Time-dependent Springback

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ABSTRACT: Draw-bend tests performed some years ago on four aluminum alloys (2008-T4, 5182-O, 6022-T4, and 6111-T4) revealed that specimens can continue to change shape for long periods, up to 15 months, following forming and unloading [1]. Contemporaneous tests of autobody steels (DQSK, AKDQ and HSLA steels) tested under identical conditions showed no such time-dependent springback over a 7 year period [2]. Current, preliminary results for a few advanced high strength steels (DP600, DP800, DP980 and TRIP780) revealed time-dependent springback at room temperature; the sign of the springback reversing for certain combinations of process conditions. Time-dependent behavior of four advanced high strength steel was measured and creep-simulated for various test conditions. Comparisons show qualitative agreement, but the simulations over-predict the magnitude of the effect

Key words: Springback, Time-dependent, AHSS, Draw-bend test, Anelasticity, Creep, Residual stress

1 INTRODUCTION

Springback, a result of bending and unbending combined with stretching for formed sheet-metal parts, is the elastically driven change of a part shape after forming and unloading. Prediction and compensation of springback are important to achieve precise final part shape to avoid assembly problems.
In previous work, aluminum alloys were observed to change shape for long periods after draw-bend tests [1, 2]. Several autobody steels were reported to have no such time-dependent behavior following similar forming and unloading [2].
Wang et al. [1] suggested two possible underlying mechanisms for the time-dependent springback in aluminum alloys; room temperature creep and anelasticity. Experimental results showed that creep plays a dominant role in long term time-dependent springback in aluminum alloys.
Similar experiments were recently performed using traditional and advanced high strength steels (AHSSs). Some AHSSs exhibit time-dependent springback behavior, an effect not reported previously for ferrous alloys. Draw restraining forces and radius to thickness (R/t) ratios were varied in the experiments. After forming and unloading, angular changes were measured for 6 months. These results were compared with simulations using a simple finite element model based on residual stress- driven creep model.

2 EXPERIMENTAL PROCEDURES

2.1 Materials

In order to compare the time-dependent springback of steels, three conventional steels (AKDQ, DQSK, HSLA steels) and four AHSSs, (DP600, DP800, DP980 and TRIP 780) were considered. Mechanical properties of tested steels are listed in Table 1.

Table 1: Mechanical properties for tested steels

Materials	AKDQ	DQSK	HSLA	DP600	DP800	DP980	TRIP780
Y.S (MPa)	190	168	398	425	537	679	505
UTS(MPa)	312	294	459	672	807	988	846
E_u (%)	26.3	24.1	16.6	16.5	11.5	9.4	14.1

2.2 Draw-bend test

Each sheet material was sheared to a length of 635mm parallel to the rolling direction and a width of 50.8mm. With one end clamped to the left grip, the strip was hand-formed around the radius to 90° and then the other side was clamped. The left hydraulic actuator was programmed to maintain a constant back force at a fraction of the material’s yield strength, while the right actuator pulls a distance of 127mm at a constant speed of 25.4 mm/sec. Tool radii varying from 9.5 to 38.1mm were used to assess the effect of R/t ratio on springback. In this work, the tool, or roller, was set to rotate at the same speed as the specimen was pulled to minimize friction.

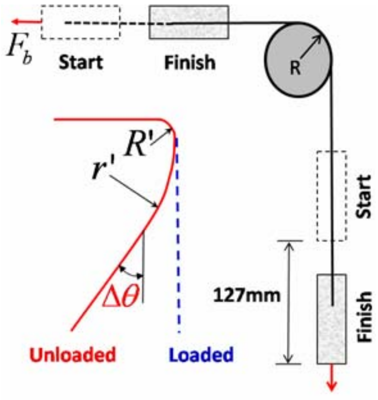

Fig. 1: Schematic drawings of draw bend test [3]

Upon starting the draw-bend test, the material underwent tensile loading, bending, and unbending at constant speed over the cylinder. At the end of the test, the strip was taken out of the grips immediately and the profile of the sample was traced onto the paper to measure the initial springback angle. Time-dependent angle changes were then measured at various time intervals up to 6 months and later were digitalized to calculate precise angles.

3 RESULTS

3.1 Static (time-independent) draw-bend tests

Initial springback angles were measured within 30 seconds of unloading the sample after forming. Initial springback angles of AHSSs at different normalized back forces are shown in Fig. 2. Both conventional steels and AHSSs showed a decline of springback angle with increasing back force and tool radius, consistent with previous works [4, 5]. AHSSs with higher yield stress showed larger initial springback angles compared to conventional steels.

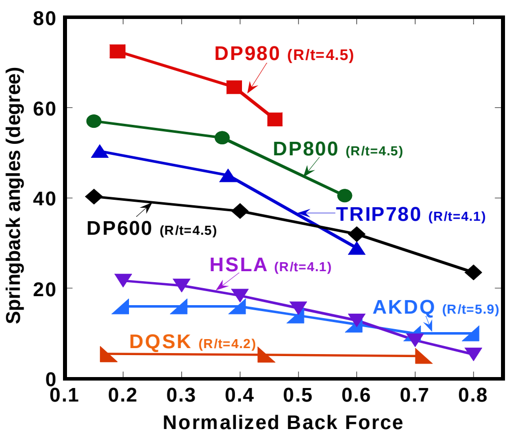

Fig. 2: Initial springback angles for tested steels

3.2 Time-dependent springback

Measurement of time-dependent springback has been carried out for both conventional steels and AHSSs at various back forces and R/t ratios. In agreement with previous work by Wang et al. [1], the tested conventional steels, AKDQ, DQSK, and HSLA steels, did not show any time-dependent behavior for 6 months after forming. However, all tested AHSSs showed angle changes after forming. Fig. 3 shows profiles of deformed samples measured at various times after forming. At long times near saturation, the angle changes are 7˚ for Al 6022-T4 and 2.6˚ for DP600. Fig. 3 (c), (d) and (e) show maximum angle changes after 2 weeks for three other AHSSs with thicknesses near 1.4mm. Materials with higher yield strength showed larger variation in the nearly saturated time-dependent springback angle, approximately proportional to the time-independent springback angle.

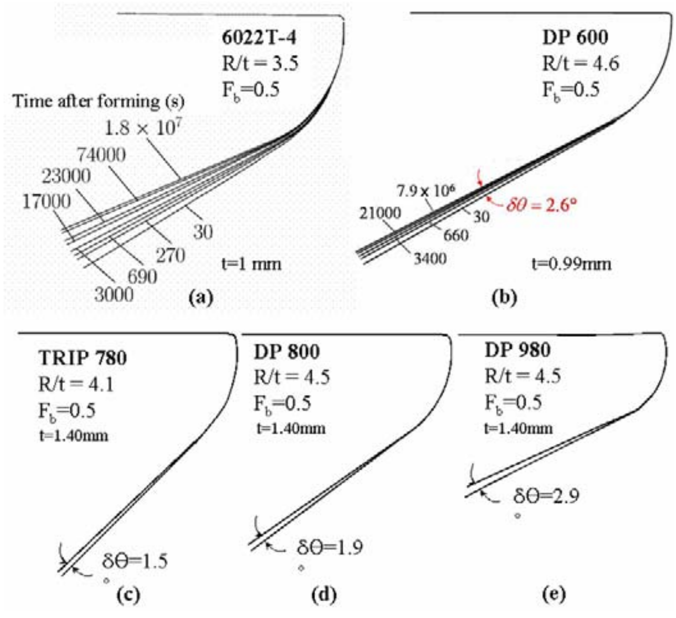

Fig. 3: Time-dependent springback of Al 6022-T4 and AHSSs (a) Al602-T4 (b) DP600 (c) TRIP780 (d) DP800 (e) DP980

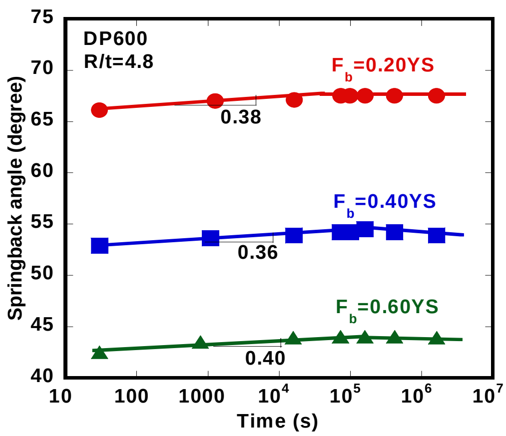

Fig. 4: Time-dependent springback angles of DP600

Fig. 4 shows springback angles of DP600 as a function of log (time). The springback angle change, $\Delta\theta$, is linear with log (time) having a slope m before it gradually saturates and the angle change becomes negligible. In some test conditions, especially with large back force, the direction of springback angle reversed and then saturates at a new smaller value. The initial linear response can be represented as follows [1];

$$\Delta\theta = \Delta\theta_0 + \delta\theta(\tau) = \Delta\theta_0(\tau_1) + m\log(\tau/\tau_0) \qquad (\tau_0 = 1s)$$

where $\Delta\theta_0$ is the initial springback ($\tau_1 = 30s$), $\delta\theta(\tau)$ is the angle change at τ (s) and m is the slope. m values of aluminum alloys and AHSSs are listed in Table 2.

Table 2. *m* values for different materials

Materials	*m*
HSLA, AKDQ, DQSK	0 [1, 2]
Al 5182-H18	1.07 ~1.58 [1]
Al 6111-T4	0.74 ~ 1.09 [1]
Al 6022-T4	1.14 ~ 1.59 [1]
Al2008-T4	0.57 ~ 0.99 [1]
DP 600	0.15 ~ 0.66
DP 800	0.46 ~ 0.68
DP 980	0.64 ~ 0.94
TRIP 780	0.43 ~ 0.54

The average m value of AHSSs is approximately one half the value for aluminium alloys as shown in Table 2. Saturation occurred at approximately 10^7 s (3.5 months) for aluminum alloys, 5×10^6 s (1 month) for AHSSs.

3.3 *Anelasticity and room temperature creep*

In order to understand the basis of time-dependent behavior in AHSS, two mechanisms were investigated [1]: anelastic deformation and residual stress driven creep. Anelastic strains were measured after unloading from 1) uniaxial tension and 2) compression and then tension, for up to an hour.

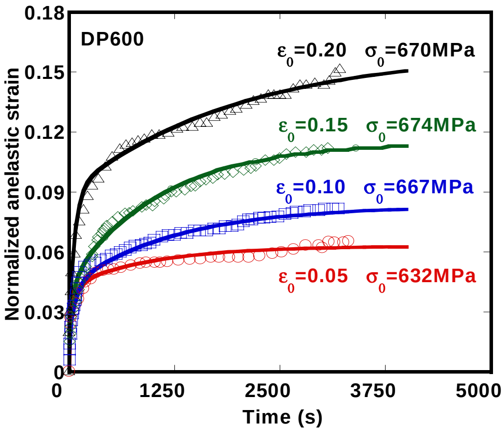

Fig. 5: Normalized anelastic strain after uniaxial tension for DP600

Similar to aluminum alloys, anelastic strain for AHSSs saturated within an hour, much shorter than the saturation time for time-dependent springback. The second mechanism considered, residual stress driven creep, was measured by applying a constant load and recording the creep strain digitally for 2 hours. Measured creep properties were fitted using simple steady-state power law [6] as shown in Fig. 6

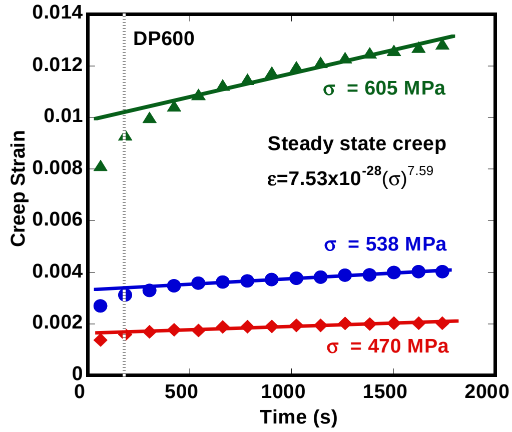

Fig. 6: Room temperature creep tests for AHSSs

3.4 *Simulation of springback*

A simple finite element model was constructed using ABAQUS/Standard to simulate time-dependent springback based on residual stress driven creep. A shell element (ABAQUS element type S4R) with 51 through-thickness integration points, Von Mises yield and isotropic hardening were employed. The simulation process consists of three consecutive stages: (1) time-independent elastic-plastic loading, (2) time-independent elastic-plastic initial unloading, and (3) creep of the unloaded specimen driven by internal residual stress. Creep properties were implemented in a form of steady state creep power law. In order to improve the accuracy, the friction coefficient (Fig. 7) between the material and the tool were determined by comparing the measured and simulated pulling forces. Fig. 7 compares measured and simulated initial springback angles (t=30s). Predicted initial springback angles showed good agreement at F_b<0.5 with deviation less then 10%.

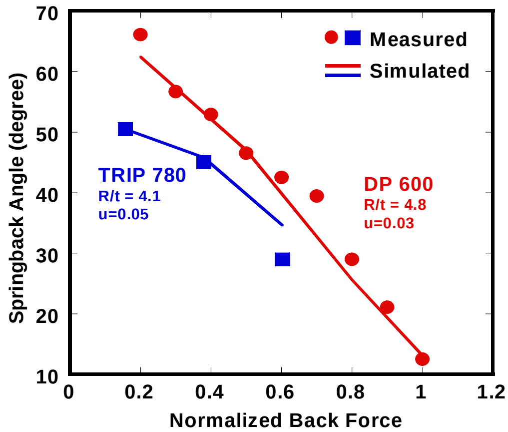

Fig. 7: Static (time-independent) springback angles: simulated

and experimental results

The internal residual stress through the thickness of the sheet after each simulation step is shown in Fig. 8. At the end of forming and unloading, the maximum tensile residual stress is reduced by 70% after 1.8×10^7s (~7 months).

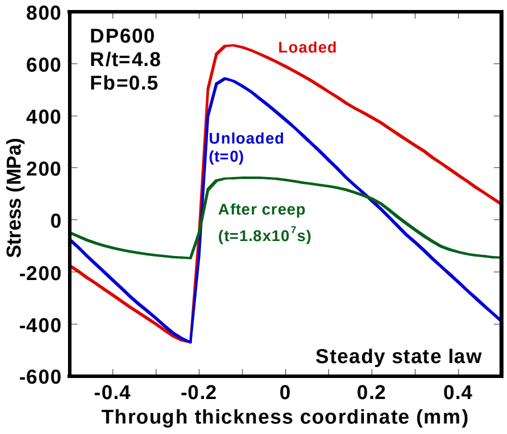

Fig.8: Simulated through thickness stress at each stages

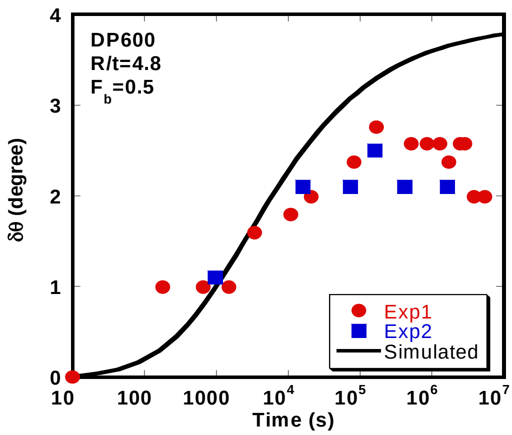

Fig. 9: Time-dependent springback angles of DP600: simulated and experimental results

Fig. 9 shows simulated and measured time-dependent springback angles for DP600. Results show good qualitative agreement but the predicted angle changes overestimate experimental results by approximately a factor of two. Previous work on aluminum alloys showed opposite results; simulated results were approximately two times smaller than the measured values [1]. Quantitative deviations between simulated and measured time-dependent springback angles may be attributed to approximate material law implemented and the complex loading states that would affect the creep behavior.

Table 3: Times to reach fractions of saturation strains ($\delta\varepsilon_\infty$) or springback angles ($\delta\theta_\infty$) for DP600.

Time (s)	0.5	0.8	0.9
Draw-bend measured	1×10^3	1.5×10^4	$\sim10^5$
Draw-bend, creep model	5×10^3	6.5×10^4	3.5×10^5
Anelasticity	2×10^2	1.2×10^3	2×10^3

Table 3 shows kinetics of measured time-dependent springback, residual stress-driven creep model and anelasticity. Times to reach fractions of saturation strains or springback angles are compared. Saturation here is defined by a zero slope of the variable with respect to time. The kinetics of anelasticity is 1-2 orders of magnitude faster than measured and simulated springback. Therefore, anelastic deformation contributes only to the short-term response of the time-dependent springback, consistent with previous work with aluminum alloys [1].

4. CONCLUSIONS

Time-dependent springback was observed in AHSSs for some combinations of sheet tension and R/t. In general, $\Delta\theta$ increases with increasing back force and started to drop when the front force exceeds yield stress.

Room temperature creep and anelasticity were tested as possible origins of the observed time-dependent behavior. Anelasticity becomes negligible 1-2 hours after unloading, making this mechanism unlikely to dominate time-dependent springback, which occurs over a period of several months.

The residual stress driven creep simulation showed good qualitative agreement with experiment but simulated results overestimated the time-dependent springback angle.

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