Effect of Microstructure on the Instantaneous Springback and Time-dependent Springback of DP600 Dual Phase Steel

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Abstract: Springback subject to tensile test of dual phase steel DP600 with different phase volume fractions has been observed and investigated in this study. Finite element simulations using representative volume element (RVE) generated from the real microstructure are carried out. It’s revealed after tensile test unloading that the instantaneous springback values \( l_{is} \) of DP600 increases with the martensite volume fraction increasing, and the proportion \( \psi \) of the time-dependent springback value \( l_{tds} \) in total springback \( l_{is} + l_{tds} \) increases with martensite volume fraction decreasing. In FE simulation of the RVEs, the effective plastic stress (EPS) \( \sigma_e \) is extracted to represent the residual stress and the higher \( l_{is} \) with more martensite volume fraction corresponds to larger variation \( \Delta \sigma_{eM} \) of martensite phase in RVE during instantaneous springback period, which agrees with the present accepted law that the instantaneous springback is the residual stress-driven elastic recovery. After unloading finishing, the time-dependent springback proportion \( \psi \) increases with the proportion \( \nu \) of EPS of ferrite phase \( \sigma_{eF} \) in total of RVE \( \sigma_{eRVE} \) increasing, which verifies the influence of the residual stress in “softer phase” on the time-dependent springback.

1. Introduction
Attributed to the good formability, metal sheets are widely used in automotive forming. Various quality defects (like springback, wrinkling and crack) in metal sheet are induced after plastic forming processes including tensile, bending, drawing and so on. Assembly precision is affected and the development of related forming technology is restricted due to the above defects. Present day with the amount applications of high strength steel, the springback has been attached great attention [1-3]. Springback is the elastic recovery after the deforming force exerted on a material is removed, leading to a dimensional change. The precise measurement, prediction and compensation for springback are quite important in industry production and the related research [4-6] have been widely carried out. The most studied springback features were under the assumption that the springback is instantaneous, time-independent and finished at the exact moment the forming load is removed [7-9].

Most of the experimental results about the springback were gained right after unloading and some were perhaps obtained after a period. However, it has been found in large amount of experiments that the springback after plastic forming consists of the instantaneous springback induced by the releasing of macroscopic elastic stress at the unloading moment and the time-dependent springback driven by residual stress, occurring with the time going [10-12]. In most experiments, the time intervals between
the two kinds of recovery were ignored. It has also been investigated that the releasing of residual stress after plastic forming results in the time-dependent springback of metal component without the external force [13, 14].

The time-dependent springback is the potential risk in the forced assembly of auto body, the geometric tolerance of gyro assembly and the high-pressure fluid tube distortion which may induce explosion in the conveying [15]. Despite the importance of time-dependent springback, only a few relevant studies have been carried out until now. The first systematic complication to time-dependent springback prediction and control was reported by Wagoner et al. in 1997 [10] and further completed by Wang et al. [14]. The continuous research of Wagoner [16] revealed that time-dependent springback took up a significant portion (e.g. 18% for 6022-T4) of the total springback. Both novel elasticity tests and finite element simulations on time-dependent springback were performed and compared with that of draw-bend tests. In the finite element simulation, the elastic-plastic material model was replaced by the residual stress-driven creep model after unloading and the simulation value of time-dependent springback was shown nearly twice as much as the experiment value. Time-dependent springback is more observed for aluminum alloys while present days the time-dependent springback at room temperature in some high strength autobody-used steels like stainless steel 1Cr18Ni9Ti [4] and TRIP steel [11] et al. are also revealed. Lim et al. [12] carried out series study of the time-dependent springback of several auto-used steels. It was revealed that the no time-dependent springback phenomenon were discovered on HSLA, DQSK and AKDQ, while the behavior was obvious on the DP600, DP80, DP980 and TRIP780 steels.

Dual phase is characterized by a composite microstructure like combination of soft ferrite matrix and hard dispersed martensite and ensures good formability and high strength, being widely used in the automotive forming. Based on the special microstructure and the time-related springback of dual phase steel, the dual phase steel DP600 with different martensite volume fractions were loaded and then unloaded in the tensile test to record the instantaneous and time-dependent springback values. Finite element simulation of the loading tensile test and the springback from unloading moment were carried out with representative volume elements (RVEs) generated from the real microstructure to discuss the influence of the two phases of DP600 on springback.

2. Experimental details
The commercial dual phase steel produced by Baosteel is studied in this paper. The chemical composition of the steel is given in table 1. The specimens with different phase volume fractions are produced by different hot rolling process. The calculation of the phase volume fraction of DP600 is shown in figure 1. The quantitative image analysis is performed by using the image-Pro Plus to calculate the volume fraction of ferrite and martensite. The volume fraction of the phases were approximately represented by the corresponding pixel numbers identified and counted by the software. As shown in figure 1(a)(b)(c), martensite is colored in green, and the volume fraction can then be calculated. The metallography of three specimens with different martensite volume fractions is shown in figure 2(a)(b)(c).

| Element | C   | Si  | Mn  | P   | S   | Al  | Nb |
|---------|-----|-----|-----|-----|-----|-----|----|
| Wt (%)  | ≤0.12 | ≤1.5 | ≤1.5 | ≤0.03 | ≤0.91 | ≤0.06 | ≤0.1 |
2.1. Uniaxial tensile test
Uniaxial tensile tests were performed with samples of different martensite volume fractions and the loading direction was parallel to the rolling direction of the sheet. The longitudinal strain was measured with a mechanical extensometer with a gauge length of 50mm and measurement precision of 0.001m. The tensile tests were carried out on standard qualified sample with the thickness of 0.9mm (figure 3). The true tensile stress-strain curves were calculated from engineering stress-strain switched from the original loading versus longitudinal displacement measured by a mechanical extensometer.

2.2. Springback experiment
The uniaxial tensile test is the basis to investigate the time-dependent springback. When the specimens were loaded to gain the pre-strain of 10%, they were instantaneously unloaded and the deformation of the calibrated part were continually recorded by the mechanical extensometer in the following 32 hours. The whole process cost about 5s. The time-dependent springback period was defined from the 30th second after unloading moment. The time-dependent springback curve was obtained by minus the instantaneous springback data from the data recorded by the extensometer.

3. Finite element modeling of springback after tensile test
The evaluating of the 2D representative volume elements (RVEs) model deformation, converted from the real metallography and SEM images, were performed in the finite element simulation using the FE
software ANSYS. The mechanical properties of the two phases in DP600 steel were considered independently based on the accepted information in the literatures [17], and were investigated to reveal the influence of the micro deformation of ferrite and martensite on the springback process of the heterogeneous material.

3.1. Model and mesh
The image is a two-dimensional continuous function essentially and the amplitude of the image is a continuous function of its location. The digital image constituted of discrete pixel units is obtained by uniformly collecting of the pixels of the two-dimensional image. As is known that the gray value of each pixel in the digital image is presented by a corresponding integer value and the digital image is constituted of pixels with different gray value. Then a discrete function $f(x,y)\ (x=1\sim M, y=1\sim N)$ is constituted by all pixels in a digital image as equation (1):

$$f(x,y)=\begin{bmatrix} f(1,1) & f(1,2) & \cdots & f(1,N) \\ f(2,1) & f(2,2) & \cdots & f(2,N) \\ \vdots & \vdots & \ddots & \vdots \\ f(N,1) & f(N,2) & \cdots & f(N,N) \end{bmatrix}$$

where $(x, y)$ is the coordinate position of pixel, $f(x, y)$ is the gray value of the pixel $(x, y)$.

Every gray value function $f(x, y)$ has a corresponding threshold $T$. The threshold segmentation is the most common image segmentation method. The pixels with different gray value could be distinguished by appropriately selected threshold. As is shown in figure 4(a), the selected RVE of DP600 steel SEM image consists of the ferrite and martensite islands and the RVE is divided into two parts according to different gray value, the binary function $f(x,y)$ is expressed as:

$$f(x,y)=\begin{cases} 1 & f(x,y) \in [0, T] \\ 2 & f(x,y) \in [T, 255] \end{cases}$$

where 1 is the martensite component , 2 is the ferrite component. The threshold $T$ is generally expressed as following:

$$T = T[(x, y), f(x, y), p(x, y)]$$

where $p(x, y)$ is the partial property of the adjacency of $(x, y)$. Then the phases with different gray value in the RVE is binarized by adaptive threshold binarization method [18], as shown in figure 4(b), white and black colors indicating the ferrite and martensite islands respectively. After being binarized into vectorized image, the RVE image is imported into the finite element analysis software ANSYS and finite element meshed model is generated in figure 4(c), taking the heterogeneity of the material into consideration. Three different RVEs (figure 5(a)(b)(c)) with different martensite volume fractions are prepared to conduct the finite element simulation.

![Figure 4. Selected RVE from real microstructure (a) SEM image (b) binarized microstructure (c) meshed finite element model](image)
3.2. Material property

In the current finite element analyses of DP steels, a dislocation density-based strain hardening model [19] is used to describe the flow curve of each phase at room temperature. The model constants are quantified by [20] and are expressed in equation (4) and (5).

\[
\sigma = \sigma_0 + \Delta \sigma + \alpha M \mu \sqrt{b} \sum \frac{1-\exp(-M_T k_r L)}{k_r L}
\]

\[
\sigma_0 = 77 + 80\% \text{Mn} + 75\% \text{P} + 60\% \text{Si} + 80\% \text{Cu} + 45\% \text{Ni} + 60\% \text{Cr} + 11\% \text{Mo} + 5000 \text{N}_s
\]

Where \(\sigma\) and \(\varepsilon\) are respectively the flow stress and true strain. The \(\alpha\) is a constant and a value of 0.33, \(M_T\) is the Taylor factor and have the value of 3. The \(\mu\) is the value of shear modulus with a value of 80GPa and \(b\) is the Burgers vector (\(b=2.5\times10^{-10}\)m). \(L\) and \(k_r\) are respectively the dislocation mean free path and the recovery rate, listed in table 2. The value of \(d_a\) is the ferrite grain size \((10^{-5})\). The \(\Delta\sigma\) provides strengthening by precipitation or the carbon in solution.

In ferrite it is:

\[
\Delta\sigma \text{ (in MPa)} = 50^{\star} (\% C_{ss}^f)
\]

In martensite it is:

\[
\Delta\sigma \text{ (in MPa)} = 30.65^{\star}(\% C_{ss}^m) - 161
\]

Where \(\% C_{ss}^f\) and \(\% C_{ss}^m\) respectively represent the wt% carbon in solid solution in ferrite and martensite.

| Parameter in equation 1 | \(\Delta\sigma\) | \(L\) (m) | \(k_r\) |
|-------------------------|-----------------|-----------|--------|
| Martensite              | 3065C_{ss}^m - 161 | (i) \(3.5\times10^{-8}\) | (ii) 41 |
| (iii) Ferrite           | (iv) 5000C_{ss}^f | (v) \(d_a\) | (vi) \(10^5/d_a\) |

3.3. Boundary and loading conditions

The boundary conditions applied to the RVE model are shown in figure 6. In the uniaxial tensile simulation, the strain \(\varepsilon_x\) is applied to the specimen edge as displacements, \(u_x = \varepsilon_x \times l_m\). The RVE was loaded to gain the plastic pre-strain of 10% and then unloaded to springback driven by residual stress releasing. The behavior of the instantaneous springback is nonlinear elastic-plastic deformation. The simulation is based on the assumption that the two phases is homogeneous and isotropic and behave separately in the deformation.

While the material constitutive model of the time-dependent springback has not been uniformly confirmed and the models used in simulations of the time-dependent springback mostly are based on some approximation and hypothesis. As it has been accepted that the time-dependent springback is driven by internal residual stress [12, 14]. The average effective stress \(\sigma_e\) in both the RVE and the two phases are calculated to correspond to the experiment law that the time-dependent springback is
influenced by different phase volume fractions.

**Figure 6. Boundary condition**

### 4. Results and discussion

#### 4.1. Tensile test results

![Stress-strain curves](image)

**Figure 7. Stress-strain curves obtained from the tensile test of all conditions**

Figure 7 shows the tensile test stress-strain curves of the DP600 steel with three different martensite volume fractions. It has been shown that the sample with martensite volume fraction of 13.8% has the yield strength of 410 MPa and fracture strain of 0.20. The sample with martensite volume fraction of 10.6% and 7.6% respectively have the yield strength of 390 MPa, 380 MPa and fracture strain of 0.23, 0.26. It has been widely investigated that the strength of dual phase steel is only influenced by the volume fraction of martensite [21]. The yield strength is found to increase with increasing of the martensite volume fraction and the fracture strain is shown to decrease with the increasing of the martensite volume fraction.
4.2. Springback after tensile test unloading

![Figure 8. Springback values after unloading](image)

The springback value measured by mechanical extensometer 32 hours (~115200s) following unloading are shown in figure 8. There are local fluctuations on curves, the curves can be divided into a fast stage and a slow stage and are shown to enter the stable period almost at the same time. The springback datas, namely instantaneous springback $l_{is}$, time-dependent springback $l_{tds}$ and the proportion $\psi$ of $l_{tds}$ in total springback value $l_{tds} + l_{is}$ are summarized in table 3.

| M%   | $l_{is}$ (mm) | $l_{tds}$ (mm) | $\psi = \frac{l_{tds}}{l_{tds} + l_{is}}$ |
|------|---------------|----------------|------------------------------------------|
| 7.6% | 0.227         | 0.0160         | 6.6%                                     |
| 10.6%| 0.250         | 0.0168         | 6.5%                                     |
| 13.8%| 0.255         | 0.0160         | 5.9%                                     |

As shown in table 3, the instantaneous springback values $l_{is}$ are respectively 0.255mm, 0.250mm and 0.227mm for samples with martensite volume fraction of 13.8%, 10.6% and 7.6%. The time-dependent springback $l_{tds}$ is 0.0160mm for the DP600 sample with martensite volume fraction of 7.6%, with the proportion $\psi=6.6\%$ of the total springback value. The $l_{tds}$ of samples with martensite volume fraction of 10.6% and 13.8% are respectively 0.0168mm and 0.0160mm, accounting for 6.5% and 5.9% of the total springback.

Combining figure 8 with table 3, the instantaneous springback value $l_{is}$ increases with increasing of the martensite volume fraction in DP600 samples. The time-dependent springback $l_{tds}$ shows no regular change with the martensite volume fraction ranging, while the proportion $\psi$ of the time-dependent springback in the total springback value decreases with the martensite volume fraction increasing. It’s accepted that [17] the martensite with a higher Young's modulus responses more obviously to the releasing of the elastic deformation energy in the instantaneous springback period, which may contribute to the regular change of the instantaneous springback value with the martensite volume fraction increasing. In the studies of the time-dependent springback, because of the similar time-related macro deformation characteristics, the time-dependent springback behavior are mostly approximated like the room temperature creep or viscoplastic behavior [22], in which the stored energy of the “softer phase” ferrite is higher than it in the “harder phase” martensite, deriving the time-dependent springback more obviously. Therefore, the proportion $\psi$ of the time-dependent springback in the total springback value increases with increasing of the “softer phase” ferrite volume fraction.

4.3. Simulation result discussion

It’s widely accepted that the time-dependent springback is attributed to the residual stress releasing. In order to study the micro mechanism of springback and the effect of martensite volume fraction on the
springback behavior of the RVE, three different models are created and the “effective plastic stress” distribution of the models in unloading process are studied. In the simulation, the residual “effective plastic stress” after unloading is considered as the deriving force of the springback. The effective plastic stress distribution in RVEs and single martensite phase at the unloading beginning moment with pre-strain of 10% are shown in figure 9(a)(b)(c)(d)(e)(f). It’s shown that the effective plastic stress in the RVE area is distinctly heterogeneous and mainly distributes to the ferrite adjacent to martensite.

The instantaneous springback deformation during the unloading period is elastic recovery and not time-related. The material model used in the finite element simulation of this instantaneous period is still the model mentioned in Section 3.2. The average effective plastic stress variation $\Delta\sigma_e$ from the unloading beginning moment to the ending moment of elastic recovery in RVEs ($\Delta\sigma_e$RVE) and in single martensite phase ($\Delta\sigma_e$M), and the proportion $u=\Delta\sigma_e$M / $\Delta\sigma_e$RVE are calculated as is shown in figure 10(a). The $\Delta\sigma_e$M of the three models are respectively 131.15 MPa (M%=7.6%), 133.62 MPa (M%=10.6%) and 137.95 MPa (M%=13.8%), accounting in $\Delta\sigma_e$RVE with proportion u of 87.8% (M%=7.6%), 92.2% (M%=10.6%) and 94% (M%=7.6%). As is revealed in figure 10(b), the instantaneous springback values $l_s$ increases with both the martensite volume fraction and the $\Delta\sigma_e$M increasing, which agrees with the present accepted law that the more releasing of plastic residual energy, the more instantaneous springback value.

Figure 9. Effective plastic stress distribution in RVEs and single martensite at unloading beginning moment (a) (d) M%=13.8%; (b) (e) M%=10.6%; (c) (f) M%=7.6%

Figure 10. Effect of martensite volume fraction on the instantaneous springback (a) releasing of effective plastic stress in RVE and single martensite (b) relation of $l_s$, $\Delta\sigma_e$M and martensite volume fraction
Driven by the releasing of residual stress, the time-dependent springback is time-related and the material model is different from that of instantaneous springback. However, at present, the material model of time-dependent springback has not been identified yet. It's not available to accurately simulate the special time-related deformation with the current elastic-plastic material models. According to the macroscopic deformation law and the influence of microstructure, the average effective plastic stress $\sigma_{eF}$ at the beginning moment of time-dependent springback (the ending moment of elastic recovery) is extracted to approximately predict the driving force, which directly influences the following time-dependent springback tendency. The effective plastic stress distribution in RVEs and single ferrite phase at the ending moment of elastic recovery (unloading ending moment) are shown in figure 11(a)(b)(c)(d)(e)(f).. In comparison with the unloading beginning moment, the effective plastic stress decreases distinctly and also distributes to the ferrite adjacent to martensite. The average effective plastic stress at the beginning moment of time-dependent springback (the ending moment of elastic recovery) in RVEs ($\sigma_{eRVE}$) and single ferrite phase ($\sigma_{eF}$), and the proportion $\nu = \sigma_{eF} / \Delta \sigma_{eRVE}$ are calculated as is shown in figure 12(a). The $\nu$ of the three models are respectively 83.5% (M%=7.6%), 78.6% (M%=10.6%) and 76.3% (M%=7.6%). In figure 12(b), no obvious corresponding relationship is observed between the martensite volume fraction and the time-dependent springback value $l_{tds}$, while the proportion $\psi$ of the time-dependent springback in the total springback value decreases with the ferrite volume fraction decreasing (the martensite volume fraction increasing). As mentioned in Section 4.2, the stored energy of the “softer phase” has effect on the time-dependent springback. The relation of phase volume fraction, and the proportion $\psi = \sigma_{eF} / \Delta \sigma_{eRVE}$ is discussed in figure 12(c). It’s revealed that the proportion $\psi$ of the time-dependent springback in the total springback value decreases with the proportion $\nu = \sigma_{eF} / \Delta \sigma_{eRVE}$ decreasing, which verifies the influence of the stored energy in “softer phase” on the time-dependent springback.

**Figure 11.** Effective plastic stress distribution in RVEs and single Ferrite at elastic recovery ending moment (a) (d) M%=13.8%; (b) (e) M%=10.6%; (c) (f) M%=7.6%

5. Conclusions
The effect of phase volume fractions on the instantaneous springback and time-dependent springback
of dual phase steel DP600 is studied in the paper. DP600 steel specimens with different martensite volume fractions were loaded in tensile test to gain the pre-strain of 10% and then unloaded to record the instantaneous springback values and time-dependent springback values. In the finite element simulation, representative volume elements (RVEs) generated from the real microstructure were also loaded and unloaded to discuss the influence of the two phases of DP600 and the residual stress in the two phases on springback.

The instantaneous springback values \( l_{is} \) of DP600 specimens are revealed to show corresponding increasing with the increasing of the martensite volume fraction, while the time-dependent springback values \( l_{tds} \) present no obvious relation with variation of the phase volume fraction. But the proportion \( \psi \) of time-dependent springback in the total springback value is shown to increase with the ferrite volume fraction increasing (namely the martensite volume fraction decreasing).

In the simulation of the RVEs deforming, the higher \( l_{is} \) with more martensite volume fraction corresponds to larger variation \( \Delta \sigma_{eM} \) of martensite, which agrees with the present accepted law that the instantaneous springback is the elastic recovery and the more releasing of plastic residual stress, the more instantaneous springback value. The proportion \( \psi \) of the time-dependent springback of the total springback value increases with both the ferrite volume fraction increasing (the martensite volume fraction decreasing) and the proportion \( \nu = \sigma_{eF} / \sigma_{eRVE} \) increasing, which verifies the influence of the stored energy in “softer phase” on the time-dependent springback.

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