THREE-DIMENSIONAL SIMULATION OF CLOSED-DIE FORGING PROCESS USING MSC/DYNA

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ABSTRACT

A three-dimensional, elastic-plastic finite element model using MSC/DYNA was used to simulate a closed-die forging process. An H-shaped cross-section forging die and a rectangular billet were modelled. Die/billet interface contact friction, and die geometry were varied to determine the effects of these variables on material flow, strain, and die force.

INTRODUCTION

In metal forging, a billet of material is plastically deformed by dies into another, more complex, shape in a very short time. The dies which are used determine the final geometric configuration of the forging. The ideal forging die design will produce a near net-shape forging. The final forging geometry may require more than one die to achieve the desired end shape due to material flow limitations.

The conventional method of forging die design has been to utilize past experience and empirical formulas as the design basis. Thus, the development of these dies has been part art and part science. If a design is an entirely new configuration, it may take several attempts to determine an acceptable die and billet configuration, which may or may not be optimized to minimize flash, internal voids, or other material irregularities. This conventional process is very costly due to the manhours required and the material waste created from attempts to manufacture an acceptable forging. In addition, the empirical approach does not predict internal material strains for complex components, which are important in predicting failure during the forging process.

During the last decade, research has been performed in the area of using finite element analysis (FEA) for simulation of metal forming operations, including forgings [1]. Recent advances in finite element analysis methods, and computer hardware and software developments make it feasible to use finite element analysis to simulate the forging process in order to predict the final forging configuration. Most research has been performed using special purpose FEA codes developed especially for metal forming simulations. These special purpose codes are expensive to purchase. Unless forging design and analysis are the primary tasks performed by a company, it is much more desirable to use a general purpose finite element code for forging simulation. The finite element approach for die design provides a means of predicting final component shape and internal stress and strain state, without the material and labor costs associated with a trial and error manufacturing technique. Three-dimensional analysis allows the prediction of material flow in all directions. Parameters such as die geometry, friction constants, and material properties are easily varied to determine the sensitivities associated with these parameters, thus producing an optimized, rather than just marginal, design.

OBJECTIVES

The objective of this study was to investigate the phenomenon of die filling in the forging process. Three-dimensional finite element analysis, using MSC/DYNA, was used to simulate the forging process. Die geometry and contact friction characteristics were varied to determine their effects on material flow. An H-shaped die and rectangular parallelepiped billet were modelled with the objective of producing a fully-filled die and flashless forging.

The die shape chosen for the forging model was H-shaped in cross-section. This shape was chosen because it contained sharp corners around which material flow can be studied, yet it is a fairly simple geometry that has wide applications. The H-shaped die was modelled both with a 90° corner on the inside corner and with a radius of 0.25 inch on this same corner to investigate material flow around corners. Friction was varied in order to study the effects of this variable on the billet material flow pattern as well as the strain state of the billet.

METHODS

The models consisted of an H-shape cross-section die and rectangular billet. Contact elements were constructed on all exterior surfaces of the billet, except for the bottom surface, and all inner surfaces of the top die. These contact elements were constructed between the die and billet surfaces to prevent penetration between the billet and die surfaces. These elements were modelled as thin shell elements, and were interpreted by MSC/DYNA as surface contact elements. Contact elements were on the inside surfaces of the die and utilized the bottom nodes of the die. Contact elements were also on the outer surfaces of the billet.

The upper die represented a closed die. The die was modelled with rigid material properties ("MATRIG" card in MSC/DYNA) and the billet was modelled with an elastic/plastic material ("DYMAT12" card in MSC/DYNA) [2]. The front and rear surfaces of the die were not explicitly modelled, but were simulated by boundary conditions. Nodes on the front of the billet were constrained from moving past the plane of the front of the upper die, thus representing the front closure. The constraints were incorporated by a "WALL" card in MSC/DYNA, which acts similarly to a contact surface. The same coefficient of friction was applied to the wall/billet interface as the other contact surfaces. Only one-eighth of the die and billet were modelled due to the fact that the rear, inside, and bottom surfaces of the billet represented planes of symmetry. The planes of symmetry were simulated by using nodal restraints which did not allow the nodes to move across the plane of symmetry. The volume of the cavity of the die was the same volume as the billet, the goal being that when the die was completely closed, the billet material would completely fill the die cavity.

The top die was moved downward over the billet with a constant imposed velocity of 760 in/sec. This magnitude velocity was chosen rather than a more typical value one-half of its magnitude in order to decrease the computer run time of the analysis for this large model.

The material model for the billet was that of an isotropic elastoplastic material with a bilinear stress-strain curve. This model incorporates isotropic hardening where the cylindrical yield surface expands as the material yields. The Young's modulus, yield stress, and the hardening modulus were specified. The stress calculated by MSC/DYNA uses the equation

$$\sigma = \sigma_y + E_p{}^* \epsilon_p \text{ where}$$

E_p, the plastic modulus is defined as:

$$E_p = E * E_h/(E\text{-}E_h)$$

and E_h is the hardening modulus.

The billet was positioned relative to the die cavity in such a manner as to allow flow of the billet material within the die cavity in all three directions. This produced a three-dimensional flow pattern. The material flow of the billet material was studied as it filled the die.

The value of the friction coefficient between the die and billet surfaces was maintained as a constant, present whenever a contact surface of the die touched the contact surface of the billet.

For the first model, the 90° corner die model, a 1 inch x 1.4 inch x 1.607 inch rectangular billet consisted of 1670 solid ("CHEXA") elements beneath an H-shaped cross section upper die. Figure 1 shows this model. A friction coefficient, m, of 0.5 was used for the contact surfaces between the die and billet. This friction coefficient was considered appropriate for the modelling of a typical lubricant at the die/billet interface [3]. The material properties modelled were:

$E = 10. \times 10^6$ psi (modulus of elasticity)

$E_h = 10. \times 10^3$ psi (hardening modulus)

$\nu = .33$ (Poisson's ratio)

$\rho = 2.64 \times 10^{-4}$ lb-sec^2/in (mass density)

$\sigma_y = 90{,}000$ psi (yield stress)

A second die model was constructed, similar to the previously described H-shaped forging model. Instead of a sharp 90° corner at the inboard edge of the H-shaped die cavity, a radius of 0.25 inches existed at the inside corner of the die (See Figure 2). Three values of the friction coefficient were used. The friction coefficient values used were 0.0 (no friction), 0.5, and 1.0 (sticking friction). Material flow was compared with the previous 90° corner model, for the case of 0.5 friction coefficient, and observations were made for the three values of friction coefficient. The volume of the billet was increased slightly from that of the 90° corner model in order to match that of the die.

RESULTS

The process of the deformation of the billet for the 90° die corner and a friction coefficient of 0.5 is shown in Figure 3. For this model, it was noted that at a die displacement of 0.7 inches, the billet corner reached the top of the die cavity. There was still a large amount of unfilled die area on the near and far sides of the cavity. The billet material began to bow out on both sides of the point of contact with the die. At a die displacement of 0.9 inches, the billet material had flowed so that it reached the far side of the die wall. The bowing of the billet material was more severe at this point. At the closure of the die at 1.12 inches, an S-shaped region on the near side of the die and a triangular region of the right side was left unfilled.

The final deformed shape of the billet revealed that some penetration occurred. This is a common problem for contact surface algorithms in the vicinity of sharp corners, and suggests that the mesh should be more refined in order to reduce or eliminate penetration. If the penetration of the elements did not occur, it could be seen where this billet material would flow. In addition, for this forging simulation, the billet material is restricted from moving past the plane of the far side die wall. Without this restriction, starting from a die displacement of 0.9 inch, some material would flow past the die, indicating that flash would form.

Studying the die filling in the x-direction (depth direction) revealed that there was a barreling effect of the billet material flow in this direction due to the friction between the die and billet; there was a lag in material flow between the bottom and top of the billet. In addition, at any y-z planar cut, the material at the top corners of the billet deformed more in the x-direction than the material between the corners. At the final closure of the die, the billet material at the top of the "H" had not fully filled the die in the x-direction. Again, some penetration of the die and billet elements occurred, explaining why the die is not completely filled in the x-direction.

Figure 4 shows the deformation of the billet as the die displaces to its final closure when the friction coefficient is 0.5 and the inside corner of the die has a radius of 0.25 inch. The flow of material for the die model with the radiused corner and a friction coefficient of 0.5 was similar to the unradiused case, but the flow more closely followed the contour of the die than in the unradiused case. At a die displacement of 0.9 inch, on the near side of the die, all but a triangular area was filled. The flow of material at the top of the die was more spread out than in the previous 90° case.

At the end of the die motion for the radiused die case, the near side of the die was filled except for a small triangular area. The far side was filled except for a slightly larger triangular area. Some penetration of the die and billet contact surfaces occurred, as in the unradiused case, accounting for unfilled volume. The die volume was filled slightly more for the radiused case than the unradiused case.

Trends in material flow in the x-direction were similar to the unradiused case for the case where the friction coefficient was 0.5. Greater material flow occurred at the billet bottom as compared to the top of the billet, the material in the top corners of the billet deformed more in the x-direction than the material between the corners, and there was incomplete filling of the die at the top of the "H" portion of the die at the end of the die stroke.

Using a value of 1.0 for the friction coefficient and a radius of 0.25 inches resulted in slightly less die filling than when the friction coefficient was 0.5. Figure 5 depicts the die filling in the yz-plane for this sticking friction case. Trends in material flow in all three directions are similar to the model using a friction coefficient of 0.5. A greater flow of material in the x-direction at the corners was more localized around the corners than when the coefficient was 0.5. There was incomplete filling in the x-direction at the top of the billet, as with the friction coefficient of 0.5.

When no friction was present, the billet material flow did not follow the contour of the radiused corner very well. Figure 6 shows the billet deformation for this case. At a die displacement of 0.3 inches, the billet's curvature followed that of the radius, but at 0.7 inch displacement, it was seen that the billet material flowed to the maximum height of the die H-shape, leaving a large gap in the near corner. For the remainder of the die stroke the billet material continued to flow in the yz-plane (height and width direction). At the die closure the far side corner was nearly filled, but the near side corner remained unfilled. The material constraints limiting the billet from moving past the far side die wall prevented the model from indicating that flash would occur starting at 0.9 inch displacement, this point in time being the time that the billet reached the far wall.

Billet material flow in the x-direction was generally uniform from top to bottom for the case with no friction. The exception to this was that the material at the top of the billet in the large cross-section of the H-shape did not quite fill the die cavity in the x-direction, whereas the lower portion of this section did fill the cavity. Again, some penetration of the die and billet occurred, resulting in some unfilled areas of the die.

Strains were studied in order to obtain data related to the likelihood of fracture of the billet material during the forging process. Some plots of maximum principal plastic strain were made to indicate magnitudes of plastic strain at various die displacements for the various models.

Figure 7 shows the isostrain contours for the billet with the sharp corner and a friction coefficient of 0.5 when the die is close to the end of its stroke. The highest strains are at the inside sharp corner, indicating that this is the area of the billet most likely to tear due to excessive strains. The lowest strains are in the two unfilled upper corners and in the top inside section of the billet. The strains are not uniform in the height nor width directions.

The overall trends in the strain condition for the radiused case when the friction coefficient equalled 0.5 are similar to the 90° corner case, though the magnitudes of the strain are lower for the radiused corner case. The strains are highest at the inside corner and lowest in the upper unfilled corners. Strains when the friction coefficient equalled 1.0 were slightly higher (5% - 10%) than when it equalled 0.5 and followed the same distribution pattern. Figures 8 and 9 show the strains with the friction coefficient set at 0.5 and 1.0, respectively, when the die is approximately at the end of the stroke.

When no friction existed between the die and billet, the isostrains were very different than when friction was present. The strains were highest in the radiused corner, but were not lowest in the two unfilled corners. Instead, the strains were lowest along the far side of the billet. The strains in the upper inside corner of the die were much higher than the friction cases. In addition, the strain gradients were much smaller when no friction existed (See Figure 10). This is due to the fact that when no friction existed, this inside corner of the billet material hit the top of the die and was deformed by the die from approximately 0.9 inch displacement onward. This corner of the billet is not physically located in the corner of the die. With friction, once the billet material reaches the inside corner of the die, it does not continue to deform as much as the center of the "H" portion of the billet as the die travels downward.

A comparison was made among the models as to the die force necessary to move a specific distance. The total forces were plotted for various displacements for all of the models described. These results are shown in Figure 11. All of the models showed an increased force at 0.2 inch, a fairly steady force between 0.2 inch and 0.9 inch, then a significant increase in force at from 0.9 inch to 1.1 inch (approximate end of analysis). The highest increase in force was for the 90° sharp corner case, followed by the case of the radiused corner with the friction coefficient equalling 1.0, then 0.5, then 0.0. The die displacement of 0.2 inch corresponded to the time at which the billet material flowed around the die corner, thus more billet material was in contact with the die and being deformed than at 0.1 inch. The 0.9 inch displacement corresponded to the billet material reaching the far side of the die. This is a transition point where significantly more billet material was being deformed by the die. This event occurred at the same time for all cases since in the model the bottom of the billet was not a friction surface, but a plane of symmetry. Therefore, the flow of the billet material on this plane was constant for all models using the same material.

SUMMARY AND CONCLUSIONS

When some amount of friction exists between the billet and die with an H-shape geometry, a radius on the lower inside corner of the die guides the flow of material around this corner, creating more die filling in the upper inside corner than if a 90° corner exists. This radius had minor effects on the filling of the upper outside corner of the die. Friction coefficients of 0.5 and 1.0 appeared to make little difference in the filling of the upper inside and outside die corners.

The lack of any friction between the die and billet causes the billet material to slide past the inside corner until the billet makes contact with the outside die wall, so that a significant unfilled volume remains in the upper inside corner. However, the filling of the upper outside corner of the die was increased when no friction was applied.

The presence of a radius for the H-shape die geometry decreased the press loads required for complete die closure. In addition, the lower the value of the friction coefficient, the lower the press load. The radiused die with no friction between the die and billet required the lowest press load.

The highest strains at die closure for all H-shape models occurred at the location on the billet where the 90° corner or 0.25 inch radius made contact with the billet. This is the predicted location of any failure of the forging due to excessive strains. The addition of the radius lowered the strain magnitudes, as did the lack of friction between the die and billet.

MSC/DYNA is a useful tool in modelling the forging process and was demonstrated to be effective in qualitative evaluation of the forging process. Three-dimensional effects can easily by considered. However, for a quantitative evaluation of the die filling process, it is important that penetration of the die and billet elements is minimized. In addition, the mesh must be fine enough, especially around corners or where gross deformations occur, so that the elements representing the billet material are small enough to fill corners, etc., without large distortions of the finite elements.

REFERENCES

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[2] MSC/DYNA User's Manual, Version 3, The MacNeal-Schwendler Corporation, Los Angeles, California, August 1992.

[3] Altan, T., Oh, S., and Geel, H.L., Metal Forming Fundamentals and Applications, American Society of Metals, 1983.

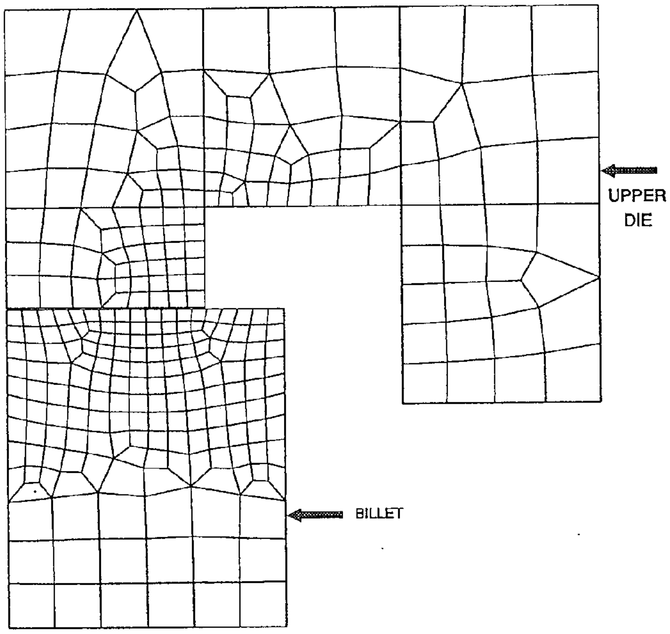

Figure 1 - H-Cross Section Die, 90° Corner

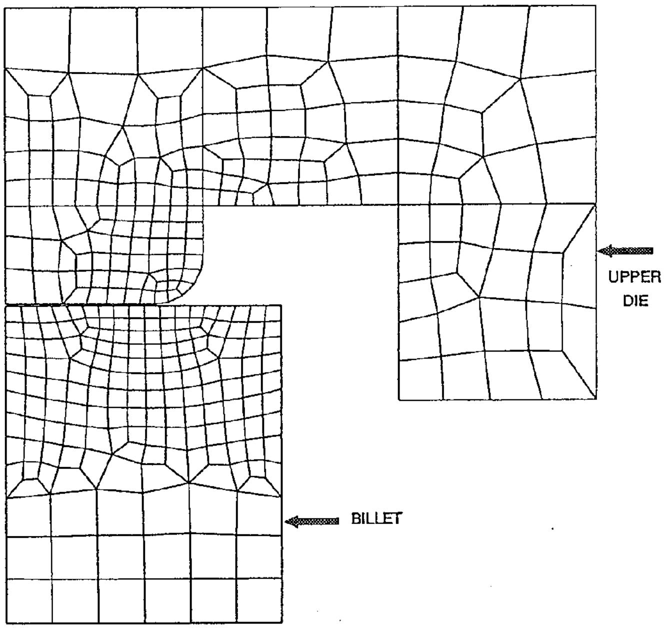

Figure 2 - H-Cross Section Die, 0.25 inch Radius

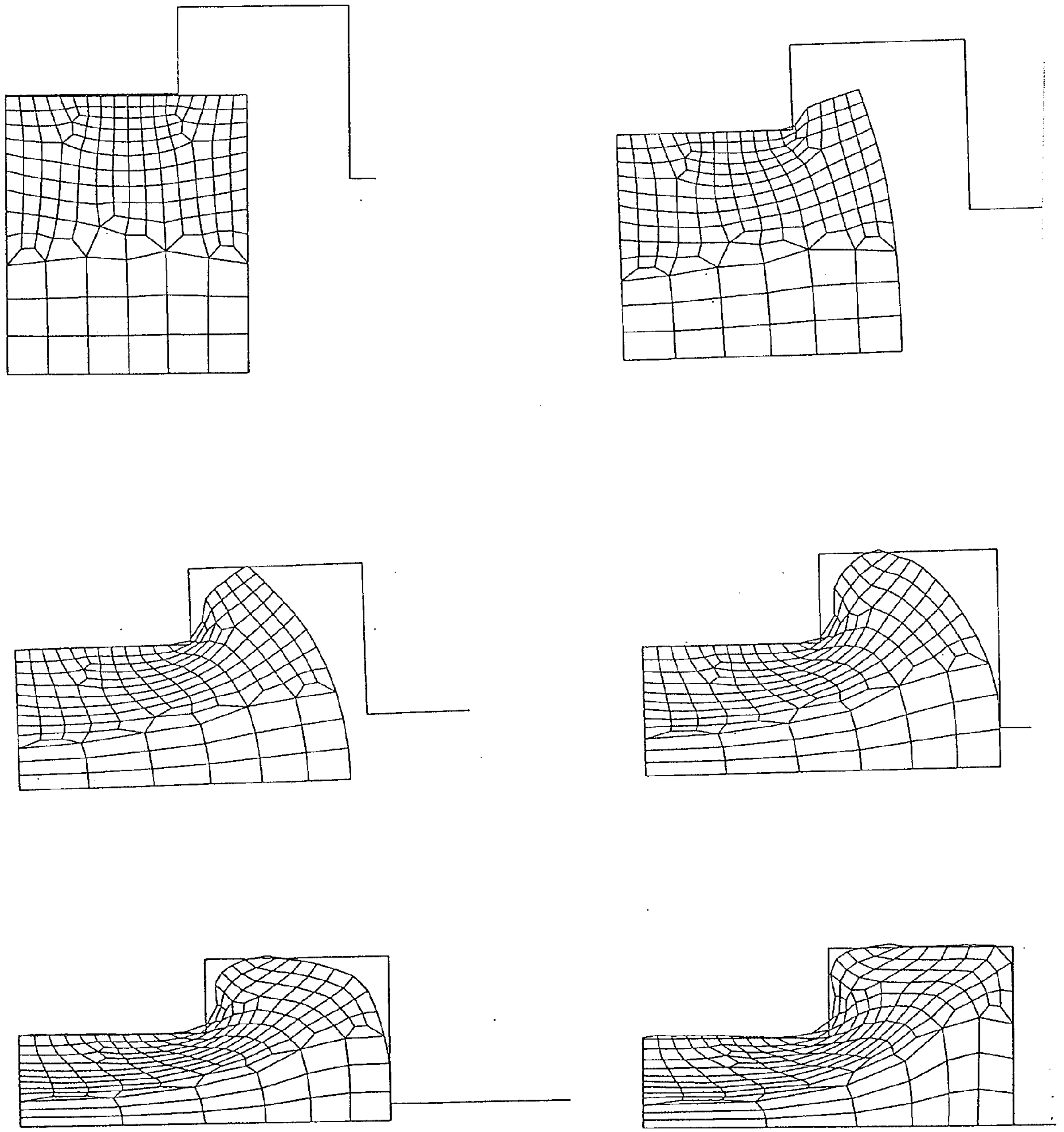

Figure 3 - H-Cross Section, 90° Corner Die at 0.0, 0.3, 0.7, 0.9, 1.0, and 1.1 inch Die Displacement, m = 0.5

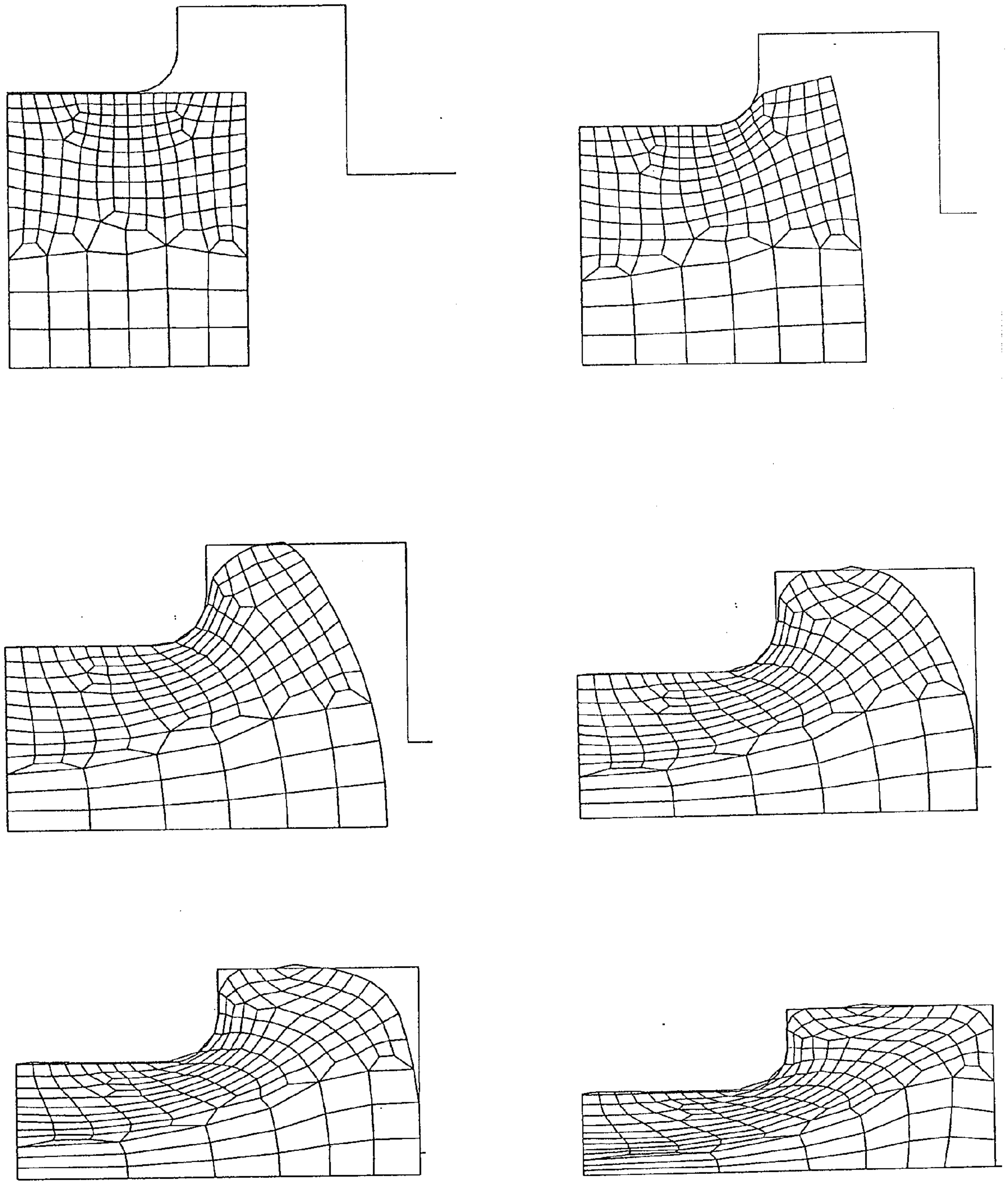

Figure 4 - H-Cross Section, 0.25 inch Radius Die at 0.0, 0.3, 0.7, 0.9, 1.0, and 1.1 inch Die Displacement, m = 0.5

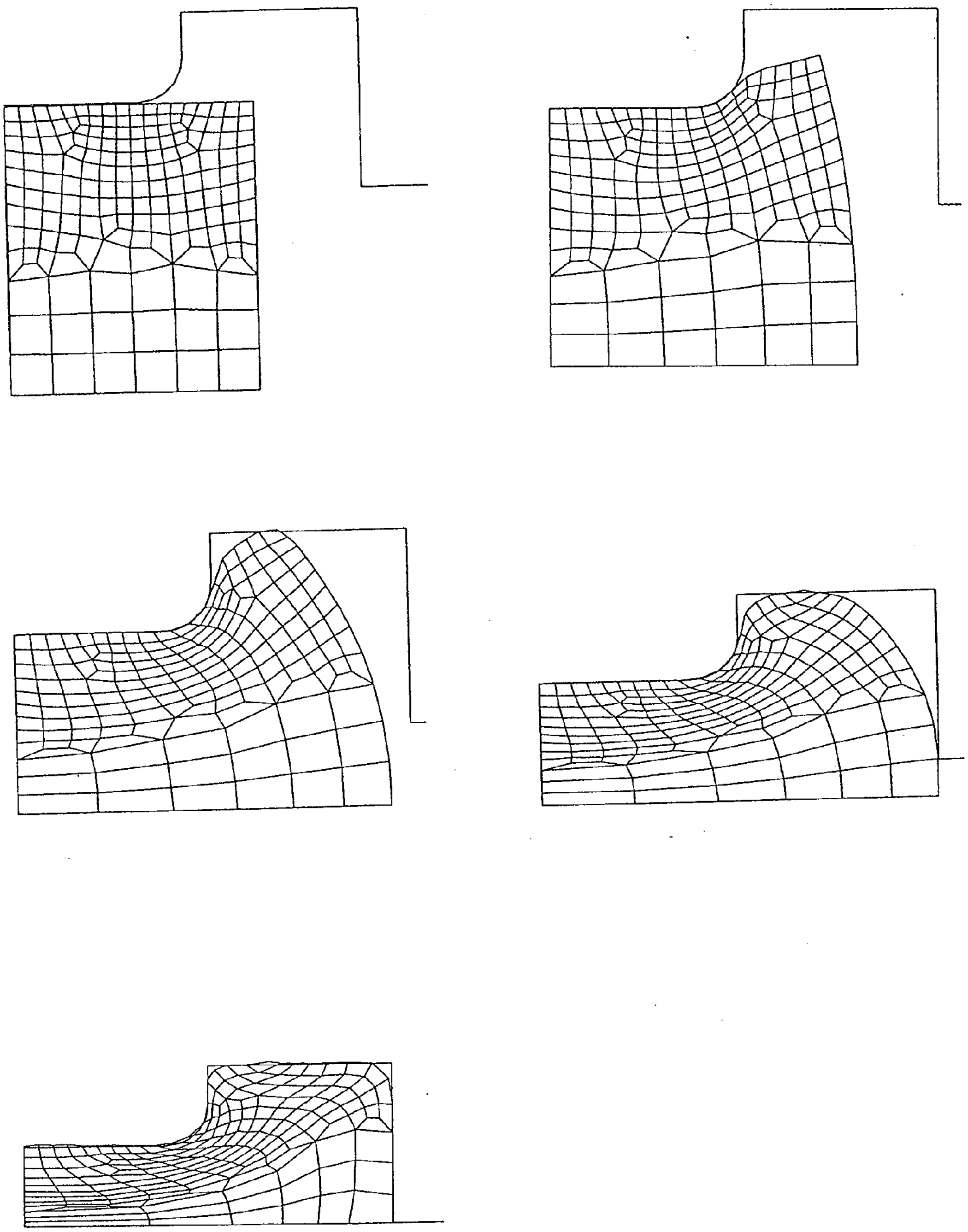

Figure 5 - H-Cross Section, 0.25 inch Radius Die at 0.0, 0.3, 0.7, 0.9, and 1.1 inch Die Displacement, m = 1.0

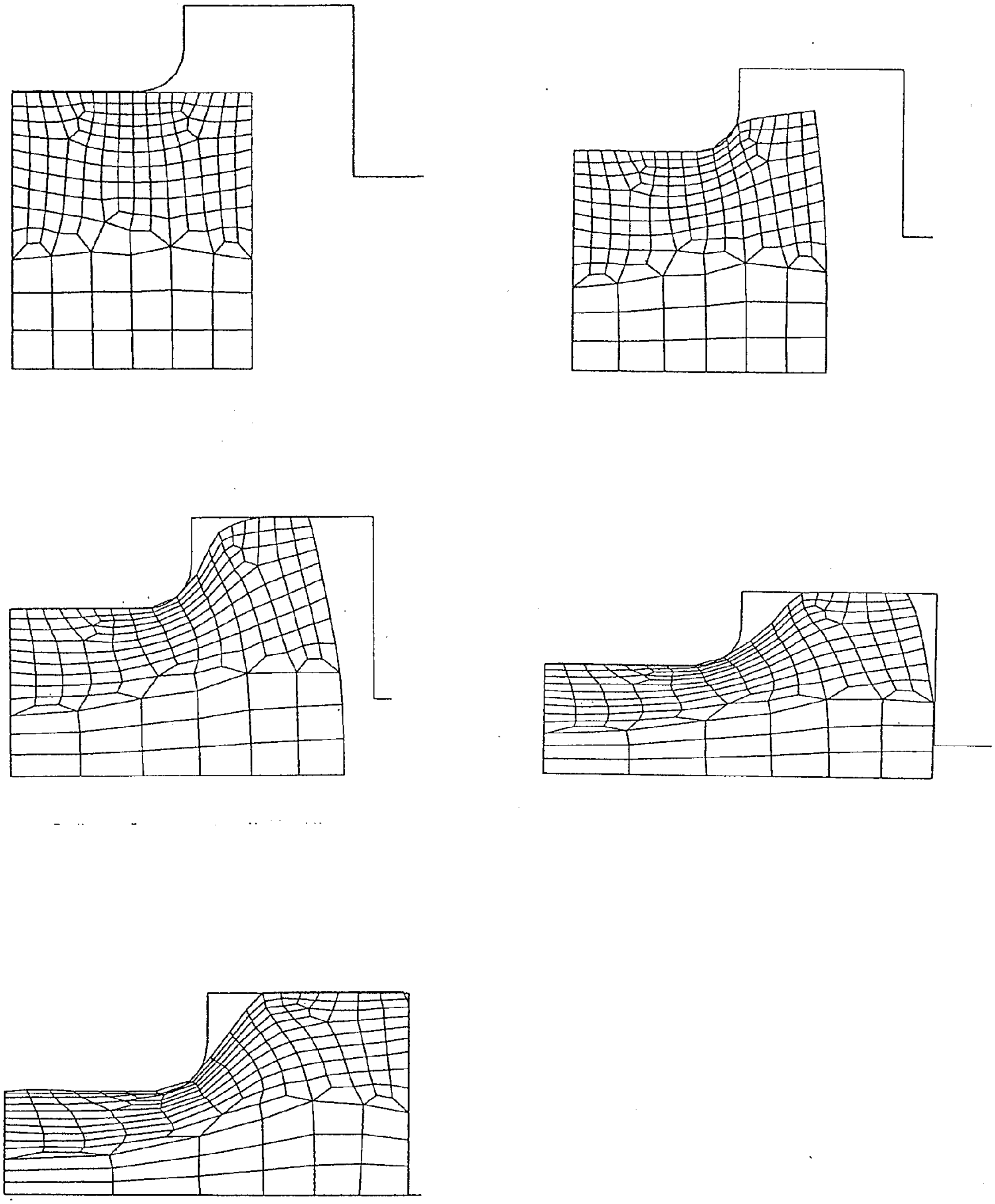

Figure 6 - H-Cross Section, 0.25 inch Radius Die at 0.0, 0.3, 0.7, 0.9, and 1.1 inch Die Displacement, m = 0.0

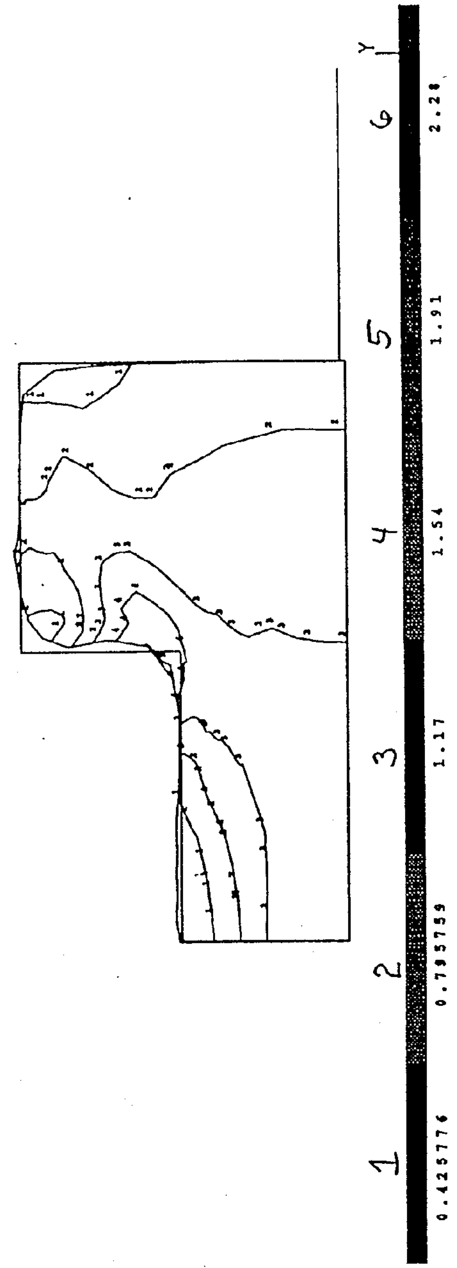

Figure 7 - H-Cross Section, 90° Corner, Strain at Closure, m = 0.5

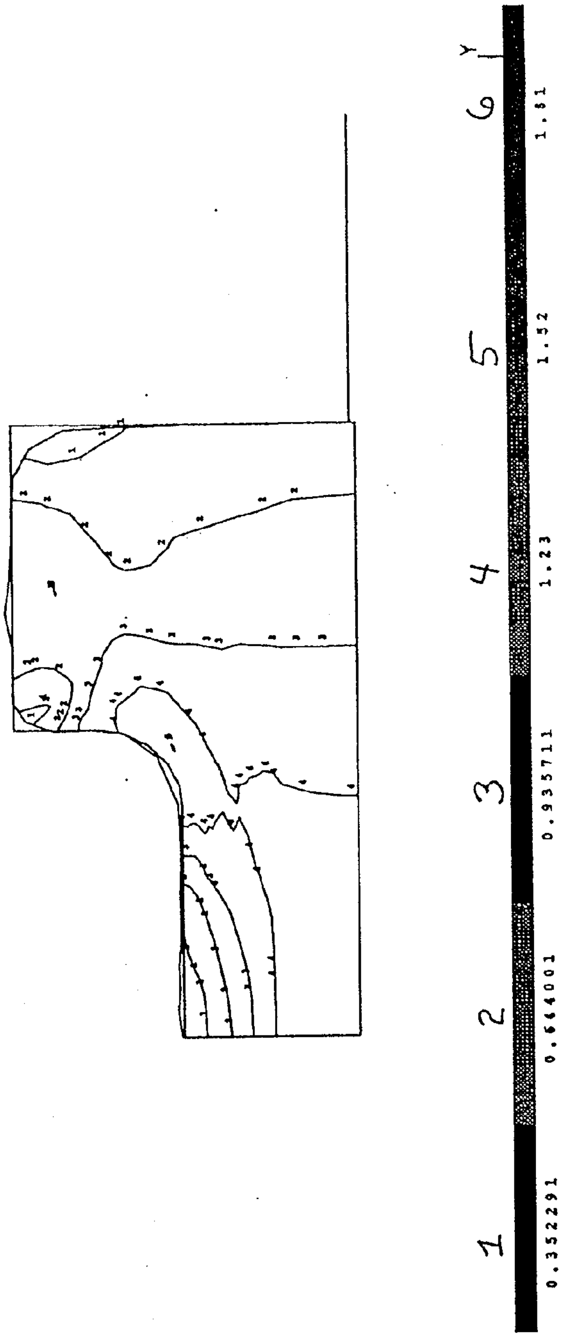

Figure 8 - H-Cross Section, Radiused Corner, Strain at Closure, m=0.5

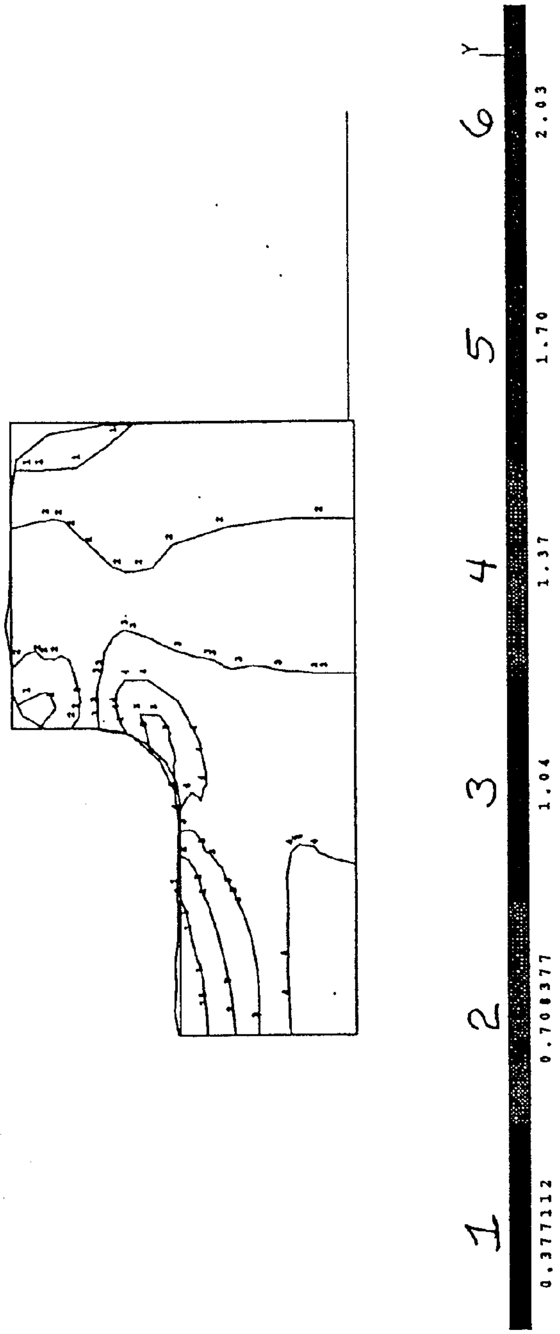

Figure 9 - H-Cross Section, Radiused Corner, Strain at Closure, m=1.0

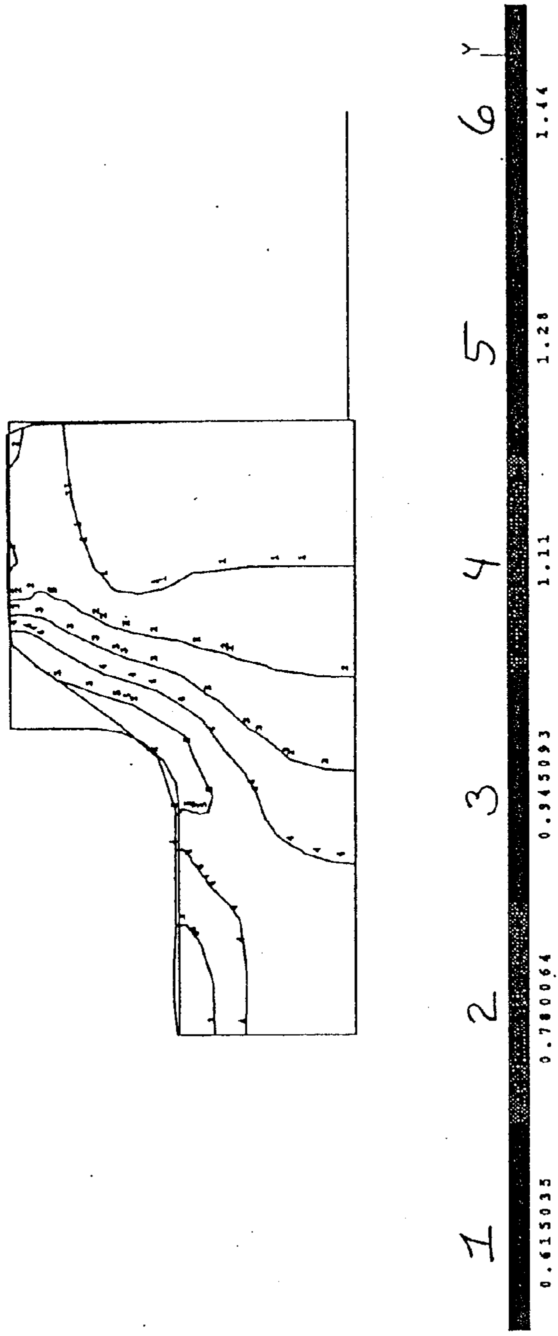

Figure 10 - H-Cross Section, Radiused Corner, Strain at Closure, m=0.0

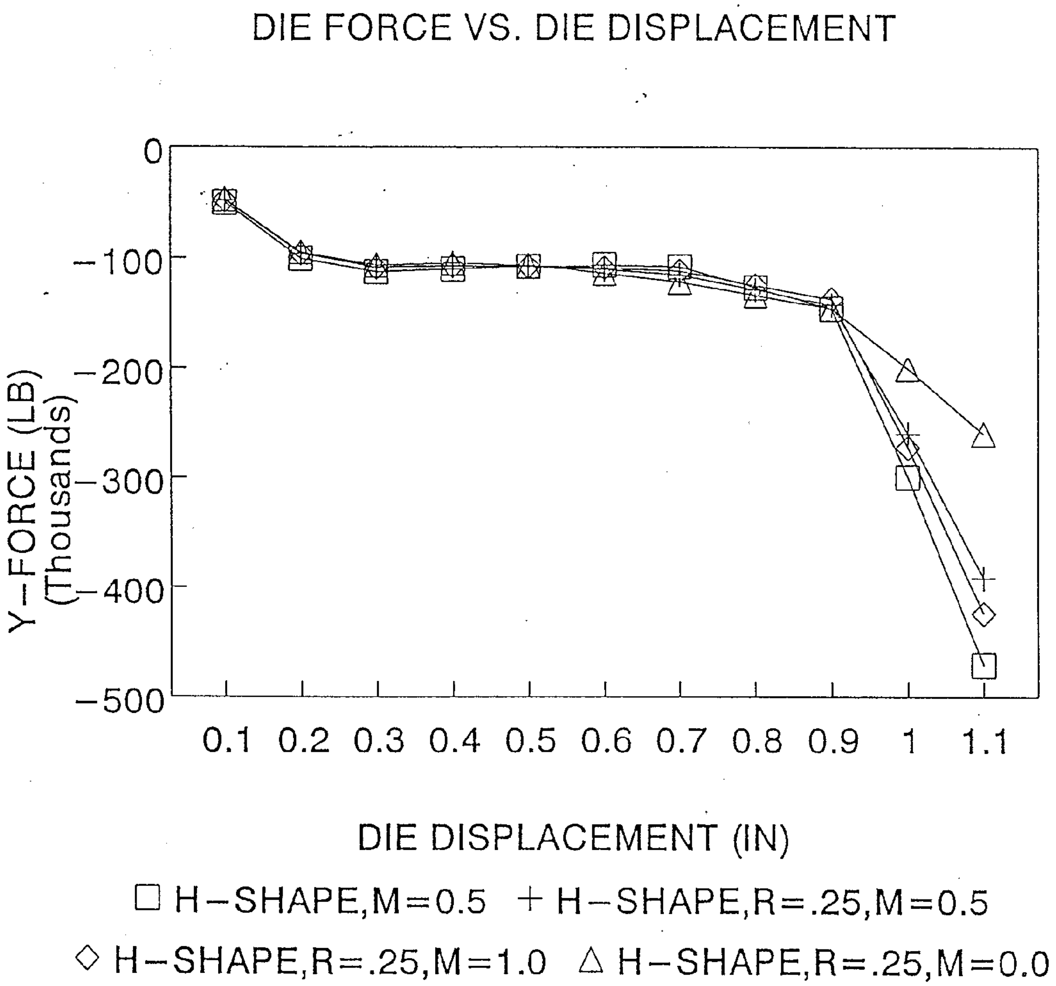

Figure 11 - Die Force Versus Displacement