In Process Control of Strain in a Stretch Forming Process

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The process of stretch forming is used extensively in the aerospace industry to form large sheet panels of mild curvature. This has traditionally been a low precision process requiring considerable hand-working at assembly. However, recent demands for faster, less wasteful production have placed new demands on the accuracy and consistency (quality) of this process. In this paper the various modes of control for this process are examined, from both an analytical and experimental point of view. It is shown clearly that the process is least sensitive to material and machine property variations if controlled to a target level of strain in specific areas of the sheet. This method is compared with the conventional methods of controlling either the force applied to the sheet during stretching or the displacement of the stretch jaws. A series of both lab scale and full production experiments concur with the analytical findings, demonstrating reduced process variation if strain feedback is used. Lab experiments and analysis indicate that far greater reductions are possible if a more precise form of strain control is used. In production trials forming wing leading edges, a manually implemented strain control showed a shape variation reduction of 50 percent over normal factory practice using force control.
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Introduction

The stretch forming of sheet metal parts involves imposing both bending and stretching strains to achieve the desired part curvature and to strain-harden the material. The stretching strains minimize the curvature springback and insure that regions of compression will not buckle during forming. The specific process of drape forming, a type of stretch forming used frequently in the aerospace industry to form mildly curved panels and extrusions, is of concern here. The steps involved in a typical drape forming process are shown in Fig. 1. Step 1: A pair of hydraulically actuated jaws grip two ends of a sheet. Step 2: The stretch cylinders snug the sheet and the die is then moved upward until the sheet conforms to the die. Step 3: The cylinders provide an additional stretch to the sheet to minimize the effects of springback.

The objective of this process is to achieve a desired part contour. As with any deformation process, the challenge is to compensate for elastic recovery (springback) of the material and to do so consistently, even when material and machine variations occur.

Other work has addressed the problems of analyzing the process for the purpose of basic process understanding or tooling design (see below). In addition, recent work by Valjavec [1] and Valjavec and Hardt [2] has considered the use of a reconfigurable tool and a closed-loop shape control strategy to achieve a highly flexible process. However, any such methods require robustness of the process to variation, which is the subject of this paper. By investigating the various modes of control for a stretch forming process with respect to robustness, it is shown that in-process control of average sheet strain is best, both analytically and practically.

Prior Work in Stretch Forming Analysis

There has been considerable research into bending and stretch-bending processes, for both sheets and extrusions. A review of the work most relevant to the problem of stretch forming and strain control follows.

Swift [3] was one of the first authors to address plastic bending under tension. He used linear strain hardening, included the effect of friction, and focused on thinning as the primary contributor to the discrepancy between theory and practice. Baba and Tozawa [4] have taken probably the most detailed look at the effect of the stretch profile, the amount of tension applied to the part before and after the wrap. They found that stretching after wrapping reduced springback more than did stretching before. The analysis was performed in three dimensions with strain hardening material and typical plasticity equations. It is, however, not clear how the complex integrals were solved. The influence of the Bauschinger effect was also studied in their investigation. Their conclusions are very similar to some of those arrived at in the work performed by Parris [5] at the Massachusetts Institute of Technology. Control of the operation and the effect of changes in other parameters were not studied.

El-Domiaty and Shabaik [6] developed springback equations for the stretch forming operation using the power law strain hardening material model. They employed a no-initial plastic deformation approach. Nondimensional parameters were used, which make the results difficult to relate to actual forming situations. El-Domiaty [7] developed equations for stretch forming beams

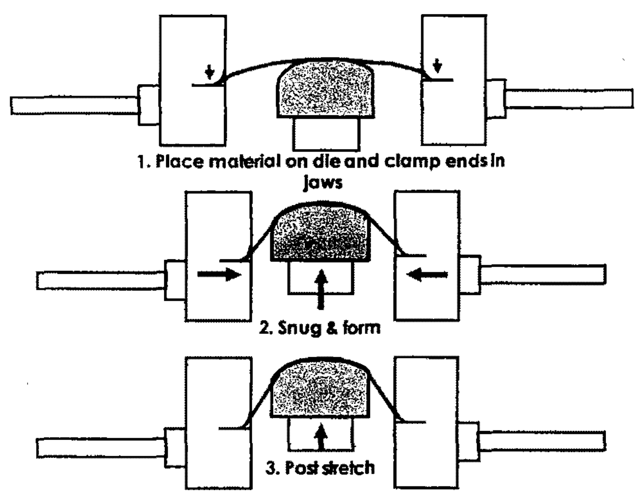

Fig. 1 Steps of drape forming operation

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with a "T" cross-section. This work extended equations developed by El-Domiaty and Shabaik [6] for power law strain hardened sheets.

Ewert et al. [8] patented a strategy for determining the stretch profile and die springback compensation to achieve the desired part shape after springback. However, some of the equations they used do not seem to have a physical basis.

Hessami and Yuen [9] used a three-dimensional numerical technique to predict stresses and strains after bending and stretching. They used nondimensional parameters and an elastic, perfectly plastic stress-strain curve; pre-and poststretches were modeled.

Tozawa [10] (in Japanese) used an analytical model to predict the effect of changing various parameters. Tozawa used beam theory (including radial stresses), as well as power law strain hardening, and took into account plane strain conditions and the Bauschinger effect. However, he did not consider friction, chemical milling, or cross sections, and he performed all calculations as a function of force, not strain. Tozawa [11] wrote one of the few papers on formed sheet metal directly aimed at improving accuracy. Stretch forming was addressed and an evaluation was made, based on results from other research as well, of the effectiveness of the application of stretch before and after bending.

Finally, Ueda et al. [12] investigated the effect of prestretches and post-stretches in the stretch forming of channels and concluded that post-stretch is more effective than prestretch in reducing springback. The authors also concluded that defining initial stretch with displacement instead of force could reduce springback variation.

Process Mechanics

The simplest embodiment of stretch forming is shown schematically in Fig. 2. Here the sheet is stretched by a pair of hydraulic cylinders about a cylindrical die of fixed radius R_d. The force F_s applied by the stretch cylinders adds a net tensile strain ε_T. This strain can be applied before the bending ("stretch-wrap forming"), after the bending ("drape forming"), or in combination. The following analysis can be applied to either mode, but since drape forming is the most common method used for sheet metal, only that specific case will be detailed.

A two-dimensional analysis of constant radius drape forming begins by imposing strains throughout the material thickness by bringing the die into contact with the sheet. The resulting strain distribution is defined by Eq. (1) and is dependent solely on die and sheet geometry if the sheet is brought into proper contact with the die. Here, K_l is the die or loaded curvature, which is equal to $1/R_d$ and y is the vertical distance from the midline of the sheet, as shown in Fig. 3.

$$\varepsilon(y)=K_l y \tag{1}$$

Next, the stretch cylinders impose additional, uniform tensile strain ε_T throughout the cross section by displacing their jaws a specified amount and thus leaving the sheet in the final strain state defined by Eq. (2). Friction at the die to sheet interface can cause some variation in the amount of strain added along the stretch axis, however this variation is ignored in this analysis.

$$\varepsilon(y)=\varepsilon_T+K_l y \tag{2}$$

At this point, we have a known strain distribution throughout the thickness of the material, as shown in Fig. 3. The stress distribution through the thickness of the material can now be defined, since we understand the stress-strain relationship of the material. The power law strain-hardening model, defined by Eq. (3) and Eq. (4) for strains below and above yield, provides an accurate model for the aluminum materials used in the aerospace industry.

$$\sigma=E\varepsilon \quad \varepsilon<\varepsilon_{\text{yield}} \tag{3}$$

$$\sigma=K\varepsilon^n \quad \varepsilon>\varepsilon_{\text{yield}} \tag{4}$$

A model is also needed to define how this stress-strain relationship changes when a portion of the material experiences compressive plastic deformation and subsequent tensile plastic deformation. This work hardening can occur in drape forming with relatively thick sheets or with dies containing curvatures that press the sheet beyond its yield curvature. There are several work hardening models to choose from, however the isotropic work hardening was shown to be a good model for reverse bending of aluminum in stretch forming if the material does not have much of a stress-strain history (Parris [5]). As a result, it is used in the analysis included in this paper. A graphical representation of this model is shown in Fig. 4.

Now that the constitutive models have been defined, stresses throughout the material thickness can be calculated. A stress dis-

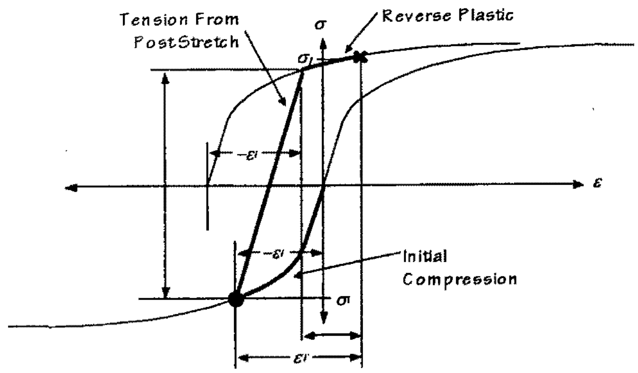

Fig. 4 Isotropic work hardening model

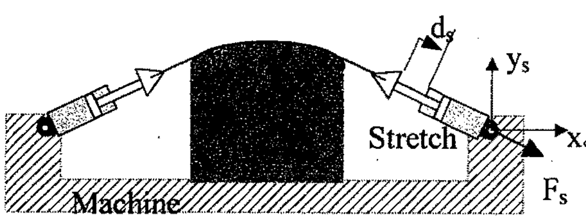

Fig. 2 Schematic and key variables for a stretch forming process

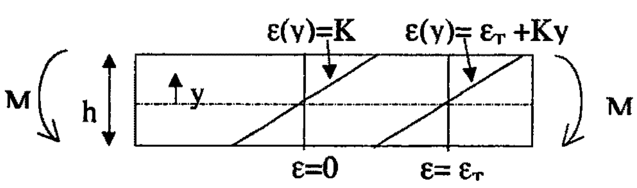

Fig. 3 Strain distribution for constant die radius in drape forming

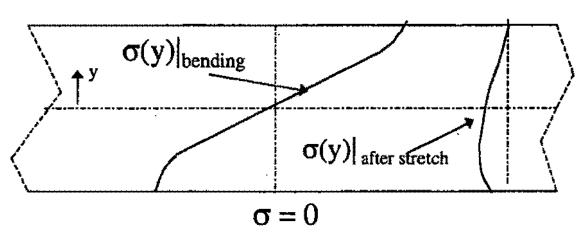

Fig. 5 Stress distribution for a forming sequence with some compressive plastic deformation and subsequent work hardening

tribution for a part that experiences some compressive plastic deformation during the bend process and subsequent work hardening during the post stretch is shown in Fig. 5.

Once the part has been released, the sheet will relax to a final state of equilibrium. This will include some axial relaxation and of greater concern here, some curvature relaxation or springback to eliminate moments through the sheet's cross section. This springback represents shape error between the loaded curvature (K_l) and the final or unloaded curvature (K_u). It is the variability in this springback that we seek to minimize.

Given the strain distribution $\varepsilon(y)$, the bending moment prior to release can be found from the stress distribution using Eq. (5).

$$M_l = \int_{-h/2}^{h/2} \sigma(y) y w dy \tag{5}$$

where

h = thickness of the sheet
w = width of the sheet

The amount of springback can be determined assuming elastic unloading with the use of Eq. (6).

$$\Delta K = M_l / EI \tag{6}$$

where

ΔK = springback
M_l = *loaded* moment on the sheet
E = modulus of elasticity
I = area moment of inertia of the sheet

This springback can be normalized by the loaded curvature with Eq. (7) to provide a springback ratio. This allows for easier comparison between parts of different curvatures.

$$\delta K = \Delta K / K_l \tag{7}$$

It can be seen through these process mechanics that springback, and thus final part shape, have a strong dependence on many material properties and geometry parameters. Some of the more prominent parameters include yield stress, strain hardening coefficient, work hardening model, die curvature, and sheet thickness.

Process Sensitivity

Of central interest here is the sensitivity of the process to changes in the material properties of the sheet, and to variations in the mechanical states of the machine. For the former, a simple graphical representation of the effect of varying constitutive properties is shown in Fig. 6. It can be seen that the same strain will produce a different stress for each of the three different curves. These different stresses will, of course, lead to different moments for the same strain distributions and thus to a different springback value.

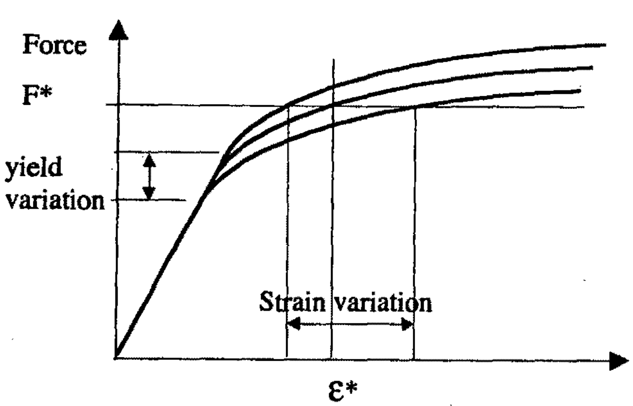

Fig. 6 Force-strain sensitivity to yield stress changes

Table 1 Model parameters

Parameter	Value
σ_Y = yield stress	76,000 MPa (11,000 psi)
h = sheet thickness	1.041 mm (0.041 inches)
n = strain hardening coef.	0.21
w = sheet width	0.10 m (3.94 inches)
E = elastic modulus	69 GPa (10000 ksi)
K = die curvature	1.1 m^{-1} (0.028 inches^{-1})

The sensitivity stretch forming has to variation in sheet thickness is not seen as readily from a stress-strain diagram. A review of Figs. 5 and 6 should help visualize the effects. Stress distributions will vary for combinations of die curvatures and material thickness that place the material into yield during bending. Again, this variation in stress distribution will lead to a different moment about the neutral axis and thus to different springback values. Die and material thickness combinations that do not place the material beyond yield during the bend stage will, however, be less sensitive to variation in such parameters, since the resulting stress distribution will be of similar form. The corresponding moments and springback values will accordingly experience less severe changes with similar stress distributions. This of course assumes that the final stress state of the entire cross section is pulled into yield during the post stretch.

Modeling Process Sensitivity. To obtain a more precise understanding of these effects and to have a point of comparison for later experiments, an analytical model of stretch forming was developed. The model, which is implemented in MATLAB, is an embodiment of the analysis given above, and uses the yield surface approach developed by Parris [5] to track the stresses of incremental portions of material thickness as they pass through the stages of prestretch,[1] bend, poststretch, and springback. The model allows the user to choose from several work hardening models, however the isotropic strain law shown in Fig. 4 is used in this analysis.

The model first sets all material stress and strain states to zero.[2] The sheet thickness is then broken into incremental sections that are defined by their distance from the sheet's mid-plane.

The part-forming module is then begun. For each portion of the part forming process (prestretch, bend, or poststretch), a change in strain for each incremental thickness of the part is defined and the yield surface method is used to calculate the associated stresses. The new material stresses and strains are then passed along to the next portion of the forming process, where revised strain changes are defined and again, new stresses are calculated via the yield surface approach. Once the final strain and stress states are reached, the moment about the mid-plane and the axial stretch force are calculated. This moment is used to calculate the released part curvature with Eq. (8). Note: this equation is only valid for elastic springback.

$$K_u = K_l \left(1 - \frac{3 M_l}{2 w K_l E (h/2)^3} \right) \tag{8}$$

where

E = elastic modulus
h = *material thickness*
w = *material width*

The axial relaxation strain is calculated from the pre-release, axial stretch force. This strain and the final part curvature are used to define a released part strain. The program then returns a value for

[1]Since only drape forming is being considered in this analysis, the prestretch strain values are simply set to zero.

[2]It should be noted that rolling of actual sheet material would induce some residual cross section strain, even if the sheet were flat.

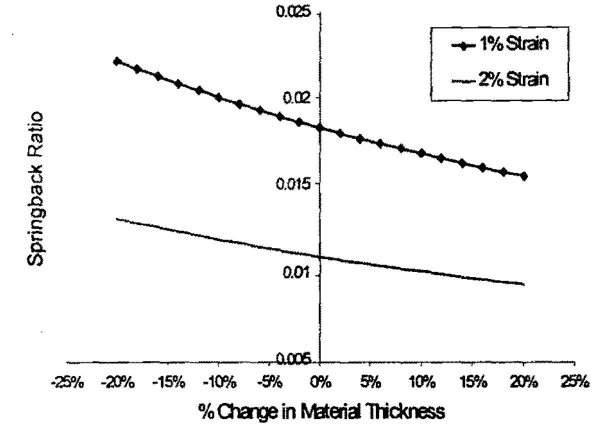

Fig. 7 Springback ratio sensitivity to material thickness

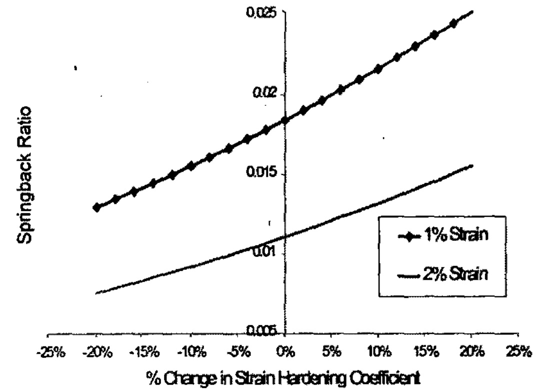

Fig. 9 Springback sensitivity to strain hardening coefficient

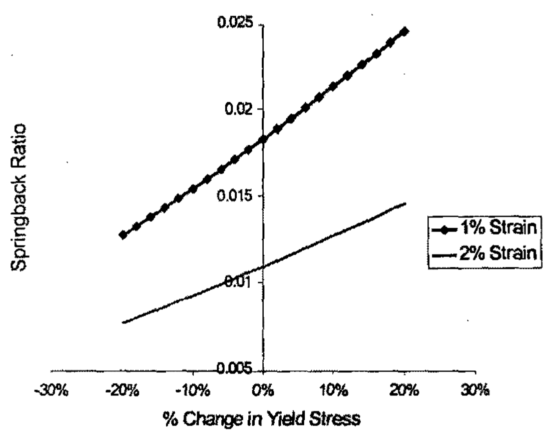

Fig. 8 Springback sensitivity to yield stress

the springback ratio and plots the stresses and strains for each portion of the process, including the residual equilibrium stresses.[3]

Effect of Material Variation. For this simulation, we will consider three dominant property variations: yield stress (σy), strain hardening coefficient (n), and thickness (h). The sensitivities will be investigated at two final average strain values of 1 percent and 2 percent strain. Other pertinent model parameters are listed in Table 1.

Figures 7 through 9 show how the springback changes when these properties are changed from the nominal conditions. In each case it is clear that higher stretching strains lead to lower springback. It is also clear that springback has a significant sensitivity to all three. As might also be anticipated, thicker material tends to have lower springback, since the bending strains are higher for given curvature as shown in Fig. 7. Likewise, in Fig. 8, higher yields are shown to lead to higher springback, a direct consequence of less overall plasticity in the cross section. Similar reasoning explains the increase in springback for high strain hardening coefficients, as shown in Fig. 9.

Sensitivities of Different Control Schemes. The previous results assumed that the final stretching strain ε_T was held fixed at either the 1 percent or 2 percent level during the forming process. However, direct feedback control of strain is not practiced in industrial stretch forming. Rather, the machine is either controlled to a desired stretching force or to a displacement, typically measured at the stretch cylinders (F_c and d in Fig. 2).

It can be argued that position control is a valid surrogate for strain control, and in the model used for this analysis, control of displacement "d" is the same as control of ε_T. However, the actual mechanics of the forming machine are ignored in this model and as will be seen, they will greatly effect a real application utilizing displacement control and will have little effect on a real application of strain control. The effect of machine stiffness is one such factor. It can be visualized in the "C" frame structure shown in the schematic of Fig. 2. Experiments by Valentin [13] on a lab scale machine at MIT and full-scale test measurements made by Parris [5] at a Northrop Grumman manufacturing facility confirm this to be a significant factor. In addition, the kinematics of a general forming geometry would require complex coordinated movement of the stretch cylinders (in the x, y, and stretch directions as shown in Fig. 2) to maintain a specified sheet displacement. Errors in initial placement of the sheet in the machine jaws would also translate directly into displacement error. A part of varying curvature, or one that has curvature along more than one axis, will also present problems in the displacement control mode.[4]

In contrast to displacement control, force control attempts to regulate the average tensile stress in the sheet. Force control is a reasonable approximation of the average stress in the sheet given the cross-sectional area of the material. It is, however, a single lumped value with no information about concentrated stresses. More important is the increased sensitivity to parameter variation that force control introduces. This again can be understood by reviewing some basic characteristics of the force-strain curve, shown in Fig. 6. Here we see that the relatively low slope of the curve beyond the yield point will cause significant strain variation for even minor material parameter or cross-section area variations. This greater error means greater variation in stress distributions and thus greater springback sensitivities.

Modeling Force Variations. To model the effect of force control, a nominal force corresponding to the desired stretching strain is computed based on an assumed material thickness and constitutive properties. For the geometry and nominal values of the previous analysis, these forces are 2790 lbf (12400 N) for 1 percent strain and 3290 lbf (1460 N) for 2 percent strain. Figures 10–12 display the results cross-plotted, with the simulated strain control results.

What is immediately apparent from both results is the increase in process sensitivity when force control is used. From this result it is obvious that controlling to a constant strain (and maximizing that value), leads to the most robust process. What is not yet clear

[3]Development of Eq. (8) is found in Parris [5].

[4]Calculation of appropriate trajectories can require extensive finite element modeling and kinematic analysis.

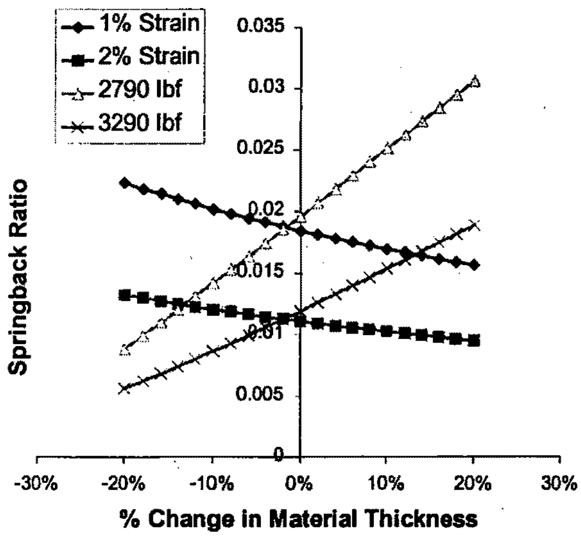

Fig. 10 Springback sensitivity to material thickness

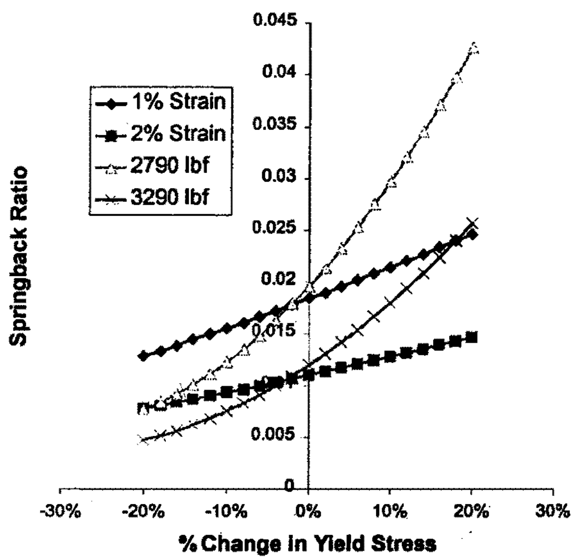

Fig. 11 Springback sensitivity to yield stress

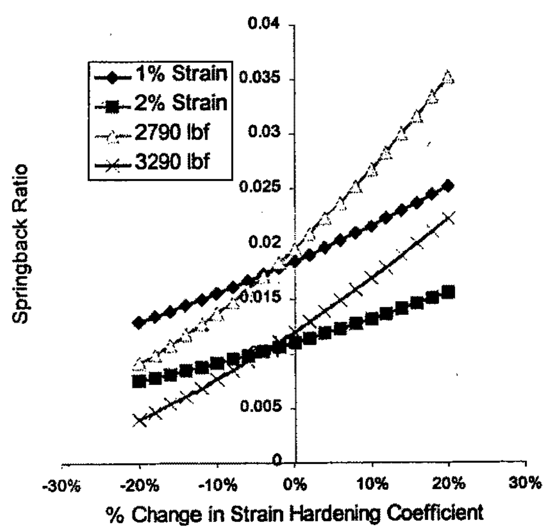

Fig. 12 Springback sensitivity to strain hardening coefficient

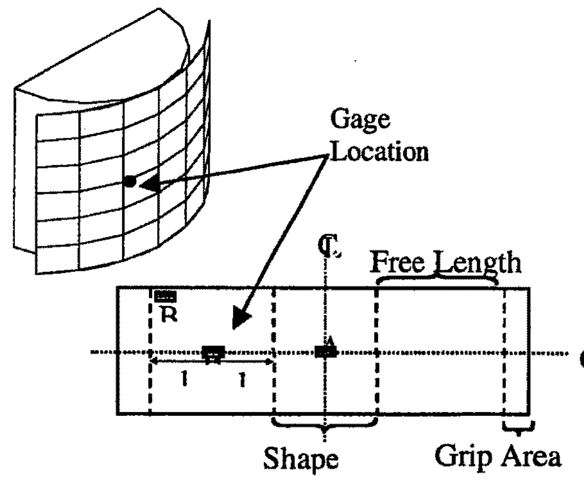

Fig. 13 Placement of the strain gage to measure average strain. The gage is located at the midpoint of the free section between last die contact with the stretch jaws.

from these results is the effect of displacement control on this sensitivity. For this we rely on experiments, where the effect of machine compliance and sheet-offset errors can be quantified.

Lab Scale Experiments

A series of lab scale experiments were performed to compare the sensitivity of the three modes of control: force, displacement, and strain. The tests were all performed on a die of constant 6 in. radius, and with a drape forming sequence. The machine geometry was essentially that of Fig. 2. (A detailed account of the machine used is contained in Valentin [13].) The nominal material was 0.063 in. (1.6 mm) thick, 2024-0 aluminum, but this was varied throughout the experiments. The formed area was a 6 in. square.

For the force control experiments the stretch cylinder forces were measured with in-line load cells and used in a real-time feedback loop to control force to a specified final value. Likewise, for displacement control the linear extension of the stretch cylinders was measured and used in a displacement control loop to maintain a specified sheet displacement as the process progressed.

The strain control involved attaching foil-based strain gages directly to the test sheets. Gage location on the cylindrical parts was chosen to obtain the minimum, maximum and average strains in the sheet. Gage placement is shown in Fig. 13. The signal from the strain gage was filtered and then used as a feedback signal to the stretch cylinder controller, creating a closed-loop strain control system.[5]

For each experiment, the final curvature of the part was measured using a coordinate measuring machine, and the normalized springback was then calculated with Eq. (7).

A series of experiments was performed testing the robustness of each controller. The test matrix is shown in Tables 2 and 3. Set 1 introduced a variation in yield stress while maintaining constant thickness. Set 2 varied thicknesses while using the same alloy with 11 ksi yield stress.

A Note on Displacement Control Testing

For displacement control, the desired system trajectory was recorded from the stretch forming process of the reference part using strain control. Because the stretch press configuration used in this research is similar to Fig 2, the actual system trajectory is

[5]To avoid any problems of stability and to minimize fast motion in the event of strain gage failure, the control gains and subsequent control system bandwidth were kept very low.

Table 2 Set 1 values for lab scale experiment. In each set the nominal values used to determine target forces and displacement are the middle value shown in bold.

Set 1: Yield Variation					
Matl.	_y (KSI)	Thickness (in)	Target Strain	Target Force (lb.)	Target Disp.
6061-0	8	0.063	1%	6680	Recorded
2024-0	**11**	**0.063**	**1%**	**6680**	from
5052-0	14	0.063	1%	6680	nominal

defined by the historical hydraulic cylinder position. Parts with different material properties were formed by re-playing the trajectory recorded during the nominal strain control test.

Results. Figure 14 is for test set 1, where variations in yield strength are introduced. From this data it is clear that the strain control is the least sensitive to the yield variations. It is also interesting to note that the nominal case, force control test varied from the strain target, this owing to uncertainty in the constitutive properties of the parts formed under strain control.

From the slope of the lines in Fig. 14 we can estimate sensitivity for each controller to the yield changes. It is significant to note that the force controller sensitivity is 10 times that of the strain controller.

In displacement control the sheet is stretched the same amount independent of the material used. Since strain is determined by the change in length, and the change in length will always be the same, the applied strain will not change. Therefore, the springback curve of the displacement controller should follow closely the curve of the strain controller. The difference between these two curves is related to the lack of compensation for machine deflection and jaw compliance in displacement control. This behavior can be seen in test set 2, where the material thickness was varied, as shown in Fig. 15.

All controllers follow similar trends as before. The only problem with the data is for the 0.032 in. thickness test. If the material

Table 3 Set 2 values for lab scale experiments. In each set the nominal values used to determine target forces and displacement are the middle value shown in bold.

Set 2: Thickness Variation					
Matl.	_y (KSI)	Thickness (in)	Target Strain	Target Force (lb.)	Target Disp.
2024-0	11	0.032	1%	4350	Recorded
2024-0	**11**	**0.041**	**1%**	**4350**	from
2024-0	11	0.063	1%	4350	nominal

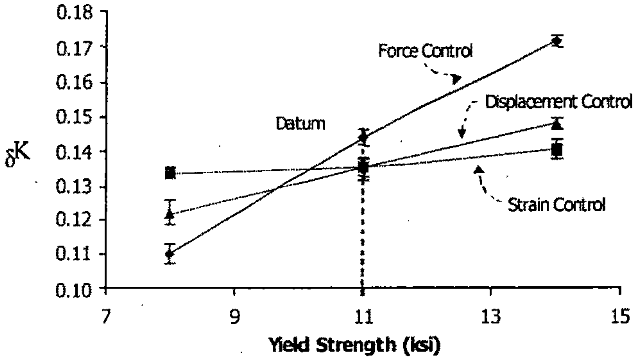

Fig. 14 Springback ratios for variations of yield strength (test set 1)

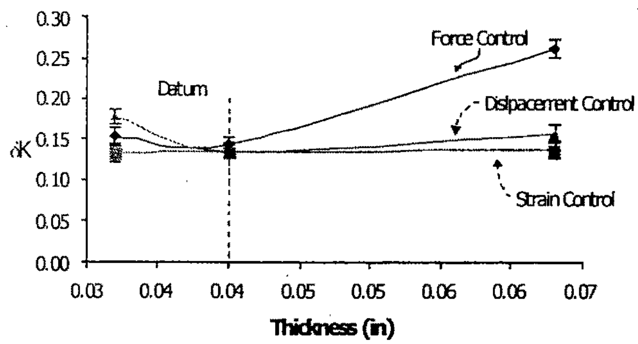

Fig. 15 Springback ratios for variations in thickness (test set 2)

behaved as expected, the springback in displacement control would be less than the springback ratio of strain control. In the same way, the springback of the force controller should be less than the springback of the displacement and strain controllers. The reason these points do not follow this trend is most likely because of operator error. The material used to obtain these data points is very thin, which makes it difficult to handle the material without altering the part shape.

Observations From the Lab Scale Experiments

These tests reveal several important findings. First of all, the difficulty of using displacement as a surrogate for strain was evident, as was the extreme sensitivity to material changes when using force control. Thus, consistent with the findings of the model, the most robust control mode for this process is clearly strain control. What was also demonstrated here, and discussed in great detail in Valentin [13], is the demonstration of stable in-process continuous regulation of stretch forming using a strain measured on the sheet.

Production Scale Experiments

In addition to the lab scale tests described above, an extensive shop floor investigation[6] examined the effect of strain control in a production environment where natural production variations occurred. The parts used in this experiment were leading edges of wings made from aluminum sheets 4 ft.×10 ft.×0.1 in. thick. They were formed on a 750-ton CNC-controlled Cyril Bath stretch forming machine, using the procedure shown in Fig. 1. Separation of the part from the die was measured and used as an indication of contour variation. Figures 16 and 17 show the shape of a leading edge, how it sits on the die after forming, and the terms used to identify ends and sides. The separation measurements were made near the ends of the part. Separation was measured with no effort made to seat the material on the die in any particular manner. To eliminate the effect of seating, separation was averaged at each end. Strain measurements were made in roughly the same locations. Forces (based on hydraulic pressure) and die table movement were automatically measured by the stretch forming press. Average stresses in the material were calculated from the force, material length and thickness.

Two typical run charts for two lots of leading edges are shown in Figs. 18 and 19. These figures show the significant variation in die movement, and separation (an indicator of contour). It is also evident from these two charts that there is an inverse relationship between the separation at the ends; that is, if one end has more separation, the other has less. This is because the operation is performed to a desired, average force; if one end stretches more

[6]All production experiments were performed at Northrop-Grumman Aerostructures Division in Dallas, Texas.

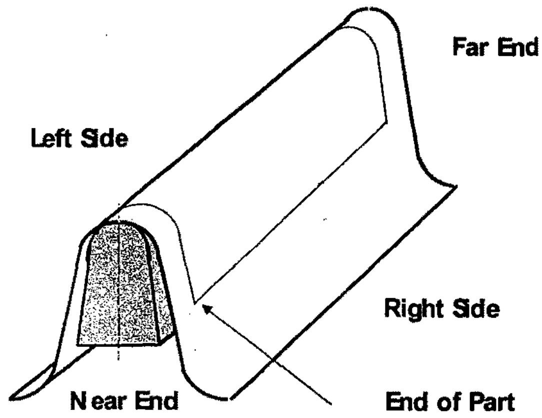

Fig. 16 Leading edge part on die

(to a higher force), resulting in less separation, the other end must stretch less (to a lower force), resulting in more separation.

Implementation of Strain Control. Machine operators already often use some visual form of strain control, because their experience has shown that it is often the best indicator of the progress of the operation. This is especially true with older machines, which do not give a reliable indication of force. The most common strain measurement and control methods are watching the part to see how it deforms on the die, watching for Lüdering or "flashing" of the part, marking the part and seeing how far the mark moves, measuring strain with a "tattle tale" (a paper device stuck with adhesive to the part surface), and measuring strain with grid lines or scribe marks. While each method can give a useful measure of part strain, they all suffer from one or more of the following weaknesses: actual strain is not indicated, there is significant variation inherent in the method, it permanently marks the part, and/or it is manually performed. These problems are avoided here with the use of an accurate and precise, automatic, in-process strain measurement device with real-time, electronic reading of the strain measurements to automatically control the operation by strain. Because of time and equipment limitations, implementation of fully automatic strain control was not achieved, however a semi-automatic control system was used.[7] Although the strain was measured automatically, control of the machine, based on the strain readings, was manual. (Details of this system are proprietary to Northrop Grumman.)

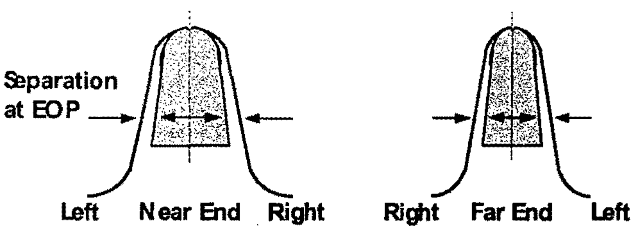

Fig. 17 Separation of part from die

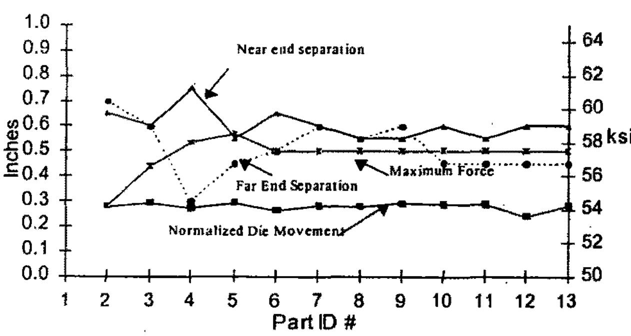

Fig. 18 Run chart for lot "A"

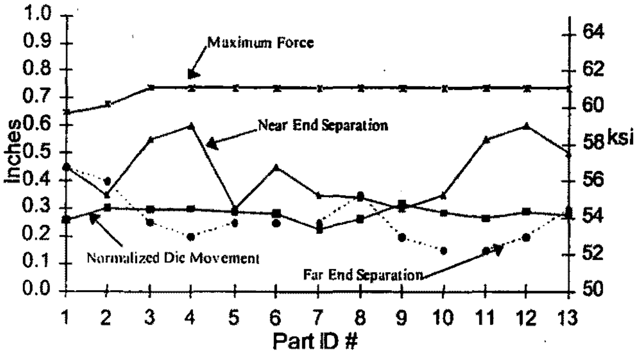

Fig. 19 Run chart for lot "B"

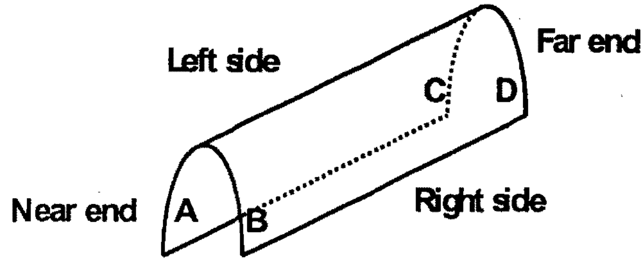

Fig. 20 Locations of strain measurements

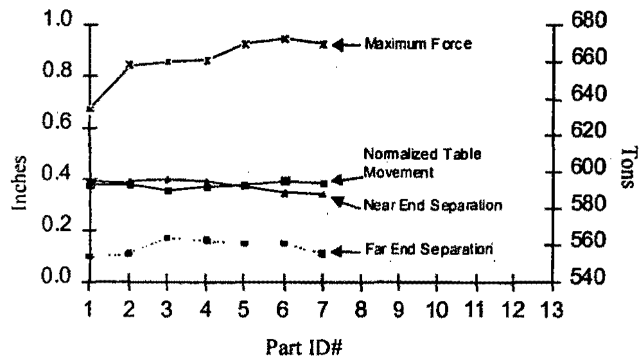

Fig. 21 Run chart for strain-controlled lot "C"

Four strain measurement devices were used: one on each side of each end of the part, as shown in Fig. 20. The strain measurement devices were attached either in the excess or on the part just on the die. They were attached after the material was clamped in the jaws, and sometimes even after the part was snug (since the jaws are essentially adjacent to the die and very close to each other for leading edges, this was difficult at best). Strain measurement device outputs went into a portable computer, and the measurements were displayed on its screen in real time. Strain control was implemented by measuring the strain in the part, starting at a 30 ton snug, and stopping the operation when the average strain at the near end reached a predetermined value. The duration of this part of the operation, the post stretch, was about 20 seconds.

The benefit of strain control can be seen in Fig. 21. While the

[7]This semi-automatic control system was developed by Northrop Grumman. Details of the system are proprietary to Northrop Grumman.

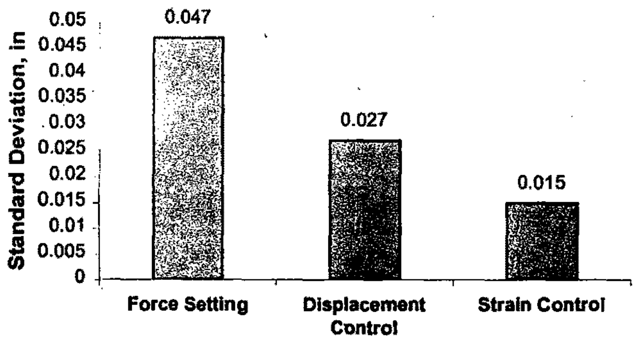

Fig. 22 Reduction of contour variation for all 3 modes of optimized settings

force variation is similar to force-controlled forming, strain control greatly reduced near and far end separation variation.

Implementation of strain control not only resulted in a significant reduction in variation, but it also gave insight into the state of the material throughout the operation.

In addition to reducing the variation in table stop position, table movement, maximum force, and strain, implementation of strain control significantly reduced the contour variation. While the results are based on limited data, they correspond to practical and theoretical expectations. Current practice for forming leading edges at the facility is force control, but with a lack of standard operating procedures. Contour variation for current practice, measured by one standard deviation of the average separation at each end was 0.190 in. Simply by achieving the same initial and final settings, still with force control, the variation was reduced to 0.047 in., about 1/4 of the current variation. Further reduction by almost one half to 0.027 in. was accomplished by switching to displacement control (controlling the operation by the displacement of the die, with optimized settings). Still further reduction of almost one half again to 0.015 in. was accomplished by switching to strain control (also with optimized settings). The combination of optimized settings and strain control reduced variation to 8 percent of the original level. The results for different control schemes under optimized settings are summarized in Fig. 22.

Observations

These results are very good, but there is reason to expect even more variation reduction in the future. The improvement achieved was accomplished with semi-automatic strain control—the operator was given verbal instruction on when to stop the operation. This led to a variation in strain of 12 percent under strain control. Even with this significant variation, it is the best of the three control methods.

Conclusions

The goal of greatly improved process control in stretch forming can be best achieved by in-process feedback control of the average stretching strain in the sheet. It was shown analytically that this leads to the most robust control method for the three options of force, displacement, and strain. Lab scale experiments, where the control system was carefully implemented and where gross material changes could be imposed, confirmed up to a 10–1 reduction in sensitivity to yield stress changes, and similar levels for thickness changes.

In a production scale experiment forming actual parts in significant lot sizes, strain control was again shown to be superior in reducing dimensional variation. In this case the variance was reduced by a factor of 2 over carefully implemented displacement control. An even greater reduction could be expected if the control system were fully automatic.

However, both the lab and production tests were on parts of simple contour, where the key strain measurements were easy to identify. In a more general implementation, a method needs to be developed to identify the best location for strain control, and a multi-dimensional control scheme needs to be devised that can control the multiple degrees of freedom of the machine to achieve several controlled strain locations.

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