D. E. Hardt
Assistant Professor.
Assoc. Mem. ASME

B. Chen
Research Assistant.

Laboratory for Manufacturing
and Productivity,
Massachusetts Institute of Technology,
Cambridge, Mass. 02139

Control of a Sequential Brakeforming Process

The process of sequential three point bending (or "bumpforming") is often used to produce smoothly varying simple curvature parts. The process involves bending and incrementing the bend line in sequence to produce the desired curvature profile along the arc length of the part. The actual shape produced represents the integration of small local shape changes, and the opportunity for error is great since knowledge of the bending properties of the material is required to accurately plan and execute the sequence. As a result, the manual process is slow and highly inaccurate. In this paper an in-process control method is presented that performs two functions: 1) sequence planning based upon an optimization between allowable variations about the desired shape and processing time; and 2) closed-loop control of the desired shape to insure accurate parts even when material properties or dimensions change.

Introduction

A common method of developing simple curvature shapes in sheets or plates is a sequential bending process, often referred to as "bumpforming." This name derives from the (generally) small local deformations or "bumps" that are made at each bend line. For example, to form a cylinder the bending sequence would involve a series of identical bends spaced uniformly along the arc length of the cylindrical cross section. Bumpforming is attractive as a general forming process since it can produce a wide variety of parts. Typical among these are aerospace panels (tanks, wings, fuselages), pressure vessel sections formed from thick plate, and conical parts from uniform and nonuniform cross-section material. The process equipment involved is no more complex than a simple pressbrake, with the only additional complication of multiple handling of the part because of the multiple bends on each piece. However, exact off-line determination of the best sequence of bends and control of each bending operation itself is impossible to perform in a purely predictive manner since both depend directly upon the bending characteristics of the workpiece material. Thus the need for on-line process-planning and individual bend shape control arises.

Because the forming process is sequential, the bending is done in discrete intervals, each of which changes only the local curvature of the part. However, these small increments of curvature integrate into the final shape, and small systematic errors in each bend can lead to considerable errors in the final part shape. Thus accurate control of the shape change at each bump is essential. Since the local bend accuracy is directly dependent upon the material and geometric properties of the workpiece, there must be some means of in-process forming property identification before control of the process can be attempted.

Contributed by the Production Engineering Division and presented at the Winter Annual Meeting, Boston, Mass., November 13-18, 1983 of THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS. Manuscript received at ASME Headquarters, August 10, 1984.

In this paper, the bumpforming process is described in terms of the required curvature distribution in the part, from which the forming requirements are derived. This leads to a definition of the level of smoothness in the final part, which in turn leads to a process planning scheme. Finally, a springback identification method is presented that involves a single calibration forming cycle to provide a springback function which can then be used to confidently control the successive bends.

Background

Automatic control of forming processes has received moderate attention over the past two decades; however, none of these investigations have addressed the specific requirements of bumpforming. For the case of local bend control, the most basic method was developed by Mergler et al. [1] for the forming of ship beams. The process was iterative, with springback identified through a sequence of loading and unloading cycles on the part at the same bend location. The bending device was then moved to another location on the part and the desired local shape in the beam was again formed. Allison [2] refined this concept in a brakeforming application to take advantage of the monotonic increase of springback with bend angle. Using this iterative approach combined with a direct measurement of the bend angle, he was able to achieve bend angle accuracies of <0.2 degrees. In a noniterative approach, Stelson and Gossard [3] identified the moment-curvature characteristics of the workpiece from measurements of forming force and displacement taken during the initial portion of the bending cycle. This was then used to determine the desired overbend. When angle measurement was included in this scheme, accuracies on the order of 0.2 degrees were achieved.

The process of roll bending has also received attention from those concerned with in-process control. Hansen et al. [4] considered the problem of in-process control of three roll

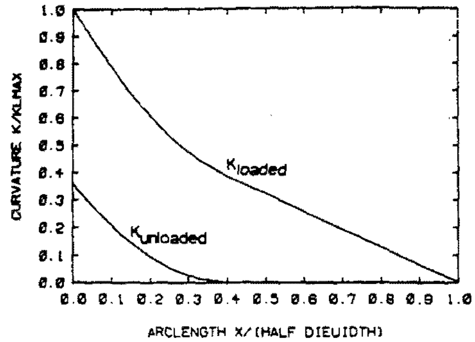

Fig. 1 Loaded and unloaded curvature distribution for an elastc perfectly plastic material in three point bending

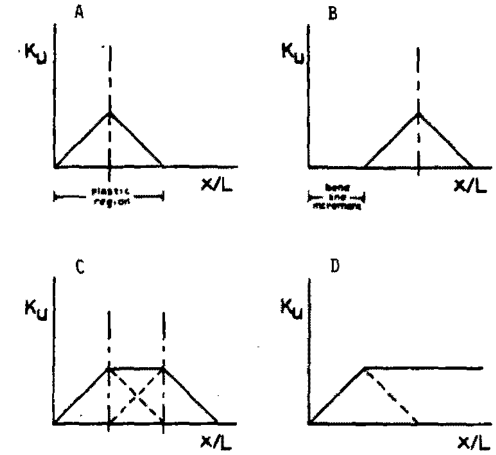

Fig. 2 Summation of idealized sequential curvature changes
A-unloaded shape of the first bump
B-unloaded shape of the second bump
C-total unloaded shape after two bumps
D-total unloaded shape after multiple bumps

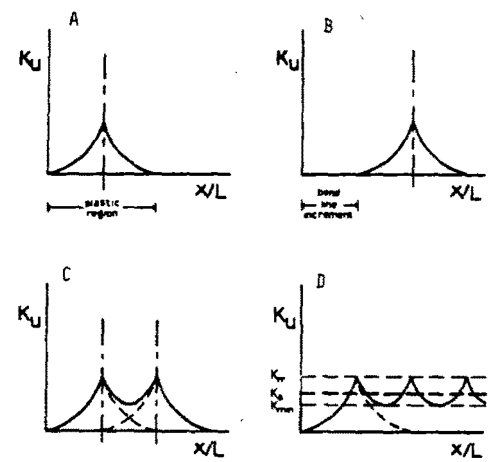

Fig. 3 Summation of sequential curvature changes with realistic curvature distributions
A-unloaded shape of the first bump
B-unloaded shape of the second bump
C-total unloaded shape after two bumps
D-total unloaded shape after multiple bumps

bending, and have addressed both the machine control and springback compensation problems. In the latter, the method chosen employed a post-forming measurement of the shape which was then used to identify the material properties of the workpiece. In a more direct method, Hardt et al. [5] developed a closed-loop shape controller that was able to accurately predict the expected springback of the material while it was still under load. This was accomplished by combining a measurement of the maximum moment and curvature of the part with knowledge of only the elastic properties of the material. In this way, the correct loaded shape could always be given to the material without any delay or identification time.

In another effort aimed at in-process shape control, Hardt and Webb [6] considered the process of die forming. Through the use of a variable configuration die surface, they demonstrated an iterative closed-loop shape control system based solely upon measurement of the unloaded shape of the part. While incorporating a minimum of information about the nature of compound curvature forming, the controller was able to force convergence to a reasonably accurate shape. Further refinement of such a controller must, however, incorporate a more detailed model of forming mechanics.

Analysis of Shapes Developed by Bumpforming

Before pursuing a method for in-process control of the part shape, the basic mechanics of bumpforming must be considered. For this analysis, the most useful shape descriptor is the local curvature, since each bend will represent a local shape (curvature) change rather than a gross angular change as is typical of brakeforming. In doing so, a method for control based solely upon a measurement of curvature will become evident.

If we consider the effect of a single bend or "bump," the mechanics are identical to the case of three point bending, except that only small values of curvature are produced. Considering the approaches of Queener [7] and Stelson and Gossard [3] this implies that no wrap-around of the material has occurred at the punch contact point. As a result, the moment distribution with arc length along the bend is continuous, and can be considered linear, because of the low curvature values. Given this moment distribution, $M(s)$, the resulting loaded curvature distribution $K_1(s)$ can be found provided the moment-curvature relationship for the workpiece material is known. If we assume that the material has a rectangular cross section and follows an elastic perfectly plastic constitutive relationship, the moment-curvature relationship can be found in closed form and is given by:

$$M(s) = EI\,K_1(s) \qquad M<M_y$$
$$M(s) = M_y(s)[1.5-0.5(K_y/K_1(s))^{3/2}] \qquad M>M_y \qquad (1)$$

where $M_y(s)$ is the yield moment and $K_y(s)$ is the yield curvature, both of which depend directly upon the yield stress and strain of the material as well as the cross-sectional thickness and width, and EI is the effective bending stiffness of the cross section. (Since bending of wide sheets and plates represents a plain strain situation the actual beam stiffness is given by $EI/(1-\nu^2)$.)

Applying equation (1) to a linear moment distibution gives the loaded curvature distribution $K_1(s)$. A typical distribution is given in Fig. 1. Also shown in this figure is the unloaded curvature distribution $K_u(s)$ that results when the punch is withdrawn from the part. This is found from the elastic unloading of each point on the sheet according to: $K_u(s) = K_1(s) - M(s)/EI$, where the last term is the local springback of the material. Since it is necessary to overbend the material so that it will springback to the desired part shape, the first task of the control system must be to identify this springback term for the specific material under load. A method appropriate to the limited curvatures of brakeforming is presented in the next section.

However, the process of bumpforming involves developing a widely distributed curvature along the entire arc length of the material. Also, to produce smooth curvatures in the final part, the sequence of discrete bends must overlap. Thus the analysis of the curvature produced in bumpforming involves more than the local curvature change described above.

Consider the task of producing a cylindrical contour. The desired curvature distribution is $K_u(s)$ = constant; however, the three point bending process can only produce an arc length dependent curvature distribution. If this distribution were linear with arc length, the bend line increment corresponded exactly to 1/2 of the arc length of the plastically deformed material from the previous bend, and if it is assumed that the curvature change caused by the second bend is identical to the first bend (even if significant overlap occurs), then a constant curvature distribution could be produced as shown in Fig. 2.[1] However, the unloaded curvature distribution shown in Fig. 1 indicates that realistic materials will not provide a linear distribution, and regardless of how the bend line sequence is chosen the resulting shape will have a variable curvature as is also shown in Fig. 3. (It should be noted that the presence of significant strain hardening will reduce the severity of this effect and tend to produce more linear curvature distributions than a perfectly plastic material.)

When the effect of several bumps, displaced according to a desired bend line increment, is integrated, the result is the actual curvature of the part. Figure 3 shows that the final part shape can be described by an average, maximum, and minimum curvature, where the latter two could be lumped into a root mean square (rms) descriptor of the shape variation:

$$K_{rms} = \left[\int_0^S (K(s) - K_a)^2 ds\right]^{1/2}$$

Also evident from this plot is that the average and rms curvature, for a given local curvature distribution, will depend directly upon the spacing of the individual bumps. Thus the command inputs to a bumpforming process must include both the desired average curvature distribution and the allowable amount of curvature variation. Since the rms value will always be nonzero for a finite bend line increment, a tradeoff between bump frequency and rms curvature is established, and an optimization can be performed that seeks to minimize the rms value subject to a production time constraint. If significant material property or geometry variations occur along the arc length of a single part, this optimization would have to be continually performed as new curvature distributions occur.

Local Bend Curvature Control

At the local level one must consider the most appropriate method for controlling the pressbrake for each bend. To accomplish the overall control of shape in this process, a curvature measurement has been assumed. The foregoing discussion implies that the objective of the bend control system is to regulate the curvature increment of each bend. However, a pressbrake is controlled by varying the relative displacement of the dies; thus one can only specify a single point curvature within the bend region and then react to the resulting curvature distribution by updating the foregoing sequencing plan.

[1]The assumption of unloaded curvatures superposing has been made only for illustrating the effect of overlapping bends. However, this assumption can be justified if: 1) The moment distribution $M(s)$ is the same for each increment even if the workpiece has some prebend; and 2) the moment-curvature relationship for a nonflat workpiece is the same as for a flat piece, except for the shift of the origin from zero curvature to a finite initial value (i.e., there is no significant work history). Under these conditions the existence of nonzero curvature in the part before a fixed curvature bend is performed, serves simply to bias the moment-curvature relationship for all points in the workpiece. This curvature bias, therefore, *adds* to the newly imparted unloaded curvature as shown in Fig. 2.

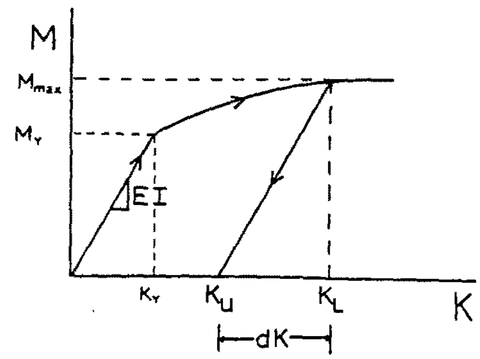

Fig. 4 A typical bending cycle illustrated on a moment-curvature diagram

From Fig. 1 it can be seen that a single bend could be controlled on the basis of the average curvature change, K_a, or the maximum curvature change, K_m. However, since the resulting distribution of curvature (rather than any one local value) will determine the integration of bumps into the final shape, K_a appears to be the superior choice. This is reinforced by the simple observation that identical values of K_m could yield vastly different shapes for $K_1(s)$, whereas the average curvature would always reflect variations in the shape of the local curvature distribution. Also, K_a can be verified by measuring the total angular change in the workpiece over the local bend section after each bump. This is an inherently more accurate measurement than trying to calculate the curvature distribution. However, $K(s)$ will still need to be measured to allow the bend integration to be evaluated.

However, the crux of this control system is identification of the bending properties of the workpiece so that a desired value of K_m or K_a can indeed be achieved automatically. A method for this identification, concentrating on the identification of an arc length dependent springback function, is presented in the next section.

On-Line Measurement of Local Springback

Since the dominant mode of deformation in brakeforming is bending, the appropriate constitutive relationship for the workpiece material is moment-curvature. This descriptor lumps the effects of the stress-strain properties of the material along with cross-sectional geometry, and is most useful for real-time control purposes. However, as has been demonstrated previously, the need is to determine the springback of the material so that the correct loaded K_a (or K_m) can be commanded to the press. Since we are dealing with continuous curvature distributions rather than gross angular changes, and the only on-line measurement during forming will be $K_1(s)$ and K_a (both of which will be derived from measurement of the profile of the sheet) what we seek is the local springback dK as a function of the corresponding local loaded curvature K_1. If dK is known as a function of K_1, the difference between any loaded and unloaded curvature distribution can be accurately predicted.

Referring to a typical moment-curvature curve shown in Fig. 4, a cycle of loading and unloading is illustrated by the arrows. From this curve an expression for the desired springback function can be derived:

$$dK = M/EI$$

and

$$M = M(K_1)$$

thus

$$dK = M(K)/EI \qquad (2)$$

where $M(K)$ is the moment curvature relationship specific to

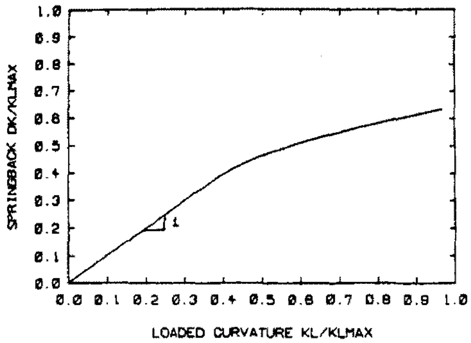

Fig. 5 Springback-loaded curvature relationship derived from Fig. 1

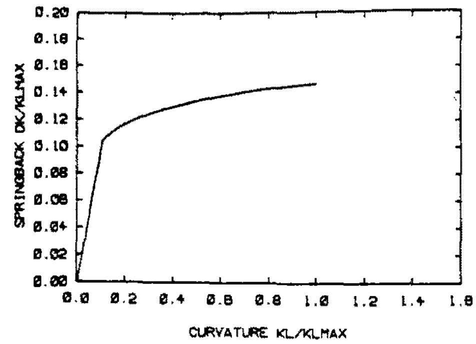

Fig. 7 Springback-loaded curvature relationship derived from Fig. 6

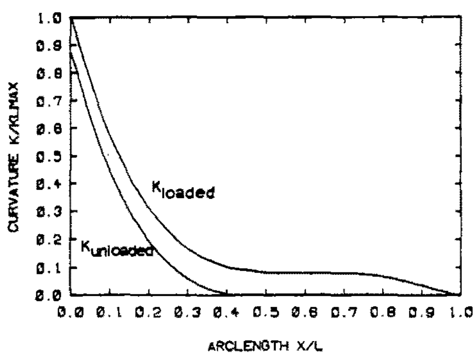

Fig. 6 Measured loaded and unloaded curvature profiles (material: 6061-T6 0.1 in. thick)

the workpiece material. However, to find $M(K)$ it is necessary to either make in-process force measurements (as well as certain restrictive assumptions about the material cross section; see e.g. Stelson and Gossard [3]), or perform an off-line material test to explicitly measure material properties. The former is quite difficult to do for mild curvatures and does not deal well with nonuniform cross sections, while the latter is not responsive to in-process variations. However, since bumpforming is often used to form parts with a nonuniform cross section, such as heavily profiled aerospace panels, it is desirable to find a control method that can deal with such a situation.

To accomplish this goal the desired springback function is derived from a curvature distribution measurement alone. The local springback is defined as $dK = K_l - K_u$, the difference between the loaded and unloaded curvature at the same arc length on the material. Consequently, if we simply measure a widely distributed set of values for K_l and the corresponding values for K_u, the springback function can be directly computed. Thus the problem of springback identification reduces to a loaded curvature measurement followed by an unloaded curvature measurement, and a point by point subtraction of these values. This will give the springback associated with each distinct value of K_l. Since the three point bending geometry gives a complete distribution of K_l up to the K_m for that bend, it is an ideal load for generating this data.

In Fig. 5 the springback function that results from the ideal data presented in Fig. 1 is given. As expected, it has an appearance similar to the parent moment-curvature relationship, and indeed one can actually derive the moment-curvature relationship from this springback function by applying equation (2) to find a moment corresponding to each value of springback.

In developing a process control scheme based upon this concept, it must first be noted that a two cycle bend is required: one to generate data for the springback function determination and one to produce the desired curvature. However, if the workpiece has a uniform cross section along the arc length, this calibration may not need to be performed on every bend, but rather the function can be checked from loaded and unloaded curvature measurements made during the actual forming cycle and corrections made as needed.

Figure 5 also indicates that the range of the springback function is limited to the maximum loaded curvature of the calibration bend. Since this first bend must be conservative to avoid overbending the material, the function will have to be extrapolated to loaded curvature values expected for the actual bend. By using *a priori* information about the material being formed, a lower bound on K_m or punch penetration can be found. In this way, the amount of extrapolation needed for the second forming bend can be made quite small. Also, the use of K_o as the control variable for the actual bend will minimize the effect of error arising from this extrapolation process because it will be sensitive to the integral of the springback data.

Experimental Determination of the Springback

The springback identification method described previously is analytically exact, provided nonmoment loading effects can be neglected. However, the effect of measurement errors must be examined experimentally. Accordingly, a series of experiments were performed to evaluate this method.

The experimental procedure consisted of imposing a three point load on the test coupon, measuring the loaded shape of the part (in cartesian coordiantes), then unloading the part and making a similar measurement. The die contact point was used as the coordinate frame reference. The actual coordinates were measured using an optical comparator with measurement resolution of 0.0001 in. (0.0025 mm), and the loader die width was 1.5 in. (38 mm). The horizontal coordinate (x) was aligned along the unloaded sheet length and the vertical coordinate (y) along the bending direction. Measurements were taken at intervals of 0.01 in. (0.25 mm) in the x direction. Although the most correct reference for these measurements is the neutral axis of the part, the bottom surface was chosen since that is the same reference that will be used when the springback calibration is used to control the part shape.

The curvature is calculated from the expression:

$$K = \frac{d^2y/dx^2}{\left[1 + \left(\frac{dy}{dx}\right)^2\right]^{3/2}}$$

thus the coordinate data must be differentiated twice. This was performed using a numerical procedure whereby a third order gaussian polynomial is fit to five consecutive data points and the derivative is evaluated analytically at the center point. However, it was found that the coordinate data contained enough noise that this procedure produced very noisy derivatives. Accordingly, the procedure was changed such that the third order polynomial was fit to points spaced ten measurement intervals apart. This procedure helped to smooth the data and gave more reliable derivatives. The resulting curvature data were still corrupted with noise, and before the springback calculation was made a polynomial of fifth order was fit to the loaded and unloaded curvature data to provide smoothing. This total procedure produced the curvature distributions shown in Fig. 6.

To calculate the springback, the curvature at identical arc lengths on the loaded and unloaded part must be known, therefore the arc length must be calculated for each calculated curvature. This was done by making a straight-line approximation between data points; thus

$$ds^2 = dx^2 + dy^2 \text{ and } s^2 = x^2 + y^2$$

From this curvature data the springback function $dK(K_1)$ can be found by subtracting values of unloaded from loaded curvature at identical locations on the part. A typical result is shown in Fig. 7. This springback curve shows the expected unity slope in the elastic region and clearly indicates the yield and strain hardening characteristics of the material.

Proposed Control Scheme

If we now assume that the springback function in Fig. 7 was generated on the actual workpiece being formed, it can then be used to determine the required overbend for the desired maximum or average curvature. This is accomplished by first extrapolating the springback relationship to the maximum expected curvature. The correct loaded curvature is then given by $K_1(s) = K_u(s) + dK(K_u(s))$, where $K_u(s)$ is the desired part curvature distribution. (This indicates that more useful expressions is springback as a function of unloaded curvature, which can be easily generated from the data of Fig. 7.)

However, since we are employing a three point bending geometry it is not possible to control a curvature distribution, rather we can only control a single variable (e.g., K_a or K_m). Thus the control scheme proposed here would use the entire springback-curvature relationship to determine the correct overbend for either of these conditions. In the former, the springback information would be used to generate an expected loaded curvature distribution from which the correct loaded average curvature would be found. In the latter, the springback information would be used to provide immediate calibration for the maximum loaded curvature. In either case, only one calibration bend would be necessary to provide accurate control over the local part curvature distribution.

Another consequence of the three point geometry is that the actual curvature distribution that results from a given K_a or K_m is unknown until the part is actually formed. Accordingly, the control system must continually update the plan of bends in both location and extent to account for the actual curvature distributions. This can be accomplished simply by using the present curvature distribution as the "best estimate" of the expected distribution on the next bend. Thus for a given desired part shape the next bend can be planned according to the optimization detailed earlier.

Conclusions

The process of sequential brakeforming or bumpforming is an inherently flexible means of forming sheet metal parts. The major drawback is the low production rate and limited accuracy of the process, caused mainly by the variability of material properties and geometry. The proposed control method would eliminate these variations and thereby allow the process to proceed without unnecessary manual iterations.

This enhanced capability should broaden the application of this process to encompass parts with variable curvature and to general ruled surfaces. In so doing, the process also will become useful in the automatic straightening of large castings and forgings, a task that now adds considerably to the production time of such parts.

The major problem with the proposed method is the need to measure the part curvature, which is an inherently noisy quantity. Our current research is concentrating on development of novel methods of such measurements, and Chen [8] describes one technique that involves the use of a mechanically sweeped linear diode array camera to provide highly accurate edge coordiante data from a low curvature ($K = 0.0023$ 1/cm) panel.

Acknowledgments

This research was supported by the National Aeronautics and Space Administration—George C. Marshall Space Flight Center, in cooperation with the Martin Marietta Aerospace Michoud Division Advanced Manufacturing Technologies group under contract AS-2950068. The authors also wish to acknowledge the assistance of Mr. Gary Drlik and the support of the Undergraduate Research Opportunities Program (UROP) at M.I.T.

References

1 Mergler, H. W., and Wright, D. K., "Self-Adaptive Computer Control of a Ship Frame Bending Machine, Part II," NSF/RA-760394, March, 1976.

2 Gossard, D. C., and Allison, B. T., "Adaptive Brakeforming," *Proc. 8th NAMRC*, 1980, pp. 252-256.

3 Stelson, K., and Gossard, D., "An Adaptive Pressbrake Control Using an Elastic-Plastic Material Model," ASME Journal of Engineering for Industry, Vol. 104, 1982, pp. 389-393.

4 Cook, G., Trostmann, and Hansen, N. E., "General Scheme for Automatic Control of Continuous Bending of Beams," *Measurement and Control for Batch Manufacturing*, D. E. Hardt (ed.), ASME, New York, 1982.

5 Hardt, D. E., Roberts, M. A., and Stelson, K. A., "Closed-Loop Control of a Roll Bending Process," ASME *Journal of Dynamic Systems, Measurement and Control*, Vol. 104, No. 4, 1982.

6 Hardt, D. E., and Webb, D. W., "Sheet Metal Forming Using Closed-Loop Shape Control," *Annals of CIRP*, Vol. 31, 1982.

7 Queener, C. A., and DeAngelis, R. J., "Elastic Springback and Residual Stresses in Sheet Metal Formed by Bending," *Trans. of ASM 61*, 1968, pp. 757-768.

8 Chen, B. S., "An In-Process Control Method for Sequential Brakeforming," S.M. thesis, Dept. of M. E., MIT, May 1984.