A New Model Based on Viscoelastic Theory for Predicting Delayed Springback in DP600 Steel Sheet (Postprint)

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Abstract

By applying different pre-strains and dwell times, the room-temperature delayed springback response of DP600 steel sheet was obtained. Based on viscoelastic theory, creep compliance functions for predicting the delayed springback process were obtained through room-temperature creep experiments under a constant stress of 309 MPa. Based on the room-temperature elastic and plastic loading responses of DP600 steel sheet, the lower integration limit of the linear viscoelastic constitutive equation was modified, and the compliance function was convolved with the modified stress rate function to obtain the loading history effect influencing the delayed springback process. Then, the loading history strain waveform was superimposed with the unloading pulse to obtain delayed springback strain predictions for different pre-deformation amounts. The results show that the strain rate is relatively high in the initial stage of delayed springback and gradually decreases thereafter; with increasing pre-strain, the absolute value of the delayed springback strain gradually increases, and the proportion of delayed springback in the total springback gradually increases; the predicted direction of delayed springback is the same as that of instantaneous springback and opposite to the loading direction; within the same time period, the creep-recovery strain is significantly lower than the delayed springback strain; compared with the delayed springback experiments, the ratio of creep constant stress to creep-recovery strain exhibits a good linear relationship with pre-strain; the predictions obtained from the modified model based on viscoelastic theory are close to the experimental measurements and can well reflect the experimental variation trends.

Full Text

Introduction

With continuous advancements in automotive and aerospace manufacturing technologies toward higher precision and lightweight design, the application of various new high-strength steel sheets and light alloy plates such as magnesium and aluminum alloys has become increasingly widespread. Consequently, research on their formability, particularly the dimensional stability after forming, has grown in importance. Springback represents the most critical factor affecting the shape stability of metal parts after plastic forming. In reality, many metal sheets or tubes experience two types of springback following plastic forming: instantaneous springback that occurs at the moment of unloading [1~4], and a subsequent, time-dependent dimensional change that continues after unloading, referred to as "time-dependent springback" or "anelastic springback" [5~8]. While recent research has made progress in understanding metal springback, the phenomenon and evolution of time-dependent springback remain poorly understood. This time-dependent characteristic, as a latent factor, directly affects the assembly precision of components and warrants sufficient attention.

Research on time-dependent behavior began in the 1940s. Zener [9] first defined and clarified the distinction between metal viscoelasticity and anelasticity. In 1972, Nowick [10] proposed that metal viscoelasticity should be distinguished from internal friction. The microscopic mechanism of time-dependent springback relates to the motion and interaction of point defects, line defects, and planar defects [11,12]. Currently, the common activation method for time-dependent springback in metals at room temperature involves the combined action of plastic deformation and subsequent instantaneous unloading; thus, the microscopic mechanism of plastic deformation is closely linked to that of time-dependent springback. Meanwhile, the activation method for time-dependent springback is essentially identical to that of creep springback, which can also be considered a special case of time-dependent springback.

Wang et al. [13] and Lim et al. [14] investigated the uniaxial tensile time-dependent springback and stretch-bend springback of several high-strength steels and aluminum alloy sheets. By adjusting process parameters such as bend radius and tensile stress, they altered the time-dependent springback amount of the bend angle and concluded that within 2 hours after unloading, the behavior was primarily controlled by viscoelastic mechanisms. However, specialized prediction models for room-temperature time-dependent springback are currently scarce, with applications of viscoelastic theory mainly limited to passive fitting of experimental results.

Wang et al. [13] employed a room-temperature creep model to simulate time-dependent springback, finding that the accuracy of the predicted springback amount strongly depended on the residual stress field after deformation and unloading. Linear viscoelastic theory, based on creep behavior and the Boltzmann superposition principle, incorporates historical effects on subsequent strain or stress through convolution, allowing for more flexible incorporation of corrections for other nonlinear effects [15]. Therefore, there is an urgent need to develop prediction models for time-dependent springback based on viscoelastic theory that can reflect different loading history effects. Models for predicting metal time-dependent springback primarily involve two aspects: prediction of the equilibrium time-dependent springback strain and prediction of characteristic time parameters such as relaxation time.

Uniaxial tensile experiments provide clear stress-strain relationships, facilitating the study of time-dependent springback patterns and serving as an important foundation for investigating strain responses under multiaxial stress states. However, current research on room-temperature tensile time-dependent springback experimental phenomena remains insufficient. To reveal the influence of different loading histories on the time-dependent springback of DP600 steel sheet, uniaxial tensile and room-temperature creep experiments were conducted on DP600 steel sheet. Different pre-strains were applied to measure the room-temperature time-dependent springback response after unloading, and a novel anelastic correction formula based on viscoelastic theory was proposed to predict the room-temperature time-dependent springback strain of DP600 steel sheet.

Experimental

The main chemical composition of the DP600 steel sheet used in the experiments (mass fraction, %) was: C 0.009, Si 0.36, Mn 1.84, S 0.005, Al 0.05, Fe balance. A WDS-10T universal electronic testing machine was used for room-temperature time-dependent springback and creep experiments. Specimens were sampled parallel to the rolling direction, with a parallel section length of 70 mm, gauge length of 50 mm, width of 15 mm, and thickness of 1.6 mm. The extensometer resolution was 0.001 mm.

Specimens with tensile pre-strains of 0.06%, 0.2%, 5%, 8%, 10%, and 15% were designated as EI-0.06, PI-0.2, PI-5, PI-8, PI-10, and PI-15, respectively. The first letter E represents elastic loading, P represents plastic loading; the second letter I indicates direct unloading time-dependent springback experiments, with the number representing the tensile pre-strain. If the second letter is C, it represents creep experiments, with the number representing the pre-strain during the creep process. The constant creep stress was taken as the stress corresponding to the pre-strain on the stress-strain curve. For DP600 steel sheet, macroscopic yield stress was below PC-0.2, PC-0.3, PC-0.33, and PC-0.4 specimens. Creep experiments were conducted using a constant loading rate of 1 mm/min, ignoring changes in specimen cross-sectional dimensions during elastic loading and creep processes. The data acquisition method for the loading process used the equipment' s preset frequency of 1.85 s^{-1}. After loading to the pre-strain, immediate unloading was performed. When the specimen completely detached from the lower grip (within 20 s after unloading), the displacement shown by the extensometer was recorded as the initial displacement for time-dependent springback. Time-dependent springback and creep springback experiments employed non-uniform time intervals for data acquisition to fully record detailed changes. The specific method was as follows: when the reading changed, if it stabilized after the change, the stable value and the instantaneous moment of change were recorded; if the reading fluctuated, the average value was taken and the instantaneous moment was recorded. For the loading stages of time-dependent springback and creep experiments, data were still collected at uniform time intervals as set by the equipment.

2.1 Uniaxial Tensile Test

[Figure 1: see original paper] shows the stress-strain curves for DP600 steel sheet in uniaxial tensile tests. The basic mechanical properties obtained from the stress-strain curves are as follows: elastic modulus of 182 GPa, yield strength of 345 MPa, tensile strength of 628 MPa, yield ratio of 0.549, maximum uniform plastic elongation of 22.17%, strength coefficient of 1062.9, and work hardening exponent of 0.207. Since actual production drawing deformation basically occurs in the uniform plastic deformation region, this region was selected as the research focus.

2.2 Initial Springback

presents the initial springback and time-dependent springback data for specimens EI-0.06, PI-0.2, PI-5, PI-8, PI-10, and PI-15 after direct unloading. The results show that as pre-strain increases, the unloading stress σ increases, while the instantaneous springback strain Δ also increases. The ratio of σ to Δ is defined as the time-dependent springback instantaneous modulus E , which physically represents the unloading stress corresponding to unit instantaneous springback strain. The ratio of σ to the time-dependent springback strain Δ is defined as the time-dependent springback modulus E , representing the unloading stress corresponding to unit time-dependent springback strain.

The E data from Table 1 are plotted in [Figure 2: see original paper]. The results indicate that E decreases monotonically with increasing pre-strain , demonstrating a softening phenomenon of the time-dependent springback instantaneous modulus [14,16]. Since E for DP600 steel sheet shows an exponential decay trend, both exponential and power functions were used to fit the data in [Figure 2: see original paper]:

$$E = 58.41 \exp(- /0.02832) + 127.93$$
$$E = 106.2 \ ^{-0.08875}$$

2.3 Time-Dependent Springback

As seen in Table 1, for the elastic loading experiment on specimen EI-0.06, the instantaneous springback strain of DP600 steel sheet after unloading equals its loading strain, and its time-dependent springback amount is minimal—below the extensometer resolution—indicating that time-dependent springback after elastic stress unloading at room temperature is very weak. When pre-strain increases to 0.2%, the absolute value of Δ for specimen PI-0.2 is only 0.006%, still extremely small. The negative signs in Table 1 indicate direction opposite to the pre-strain. When reaches 5%, after DP600 steel sheet undergoes certain plastic deformation, the absolute value of Δ for specimen PI-5 reaches 0.02%, nearly an order of magnitude higher than PI-0.2, making the time-dependent springback phenomenon more pronounced. As continues to increase, the absolute value of Δ also gradually increases. At = 15%, the absolute value of Δ for DP600 steel sheet reaches its maximum of 0.042%, more than double that of PI-5.

The proportion of Δ in the total springback (Δ + Δ) is defined as the time-dependent springback proportion p:

p = Δ /(Δ + Δ)

[Figure 3: see original paper] shows the relationship between p and for DP600 steel sheet. The results demonstrate that p increases with , rising from 3.53% for specimen PI-0.2 to 6.77% for specimen PI-15, with the variation pattern approaching a linear distribution. Linear fitting yields:

p = (21.927 + 3.4287) $\times 10^{-2}$

[Figure 4: see original paper] presents the relationship between Δ and time within 15 hours after unloading for specimens PI-5, PI-8, PI-10, and PI-15. The results show that Δ exhibits exponential decay with time. During the initial stage of time-dependent springback, the strain recovery rate is relatively high, gradually decreasing over time. The relaxation saturation time for specimen PI-5 is approximately 15,000 s. The relaxation saturation time gradually increases with , with each curve basically reaching springback saturation at approximately 30,000 s.

2.4 Room-Temperature Creep and Creep Springback

The room-temperature creep response of metals depends on both internal microstructure and external loading conditions. Room-temperature creep can be understood as time-dependent plastic behavior that typically occurs below the macroscopic yield stress Rp0.2 [17~20]. The DP600 steel sheet room-temperature creep experiments served two purposes: first, to obtain room-temperature creep patterns under different stress levels for constructing the compliance function in the viscoelastic prediction model [21]; second, to obtain the variation of room-temperature creep springback with pre-strain.

To obtain the creep compliance function, constant-stress creep experiments were conducted at lower stress levels. The constant stresses were 309, 362, 371, and 384 MPa, corresponding to strains of 0.20%, 0.29%, 0.35%, and 0.41% on the true stress-strain curve in [Figure 1: see original paper]. The room-temperature creep curves of DP600 steel sheet under these lower stresses for 4 hours are shown in [Figure 5a: see original paper]. The results indicate that creep strain gradually increases with constant stress level. During the initial flow stage (primary creep stage), strain increases rapidly with a high strain rate, then gradually decreases with time. At the end of the 4-hour holding period, the strain rates are 0, 2.7$×10^{-9}, 5.1×10^{-9}, and 1.4×10^{-8}$ s^{-1}, respectively. Notably, the creep strain at 309 MPa basically reaches saturation within 4 hours, which aligns well with the variation pattern of the creep compliance function. Moreover, the creep strain magnitude (10^{-4}) matches that of DP600 time-dependent springback strain, so the creep curve at 309 MPa was selected for fitting to obtain the creep compliance.

The room-temperature creep curves of DP600 steel sheet under higher stresses for 4 hours are shown in [Figure 5b: see original paper]. The constant stresses correspond to the true stresses at strains of 5%, 10%, and 15% in [Figure 1: see original paper]: 593, 678, and 729 MPa. The results show that creep strain also gradually increases with constant stress level and is significantly higher than that under low stress levels. At the end of the 4-hour creep experiments under high stress levels, the strain rates are 9.7$×10^{-8}, 5.8×10^{-7}, and 1.6×10^{-6}$ s^{-1}, respectively.

[Figure 6a: see original paper] shows the creep springback curves of DP600 steel sheet under different constant stresses, with relevant experimental results listed in . The results demonstrate that as the creep holding stress σ c gradually increases, both the instantaneous creep springback strain Δ c and the absolute value of creep springback strain Δ c increase. The ratio of σ c to Δ c is defined as the creep springback instantaneous modulus E c, representing the unloading stress corresponding to unit instantaneous springback strain. The ratio of σ c to Δ c is defined as the creep springback modulus E c, representing the unloading stress corresponding to unit creep springback strain. The proportion of Δ c in the total springback (Δ c + Δ c) is defined as the creep springback proportion .

For specimens PC-0.3, PC-0.33, PC-0.4, PC-5, PC-10, and PC-15, E c shows a similar trend to E from time-dependent springback experiments, gradually decreasing with increasing stress. In contrast, E c exhibits good stability with increasing unloading stress compared to E from time-dependent springback experiments. Meanwhile, shows slight decrease with increasing unloading stress, with overall stable variation. Thus, both E c and demonstrate certain stability. Comparing the experimental curves for specimens PI-5, PI-10, and PI-15 in [Figure 6a: see original paper] with those for PC-5, PC-10, and PC-15 in [Figure 4: see original paper] reveals that after a 4-hour holding process, the absolute value of Δ c is significantly lower than that of Δ . Using Δ from specimens PI-5, PI-10, and PI-15 as the standard, the creep springback reduction proportion k is defined as the ratio of the reduction in Δ c to Δ :

k = (Δ - Δ c)/Δ

The relationship between k and is shown in [Figure 6b: see original paper], demonstrating a good linear relationship. Linear fitting yields:

k = 0.143 + 3.19

2.5 Creep Compliance

According to viscoelastic theory, the creep compliance J(t) represents the strain response of a material under unit step stress:

J(t) = (t)/σ_0

where σ_0 is the applied constant stress and (t) is the material' s strain response. Since instantaneous loading is difficult to achieve experimentally, creep experiments under different loading conditions all have loading histories that affect subsequent strain changes in viscous materials [22,23]. To obtain creep compliance without loading history effects and considering the constant stress rate loading of specimen PC-0.2, the Prony series compliance fitting method was employed [24~26].

The one-dimensional viscoelastic integral constitutive equation is [15]:

(t) = J(t)σ(0) + $_0$ J(t-) dσ( )/d d

where is the integration variable, J(t-) is the time-shifted and inverted creep compliance function, and dσ( )/d is the stress rate function (first derivative of stress with respect to time). Noting the experimental initial condition $\sigma(0) = 0$, substitution yields:

(t) = $_0$ J(t-) $\dot{\sigma}$( ) d

Taking the unloading moment t_1 as the boundary point for the integration limit in Eq. (11), it can be rewritten as:

(t) = $_0$^{t_1} J(t-) $\dot{\sigma}$( ) d + _{t_1} J(t-) $\dot{\sigma}$( ) d

For creep experiments, the stress rate is zero after loading, so the second term in Eq. (12) is zero, simplifying to:

(t) = $_0$^{t_1} J(t-) $\dot{\sigma}$( ) d

For specimen PC-0.2 with constant stress rate loading, $\dot{\sigma}$( ) = σ_0/t_1, allowing Eq. (14) to be further expressed as:

(t) = (σ_0/t_1) $_0$^{t_1} J(t-) d

For analyzing time-dependent springback, a 4-parameter Kelvin chain without impulse response was selected [15]. The compliance function can be expressed as:

$J(t) = 1/E_1\ (1 - \exp(-t/\tau_1)) + 1/E_2\ (1 - \exp(-t/\tau_2))$

where τ_1 and τ_2 represent the retardation times of the first and second Kelvin units, and E_1 and E_2 represent the elastic moduli of the springs in the first and second Kelvin units, respectively. Therefore, the strain-time function under step stress (excluding transient response) is:

(t) = σ_0/E$_1$ (1 - exp(-t/τ_1)) + σ_0/E$_2$ (1 - exp(-t/τ_2))

Substituting Eq. (16) into Eq. (15) and integrating yields the strain function accounting for constant stress rate loading history effects:

(t) = (σ_0/t$_1$)[τ_1(1 - exp(-t$_1$/τ_1)) + τ_2(1 - exp(-t$_1$/τ_2))] - ($\sigma_0\tau_1$/t$_1$)(1 - exp(-t$_1$/τ_1))exp(-(t-t$_1$)/τ_1) - ($\sigma_0\tau_2$/t$_1$)(1 - exp(-t$_1$/τ_2))exp(-(t-t$_1$)/τ_2)

Since t$_1$ = 20 s for specimen PC-0.2, substituting into Eq. (18) and simplifying the fitting yields:

(t) = A$_1$ exp((t-20)/τ_1) + A$_2$ exp((t-20)/τ_2) + A$_0$ + A$_3$ exp(-t/τ_1) + A$_4$ exp(-t/τ_2)

where A$_1$ and A$_2$ are undetermined coefficients for exponential terms, and A$_0$ is the undetermined constant term. Using Eq. (19) to fit the creep curve of specimen PC-0.2 yields A$_0$ = 0.00029, A$_1$ = -0.00105, τ_1 = 107, A$_2$ = -0.00826, and τ_2 = 2283, as shown in [Figure 7: see original paper].

Substituting the relevant coefficients into Eq. (17) gives the strain response of DP600 steel sheet under step stress of 309 MPa:

(t) = -1.9536 $\times$ 10^{-4} exp(-t/107) - 0.7242 $\times$ 10^{-4} exp(-t/2283) + 2.94559 $\times$ 10^{-3}

The corresponding creep compliance function is:

J(t) = -6.322 $\times$ 10^{-6} exp(-t/107) - 2.3436 $\times$ 10^{-6} exp(-t/2283) + 9.5338 $\times$ 10^{-5}

2.6 Stress Rate Function

Using a central difference numerical method to process experimental data, the resulting stress rate-time relationship curve is shown in [Figure 8a: see original paper], with the corresponding stress-time curve in [Figure 8b: see original paper]. [Figure 8a: see original paper] shows that the stress rate no longer maintains a linear relationship with time, so the effect of loading history e (t) on time-dependent springback should be obtained through convolution of the stress rate function and compliance function, i.e., Eq. (14). Based on experimental results from specimen EI-0.06, during the elastic loading stage, the viscous behavior of DP600 steel sheet at room temperature is extremely weak, with essentially no time-dependent springback process. Therefore, according to [Figure 8b: see original paper], the starting moment for the stress rate accounting for history effects was taken as 40 s after loading, shown as point t in [Figure 8a: see original paper] and [Figure 8b: see original paper], corresponding to a strain of approximately 0.2%. The lower integration limit in Eq. (14) was modified to a:

e (t) = (t) = ^{t$_1$} J(t-) $\dot{\sigma}$( ) d

The unloading moments for time-dependent springback experiments on specimens PI-5, PI-8, PI-10, and PI-15 are t , t , t , and t , respectively, as shown in [Figure 8a: see original paper]. Therefore, for these specimens, the stress rate-time curve segments affecting the time-dependent springback process are t -t , t -t , t -t , and t -t segments.

2.7 Prediction of Time-Dependent Springback Under Different Pre-strains

According to Eq. (25), the convolution sum of discrete sequences of the stress rate function and compliance function was calculated using Matlab numerical analysis software. By fitting the convolution sum, the loading history effect curves e (t) for specimens PI-5, PI-8, PI-10, and PI-15 were obtained, as shown in [Figure 9a: see original paper], with an enlarged view of the first 1000 s in [Figure 9b: see original paper], where the unloading moments t , t , t , and t for specimens PI-5, PI-8, PI-10, and PI-15 are marked.

From the above discussion, t_1 in the experiments for specimens PI-5, PI-8, PI-10, and PI-15 corresponds to t , t , t , and t , respectively. According to Eq. (9), the unloading impulse effect function -e (t) can be expressed as:

$$e\ (t) = \sigma\ \ J(t)$$

where σ is the unloading stress in the time-dependent springback experiment. The negative sign in Eq. (26) indicates that the stress increment during unloading is negative. Based on the Boltzmann superposition principle, superimposing the unloading impulse effect function -e (t) at moments t , t , t , and t shown in [Figure 9b: see original paper], the anelastic strain function (t) can be expressed as:

$$(t) = e\ (t) - e\ (t-t_1) = \ \hat{}\{t_1\}\ J(t+t_1-)\ \dot{\sigma}(\ )\ d$$

where e $(t+t_1)$ is the time-shifted loading history effect function.

Substituting Eqs. (25) and (26) into Eq. (27) yields:

$$(t) = \ \hat{}\{t_1\}\ J(t+t_1-)\ \dot{\sigma}(\ )\ d\ \ - \sigma\ \ J(t)$$

Substituting the convolution function from [Figure 9a: see original paper] and the compliance function from Eq. (24) into Eq. (28) gives the anelastic strain curves for specimens PI-5, PI-8, PI-10, and PI-15, as shown in [Figure 10a: see original paper]. To facilitate comparison of time-dependent springback strains among different specimens, subtracting the initial strain at zero time (0) from the anelastic strain (t) yields the prediction formula for time-dependent springback strain Δ (t):

$$\Delta\ \ (t) = \ \ (t) - \ \ (0) = \ \hat{}\{t_1\}\ [J(t+t_1-) - J(t_1-)]\ \dot{\sigma}(\ )\ d\ \ - \sigma\ \ J(t)$$

The resulting time-dependent springback strain waveforms from Eq. (29) are shown in [Figure 10b: see original paper]. The results demonstrate that Eq. (29) effectively reflects the trend shown in [Figure 4: see original paper], where the absolute value of time-dependent springback strain increases with .

[Figure 11: see original paper] compares the predicted and experimental values of time-dependent springback strain. The predicted values are relatively close to the experimental measurements, and both show approximately linear variation patterns with increasing . When each predicted curve basically reaches relaxation saturation, the saturation time is about 500 s, as shown in [Figure 10b: see original paper], approximately 1/60 of that shown in [Figure 4: see original paper]. Thus, the relaxation saturation time prediction can be approximately estimated by the ratio of 1/60.

Considering the effect of the creep holding process on creep springback, a factor (1-k) can be introduced from Eq. (8) and multiplied by Eq. (29) to incorporate the holding process effect:

$\Delta \ c(t) = \Delta \ (t)(1 - k)$

where $\Delta \ c(t)$ is the creep springback strain accounting for the holding process. Substituting Eq. (8) into Eq. (30) yields:

$\Delta \ c(t) = \Delta \ (t)(0.857 - 3.19 \quad)$

Conclusions

(1) In time-dependent springback experiments on DP600 steel sheet, the time-dependent springback instantaneous modulus exhibits a decreasing trend with increasing pre-strain. The initial stage of time-dependent springback features high recovery driving force and strain rate, which gradually decrease over time. With increasing pre-strain, the proportion of time-dependent springback in the total springback gradually increases.

(2) In creep experiments on DP600 steel sheet, the creep springback instantaneous modulus also shows a decreasing trend with increasing pre-strain. Under the same springback duration, creep springback strain is significantly smaller than time-dependent springback strain from direct unloading. After a 4-hour creep holding process, the creep springback modulus shows small variation with increasing unloading stress, approaching a linear relationship, while the time-dependent springback modulus shows a decreasing trend.

(3) By modifying the lower integration limit of the linear viscoelastic constitutive equation, a novel time-dependent springback prediction model reflecting nonlinear effects was constructed. The predicted direction of time-dependent springback matches the measured direction, and the predicted time-dependent springback strain values are close to the measured values. The absolute values of predicted time-dependent springback strain increase monotonically with pre-strain, showing a linear distribution that effectively reflects the variation pattern of measured time-dependent springback strain.

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Note: Figure translations are in progress. See original paper for figures.