Evaluation of tension-compression asymmetry of a low-carbon steel sheet using a modified classical compression test method

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Abstract. A modified classical compression test method was used to examine in-plane tension-compression asymmetry in a low carbon steel sheet. In this compression test method, interfacial friction between the compression platens and specimen surfaces was significantly reduced by use of polycrystalline diamond plates installed on the compression dies. Furthermore, crosshead displacement of the universal testing machine, which inherently includes deflection of the machine itself, was corrected to the net deformation of the specimen based on a series spring model. Consequently, precision of the compressive strains obtained with the present test method is equivalent to that attained in the standard tension tests using wire strain gauges. For tension and compression tests performed at in-plane directions of 0˚, 45˚ and 90˚ relative to the rolling direction (RD), significant tension-compression asymmetry (i.e. strength differential effect (SDE)) was observed. In all the mechanical tests in the three testing directions, flow stresses in tension tests were smaller than those in compression tests.

1. Introduction
For various metals, it has been reported that yield (or flow) stresses in tension and compression are clearly different [1-7]. This phenomenon is known as the strength differential effect (SDE). Kuwabara et al. [8] observed SDE in a low carbon steel sheet. By contrast, Shirakami [9] reported that an interstitial free (IF) steel sheet exhibited almost no SDE. These studies employed an in-plane compression test method with comb-shaped jigs that was introduced to prevent occurrence of buckling of the sheet specimen [10]. It is unknown at present whether the observed SDE was a real material behavior or was caused by an improper testing condition such as an unexpectedly high friction force related to occurrence of plastic buckling of the sheet specimen inside the jigs. Therefore, accumulation and verification of data of SDE using other testing methods free of friction effects are needed. In this study, we introduce a modified classical compression test method recently developed by the authors [11] to re-examine SDE in low carbon steel sheets.

2. Modified classical compression test method
2.1. Reduction of interfacial friction between compression platens and specimen surfaces
In order to let the interfacial friction between compression platens and loading surfaces of the specimen be negligible, polycrystalline diamond (PCD) plates were installed on the compression dies [11] and silicone oil (Dow Corning Toray, SRX310) was used as a lubricant. Figure 1(a) and (b) shows examples of deformed specimens (JIS A6061-T6 rods whose initial diameter and initial height were both 10 mm) after testing (at a logarithmic strain of 30%) when PCD and SUS304 were used as the compression platens, respectively. By using PCD, barrel-shape deformation that was observed when SUS304 was used (Figure 1(b)) was remarkably suppressed (Figure 1(a)).

Figure 1. Specimen shapes after compression test at a logarithmic plastic strain of 30% when PCD (a) and SUS304 (JIS) (b) were used with silicon oil.

2.2. A precise evaluation of compressive strain from the crosshead displacement of a universal testing machine

The crosshead displacement of a universal testing machine, which inherently includes elastic deflection of the machine itself, was corrected to the net deformation of the specimen based on a series spring model. The net deformation of the specimen can be calculated by subtracting the elastic deflection of the testing machine from the crosshead displacement recorded during a monotonic uniaxial compression test. It is not easy to directly measure the axial stiffness of the testing machine. In the present method, the axial stiffness of the testing machine was evaluated using a slope of an elastic unloading line on the load-crosshead displacement relationship and the axial elastic stiffness of the specimen, which is easily computed from its dimensions and Young’s modulus [11]. The actual procedure is explained by reference to a schematic diagram in Figure 2.

Figure 2. Schematic diagram of corrected compression load–crosshead displacement relationship.
The axial elastic stiffness of the specimen is evaluated as

\[ k_s = \frac{EA_0}{I_0} = \frac{p}{u_{el}}, \]  

(1)

where \( p \) is the compression force in a monotonic compression test, \( u_{el} \) is the elastic deformation amount of the specimen, \( E \) is the Young’s modulus of the specimen, \( A_0 \) is the initial cross sectional area of the specimen and \( I_0 \) is the initial length of the specimen. Usually, Young’s modulus \( E \) is separately measured in a monotonic tensile test in advance.

The apparent elastic deformation amount, \( u_t \), is the sum of the elastic deformation amount of the specimen, \( u_{el} \), and the elastic deformation amount of the testing machine, \( u_m \), that is,

\[ u_t = u_{el} + u_m = \frac{p}{k_s} + \frac{p}{k_m}, \]  

(2)

where \( k_m \) is the axial stiffness of the testing machine, which is an unknown quantity. As the compressive force \( p \) is the product of \( u_t \) and \( k_t \), we write

\[ p = k_t u_t, \quad k_t = \frac{1}{k_s} + \frac{1}{k_m}. \]  

(3)

By rearranging equation (3), the axial stiffness of the testing machine \( k_m \) is calculated as

\[ k_m = \frac{1}{\frac{1}{k_t} - \frac{1}{k_s}}. \]  

(4)

Thus, the net deformation amount of the specimen, \( u_{real} \), is obtained as

\[ u_{real} = u_{exp} - u_m = u_{exp} - \frac{p}{k_m}. \]  

(5)

2.3. Testing conditions, equipments and evaluation of SDE
The mechanical tests were carried out using a universal testing machine (Shimadzu Autograph AG-IS 50 kN). The sample was a low-carbon steel sheet (JIS-SPCE equivalent) with a thickness of 1.2 mm. The specimens were cut from the sheet at three directions, i.e. RD, 45°, and transverse direction (TD). The nominal strain rate was set to 0.0005 /s. For compression tests, cubic shape specimens with four sheets stacked using a bond (CEMEDINE, Y610) were employed to prevent occurrence of buckling during compressive loading. Dimensions of the specimens were as follows: the loading and transverse sides were both 10 mm and the thickness was 4.8 mm = (1.2 mm × 4 sheets). The compressive strain was computed from \( u_{real} \) defined in equation (5). For tensile tests, JIS 13 B-type specimens with a gauge length of 60 mm, a width of 12.5 mm and a thickness of 1.2 mm were used and the strain was measured using wire strain gauges (Tokyo Sokki YEFLA5). In order to evaluate SDE in detail, the amount of SDE, \( \beta_{SDE} \), is defined [1, 2] as

\[ \beta_{SDE} = 2(|\sigma_C| - |\sigma_T|)/(|\sigma_C| + |\sigma_T|), \]  

(6)

where \( \sigma_C \) is a true stress in compression, \( \sigma_T \) is a true stress in tension.

In reference [11], the present compression test method was employed and it was shown that an A6061-T6 (JIS) sheet did not exhibited SDE. Kuwabara et al. [10] also observed no SDE in the similar type of aluminum alloy sheet (AA6016-T4) using their in-plane compression test method with comb-shaped jigs.
3. Results and discussion

Figure 3(a)-(c) shows true stress-logarithmic strain relationships corresponding to the three testing directions (RD, 45° and TD), respectively. We carried out three experiments for each condition. Figure 4 shows relationships between $\beta_{SDE}$ and logarithmic plastic strain for the three test directions. Table 1 shows true stresses and corresponding values of $\beta_{SDE}$ at logarithmic plastic strains of 0.2%, 1%, 5% and 10%. The $\beta_{SDE}$ values were calculated using average stress values for the three experimental data, and also the true stresses shown in Table 1 are the average values. All the experimental results show that the compressive stress exceeded the tensile stress, i.e. a clearly SDE was observed in all the testing directions and in the whole strain range (Figure 3). The amount of $\beta_{SDE}$ in the range of logarithmic plastic strain smaller than 4% was in order of RD < TD < 45°. After that the $\beta_{SDE}$ was in order of RD < 45° ≈ TD (Figure 4). Values of $\beta_{SDE}$ are also shown in Table1. The $\beta_{SDE}$ in RD was 5.2% at a logarithmic plastic strain of 1% and it was 5.4% at a logarithmic plastic strain of 10%. Thus, no variation in SDE was observed in the tests at RD. In the 45° direction, $\beta_{SDE}$ is 7.2% at a logarithmic plastic strain of 1% and increased to 8.7% at a logarithmic plastic strain of 10%. In the TD, the $\beta_{SDE}$ was 6.1% at a logarithmic plastic strain of 1% and increased to 8.9% at a logarithmic plastic strain of 10%. As the strain increased, the SDE became larger in the tests at 45° and TD. Thus, the amount of SDE varies depending on the testing direction. At present, reasons for the appearance and variation of SDE are not known. Clarification of the mechanism is a subject of further studies in future.

![Figure 3. True stress–logarithmic strain curves; (a) RD, (b) 45° and (c) TD.](image)

![Figure 4. $\beta_{SDE}$–logarithmic plastic strain curves.](image)
Table 1. True stress and $\beta_{SDE}$ at logarithmic plastic strains of 0.2, 1, 5 and 10%.

| Logarithmic plastic strain | RD  [MPa] | 45˚ | TD  [MPa] |
|----------------------------|-----------|-----|----------|
| 0.2%                      | 153.5     | 177.3 | 251.7     |
| 1%                        | 300.7     | 158.2 | 179.0     |
| 5%                        | 251.4     | 143.4 | 162.8     |
| 10%                       | 181.7     | 251.5 | 299.3     |
| 0.2%                      | 158.2     | 179.0 | 251.4     |
| 1%                        | 314.4     | 326.1 | 314.4     |
| 5%                        | 162.8     | 181.7 | 251.5     |
| 10%                       | 169.4     | 193.1 | 269.8     |

$\beta_{SDE}$: 4.1% 5.2% 4.2% 5.4% 7.2% 7.1% 8.7% 4.0% 6.1% 7.0% 8.9%

4. Conclusion
The strength differential effect (SDE) in a low carbon steel sheet was investigated by use of standard uniaxial tensile tests and uniaxial compression tests performed with the modified classical compression test method [11]. In all the mechanical tests in the three testing directions (RD, 45˚ and TD), the 0.2% proof stress and the subsequent flow stress in compression were clearly higher than those observed in tension.

A direct comparison of the present results to those obtained with other compression test methods (e.g. that with comb-shaped jigs) is a remaining subject and it should be carried out in future.

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