint; Strain field; Displacement field; Strength mismatching; Digital image correlation; Tension

1. Introduction

A welded joint is generally composed of base metal (BM), heat-affected zone (HAZ), and weld metal (WM). The mechanical properties of the three regions are different. A strength over-matching welded joint, i.e., the strength of weld metal is higher than that of base metal, is predominant in practical applications. Because of different mechanical properties, deformation over the whole welded joint is not uniform. For this reason, it is difficult to estimate the strain field and its evolution in each region under tension. Hitherto, the finite element method (FEM) has been the most commonly used tool to estimate the strain field in a welded joint.1-5) However, the FEM is only a calculation method, and its result needs to be verified by experimental data. Furthermore, in the FEM, it is difficult to accurately consider the information of mechanical properties corresponding to the complicated microstructure changes in the HAZ and the WM. Unfortunately, there is no effective method for directly measuring the full-field strain over the whole welded joint.

Strain gage measurement is a conventional method. However, it can only measure the strain at one point. Comparing with the strain gage measurement, digital image correlation (DIC) is a computer-based, non-contacting, surface deformation measurement method that was developed in the 1980s and matured in the late 1990s.6) It has been shown that DIC is a useful tool to directly measure local strain and full-field strain on a surface.7-9) It has been successfully applied to steel. Using similar method, applying DIC to a welded joint will show the full-field strain of each region. Although it provides only surface information, the obtained results will reflect the characteristics of the strain-field evolution in the welded joint in perspective.

In this study, the focus is on an over-matching welded joint as follows: (1) evaluating the characteristic of the whole welded joint in terms of the stress-strain curve obtained using an extensometer and (2) using two-dimensional DIC (2D-DIC) to measure the local strain and strain field in each region of the welded joint and revealing the evolution of the strain field in the tension process.

2. Experimental

An over-matching welded joint was produced by welding an HT980 steel plate (25 mm thickness; chemical composition: 0.13C-0.32Si-1.43Mn-0.55Mo in wt%) in five passes with solid welding wire (0.049C-0.61Si-0.71Mn-17.7Cr07.13Ni in wt%) under pure Ar shielding gas. The welding method used is gas metal arc welding. The heat input is 19-20 kJ/cm (current: 380-400 A; voltage: 27-30 V; welding speed: 35 cm/min), and the groove of the base metal is X-type. The profile of the welded joint is shown in Fig. 1(a).

A round tensile specimen was used for the base metal (HT980) and weld metal to estimate their mechanical properties. The sizes of the tensile specimen of the BM are 4 mm in diameter and 20 mm in gage length. The two circles in the WM in Fig.1(a) show the directions along which round specimens were machined. Its diameter is 6 mm, and the gage length is 30 mm. The up and down specimens are for the up- and down-weld metal, respectively.

A dog bone-type planar specimen was used for the welded joint (HT980) and weld metal to estimate their mechanical properties. The sizes of the tensile specimen of the BM are 4 mm in diameter and 20 mm in gage length. The two circles in the WM in Fig. 1(a) show the directions along which round specimens were machined. Its diameter is 6 mm, and the gage length is 30 mm. The up and down specimens are for the up- and down-weld metal, respectively.

A dog bone-type planar specimen was used for the welded joint to measure the characteristic of the whole welded joint and the strain field in each region of the welded joint. Its width is 20 mm, and the gage length (GL) is 50 mm. Within the gage length, the BM, HAZ and WM are involved, and the WM is in the center of the specimen. All tension tests were performed at room temperature and at a crosshead speed of 0.01 mm/s.

2D-DIC was applied to measure the full field of strain. Its
principle has been described in detail elsewhere. It has been extracted as follows. The basis of 2D-DIC for the measurement of surface displacements is the matching of one point from an image of an object’s surface before loading (the undeformed image) to a point in an image of the object’s surface taken at a later time/loading (the deformed image). Assuming a one-to-one correspondence between the deformations in the image taken by the camera and the deformations of the surface of the object, an accurate point-to-point mapping from the undeformed image to the deformed image will allow the displacement of the object’s surface to be measured. The imaging process of the camera converts the continuous intensity field reflected from the surface \( O(\mathbf{X}, \mathbf{Y}) \) into a discrete field \( I(\mathbf{X}, \mathbf{Y}) \) of integer intensity levels.

The process of deformation in two dimensions is shown schematically in Fig. 2. The functions are defined as follows: (a) \( O(\mathbf{X}, \mathbf{Y}) \) denotes the continuous intensity pattern for the undeformed object, (b) \( O'(\mathbf{X}, \mathbf{Y}) \) is the continuous intensity pattern for the deformed object, (c) \( I(\mathbf{X}, \mathbf{Y}) \) is the discretely sampled intensity pattern for the undeformed object and (d) \( I'(\mathbf{X}, \mathbf{Y}) \) is the discretely sampled intensity pattern for the deformed object. It is important to note that a basic tenet of the 2D-DIC method is that points in \( I(\mathbf{X}, \mathbf{Y}) \) and \( I'(\mathbf{X}, \mathbf{Y}) \) are assumed to be in one-to-one correspondence with points in \( O(\mathbf{X}, \mathbf{Y}) \) and \( O'(\mathbf{X}, \mathbf{Y}) \), respectively. Thus, one can use \( I(\mathbf{X}, \mathbf{Y}) \) and \( I'(\mathbf{X}, \mathbf{Y}) \) to determine the displacement field for the object \( O(\mathbf{X}, \mathbf{Y}) \).

For the small subset centered at \((\mathbf{X}, \mathbf{Y})\) on the undeformed object in Fig. 2, the discretely sampled and continuously interpolated intensity pattern at points \( P \) and \( Q \), located at positions \((\mathbf{X}, \mathbf{Y})\) and \((\mathbf{X} + \mathbf{dX}, \mathbf{Y} + \mathbf{dY})\) respectively, can be written as

\[
I(P) = I(\mathbf{X}, \mathbf{Y}), \quad I(Q) = I(\mathbf{X} + \mathbf{dX}, \mathbf{Y} + \mathbf{dY}),
\]

(1)

where \((\mathbf{dX}, \mathbf{dY})\) represent small distances in the \((\mathbf{X}, \mathbf{Y})\) coordinate system. Note that if the values for \( \mathbf{dX} \) and \( \mathbf{dY} \) are integer pixel values, then no interpolation is required for the undeformed image. As shown in Fig. 2, after the deformation of an object, points \( P \) and \( Q \) are deformed into positions \( p \) and \( q \), respectively. Assuming that the intensity pattern recorded after deformation is related to the undeformed pattern by the object deformations and defining \( \{u(\mathbf{X}, \mathbf{Y}), v(\mathbf{X}, \mathbf{Y})\} \) as the displacement vector field, we can write

\[
x = \mathbf{X} + u(\mathbf{X}, \mathbf{Y}), \quad y = \mathbf{Y} + v(\mathbf{X}, \mathbf{Y})
\]

(2)

Assuming that the subset is sufficiently small so that the displacement gradients are nearly constant throughout the region of interest, each subset undergoes uniform strain resulting in the parallelogram shape for the deformed subset as shown in Fig. 2. Conceptually, determining \( u, v, \partial u/\partial \mathbf{X}, \partial u/\partial \mathbf{Y}, \partial v/\partial \mathbf{X}, \) and \( \partial v/\partial \mathbf{Y} \) for each subset is simply a matter of determining all six parameters so that the intensity values at each point in the undeformed and deformed regions match. To obtain these values, a normalized cross-correlation function is used to obtain the best estimates for the displacement field and it is defined as

\[
1.0 - C_0 \left[ \sum_{\mathbf{X}, \mathbf{Y}} |I(\mathbf{X}, \mathbf{Y})|^2 \right] = \frac{\sum_{\mathbf{X}, \mathbf{Y}} \sum_{\mathbf{X}', \mathbf{Y}'} J(\mathbf{X}, \mathbf{Y}) J(\mathbf{X}' + u(\mathbf{X}, \mathbf{Y}), \mathbf{Y}' + v(\mathbf{X}, \mathbf{Y}))}{\sum_{\mathbf{X}, \mathbf{Y}} \sum_{\mathbf{X}', \mathbf{Y}'}} (3)
\]

(3)
The values for $u$, $v$, $\partial u/\partial X$, $\partial u/\partial Y$, $\partial v/\partial X$, and $\partial v/\partial Y$, which minimize the quantity $(1.0-C_l)$, are assumed to represent the best estimates of the subset's displacement and strain components. It is noted that the quantity $(1.0-C_l)$ is zero for a perfect match and one for orthogonal (completely mismatched) patterns, providing a quantitative measure of the accuracy of the match between deformed and undeformed subsets. The digital image correlation for the images of the tension process was performed with a commercial software, Vic-2D 2009, produced by Correlated Solutions, Inc. It has been shown that the typical accuracy in strains is $\pm 2 \times 10^{-4}$ for 2D-DIC. 6)

The speckle pattern and the area of the 2D-DIC measurement are shown in Fig. 1(b) and (c), respectively. The experimental setup for uniaxial loading of the planar specimen is shown in Fig. 3.

3. Results and discussion

3.1 Mechanical properties of the base metal and weld metal

The stress-strain curves of the BM and WM are shown in Fig. 4. The shapes of the stress-strain curves are quite different between the BM and WM. The 0.2% proof stress, $\sigma_{0.2}$, and tensile strength, $\sigma_{TS}$, are given in Fig. 4. Because the dilution ratio of the base metal for each welding pass is different, the chemical composition in the weld metal is not uniform, resulting in a variation in strength. Figure 4 shows that the up-weld metal has higher $\sigma_{0.2}$ and $\sigma_{TS}$ than the down-weld metal. The weld metal has lower $\sigma_{0.2}$ but higher $\sigma_{TS}$ than the base metal. If the tensile strength is used to define the welded joint, since the $\sigma_{TS}$ of the weld metal is higher than that of the base metal, it produces a strength over-matching welded joint. The differences in $\sigma_{0.2}$ and $\sigma_{TS}$ between the BM and WM cause the deformation to be non-uniform over the whole welded joint.

3.2 Mechanical properties of the whole welded joint

The hardness (Hv) distributions along 1/4t, 1/2t, and 3/4t (t: thickness) (cf. Fig. 1(a)) are shown in Fig. 5. The hardness of the WM is larger than that of the BM. Even in the WM, the hardness is not uniform. The average hardness of the WM is given in Fig. 5. The order of hardness from large to small is up-weld metal (Hv=373), center-weld metal (Hv=366), and down-weld metal (Hv=351). Softening occurs in the HAZ, resulting in a HAZ with the lowest strength in the welded joint.

The tensile properties of the whole welded joint were evaluated in terms of the stress-strain curve, which is given in Fig. 6. The engineering strain is measured by an extensometer with a GL of 50mm. Within the GL, the WM, HAZ, and BM are involved. Thus the obtained engineering strain is an average value of the three regions, and the stress-strain curve reflects the characteristic of the whole welded joint.
It is noted that the specimen was tensioned up to a certain stress level, instead of final failure, and then unloaded. The picture of the post-test specimen shows that necking occurred in the base metal, and the specimen would break in this region if it was tensioned up to fracture. The $\sigma_{0.2}$ of the welded joint is 889 MPa between the $\sigma_{0.2}$ of the BM (1035 MPa) and WM (461 MPa for the up-weld metal, 419 MPa for the down-weld metal). It is a compromise between them. Because the necking occurred in the BM, the $\sigma_{TS}$ of the welded joint should be equal to that of the BM. Figures 4 and 6 show that there is a little difference in $\sigma_{TS}$ between the BM and the welded joint. It should be attributed to the scatter of data for different specimens. It is noted that we tensioned another specimen up to fracture, confirming that final failure occurred in the base metal, indirectly indicating that the welding conditions are appropriate.

3.3 Evolution of the strain field in the welded joint

To show the evolution of the strain field as deformation advances, nine points ((a) through (i)) on the stress-strain curve shown in Fig. 6 were selected. The round mark (○) represents a picture taken at that point. The strain fields corresponding to the nine points were measured with 2D-DIC. The area and position for the 2D-DIC measurement (the red region) are shown in Fig. 1(c). The obtained $\varepsilon_{xx}$ and $\varepsilon_{yy}$ fields are given in Fig. 7 (a)–(i). It is noted that the strain in Fig. 7 is true strain, also called Hencky strain.

The specific points (images) among (a)–(i) shown in Fig. 6 are as follows: image (d), at the plastic strain of 0.2%; image (h), near the maximum stress point; and image (i), test termination point.

When the specimen of welded joint began to be tensioned, it uniformly deformed over the whole welded joint. Up to image (a), as shown in Fig. 7, the deformation is essentially uniform over each part (BM, HAZ, and WM) of the welded joint. After that point, deformation in each part continued to advance, but some
local strains in the WM are larger than the strain in the BM; i.e., deformation began to concentrate in the WM, as shown in image (b). The true strain ranges for the elastic region of the BM and WM (i.e., the linear region of the stress-strain curve) can be obtained from Fig.4. They are 0 - 0.005628 and 0 - 0.001738, respectively. The strain in the BM is still within the elastic region, but some local strains in the WM have been beyond it. This means that plastic deformation has occurred in the WM in image (b).

Up to image (c), local strains in the HAZ became larger (circled in image (c)), indicating that strain concentration occurred there in addition to in the WM. Advancing to image (d), i.e., the upper limit of the linear region of the stress-strain curve of the welded joint (cf. Fig.6), the BM and HAZ have been yielded, while the BM is still in the elastic region.

When the applied stress continued to increase and attained the 0.2% proof stress ($\sigma_{0.2}$) of the welded joint, the strain field evolved to that shown in image (e) (cf. Fig.7(e)). There are four circles in Fig.7(e). The figures in the circular regions are the average true strains within each one. They ($\varepsilon_{\text{xx}}$) are 0.00512491 (left in the BM), 0.00438763 (right in the BM), 0.00650291 (up in the WM), and 0.0213213 (down in the WM). Apparently, the BM is still in the elastic region while other parts have been in the plastic region.

Moreover, strain in the WM is not uniform.

Advancing to image (f), the BM began to yield, and the strains in the other parts continued to increase. Until image (g), the strain in the WM was larger than that in the BM. When the strain field evolved to that shown in image (g), this relation began to reverse: the strain in the WM became the lowest in the welded joint. This tendency remained through images (h) and (i). At image (h), the specimen began to neck. The localized region is beyond the 2D-DIC measurement region and is on the left side of this region. As shown in Fig.7(h), the left side of the 2D-DIC measurement region is adjacent to the localized region, and the local strain in this region (cf. the small circle on the left-up corner in Fig. 7(h)) is much higher than in other parts. After image (h), deformation concentrated in the localized region, and the strain field in the other parts remained almost constant.

In Fig.7(i), five circles are drawn. Circles 1 and 2 are, respectively, in the left and right sides of the BM; circles 3 and 4 are in the center and down parts of the WM, respectively; circle 5 is in the HAZ. The evolution of the average strain ($\varepsilon_{\text{xx}}$ and $\varepsilon_{\text{yy}}$) within circles 1 - 5 from the beginning to the termination of the test is shown Fig.8. It is noted that the strain in Fig.7 is the true strain, and the obtained average true strains with respect to the circular regions were converted to engineering strains and are plotted as ordinates in Fig.8. To express the tension process, i.e., deformation process, the longitudinal average strain obtained using an extensometer is selected as the abscissa of Fig.8.

The strain obtained from the extensometer is the average strain over the GL. In a sense, it represents the deformation behavior of the whole welded joint. In Fig.8(a), the data above the diagonal line (dotted line) mean that the local strains are larger than the average strain of the welded joint. In other words, strain concentrations occurred in these local sites. Figure 8(a) indicates that the BM in the right side (circle 2) has very small strain concentration only below strain of 0.004, while above that strain level having no strain concentration during the whole tension process. Strain concentration in the HAZ is the most serious. This is attributed to the presence of softening regions in the HAZ (cf. Fig.5). At low strain levels, the strain concentration occurred in the center of the WM (circle 3); above ~0.02, the strain in this region is the lowest in the welded joint. As shown in Fig.5, the strength in this region is not the highest in the whole WM. Therefore, strength itself is not the main reason for this low strain. It is known that constrain from the around is the most intense in the center of the WM. This high constrain is probably the main reason. It can be concluded from Fig.8 that more attention should be paid to the HAZ whose strain concentration is the most intense.

Figure 8 also shows a tendency that when the engineering strain of extensometer exceeds 0.07, the local strains of circles 1-5 Fig. 8

Evolution of the average engineering strain of (a) $\varepsilon_{\text{xx}}$ and (b) $\varepsilon_{\text{yy}}$ with respect to the circles shown in Fig.7(i) during the tension test.
remain constant. As mentioned before, necking occurred in the base metal. After necking, deformation began to concentrate in that position, and other parts stopped continuing deformation. This causes the local strains in Fig. 8 keep constant above the strain of 0.07. Because the necking position is beyond the area of 2D-DIC measurement, strain concentration in that region is not reflected in Fig. 7. The strength of the HAZ is the lowest in the welded joint (cf. Fig. 5), but final failure is in the BM instead of the HAZ. This is attributed to the plastic restraint from the regions adjacent to the HAZ.

Figure 5 shows that strength distribution is not uniform, even in the same weld pass. As we know, the relation between the stress and strain is the basis for the FEM calculation. Because of this inhomogeneous mechanical property, it is almost impossible to accurately summarize this relation in the WM, thus inevitably lowering the reliability of the FEM calculation. In contrast, the 2D-DIC measurement is a reliable tool for estimating the strain field in the welded joint, though it can only provide surface information.

4. Summary

Two-dimensional DIC was used to measure the strain field of an over-matching welded joint. Using this method, local strain in each part of the welded joint was accurately measured. The 2D-DIC measurement results elucidate the evolution of deformation in the welded joint, not only from a global point of view, but also from a local point of view. The experimental results show that 2D-DIC measurement is a reliable tool to estimate the strain field of a welded joint.

References

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