Pergamon

Int. J. Mach. Tools Manufact. Vol. 36, No. 4, pp. 423–434, 1996
Copyright © 1996 Elsevier Science Ltd
Printed in Great Britain. All rights reserved
0890–6955/96$15.00 + .00

0890–6955(95)00072-0

FINITE ELEMENT ANALYSIS AND OPTIMIZATION OF SPRINGBACK REDUCTION: THE "DOUBLE-BEND" TECHNIQUE

JAW-SHI SHU† and CHINGHUA HUNG†

(*Received* 4 *November* 1994; *in final form* 17 *July* 1995)

Abstract—According to the double-bend technique, springback can be reduced if the U-channel is unbent and bent again at a new site. Thus springback is a function of both the forming die gap and the plate opening. The purpose of this research is first to use the finite element method to analyze the relationship between springback and the forming variables, and then to combine an optmization technique with the finite element analysis to find the optimum forming parameters to reduce the springback. The solutions are compared with experimental data in the literature.

1. INTRODUCTION

1.1. *Springback*

Springback is a function of both material properties and die configuration; the greater the strength and the lower the elastic modulus of the material, and the larger the bend radius and die gap, the greater the springback will be [1]. For a given steel, the springback may be minimized by a proper die design, but it cannot be totally eliminated. Minimizing springback is one of the most troublesome problems in die design. If the springback cannot be predicted exactly, one may have to try repeatedly to obtain suitable forming parameters to compensate for the springback. Therefore, predicting springback is important when designing a die for a bending process.

1.2. *The "double-bend" technique*

The focus of this investigation is on the "double-bend" technique proposed by Liu [2]. The basic concept behind this technique is to bend the channel walls twice at different sites. As shown in Fig. 1(a), when a U-channel is bent at a site A, after unloading the channel walls become slanted and are not parallel. If the bend corner is now either compressed or pulled between two parallel blocks with a plate opening d, the blank will not resume its original flat shape; there is always a residual springback of θ', as shown in Fig. 1(b). If the blank is bent again into a U-channel at a site B, some distance away from the previous site A, the wall inclination or apparent springback will be $\theta-\theta'$, instead of θ, as shown in Fig. 1(c). Thus, a reduction in the wall inclination by an amount of θ' has been realized. In practice the distance between A and B will frequently be indistinguishable and B can be blended into the bend radius.

The double-bend technique has been used as the basis for many bending operations that have been proven experimentally to be effective in reducing springback [3]. Variation of the die width is a typical operation used with the double-bend technique. In this operation, two punches of slightly different width are employed; one punch is used to preform channels with slanted walls, and the other restrikes the walls to reduce the slant. The punch widths can be varied to perform two different processes: (1) restrike with a narrower punch (reducing); and (2) restrike with a wider punch (expanding).

---

†Department of Mechanical Engineering, National Chiao Tung University, Hsinchu, Taiwan.

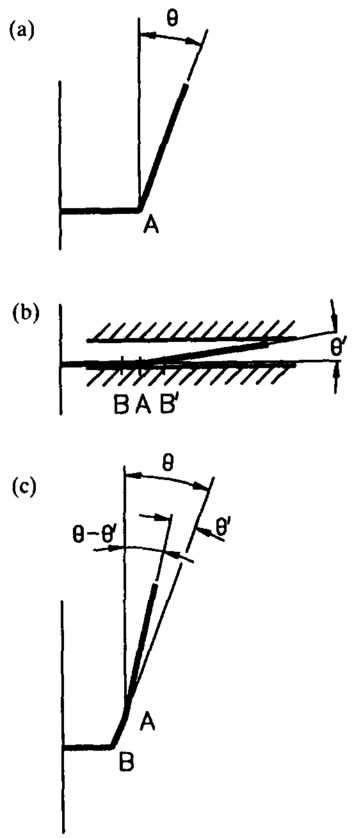

Fig. 1. Basic mechanism of the double-bend technique (refer to [2]).

In the first process, the second bending site is located at B, and site A has been moved to a vertical plane, as shown in Fig. 1(c). The plate opening referred to above is now the restrike die gap. The deformation mechanism is shown in Fig. 2(a).

In the second process, the second bending site is located at B′, and site A remains at the base of the channel, as shown in Fig. 1(b). The plate opening is now the gap

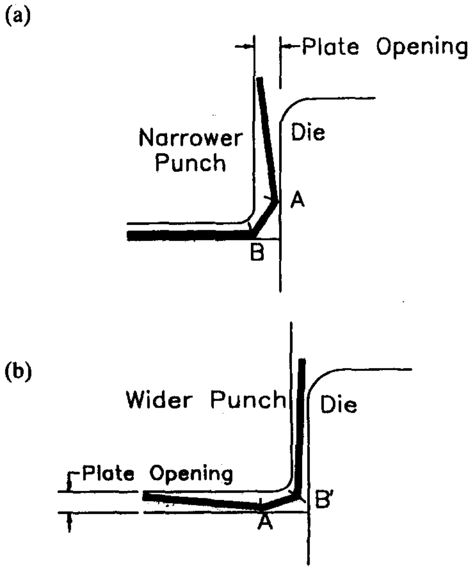

Fig. 2. (a) Plate opening in the reducing process. (b) Plate opening in the expanding process.

between the punch bottom and pressure pad. The deformation mechanism is shown in Fig. 2(b).

1.3. *Scope of the research*

The purpose of this research is to find an effective way to predict the optimum forming parameters and thus reduce the time and money wasted on trial-and-error in designing double-bend techniques. Since the finite element method and optimization techniques are effective, reliable modeling tools, we shall attempt to combine these methods to simplify and speed up the process of designing double-bend techniques and to reduce springback effectively. In this research, the two punch width variation processes described above are analyzed and compared with experimental results to test the validity of the proposed idea.

2. FINITE ELEMENT AND OPTIMIZATION CODE

Optimization techniques have been developed to the point where they can efficiently analyze problems with an explicit objective function by the optimization rules for a normal objective. However, in practical problems, the objective function (sometimes called the cost function) should be represented as a function of the relevant design variables. To meet this requirement, an optimization technique for implicit form problems must be developed. Recently, many software packages have been developed for solving complicated engineering problems. In this research we attempted to find the optimum forming parameters by using finite element analysis in conjunction with an optimization technique. The optimization program MOST [4] and the finite element program ABAQUS [5] were used to test the validity of this idea.

In this research, the optimization program MOST serves as the backbone of the analysis system. When executed, MOST will call the program ABAQUS to execute the analysis with the given forming parameters. It will then evaluate the objective function and constraint functions by calculating the output from ABAQUS. The objective function gradient that is found will then be used to determine the searching direction and step size and thus obtain the optimum solution. The entire process can be accomplished with the aid of a program to serve as an interface between MOST and ABAQUS. The overall structure of the optimum design program is shown in Fig. 3.

3. THE ANALYSIS PROCEDURE AND OPTIMUM DESIGN

3.1. *Dimensions and materials*

In order to compare the simulation results with existing test data, the materials used in the current investigation were HS110 and AKDQ (aluminum killed drawing quality) steel sheet, which are the materials used in [3]. The dimensions of the specimen and the dies are: blank size, 76 × 152 mm; material thickness, 0.8 mm; wider punch width, 29 mm; narrower punch width, 25.4 mm; corner radius of all punches, 3.18 mm; die entrance radius, 6.35 mm; and intended bending angle, 90°.

The high-strength steel HS110 was selected because it displays excessive springback after forming while the AKDQ steel was used for comparison.

3.2. *Preprocessing of finite element analysis*

3.2.1. *Mesh and boundary conditions.* The mesh and boundary conditions used in this simulation are represented in Fig. 4. In this problem, by assuming a plane-strain condition in the direction of width, we can reduce the 3D problem to a 2D problem, which simplifies the analysis greatly. Moreover, since the specimen is symmetric, this problem can be simulated using only half of the specimen. Along the symmetric line, displacement in the x-direction and rotation about the z-axis of these nodes are restricted. This simplifies the problem and facilitates the analysis without loss of accuracy.

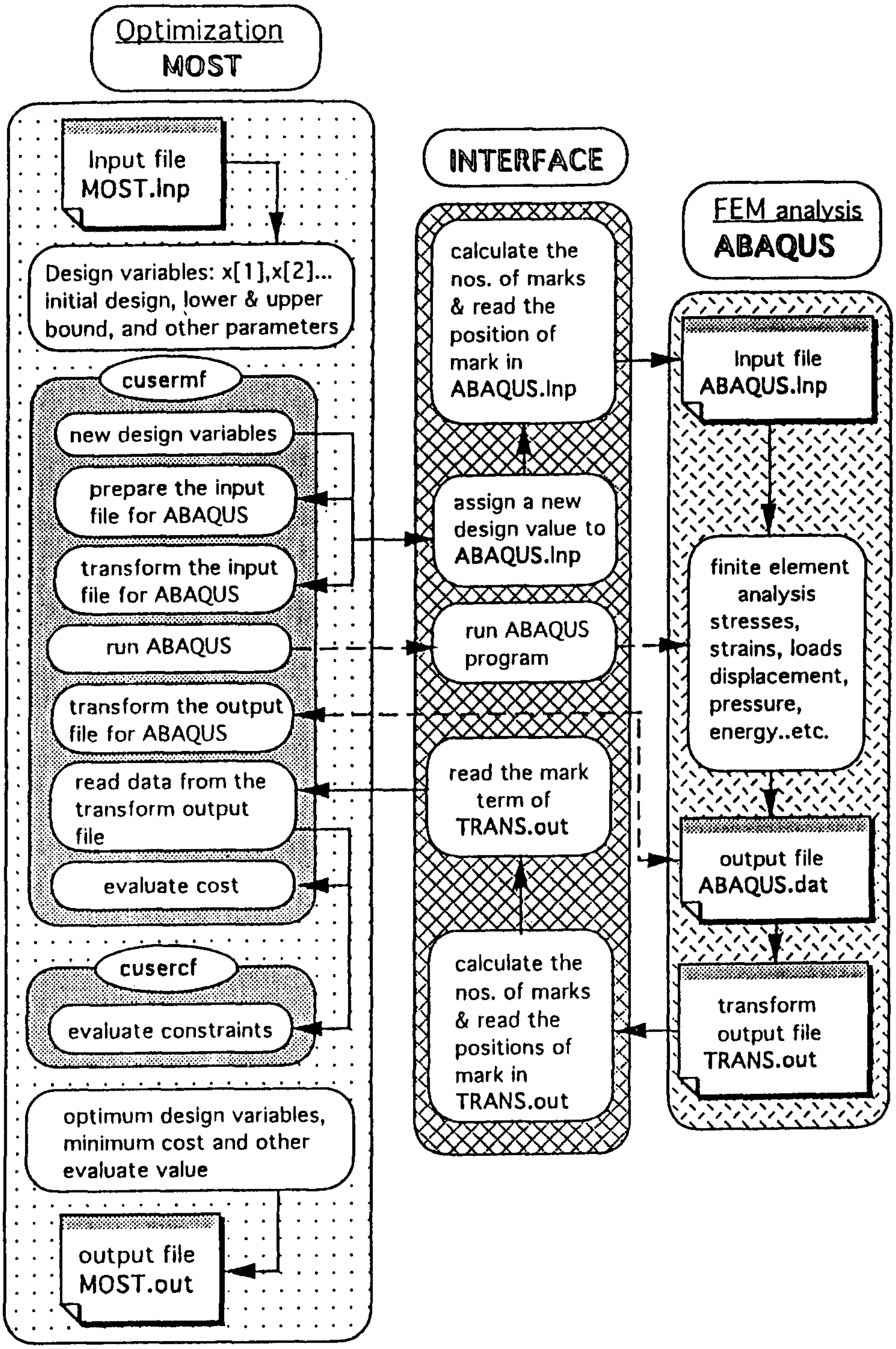

Fig. 3. Combination of optimization and finite element analysis.

3.2.2. *Element and hardening model.* The element type and the work hardening model related to the finite element model of this problem were selected as follows.

(1) Four-node bilinear, reduced integration, hourglass control solid element: in the plane strain condition, when the material is almost incompressible or becomes very thin, the over-constraining will occur. Hence the reduced integration method was adopted, and to avoid the zero energy mode hourglass control was necessary.

(2) Isotropic hardening: this is a widely adopted model that predicts purely elastic

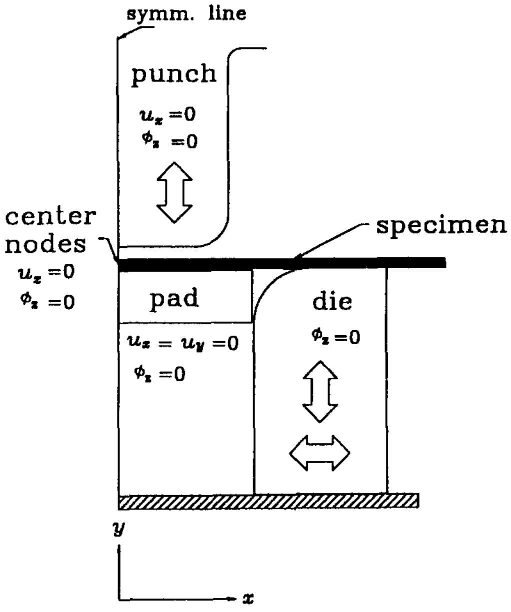

Fig. 4. Mesh and boundary conditions.

springback. According to this model, the yield surface expands isotropically in deviatoric stress space during plastic deformation. Although it is well known that the isotropic hardening model is insufficient for modeling the Bauschinger effect, it is simple to employ and serves as a good approximation when reversed loading occurs to only a limited extent, as in the cases under consideration here.

3.3. *Description of the optimization problem for MOST*

The four subroutines that describe the design problems are: (1) the objective function evaluation subroutine; (2) the constraint functions evaluation subroutine; (3) the gradients of objective function evaluation subroutine; and (4) the gradients of active constraint functions evaluation subroutine. To find the optimum design of a non-linear problem such as ours, the user does not program the gradient expression in subroutines (3) and (4). Instead, the program will be set to calculate automatically the gradients using either forward, backward, or central finite differences. The objective function, design variables, and constraints, will be described below.

3.3.1. *Objective function.* The optimum design must satisfy one of two important criteria. First, it must significantly reduce springback in the double-bend technique. To achieve this aim, we shall adopt the following objective function, which is the wall inclination or the apparent springback

$$f = \theta - \theta', \tag{1}$$

where θ is the springback angle in the restrike process and θ' is the residual springback on the first bending site after the restrike operation.

The second criterion is that, with the assistance of the optimization technique, the optimum design must provide optimum forming parameters so that the resultant angle is close enough to the intended angle. To achieve this aim, we adopt the following the objective function:

$$f = \theta - \theta', f \geq 0, \tag{2}$$

where f is the apparent springback. $f \geq 0$ is employed in order to prevent the springback from being overcorrected, resulting in a "toe-in" configuration. In practice, only

$f = \theta - \theta'$ is written in the objective function subroutine; $f \geq 0$ is regarded as a constraint function.

3.3.2. *Design variables*. The major effective factors in the double-bend technique are the bending die gap and the plate opening. If only the restrike operation is taken into account, the design variables in the reducing process are combined into the restrike die gap, but in the expanding process, they are the restrike die gap and the bottom die gap.

3.3.3. *Constraints*. In order to avoid fractures on the bending sites, we stipulate that the effective plastic strain and effective stress of the elements around the bending sites must be less than the safe value for each kind of material.

3.3.4. *Other preset parameters*. There are parameters that must be set before the simulation of optimization processes. Typical values for these parameters are: increment of the design variables, 0.01; tolerance for the convergence check of objective function, 1×10^{-3}; and tolerance for the constraints, 1×10^{-3}.

After all values are specified in the input file, the optimization process will be executed automatically until converge solutions are found.

4. RESULTS AND DISCUSSION

4.1. *Results of finite element analysis on the double-bend technique*

The results of the simulation completed by ABAQUS (without optimization) for the two processes in the "punch width variation" operation are given in the following sections.

4.1.1. *Restrike with a narrower punch (reducing process)*. Figure 5 depicts the effects of the restrike die gap on springback when the preform die gap was kept at 1.25 mm. In the HS110 material, the analytical results show that springback decreases initially with increasing die gap and reaches a minimum at a die gap of approximately 1.5 mm. The trend is then reversed with further increases in the die gap. These trends are consistent with the experimental data. The numerical predicted springback is larger than that found experimentally, and it tends to reach a maximum value that is not observed in the experimental results.

In the AKDQ material, the trend is the same as in the HS110 case, but the deviation is smaller, especially at the points around the minimum springback setting, which is approximately half the difference in the widths of the two punches.

The observed initial decrease in springback with the increase in the die gap can be attributed to the continuous increase in residual springback, θ'. After reaching the local minimum value, the increasing die gap is no longer effective to perform a significant second bending; thus overall springback increases.

4.1.2. *Restrike with a wider punch (expanding process)*. As stated in section 1, two factors affect the springback in the expanding process. The effect on springback of each individual factor is discussed below.

(1) Variation in restrike die gap (d): Fig. 6 shows the observed springback of the two specimens as a function of the restrike die gap, while the bottom die gap was kept at a constant value of 0 mm using a simple flat-top pressure pad. In both materials, the springback seems to increase in proportion to the increase in restrike die gap. The analysis results for both materials agree very well with the experimental results, especially in the region where the restrike die gap is less than 1.5 mm. The deviation seems to increase slightly once the die gap exceeds this value.

(2) Variation in bottom die gap (d_B): Fig. 7 shows the springback as a function of d_B at the two restrike die gaps, $d = 0.9$ mm and $d = 1.25$ mm. As d_B approaches 0.75–1.0 mm, which is about the thickness of the sheet, springback seems to remain unaffected, and it then decreases with increasing d_B. After d_B reaches 1.5 mm for HS110 steel and 2.0 mm for AKDQ steel, a further increase in d_B has no effect on the springback of the channel.

In both materials, the two curves ($d = 0.9$ mm and $d = 1.25$ mm) generated by simulation are very similar in configuration. The constant difference between the two

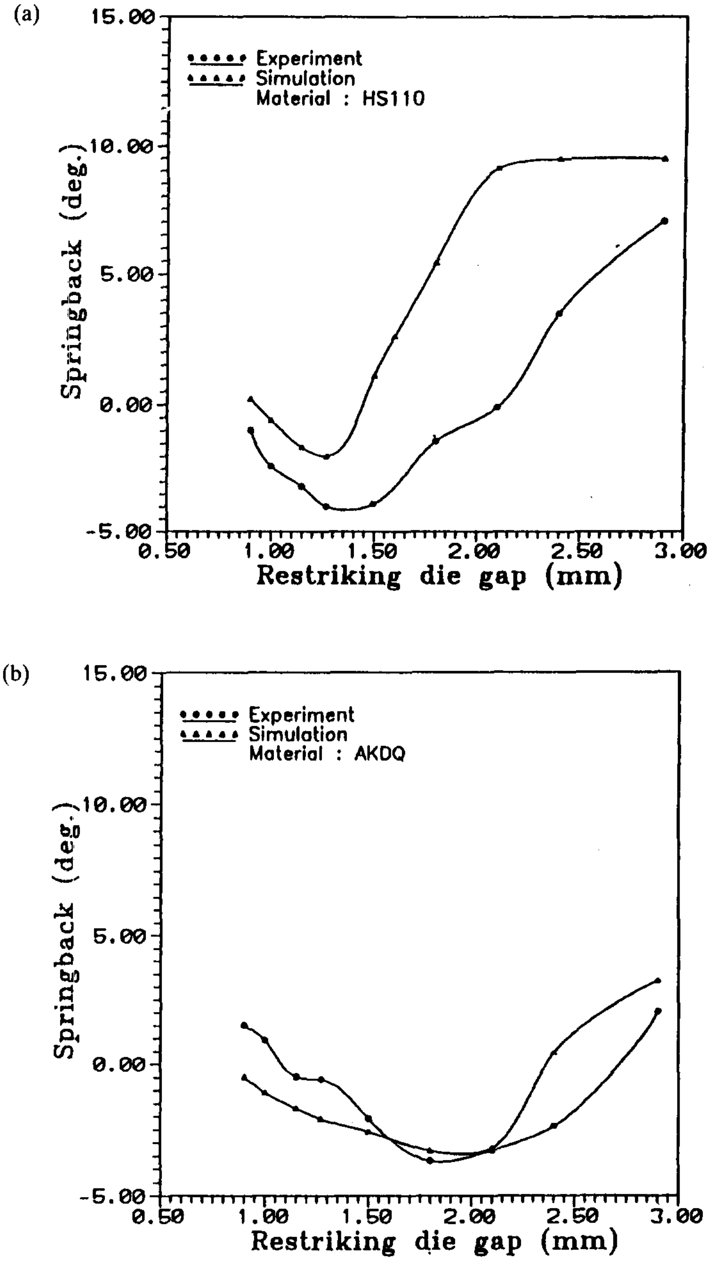

Fig. 5. Effect of restrike die gap on springback using a narrow punch.

lines can be attributed to the different θ, which was formed by the different restrike die gap. In the HS110 material, for d = 1.25 mm, the analysis results are very close to the experimental results with a maximum error of 0.5°, just before the bottom die gap reaches 2.0 mm. For d = 0.9 mm, the agreement between simulation and experiment is also good, but with a little larger deviation.

In the AKDQ material, for both die gaps, the results of the finite element analysis are very accurate, with a maximum error of about 0.6°, except at d_B = 1.52 mm. The obvious decrease in springback seems to occur earlier than that in the experimental work.

4.2. *Results of optimization*

The dependence of springback on the forming parameters was shown in the last section. The results of optimization for two objective functions obtained by the combination of MOST and ABAQUS will be summarized in this section.

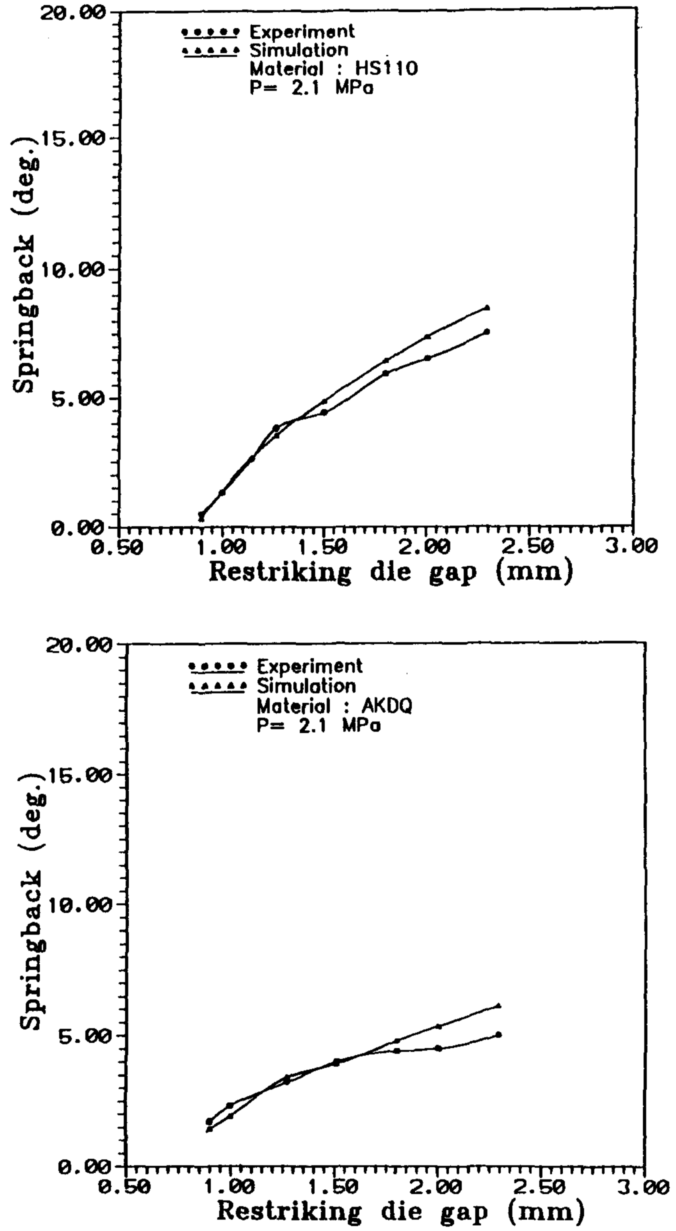

Fig. 6. Restrike with a wider punch.

4.2.1. *Design for minimizing springback.* For this objective, the purpose of the optimization is to find the minimum point on the springback-forming parameter curve. The result for both processes will be described below.

(1) Reducing process: the design variable in the reducing process is the restrike die gap. The common constraint in the following designs is that the maximum effective stress must be less than 500 MPa for AKDQ and 800 MPa for HS110, unless noted otherwise. The MOST results indicate that the springback can be reduced to −2° for HS110 by a restrike die gap of 1.26 mm, and to −3.26° for AKDQ by a restrike die gap of 1.795 mm.

Take the case of the AKDQ material as an example. Figure 8 shows the search path of the optimum design. In comparison with Fig. 5(b), the optimum setting found by MOST is located at the local minimum of the simulated curve, generated by using ABAQUS only. Thus this is a successful example of optimum design using the combination of MOST and ABAQUS.

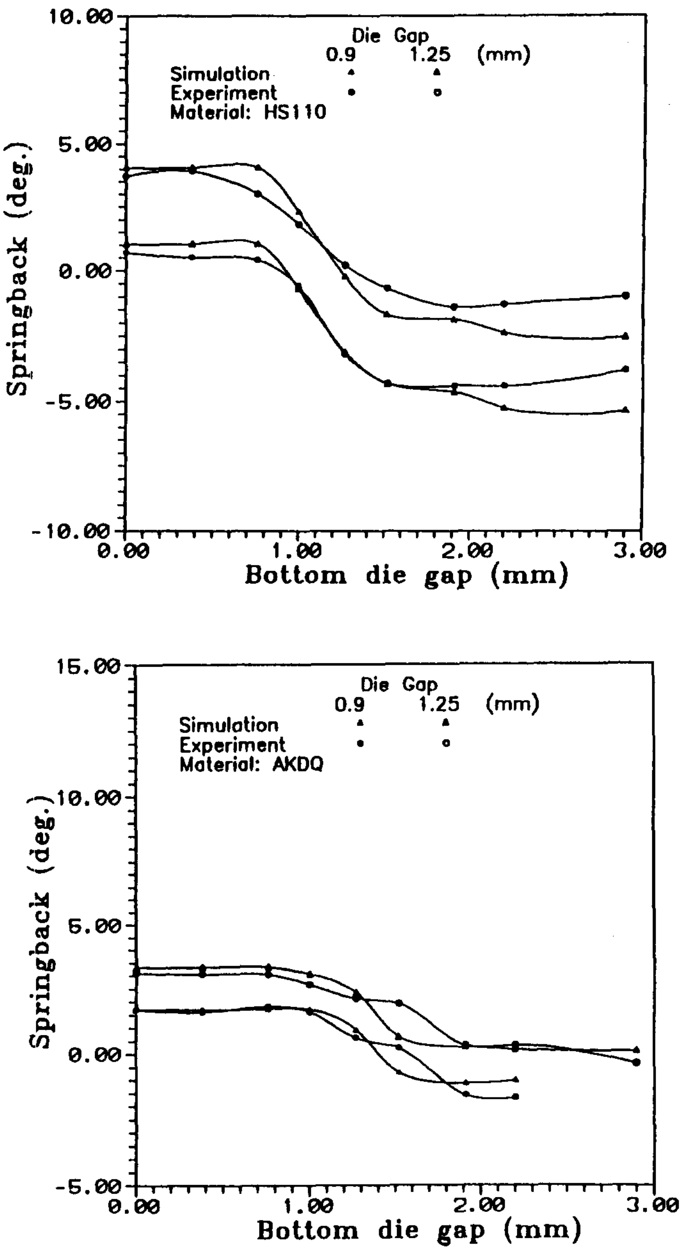

Fig. 7. Effect of bottom die gap on springback in U-channels.

(2) Expanding process: in this design, only the restrike die gap was selected as the design variable in order to explore how it affects springback. In this case, for both materials, the optimum solution is located at the lower limit of the design variable. The minimum springback is 0.327° for HS110 and 1.413° for AKDQ. If we compare these values with Fig. 6, the final designs agree well with the results introduced in section 4.2.2. Clearly, however, the springback cannot be completely corrected; that is, the expanding process does not reduce springback effectively when only the restrike die gap is varied.

4.2.2. *Design for correcting springback.* The aim of research on springback is to find forming parameters that will yield the intended bending angle. In the following cases, by adding a constraint ($f \geq 0$) into the constraint function subroutine, we achieve this aim using the same problem models as those used in section 4.3.1 to minimize the springback.

(1) Reducing process: Fig. 9 shows the search path during the optimization process

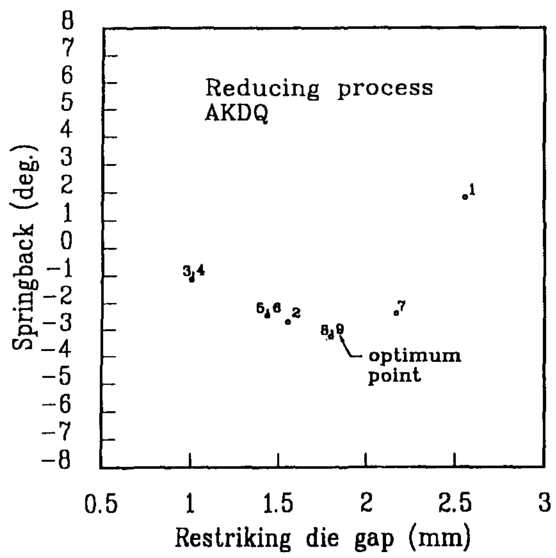

Fig. 8. Search path of optimum design for minimizing springback.

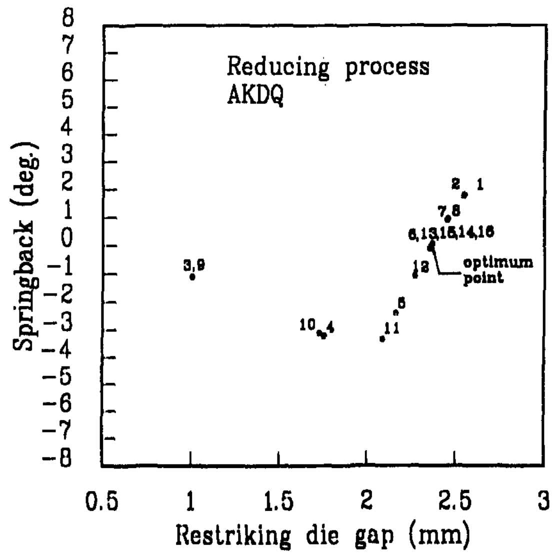

Fig. 9. Search path of optimum design for correcting springback.

for correcting springback. The results of MOST were that the predictive restrike die gap for minimizing the deviation from the intended angle is 1.428 mm for HS110 and 2.326 mm for AKDQ and the corresponding springback is -5.25×10^{-4} and 3.134×10^{-3}, respectively. Although the springback in the final design for the HS110 material violates the constraint that f must be greater than zero, the magnitude -5.25×10^{-4} is within the range of acceptable violation of the constraint and thus can be an optimum solution.

(2) Expanding process with both design variables: as shown in section 4.3.1, the springback cannot be corrected completely by varying only the restrike die gap in the expanding process. Thus for the expanding process both the restrike die gap and the bottom die gap were selected as design variables. A new constraint—that the effective plastic strain must be less than 0.2 for HS110 and 0.3 for AKDQ—was adopted, in order to avoid tensile fracture on the bend corner.

In the final design for HS110, the restrike die gap, d, was 1.71 mm and the bottom die gap, d_B, was 2.89 mm at the optimum point, where springback was $1.03 \times 10^{-7\circ}$.

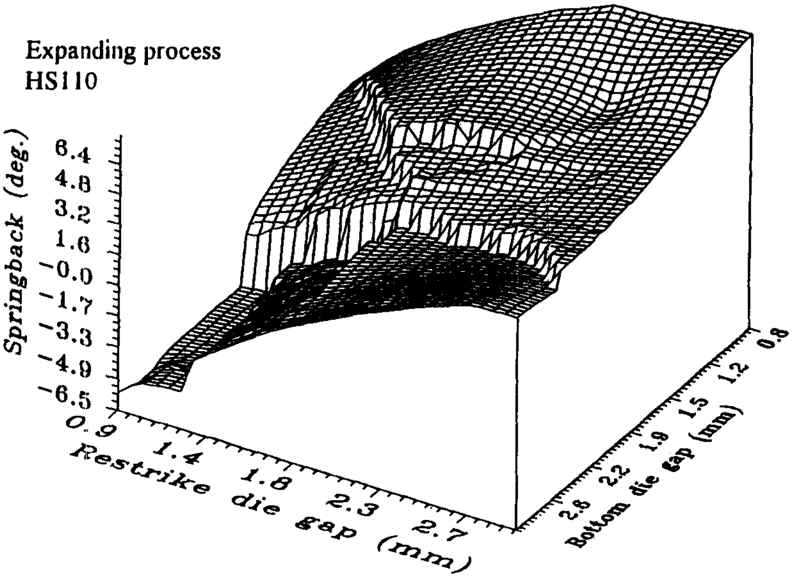

Fig. 10. Contour of springback against bottom die gap and restrike die gap (HS110).

For AKDQ material, the optimum forming parameters were $d = 1.68$ mm and $d_B = 2.90$ mm, and the resulting springback was $1.03 \times 10^{-7\circ}$, which is very close to zero.

Figure 10 and Fig. 11 show the contour of springback against the bottom die gap d_B and restrike die gap d for HS110 and AKDQ, respectively. Because of insufficient numerical data the contour surface is rough. Still, it is clear that minimum springback occurs at maximum d_B and minimum d, and that there is a critical region where springback seems to be very sensitive to d_B and d.

4.3. *Discussion*

In this research, the finite element analysis was shown to be accurate in solving springback problems for most forming situations. The simulation results showed good agreement with experimental results not only in the single U-bend operation but also in the double-bend cases. However, for the HS110 material, the simulation results

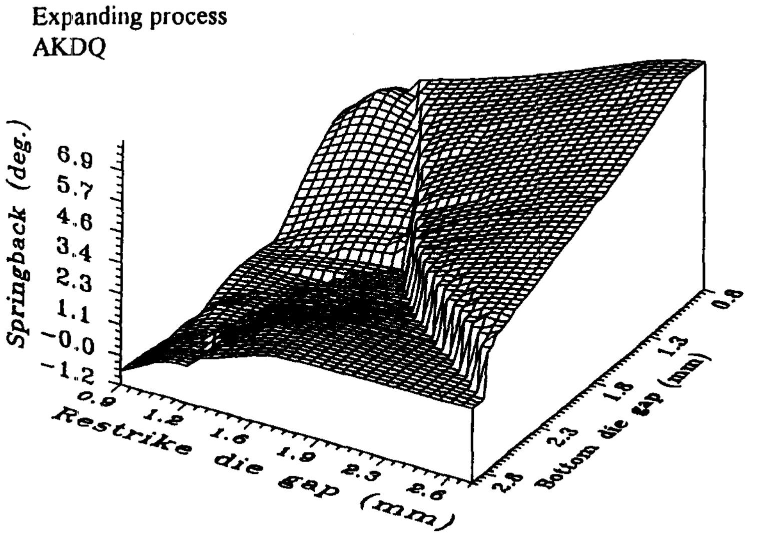

Fig. 11. Contour of springback against bottom die gap and restrike die gap (AKDQ).

show slightly larger deviation in some forming situations, and this deviation is significant in cases with springback of relatively large magnitude.

It is well known that the Bauschinger effect is important and cannot be indiscriminately ignored in plastic deformation processes where there are different strains and reversal of stresses, as in unloading during a bending operation [6–8]. Nevertheless, in the preprocessing stage of the finite element analysis, none of the three models (perfectly plastic, kinematic hardening, and isotropic hardening [9]) provided in ABAQUS considers the Bauschinger effect. We believe this is one of the main factors that influence the accuracy of the springback prediction. Therefore, if the material model which describes the stress–strain relationship during both loading and unloading (the work-hardening model) can be made more complete, an improvement in accuracy in springback prediction can be expected. This hypothesis could be explored by using the user subroutine capability provided in ABAQUS.

In multi-design-variable optimizations, more than one optimal point sometimes exist. In our problem, because the increment of design variables must be preset, only finite numbers of design variables were tested. This fact together with stress and strain constraints resulted in a unique optimal design point, as shown in our results.

5. CONCLUSIONS

The main conclusions of this research are as follows.

(1) The finite element analysis solves springback prediction problems for the double-bend technique accurately for most forming situations. Therefore, the predicted springback may be used as a reference in the design of a die for use with the double-bend technique.

(2) A quantitative improvement in springback prediction can be expected if a more precise work-hardening model for unloading behavior is developed.

(3) The success of the proposed method in minimizing the magnitude of springback has proved the feasibility of solving metal-forming optimization problems by using a combination of MOST and ABAQUS. The proposed technique can help us to design proper double-bend dies to obtain the intended angle efficiently.

Acknowledgements—The authors would like to thank the National Science Council of R.O.C. for grant NSC84-2212-E-009-017, under which the investigation was possible. The authors would also like to thank Prof. C. H. Tseng for offering the optimization code.

REFERENCES

[1] N. M. Wang, Efficiency in sheet metal forming, *Proc. 13th Biennial Congress IDDRG*, Melbourne, Australia (1984).
[2] Y. C. Liu, U.S. Patent No. 4,373371, February (1983).
[3] Y. C. Liu, Springback reduction in U-channel-"Double-Bend" Technique, *J. Appl. Metalworking* **3**, 148–156 (1984).
[4] C. H. Tseng, W. C. Liao and T. Yang, MOST User's Manual Version 1.0, Technical Report No. AODL-91-01, National Chiao Tung University (1991).
[5] Hibbitt, Krlsson & Sorensen, Inc., ABAQUS Manual (1993).
[6] C. C. Chu, Elastic–plastic springback of sheet metals subjected to complex plane strain bending histories, *Int. J. Solids Structures* **22**, 1071–1081 (1986).
[7] C. C. Chu, A three-dimensional model of anisotropic hardening in metals and its application to the analysis of sheet metal formability, *J. Mech. Phys. Solids*, **32**, 197 (1984).
[8] R. G. Davies and Y. C. Liu, Control of springback in a flanging operation, *J. Appl. Metalworking* **3**, 142–147 (1984).
[9] R. Hill, *The Mathematical Theory of Plasticity*. Oxford University Press, London (1950).