Influence of the Effect of Strain Rates on Springback in Aluminum 2024 (ISO AlCu4Mg1)

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ABSTRACT

Forming of aluminum sheets in T-temper is a much sought after industrial process, especially in the aircraft industry. However, the success of this process largely hinges on the ability to predict springback accurately. Aluminum sheets in T-temper exhibit approximately twenty percent variability in material properties and also the amount of springback is very large. This makes tool design for aluminum in T-temper an iterative and difficult to control process. Traditionally aluminum has been formed in the O-temper and then heat-treated to T–temper, as recourse to reduce springback. This research is aimed at developing a predictive finite element technique for springback, using experimental validation. A parametric study was conducted to determine the influence of geometric parameters and tempers on springback. The study characterizes springback of aluminum in different tempers and investigates the effect of forming strain-rates on springback. The study focuses on springback in Aluminum 2024 using hydroforming process.

INTRODUCTION

A significant portion of the airframe consists of formed sheet metal details. Forming of sheet metal details frequently involves shaping it into complex patterns by bending through a certain angle so that the metal is stressed beyond its yield point. After the pressure has been relieved, the metal has a permanent set which is less than the angle through which it was bent. The difference between the permanent angle of bend and the maximum angle, to which the metal was forced, is commonly known as "Springback" [1]. Springback is one of the key factors influencing the quality of formed sheet parts. Origin of springback lies in the elastic recovery of metals. When the deforming forces are removed, the elastic part of strain is recovered causing a change in shape of the metal. Accurate prediction of springback is precondition to control springback.

Aluminum is the material of choice in aircraft industry because of its high strength to weight ratio. Most parts on the aircraft must be in T-temper from strength considerations. Hence, it's desirable to form aluminum in T-temper. However, aluminum in T-temper exhibits large angular springback, and springback varies non-linearly with bend angle. Consequently, tool design to compensate for springback is an iterative procedure. It is very difficult to converge on the amount of springback compensation needed to achieve the required bend angle. Aircraft parts generally have free-formed lofts or continuously varying contours, which, makes it all the more difficult to predict the amount of springback, and springback compensation.

Springback in O-temper 2xxx aluminum is an order of magnitude lower than T-temper, hence, components are formed in O-temper and solution heat-treated to W-temper. The heat-treated parts are naturally aged to T42-temper. This process yields acceptable results. This procedure makes the process costly and also leads to loss of cold work set in the original T3-temper sheet. Further, W-temper is an unstable condition and consequently leads to non-uniform quality of form between successive parts. Hence, it is preferred that parts be formed in T3-temper. This makes a strong case for the need to develop a reliable computational method to predict springback and springback compensation for T3-temper aluminum alloys.

In this research a finite element simulation technique was developed, to predict springback, for O & T3-temper 2024 aluminum alloy, using LS-Dyna. O-temper predictions were used to benchmark the simulation parameters. The simulations were validated using in-house experiments, and published data. The benchmarked parameters and physical experiments were used to develop a reliable simulation technique for T3-temper alloys.

EXPERIMENTAL DETERMINATION OF SPRINGBACK

Bladder hydroforming is a cost effective process, as it uses a single die as against a set of matched dies in draw forming/stamping, and hence, is the process of choice in the aircraft industry. Figure 1 shows a schematic transverse section of the ASEA bladder hydro press. In bladder hydroforming, the tool is placed on a movable feeding table (not shown in figure). The table is rolled into the press. Fluid under high pressure is pumped into the bladder. A wear pad on the outside protects the bladder. As the bladder is pressurized it is pushed against the blank placed on the tool, and the blank is drawn into or bent around the tool.

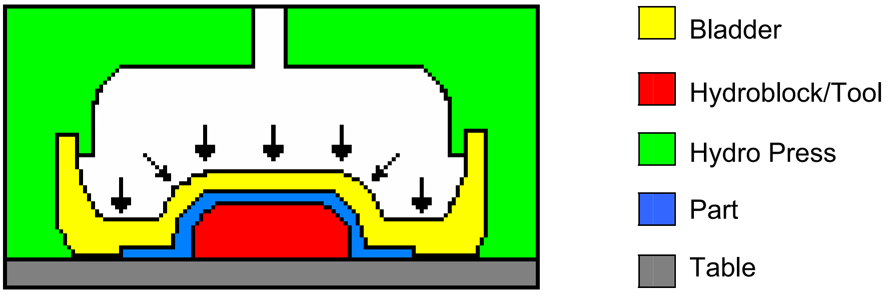


Figure 1 Schematic Transverse Section of the ASEA Bladder Hydro Press

Springback in straight flange bending using the hydroforming process was selected for the initial study. Dependency of springback on geometric parameters: bend radius, sheet thickness and bend angle, and material temper, was studied. A matrix of experiments were setup, shown in Table 1.

Parameter	Values
Aluminum Alloy - Temper	2024-O, 2024-T3
Bend Angle	60°, 90°, 120°
Bend Radius	0.125”, 0.25”
Sheet Thickness	0.032”, 0.04”, 0.05”, 0.063”

Table 1 Experimental Parameters used in Test Matrix

EXPERIMENTAL DETERMINATION OF SPRINGBACK – Forming Setup

Physical flanging experiments were conducted on a ASEA bladder hydropress, at a pressure of 4000 psi. To ensure consistency in the process three identical blanks were formed per setup. The blanks were located on an aluminum hydroblock using locator pins. Blank size and grain direction are shown in Figure 2. The blanks were laser cut and deburred, and the die was hand polished. No lubricant was used in the forming operation. To ensure that the forming pressure was sufficient to form the blanks the die surface was coated with wax and the markings made by the blank in the wax were observed. This was taken as verification that the parts formed to the bend angle before springback.

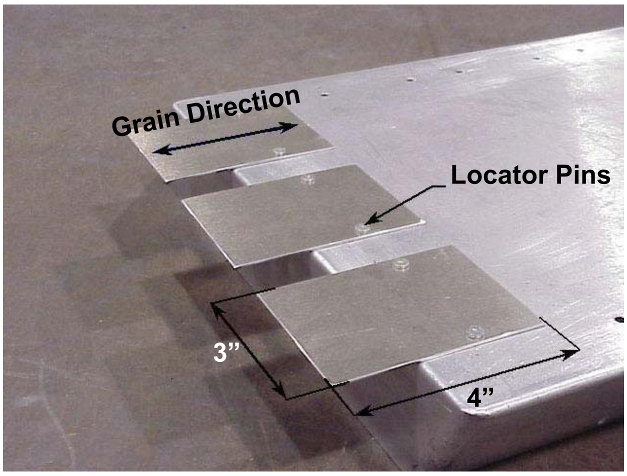
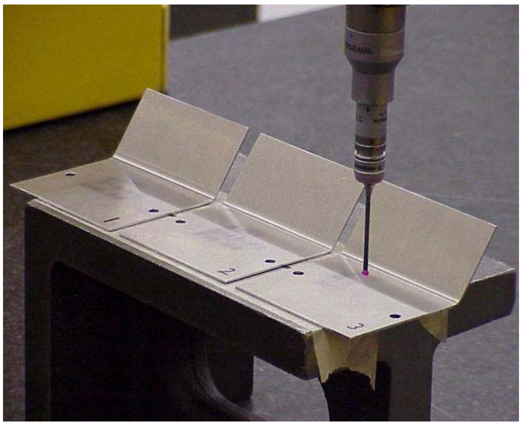
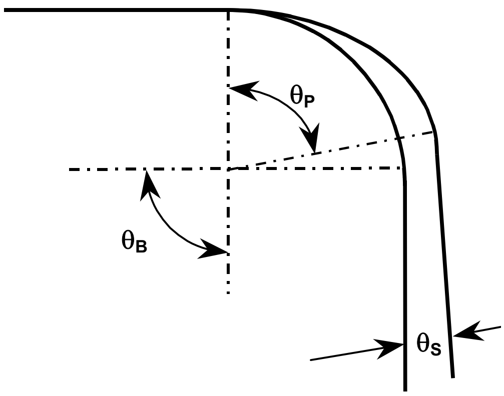


Figure 2 Experimental Setup

EXPERIMENTAL DETERMINATION OF SPRINGBACK - Measurement

Springback in formed parts was determined by calculating the difference between the measured die angle and the formed part angle. All measurements were carried out on a coordinate measuring machine (CMM). The measurement setup is shown in Figure 3a, and the various angles of significance in determining springback are shown in the schematic Figure 3b. Results for only 90° bend angle are presented in the paper, due to proprietary nature of the data (see Table 2). Data procured from Cessna experiments were compared against published data [4].





θ_B: Part angle before springback
θ_P: Part angle after springback

$\theta_S = \theta_B - \theta_P$: Angular Springback

Figure 3(a) Setup for Measurement on CMM

(b) Springback Nomenclature

Bend Radius 0.25 inches					
Sheet Thickness	Bend Angle		Bend Angle after Springback		
	Cessna Experiment	Published Data	Cessna Experiment (4000 psi)		Published Data (1200 psi)
			2024-O	2024-T3	2024-T3
(inch)	(degree)	(degree)	(degree)	(degree)	(degree)
0.032	90	95	96.29	107.07	109.3
0.040	90	95	95.05	105.75	108.3
0.050	90		93.97	103.15	
0.063	90	95	93.90	101.26	104.3

Table 2 Experimental Values for Bend Angle after Springback

FINITE ELEMENT SIMULATIONS

Simulation of straight flange hydroforming was modeled using a deformable blank and rigid tool, using 3D shell elements. The hydroblock was modeled as a rigid body. The bladder was not modeled, as the frictional effects between the bladder and the blank under high pressure is very small because of the fact that incompressible rubber behaves quite similar to a fluid. In order to simulate the effect of locator pins used in the experiments in plane motion of the blank was constrained, shown in Figure 4a. A hydroforming pressure of 4000 psi was used for the simulations. Aluminum 2024 exhibits anisotropic behavior; hence, Barlat 3-parameter anisotropic material model was used to model the material. Mechanical properties required to represent 2024 aluminum were obtained from uniaxial tension tests, based on ASTM E8, conducted at Cessna. A friction coefficient appropriate for sliding of clad aluminum on polished aluminum was used (data was obtained from experiments conducted at Cessna). In order to accurately capture the stress profile through the thickness, nine integration points were used for each sheet element. The forming operation was simulated using LS-Dyna explicit solver. Plastic strain distribution in the bend at the end of forming was found to be uniform, shown in Figure 4b. Springback was simulated using LS-Dyna implicit solver. An overlay of formed part and part after springback is shown in Figure 5.

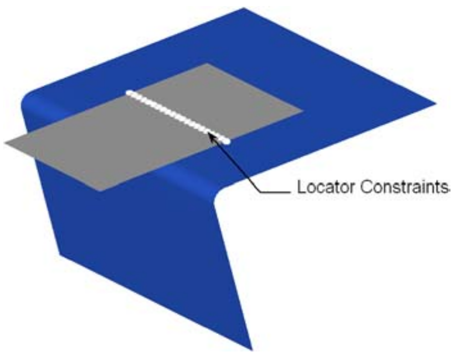
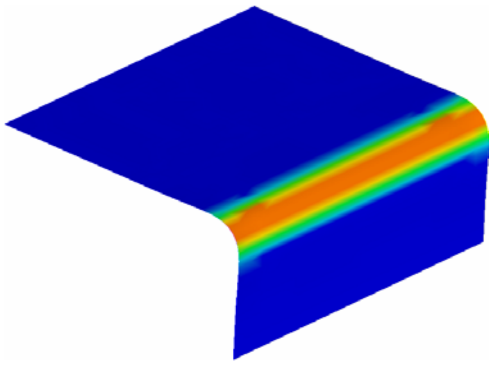


Figure 4(a) Simulation Setup - In plane motion of the blank was constrained to simulate the effect of locator pins



(b) Formed Part - Maximum plastic strain in the bend is 0.09 (sheet thickness is 0.05”)

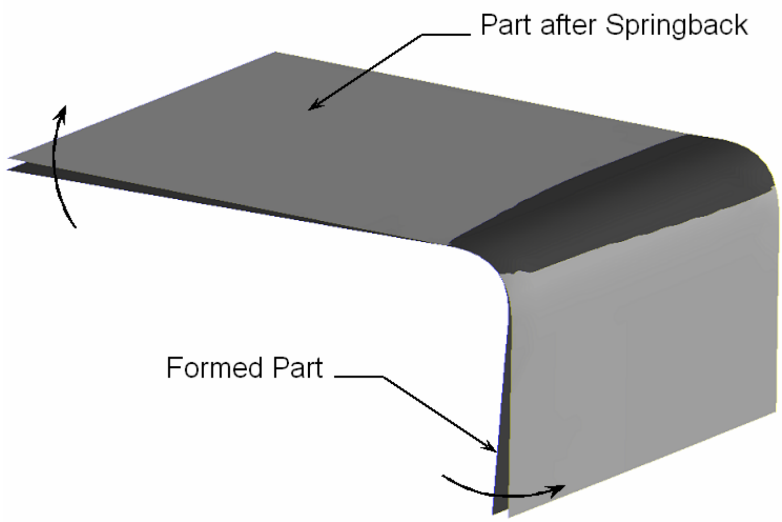


Figure 5 Overlay of Formed Part and Part after Springback

RESULTS AND DISCUSSION

Springback predicted from simulations of 2024-O aluminum showed good agreement with experimental results. For 90º bend angles: the maximum deviation of predicted angle after springback from experimental results was ±1.79%, shown in Table 3, and shop practice for acceptable deviation of parts from design is ±2.2%. These results indicated that finite element analysis (FEA) can be reliably used to predict springback for 2024-O alloy, and was implemented as standard practice in tool design.

2024-O Aluminum Alloy – Strain Rate 0.05 in/in/min			
Sheet Thickness (inch)	Bend Radius 0.25" Experimental (degree)	FEA (degree)	Deviation (%)
0.032	96.29	95.65	0.67
0.063	93.90	92.22	1.79

Table 3 Experimental vs. FEA Prediction of Bend Angle after Springback for 2024-O

Springback for 2024-T3 aluminum alloys was predicted using the FE model validated for 2024-O alloy by altering the material properties. However, FEA predicted springback was off the experimental values by a minimum of 5.45%, shown in Table 4. On the other hand the predicted and experimental values demonstrated similar trends. It was hypothesized that the difference in experimental and FEA predicted values may be due to a mismatch in the rate of forming of the parts on the ASEA bladder hydropress and the strain rate at which material properties were obtained. The uniaxial tension tests used to obtain 2024-T3 alloy properties were conducted at a strain rate of 0.05 in/in/min. The forming rate of the ASEA bladder hydropress was determined by measuring the pressure cycle time, and correlating it with the forming strain. It was found that the strain rate in forming was approximately 2.4 in/in/min.

2024-T3 Aluminum Alloy – Strain Rate 0.05 in/in/min			
Sheet Thickness (inch)	Bend Radius 0.25”		
	Experimental (degree)	FEA (degree)	Deviation (%)
0.032	107.07	100.53	6.11
0.063	101.26	95.75	5.45

Table 4 Experimental vs. FEA Prediction of Bend Angle after Springback for 2024-T3 using Material Properties obtained at Strain Rate of 0.05 in/in/min

Uniaxial tension tests for 2024-T3 alloy were repeated at a strain rate of 2.14 in/in/min. The strain rate used for obtaining material properties could not be matched with the estimated forming strain rate due to machine limitations. From practical considerations an approximately 10% error between testing and estimated forming strain rates will not result in a significant effect on predicted springback values. The tension tests at higher strain rates showed a significant increase in values of yield strength, and strength coefficient (K), and a decrease in Young’s modulus and work hardening exponent (n). The observed change in material properties with increased strain rates exhibited trends similar to published data [5]. The actual material properties obtained from high strain rate tests are not shared in this paper due to proprietary reasons.

The forming and springback analysis for 2024-T3 aluminum alloys were rerun using the high strain rate material properties. It was found that the FEA predicted bend angle after springback exhibited good agreement with experimental values. The maximum deviation of predicted angle after springback from experimental results was ±1.66%, shown in Table 5, which was well within the shop acceptable deviation of ±2.22%, for 90º bend angles.

2024-T3 Aluminum Alloy – Strain Rate 2.14 in/in/min			
Sheet Thickness (inch)	Bend Radius 0.25”		
	Experimental (degree)	FEA (degree)	Deviation (%)
0.032	107.07	107.52	-0.42
0.063	101.26	99.58	1.66

Table 5 Experimental vs. FEA Prediction of Bend Angle after Springback for 2024-T3 using Material Properties obtained at Strain Rate of 2.14 in/in/min

CONCLUSIONS

This research demonstrates that springback in 2024-T3 aluminum alloy is sensitive to forming strain rates. Consequently, accurate prediction of springback for 2024-T3 aluminum is contingent upon correct determination of strain rate experienced by the material in the forming technique used. Further, this work also demonstrates that 2024-O is relatively less sensitive to forming strain rates, when compared with 2024-T3 alloy.

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REFERENCES

1. ENROTH, E. (1980), ASEA, “Sheet Metal Forming in the Quintus Fluid Press”, Quintus Department Metallurgical, Industries Division.

2. HALLQUIST, J.O. (1998) "LS-DYNA Theoretical Manual", Livermore Software Technology Corporation.

3. MAKER, B.N. (1998), “"Implicit Springback Calculation using LS-DYNA", 5th International LS-DYNA Users Conference, Metal Forming Simulation I, II, III.

4. SCHROEDER, W. (1943) “Mechanics of Sheet Metal Bending”, Transaction of A.S.M.E., Burbank, CA, pp 817-827.

5. WAGONER, R.H., CHENOT, J.L. (1997) “Fundamentals of Metal Forming”, John Wiley and Sons Inc., pp10-11.