Effects of strain paths on the fracture forming limit of high strength structural steel sheets

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Abstract. The cruciform two-axial tensile specimen was designed and the two-axial tensile test scheme for different strain paths was developed. The effect of strain paths on the forming limit of high strength structural steel plates was obtained by the DIC method. The results show that for the unidirectional alternating loading test scheme, the equivalent strain of the ultimate strain is less than the sum of the equivalent strains from each step. When the main strain direction of the specimen pre-strain is perpendicular to the final strain path, the forming limit decreases with the increase of the pre-strain.

1. Introduction
During actual sheet metal forming, the strain path is usually nonlinear due to limitations of the geometric boundary, friction, and other conditions. Forming Limit Diagram (FLD) that generally adopted in deformation simulation analysis is usually established based on the simple strain path, which cannot precisely predict the occurrence of fractures; thus, the complex strain path consistent with the actual forming should be adopted to establish the FLD[1]. Recently, DIC has been developed as a new experimental mechanical method to analyze the total displacement and strain [2]. NamsuPark et al[3] conducted the equi-biaxial fracture strain Tensile tests of the DP980 steel sheet with Digital Image Correlation (DIC) method, the modeling of anisotropic fracture forming limit diagram of which was obtained. Yu et al[4] analyzed variations of the instantaneous strain hardening rate with the strain level of TRIP780 steel during cold rolling through the combination of large sample and small sample stretching. They discussed the hardening characteristics of the stress-strain curve of TRIP steel under different strain pathways. While the forming limits of high strength structural steel sheets achieved using multiple loading paths of differently proportioned strains have rarely been reported.

In this paper, the variation information of the strain at the local instability of the high strength structural steel plates under different strain paths has been measured by the DIC method, and the impact rule of the strain path on the forming limit of high strength structural steel was explored.
2. Tensile experiment scheme of S355 with different strain paths

The displacement and deformation information of each point on the sample can be calculated by tracking the changes in the pixels [5]. The displacement field of the acquired pixel information was obtained from the DIC data processing software (DIC_GUI) [6] developed using MATLAB. The related strain field was achieved by processing the displacement field.

Figure 1 shows the structure of the cross-shaped two-axial tension specimen designed for this paper. The specimen was made of S355 type high strength structural steel sheet with a center zone thickness of 0.7 mm and the remaining zones at 2.5 mm thick. The slits were designed in the two axes to reduce the eccentric load and guarantee a uniform stress in the central thinning zone to achieve the following purposes [7,8]. The DIC device for the two-directional tensile test of the S355 sheet is shown in Figure 2.

Two schemes were designed, as shown in Figure 3(a) unidirectional pre-stretching and unidirectional loading test scheme, and in Figure 3(b), two-unidirectional pre-stretching and unidirectional loading test scheme. In which the cross-shaped two-axial tension specimen is pre-tensioned at one direction by different elongations, then the specimen is tensioned for one or more times that perpendicular to the previous stretch at different elongations, until the material fracture. By using the DIC method, the pre-strain and local instability strain of the cross-shaped two-axial tension specimen in each scheme were obtained.

![Figure 1. Tension specimen.](image1)

![Figure 2. DIC device for the tensile test.](image2)

![Figure 3. Tensile test scheme.](image3)

3. Result and discussion of Forming limit under different strain paths

3.1. Limit strain under different strain paths

3.1.1. Unidirectional pre-stretching and unidirectional loading. The specimens after this test scheme are shown in Figure 4(a). For the reason that accuracy error exists in installation and clamping of the fixture and samples, cracking located near the transition from the sample plane to the handle plane. The instability strain paths for scheme 1 are shown in Figure 4(b), in which \(i-j\) represents the scheme number and the related loading variant. The strain state and equivalent strain of the results are shown in Table 1, where the limit strain refers to the strain state of the specimen from the original state to the local instability. The strain state of the forming limit is expressed by the first and secondary principle strain \(\varepsilon_1\) and \(\varepsilon_2\). The equivalent strain of the second-step is overall greater than the limit equivalent strain.
3.1.2. Two-unidirectional pre-stretching and unidirectional loading. The specimens after the two-unidirectional pre-stretching and unidirectional loading test scheme are shown in Figure 5(a). The strain paths at the instability point of scheme 2 are shown in Figure 5(b). It can be seen that, with the increase of the strain in the second step, the overall variation trend of the limit strain increases first and then decreases. The strain state and equivalent strain in scheme 2 are shown in Table 2. The overall level of the equivalent strain of the third stage is less than the limit equivalent strain.

Table 1. Strain state and equivalent strain of S355 specimens for variants in scheme 1.

| Variant | 1-1 | 1-2 | 1-3 | 1-4 | 1-5 | 1-6 |
|---------|-----|-----|-----|-----|-----|-----|
| Strain state | $\varepsilon_1$ | $\varepsilon_2$ | $\varepsilon_1$ | $\varepsilon_2$ | $\varepsilon_1$ | $\varepsilon_2$ |
| First pre-strain | Value | 0.077 | -0.028 | 0.063 | -0.019 | 0.071 | -0.025 | 0.108 | -0.036 | 0.145 | -0.065 | 0.172 | -0.058 |
| $\varepsilon_{i1-pre1}$ | 0.100 | 0.079 | 0.092 | 0.137 | 0.194 | 0.220 |
| Second pre-strain | Value | 0.155 | -0.051 | 0.265 | -0.061 | 0.237 | -0.064 | 0.241 | -0.080 | 0.194 | -0.065 | 0.117 | -0.027 |
| $\varepsilon_{i2}$ | 0.197 | 0.325 | 0.295 | 0.307 | 0.248 | 0.144 |
| Limit strain | Value | 0.102 | 0.024 | 0.246 | 0.002 | 0.212 | 0.007 | 0.205 | 0.027 | 0.145 | 0.059 | 0.133 | 0.077 |
| $\varepsilon_{i3-lim}$ | 0.238 | 0.284 | 0.243 | 0.233 | 0.170 | 0.164 |

Where $\varepsilon_{i1-pre1}$ is the equivalent strain of the first pre-strain; $\varepsilon_{i2}$ is the equivalent strain of the second strain; and $\varepsilon_{i3-lim}$ is the total limit equivalent strain in schemes 1.

Table 2. Strain state and equivalent strain of the S355 specimens for variants in scheme 2.

| Variant | 2-1 | 2-2 | 2-3 | 2-4 | 2-5 | 2-6 |
|---------|-----|-----|-----|-----|-----|-----|
| Strain state | - | $\varepsilon_1$ | $\varepsilon_2$ | $\varepsilon_1$ | $\varepsilon_2$ | $\varepsilon_1$ | $\varepsilon_2$ |
| First pre-strain | Value | 0.041 | -0.021 | 0.049 | -0.013 | 0.101 | -0.014 | 0.056 | -0.023 | 0.056 | -0.019 | 0.059 | -0.013 |
| $\varepsilon_{i1-pre1}$ | 0.056 | 0.061 | 0.121 | 0.074 | 0.072 | 0.072 |
| Second pre-strain | Value | 0.047 | -0.017 | 0.046 | -0.022 | 0.066 | -0.030 | 0.076 | -0.033 | 0.129 | -0.054 | 0.151 | -0.060 |
| $\varepsilon_{i2}$ | 0.061 | 0.063 | 0.143 | 0.102 | 0.171 | 0.199 |
| Pre-Strain1-2 | Value | 0.031 | 0.019 | 0.039 | 0.022 | 0.075 | 0.049 | 0.054 | 0.021 | 0.110 | 0.002 | 0.140 | -0.002 |
| $\varepsilon_{i1-pre1-2}$ | 0.039 | 0.048 | 0.095 | 0.063 | 0.126 | 0.162 |
| Third strain | Value | 0.138 | -0.071 | 0.201 | -0.085 | 0.201 | -0.050 | 0.248 | -0.068 | 0.214 | -0.070 | 0.112 | -0.026 |
| $\varepsilon_{i3}$ | 0.207 | 0.286 | 0.248 | 0.309 | 0.273 | 0.138 |
| Limit strain | Value | 0.162 | -0.044 | 0.229 | -0.052 | 0.272 | 0.003 | 0.270 | -0.016 | 0.217 | 0.040 | 0.126 | 0.099 |
| $\varepsilon_{i3-lim}$ | 0.331 | 0.321 | 0.314 | 0.316 | 0.247 | 0.169 |

Where $\varepsilon_{i1-pre1-2}$ is the total equivalent strain of the first pre-strain and second pre-strain; $\varepsilon_{i3}$ is the equivalent strain of the third strain; and $\varepsilon_{i3-lim}$ is the total limit equivalent strain in scheme 2.

3.2. Comparison of Forming Limit Diagrams under Different Strain Paths

A comparison of the forming limits between schemes 1 and 2 of S355 sheet is shown in Figure 6. It can be seen that the forming limit values in scheme 2 are overall higher than those in scheme 1. The overall forming limit level in scheme 2 is higher than that in scheme 1. It can be seen from the above that when
the principle strain direction of the pre-strain is perpendicular to final strain path, a larger reciprocating strain appears in both cross directions of the specimens, and their forming limits would decrease. By comparing the Table 1 and Table 2, it can be seen that the average pre-strain in the vertical direction of scheme 1 is larger than that for scheme 2, resulting in a significantly decreased forming limit in scheme 1. The average value of the limit equivalent strain in scheme 1 is less than that in scheme 2.

![Figure 5. Test results of schemes 2.](image1)

![Figure 6. Comparison of forming limits.](image2)

The sum of equivalent strain of each step tension of the S355 sheet in schemes 1 and 2 are shown in Table 3. The average of the equivalent strain for the two strain paths in scheme 1 is 88.21% larger than that of the limit strain. The sum of the average equivalent strain for the three strain paths in scheme 2 is 58.01% larger than that of the limit strain. For the unidirectional alternative direction loading scheme, when the main strain direction of the pre-strain is perpendicular to the main strain direction of the final strain path, the forming limit decreases with the increasing of the equivalent strain of the pre-strain.

Table 3. Sum of equivalent strain of each step tension of S355 sheet in schemes 1 and 2.

| Variant | - | i-1 | i-2 | i-3 | i-4 | i-5 | i-6 | Average |
|---------|---|-----|-----|-----|-----|-----|-----|---------|
| Scheme1 | \(\varepsilon_{\text{Pr}1}^1+\varepsilon_{\text{Pr}1}^2\) | 0.297 | 0.387 | 0.403 | 0.444 | 0.442 | 0.363 | 0.389 |
| Scheme2 | \(\varepsilon_{\text{Pr}1}^1+2\varepsilon_{\text{Pr}1}^2+\varepsilon_{\text{Pr}1}^3\) | 0.286 | 0.375 | 0.464 | 0.446 | 0.471 | 0.373 | 0.402 |

4.Conclusions

In this research, a DIC measurement setup was proposed to explore the forming limit of a two-directional tensile specimen made of high strength structural steel sheets under different strain paths. The following conclusions are drawn from the results of the research.

1. For the one-way alternating loading test scheme, the limit equivalent strain is less than the sum of equivalent strain in each step.
2. When the principle strain direction of the pre-strain is perpendicular to the principle strain direction of the final strain path, a larger reciprocating deformation appears in both cross directions of
the specimen, the forming limit of the specimens decreases; and the forming limit decreases with the increasing of the equivalent strain of the pre-strain.

(3) Comparing with the unidirectional pre-stretching and unidirectional loading, generally large limit equivalent strain would be obtained by the two-unidirectional pre-stretching and unidirectional loading with the same specimen.

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