Effect of microstructure and mechanical properties on tensile loading-unloading characteristics of cold-rolled DP780 steels

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Abstract. Tensile loading-unloading characteristic of three cold-rolled DP780 steels was studied. Similar hardening behaviour was showed by these steels even with different chemical composition and microstructures. Tensile loading-unloading tests with prestrain between 0.5% and 8% were carried out on Instron tensile testing machine. Sample microstructures were analysed by EBSD and SEM. Hardness of ferrite and martensite were measured by nanohardness instrument. Total unloading recovery strain, which is related to unloading chord modulus (Echord), can be divided into elastic strain and microplastic strain. The results showed that there was no correlation between unloading microplastic strain (εmp) and phase fraction or phase size within the scope of this study. However, with the increase of flow strength increment, εmp increases while Echord reduction becomes larger. Furthermore, εmp depends on the phase yield strength ratio between martensite phase and ferrite phase (σm/σf), εmp increases as the σm/σf increase for a given flow strength increment. The results showed that the springback of DP780 steels can be improved by reducing the yield strength difference between martensite and ferrite.

1. Introduction

With the development of automobile lightweight and the improvement of energy saving and emission reduction requirements, the proportion of advanced high strength steel (AHSS) in car body is gradually increasing in recent years. However, springback is a major technical challenge of AHSS in stamping or bending process. The existence of springback will lead to poor forming accuracy of parts. Springback depends on many conditions such as forming parameters, die shape and material properties. Mechanical properties of materials such as elasticity modulus, yield strength, yield ratio and strain hardening index all have influence on springback [1-2].

As is well known, the unloading elastic strain can be calculated by the ratio between the unloading stress and the elasticity modulus. Generally, the elasticity modulus is considered as a constant in simulation analysis, so the springback amount increases with the increase of steel strength, especially for AHSS. For solving the springback challenge effectively, some researchers have studied the springback prediction and compensation in the forming process of AHSS by finite element analysis [2-3]; some other researchers focused on springback minimization of TRIP and DP steels by statistical analysis [4-5].

The aims of this study are to investigate the tensile loading-unloading characteristic of three DP780 steels with similar hardening behavior and different composition and microstructure, and to further
investigate the effects of chemical composition, microstructure such as phase fraction, ferrite and martensite size, and micromechanical properties such as martensite and ferrite nanohardness on springback of the DP780 steels.

2. Experimental methods

2.1. Experimental materials

Three kinds of cold-rolled DP780 steels were prepared for this experiment. The chemical composition was listed in table 1, these steels all belong to low carbon series. Among them, the carbon content of DP780-A is slightly higher, while that of DP780-B and DP780-C is basically the same level. Chromium and molybdenum elements, which can significantly delay pearlite and bainite transformation during cooling process, were both added to DP780-A and DP780-B steels, niobium element which can refine ferrite grains was only added to DP780-B steel. DP780-C steel contains 0.88 percent silicon, but no microalloy element was added.

| Material  | Thickness/mm | Carbon | Manganese | Silicon | Chromium+Molybdenum | Niobium |
|-----------|--------------|--------|-----------|---------|--------------------|---------|
| DP780-A   | 1.01         | 0.10   | 2.02      | 0.03    | >0.30              | –       |
| DP780-B   | 1.62         | 0.08   | 1.91      | 0.05    | >0.50              | 0.015   |
| DP780-C   | 2.03         | 0.07   | 1.99      | 0.88    | –                  | –       |

2.2. Microstructure analysis

Three DP780 steel samples were inlaid with conductive powder. After being grinded and polished, these samples were put into LEO 1530 field emission SEM to observe microstructures using backscatter electron diffraction (EBSD). The acceleration voltage of electron gun is 20 KV and the working distance is about 10 mm. 4×4 binning value was used. Ferrite grain size and hard phase fraction were analyzed by EBSD; hard phase was distinguished from ferrite by band contrast.

2.3. Nanohardness measurement

Three DP780 steel samples were inlaid with conductive powder. After being grinded and polished, these samples were put into UMIS II indentation instrument for nanohardness testing. Four arrays of 16×16 indentation tests were conducted for each sample. The load of the test is 3mN and the spacing of indentation and array was 6 μm and 30 μm respectively, totally 1024 indentations. Then these samples were put into SUPRA 55VP SEM to observe and record the indentation location in microstructure. As shown in figure 1, only the indentation that completely landed on the martensite island can be used to measure its’ hardness. Based on a large number of random nanohardness values, the hardness histograms of each sample were plotted. Assuming that the hardness values exhibited a bimodal normal distribution as Eq 1, the relative fraction \( f \), which is related to phase hardness, could be calculated. The constants in Eq 1 include \( a, c, b \) and \( d \), while \( H_f \) and \( H_m \) represent ferrite and martensite average nanohardness respectively. The other parameters are obtained by regression calculation.

\[
f = a \cdot \exp \left(-\frac{1}{2} \left(\frac{H - H_f}{b}\right)^2\right) + c \cdot \exp \left(-\frac{1}{2} \left(\frac{H - H_m}{d}\right)^2\right) \quad \text{(Eq 1)}
\]

2.4. Tensile and loading-unloading test

Tensile and loading-unloading specimens were prepared in accordance with the requirements of ASTM E8 standard. The specimen is in longitudinal direction and its gauge length is 50mm. Tensile and loading-unloading tests were conducted on INSTRON 5967 tensile machine, the strain rate of all tests is 10^-5 s^-1. The setting range of unloading prestrain was between 0.5% and 8%. A high elongation strain gauge, which was used to record strain data during loading and unloading process, was attached to the central surface of the specimen. The strain gauge type is YEFLA-5-1 and the manufacturer is...
Tokyo Sokki Kenkyujo. Figure 2 shows an example of loading-unloading true stress-strain curve. Calculation of unloading microplastic strain (i.e., $\varepsilon_{\text{mp}}$) and chord modulus (i.e., $E_{\text{chord}}$) was illustrated in figure 3; $E_0$ is the initial modulus of the steel.

![Figure 1. The indentation wholly on martensite (DP780-A)](image1)

3. Experimental results

3.1. Microstructure and mechanical properties

Three DP780 steels’ microstructures which were obtained by EBSD band contrast method are shown in figure 4. The microstructures of DP780-A and DP780-B steels are both composed of ferrite and martensite, while that of DP780-C steel is composed of ferrite, bainite and martensite. Microstructure quantitative analysis results of the DP780 steels are showed in table 2. The results indicate that the martensite volume fraction (MVF) in DP780-B is the lowest (22.6%) and the average size of ferrite grain and martensite are both the smallest (1.91μm and 0.92μm, respectively). The hard phase volume fraction of DP780-C steel is the highest (28.1%) and the average size of ferrite grain and hard phase are both the largest (4.73μm and 1.52μm, respectively), while that of DP780-A steel is in between; the martensite volume fraction is 24.2%, and the average size of martensite and ferrite is 1.39μm and 2.92μm respectively.

Figure 5 and table 3 shows the tensile stress-strain curve and the testing results of the three DP780 steels respectively. DP780-A has the lowest yield ratio and DP780-C has the highest yield ratio. The yield and ultimate strength of the three DP780 steels are different, however, similar strain hardening behavior was showed during the yield stage, and the uniform elongation was nearly the same.

![Figure 2. Example of loading-unloading true stress-strain curve](image2)

![Figure 3. Illustration diagram of $\varepsilon_{\text{mp}}$ and $E_{\text{chord}}$](image3)
Figure 4. EBSD band contrast image of: (a) DP780-A (b) DP780-B (c) DP780-C

Table 2. Microstructure quantitative analysis results of the three DP780 steels

| Material | MVF (%) | d_f (μm) | d_m (μm) |
|----------|---------|----------|----------|
| DP780-A  | 24.2    | 2.92     | 1.39     |
| DP780-B  | 22.6    | 1.91     | 0.92     |
| DP780-C  | 28.1    | 4.73     | 1.52     |

Figure 5. Engineering stress-engineering strain curves of the three DP780 steels

Table 3. Tensile testing results of the three DP780 steels

| Material | Ultimate Strength (MPa) | Yield Strength (MPa) | Total Elongation (%) | Uniform Elongation (%) | $E_0$ (GPa) |
|----------|-------------------------|----------------------|----------------------|------------------------|-------------|
| DP780-A  | 880                     | 526                  | 12.4                 | 10.6                   | 203         |
| DP780-B  | 848                     | 551                  | 15.8                 | 10.7                   | 194         |
| DP780-C  | 816                     | 569                  | 19.1                 | 10.8                   | 204         |
3.2. Nanoindentation of DP780 Steels
Nanohardness histograms and fitting curves of ferrite and martensite hardness for the DP780 steels are showed in figure 6. The maximum, minimum and average hardness of martensite and ferrite are listed in table 4. The average nanohardness values are calculated by regression, and the maximum and minimum values are measured values. The maximum, minimum and average martensite nanohardness of DP780-A steel are all the highest, while those of DP780-C steel are the lowest. Although the minimum nanohardness of ferrite in DP780-A is the lowest, its average value is almost the same level as that of the other steels.

![Nanohardness histograms and nanohardness fitting curves of martensite and ferrite](image)

Figure 6. Nanohardness histograms and nanohardness fitting curves of martensite and ferrite: (a) DP780-A (b) DP780-B (c) DP780-C

![Table 4](image)

Table 4. Martensite and ferrite nanohardness (GPa) of the steels

| Material  | \(H_m,\min\) | \(H_m,\max\) | \(\bar{H}_m\) | \(H_f,\min\) | \(H_f\) |
|-----------|---------------|---------------|---------------|---------------|----------|
| DP780-A   | 5.64          | 8.56          | 6.62          | 0.86          | 3.31     |
| DP780-B   | 5.38          | 7.44          | 6.22          | 1.16          | 3.33     |
| DP780-C   | 4.14          | 7.08          | 5.32          | 0.87          | 3.29     |

3.3. Loading-unloading results of the DP780 Steels
Effect of unloading flow strength and flow strength increment (i.e., \(\sigma-\sigma_0\)) on \(\varepsilon_{mp}\) of the DP780 steels is showed in figure 7. It is obvious that \(\varepsilon_{mp}\) increases with the increase of unloading flow strength or \(\sigma-\sigma_0\). For a given unloading flow strength or \(\sigma-\sigma_0\), \(\varepsilon_{mp}\) of DP780-A is obviously higher than that of the other steels; \(\varepsilon_{mp}\) of DP780-B steel is the smallest, while that of DP780-C steel is slightly higher than DP780-B steel's.

Unloading microplastic strain can be expressed by Eq 2 [6]. Where \(\sigma\) is unloading flow strength, \(\sigma_0\) is steel's yield strength, \(K\) represents dislocation density constant and the value is less than 1; \(M, \alpha\) and \(\mu\) represents Taylor factor, empirical factor and shear modulus respectively. Equation 2 shows if the flow strength increment is zero, microplastic strain should be zero. However, the linear regression
results (Figure 7) indicate the intercept is nonzero. Because $\sigma_0$ is the macroscopic yield strength of the steel, and micro yield occurred before macro yield, a nonzero $\varepsilon_{mp}$ can be expected for $\sigma-\sigma_0=0$.

Effect of unloading flow strength on $E_{chord}/E_0$ and $\varepsilon_{mp}/\varepsilon_{total}$ of the DP780 steels are showed in Figure 8a and figure 8b respectively. It is obvious that the chord modulus reduction becomes greater as the unloading flow strength increment increases. For a given $\sigma-\sigma_0$, the chord modulus reduction of DP780-A is obviously greater than that of the other two steel, while that of the others is nearly in the similar level. The $E_{chord}$ reduction depends on the proportion of microplastic strain in the total recovery strain (i.e., $\varepsilon_{mp}/\varepsilon_{total}$). With the increase of $\varepsilon_{mp}/\varepsilon_{total}$, the $E_{chord}$ reduction increases. Because the $\varepsilon_{mp}/\varepsilon_{total}$ of DP780-A is bigger than that of the other two steel, the $E_{chord}$ reduction of DP780-A is larger than theirs.

$$\varepsilon_{mp} = \frac{K}{M\mu\sqrt{1-K}}(\sigma - \sigma_0) \quad (Eq \ 2)$$

Figure 7. (a) Effect of unloading flow strength on $\varepsilon_{mp}$ of the DP780 steels (b) Effect of $\sigma-\sigma_0$ on $\varepsilon_{mp}$ of the DP780 steels

Figure 8. (a) Effect of unloading $\sigma-\sigma_0$ on $E_{chord}/E_0$ of the DP780 steels (b) Effect of unloading $\sigma-\sigma_0$ on $\varepsilon_{mp}/\varepsilon_{total}$ of the DP780 steels

4. Discussion

Eq 2 indicates that $\varepsilon_{mp}$ has a linear relationship with $\sigma-\sigma_0$. In order to compare microplastic strain difference among the DP780 steels with a same flow strength increment, a linear regression analysis based on Eq 3 was carried out using the data plotted in figure 7. The regression coefficient ($n$) and constant ($A$) for the DP780 steels are listed in table 5.

$$\varepsilon_{mp} = n(\sigma - \sigma_0) + A \quad (Eq \ 3)$$

In ferrite and martensite dual phase steels, strain partitioning to ferrite occurred during micro deformation [7]. Inhomogeneous deformation is the main cause of higher dislocation density in ferrite. According to Eq 2, there is a correlation between microplastic strain and the dislocation density, so it can be expected that the $\varepsilon_{mp}$ increases with the increase of yield strength ratio between hard phase and soft phase.
Table 5. Regression coefficient and constant for the DP780 steels

| Material | A   | n  |
|----------|-----|----|
| DP780-A  | 337 | 2.41 |
| DP780-B  | 155 | 1.69 |
| DP780-C  | 216 | 1.90 |

Eq 2 indicates that the ferrite yield strength can be obtained by conversion from nanohardness. The unit of the nanohardness and the yield strength is GPa and MPa respectively. According to Eq 4 [8], the ferrite yield strength (i.e., \( \sigma_f \)) of DP780 steels, which was calculated using the minimum nanohardness values listed in table 4, is between 229MPa and 309MPa (shown in table 6).

\[ \sigma_0 = 266H \]  
(Eq 4)

Generally, for a given composition, the martensite carbon content of DP steel decreases with the increase of martensite volume fraction (MVF). Assuming that the carbon of the steel all exist in martensite, the martensite carbon content (i.e., \([C]_m\)) can be calculated with the steel carbon content and the martensite fraction. \([C]_m\) of the three DP780 steels which was calculated on the basis of this assumption is showed in table 6. The Vickers martensite hardness (\(HV_{m, max}\)), which is obtained by converting from maximum martensite hardness (\(H_{m, max}\)), is also listed in table 6. The hardness of martensite is obviously related to the \([C]_m\). With the increase of \([C]_m\), the measured hardness of martensite increases. As shown in table 6, martensite yield strength (i.e., \(\sigma_m\)), which is obtained by converting from Vickers hardness [9], is between 1358MPa and 1727MPa. The ratio between martensite yield strength and ferrite yield strength (i.e., \(\sigma_m/\sigma_f\)) is listed in table 6. The result shows that the ratio value of DP780-A is obviously higher than that of the other two steel.

Table 6. Martensite and ferrite micro properties of the steels

| Material | MVF (wt%) | C (wt%) | \([C]_m\) (wt%) | \(H_{m, max}\) (GPa) | \(H_{f, min}\) (GPa) | \(HV_{m, max}\) | \(\sigma_m\) (MPa) | \(\sigma_f\) (MPa) | \(\sigma_m/\sigma_f\) |
|----------|-----------|--------|-----------------|-----------------------|---------------------|-----------------|-----------------|-----------------|-----------------|
| DP780-A  | 24.2      | 0.10   | 0.41            | 8.56                  | 0.86                | 632             | 1727            | 229             | 7.54            |
| DP780-B  | 22.6      | 0.08   | 0.33            | 7.44                  | 1.16                | 543             | 1471            | 309             | 4.76            |
| DP780-C  | 28.1      | 0.07   | 0.25            | 7.08                  | 0.87                | 514             | 1388            | 231             | 6.01            |

Figure 9. Effect of \(\sigma_m/\sigma_f\) on \(\varepsilon_{mp}\) for different \(\sigma - \sigma_0\).

Effect of martensite and ferrite yield strength ratio on \(\varepsilon_{mp}\) for different \(\sigma - \sigma_0\) of DP780 steels is showed in figure 9. According to the regression parameters showed in table 5, the \(\varepsilon_{mp}\) of the DP780 steels were calculated for the flow strength increments of 100, 200 and 300MPa. The \(\sigma_m/\sigma_f\) is obviously correlated with \(\varepsilon_{mp}\). For a given \(\sigma - \sigma_0\), the \(\varepsilon_{mp}\) of DP780-A was the largest because the \(\sigma_m/\sigma_f\) of DP780-A was the highest. Further mechanism analysis shows that worse inhomogeneous deformation, which can result in higher dislocation density, will occur in the ferrite as \(\sigma_m/\sigma_f\) increase. Correspondingly, higher dislocation density will lead to larger unloading microplastic strain.
Generally, the flangeability or hole expansion property of dual phase steel is worse than single phase or multi-phase steel at the same strength level. For a given martensite fraction, flangeability and hole expansion property can be improved by reducing $\sigma_m/\sigma_f$ [10]. The present results indicate that the springback of flangeable dual phase steel may be smaller than that of common dual phase steel with a similar martensite fraction and an equivalent strength level, the reason is that the $\sigma_m/\sigma_f$ of flangeable dual phase steels is relatively lower.

5. Summary

Three cold-rolled DP780 steels with different chemical composition and microstructure have been used to study the characteristics of tensile loading-unloading process. Total unloading recovery strain, which is related to chord modulus, can be divided into elastic strain and microplastic strain two components.

(1) There is no correlation between unloading microplastic strain ($\varepsilon_{mp}$) and phase fraction or phase size within the scope of this study. Both $\varepsilon_{mp}$ and unloading chord modulus (E_{chord}) have a linear relation with the flow strength increment. With the increase of flow strength increment, $\varepsilon_{mp}$ increases while E_{chord} reduction becomes larger.

(2) For a given flow strength increment, unloading microplastic strain ($\varepsilon_{mp}$) depend on the phase yield strength ratio of martensite phase (or hard phase) to ferrite phase ($\sigma_m/\sigma_f$), unloading microplastic strain increases as the $\sigma_m/\sigma_f$ increases. The higher dislocation density, which results from the worse inhomogeneous deformation in the ferrite, could result in larger unloading microplastic strain as $\sigma_m/\sigma_f$ increase.

(3) For a given martensite fraction, the springback of DP780 steel can be improved by reducing the yield strength difference between martensite and ferrite.

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