

**EVALUATION OF A
VARIABLE-CONFIGURATION-DIE
SHEET METAL FORMING MACHINE**

by

JOSEPH A. KNAPKE

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Mechanical Engineering
in Partial Fulfillment of the Requirements
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Signature of Author _____
Department of Mechanical Engineering
August 5, 1988

Certified by _____
Professor David E. Hardt
Thesis Supervisor

Accepted by _____
Professor A.A. Souin
Chairman, Mechanical Engineering Department Committee

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ABSTRACT

The implementation of a Variable Configuration Die Forming Machine is presented. This 120,000 lb. hydraulic forming press uses a unique forming process utilizing variable configuration dies. These dies consist of a 12" x 12" die pin matrix in which the die pin locations are controlled by a positioning system, offering an infinite number of die shapes. The machine is an attempt at flexible tooling for the press forming process and supports the implementation of a closed-loop shape control strategy. The machine can be used to investigate experimental forming techniques, die prototype tryout, and low volume batch production.

A complete documentation of the machine including the modes of operations and test procedures is presented. Design modifications were made to this machine in response to some peculiar characteristics exhibited by this machine such as bent and warped die pins and their effect on pin registration and location, the rubber pad effects in interpolating contact forces to their effects on part formation, and the discrete nature of the parting line and how a spatial frequency based control algorithm will handle this disturbance. 2-D and 3-D experiments were performed to investigate these characteristics and part shape forming was found to be very repeatable using the variable configuration dies. A part measurement procedure is developed and a discussion on error observation and elimination is included. This work clearly shows the promise of this forming technique and suggests the implementation of a spatial frequency based control algorithm for the next research phase.

Thesis Supervisor: David E. Hardt

Title: Associate Professor of Mechanical Engineering

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Introduction

1.1 Conventional Sheet Metal Forming : Background

How do you make a die to form a particular sheet metal part? This seems to be a straight forward question but the answer has eluded many academics. Die makers may not be able to put an answer down on paper but they can show you. This is why sheet metal forming has over the centuries been categorized as an artisan system. The skill or art comes from trial and error experiences and a certain feel developed over the years. This artisan system works, but the problem is that it doesn't provide any documented data, facts or techniques. Even computers and current technologies like Finite Element Methods (FEM) and Forming Limit Diagrams can provide only ball park approximation of what actually happens when sheet metal is formed.

The skill of the artisan is even more important as many new challenges arise, cost-effectiveness is being stressed and one way to get this is to reduce die design lead times. This effects die tryouts by constantly changing target dates, requirements, or competition, not to mention the increase in the number of new materials and part complexity.

Despite these problems, conventional sheet metal forming continues to be one of the most economical part manufacturing methods, especially in dealing in high volume part production. For low volume part production, the high die development costs are harder to justify, creating a need for a more economical approach.

The sheet metal forming process is inherently an open loop process. The desired tooling and materials are chosen and formed to a shape. Once formed, the part is inspected by the artisan, who “closes the loop”, die modifications are made and eventually the correct part is formed. This process is very time consuming and expensive and not justifiable for low volume part production. It also will not compensate for changes in material properties between samples or inconsistent forming conditions.

The most difficult part of the process is the compensation for springback. Springback is the elastic phenomenon exhibited by metals when they attempt to return to their original shape after unloading in a forming process. To compensate for springback, the die maker must make adjustments to over-form an area such that after unloading, it will assume the correct shape. This iterative process, as mentioned earlier, is very time consuming and expensive.

In the classic areas of research: 1) material properties, 2) lubrication and friction, and 3) deformation mechanics, FEM and mathematical modelling have been the major focus. On well modelled, simple geometries, FEM has been very effective, but by increasing the complexity of a part, there become too many variables to accurately predict the final part outcome. A different approach has been through the use of control theory, which has in turn lead to the concept of a variable configuration die.

1.2 Closed-loop Control Theory for Sheet Metal Forming

Closed loop control theory uses a more global approach to solve problems. Figure 1.1 shows the general block diagram for closed loop shape control applied to sheet metal forming. According to Ogata [1], a closed-loop control system is one in which

the output signal, (part shape measurement), has a direct effect on the control action through the feedback loop. The actuating error signal, (part shape error), which is the difference between the input signal, (desired part shape), and the feedback signal, (actual part shape), is fed to the controller to reduce the error and bring the output of the system to a desired value. The real value of this control system is its insensitivity to varying material properties and boundary conditions like binding force, lubrication and friction, which are problems for FEM to define and model.

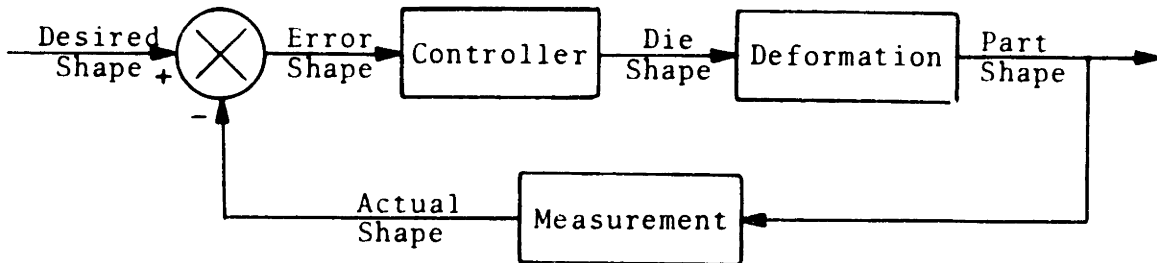


Figure 1.1 Closed Loop Shape Control Block Diagram

In early work by Hardt and Gossard [2], a 4-element module was used in stretch forming and hydroforming with a control scheme to form aluminum samples to a desired single direction curvature. This early set up and an eventual 8-element opposed die

forming experiments gave the control system approach to forming the credibility and financial support needed for continued research. With Hardt, Olsen, Allison and Pasch [3], a Discrete Die Surface (DDS) was introduced and composed of an array of small, individually positioned elements. Using a neoprene pad to interpolate between the discrete die contact points, smooth parts were produced that compared closely to parts formed on an identical continuous die.

Webb [4] created a test fixture to demonstrate the concept that, independent of material properties, the correct final part geometry can be formed adaptively with a discrete die through in-process measurements to iteratively modify the die shape. However, the simplicity of this control scheme caused long set up times and persistent errors.

The problem of springback has also been addressed through much research. Stelson and Gossard [5] demonstrated a real time adaptive pressbrake control system, by knowing the tooling and sheet geometry, the force and displacement data could be transformed to a moment vs. curvature relationship. Hardt, Roberts and Stelson [6] worked with material adaptive control of sheet metal roll bending and found springback directly related to the moment loading of a point on the sheet. Similar work was done by Hardt, Jenne, Domroese and Farra [7] with the twisting process. All this work points to the promise of closed loop control theory in respect to sheet metal forming.

In order to implement the control system shown in the earlier block diagram of Figure 1.1, the following is needed: 1) three-dimensional part shape descriptor, 2) a control algorithm, 3) a variable configuration die forming machine, and 4) a coordinate measuring machine.

Hardt and Webb [8] chose to use Fourier Transforms for the part shape descriptor. In Fourier Transforms, a two-dimensional shape is transformed into a sum of sine and cosine curves, where the amplitude and frequency components replace the 2-D shape coordinates. For three-dimensional shapes, the amplitudes and frequencies of orthogonal sine waves replace the 3-D shape coordinates.

The spatial frequency transform leads to frequency domain based control theory for dynamic systems. While this theory is developed for time-varying signals, it can be applied to spatial-varying shape processes. The process can now be characterized by its frequency response, which in turn can be used to develop a causal input-output relationship for the process.

This input-output relationship is defined as the deformation transform function $H(\omega_1, \omega_2)$ and is the ratio:

$$H(\omega_1, \omega_2) = \frac{P(\omega_1, \omega_2)}{D(\omega_1, \omega_2)}, \quad (1.1)$$

where ω_1 and ω_2 are the orthogonal spatial frequencies and H is the corresponding amplitude at each pair. $P(\omega_1, \omega_2)$ is the part shape (output), while $D(\omega_1, \omega_2)$ is the die shape (input).

Assuming H is known, then the part shape $P(\omega_1, \omega_2)$ can be predicted given the die shape $D(\omega_1, \omega_2)$ by:

$$P(\omega_1, \omega_2) = H(\omega_1, \omega_2)D(\omega_1, \omega_2). \quad (1.2)$$

A control algorithm was developed based upon updating an approximation to shape change transfer functions that operate on discrete spatial frequency based descriptions

of the tooling shape and the resultant part shape. This algorithm was able to determine the correct tooling and converge to the desired part shape.

Robinson [9] was given the task to design a full scale sheet metal forming machine for continued closed-loop control research. The most important component of the machine he designed is the variable configuration dies. They consist of a die pin matrix capable of being contoured into discrete die surfaces (See Figure 1.2). Through the use of a computer controlled positioning system, these dies can be reconfigured as needed in response to the controller commands. A hydraulic forming press completes the components of the forming machine. A coordinate measurement machine (CMM) made from a modified Bridgeport milling machine and salvaged components from a previous CMM will measure the parts and give corresponding XYZ representation. Work to convert this representation to a continuous surface representation will be needed to implement a closed-loop control system.

It was the responsibility of the author to assemble the forming press, build the die pin positioning system and do initial experiments to evaluate the characteristics of this variable configuration die forming machine. Actual control implementation will occur in continued research of this project.

1.3 Thesis Overview

The implementation of the variable configuration die forming machine presents the opportunity to investigate a new forming process. The forming machine was created to handle relatively large forming shapes (12" x 12") and address low volume batch production modes with an emphasis on varied experimental set ups. Possible modes include

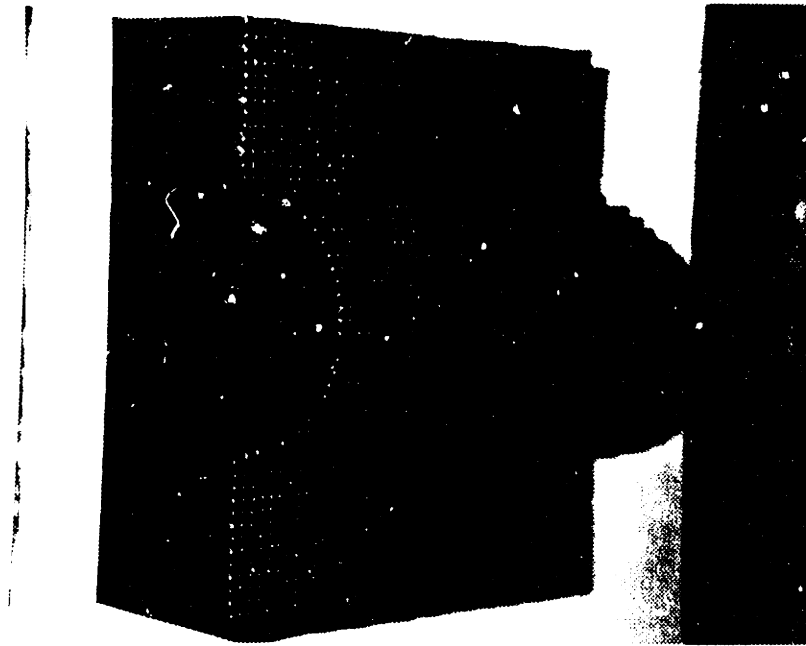


Figure 1.2 VCD Die Pin Matrix (Male Die Half)

prototype die tryout, with an infinite number of shapes available within the variable configuration dies, and experimental forming technique evaluation. More importantly, the variable configuration dies enable the future implementation of a closed-loop shape control system. The variable configuration die forming machine is on the forming edge of technology.

A major concern of this thesis is the documentation of the current implementation of the Variable Configuration Die Forming Machine. Chapter 2 describes the general hardware set up of the machine, including many photos of the actual components. This chapter also contains the modes of operations and procedures used to run experiments, plus a description of the coordinate measurement machine.

Chapter 3 describes certain design modifications made to the original machine. The modifications were made in response to characteristics exhibited by the machine during initial experiments. Some modifications are just alternate designs to simplify a machine part, while others directly address some of the peculiar characteristics of the machine.

Chapter 4 describes the initial forming experiments used to evaluate the forming characteristics of the machine. The experiments investigate 2-D bending and 3-D stretch forming with topics ranging from optimum forming conditions and part shape repeatability to measurement procedures. Data plots are presented to evaluate the forming experiments on the basis of part shape repeatability, error analysis and design modifications. As a result of the forming properties exhibited by this machine, a discussion on part shape errors observed and suggested solutions is included.

Chapter 5 offers conclusions and recommendations on future research with this new forming machine and the implementation of previous research done within the Laboratory for Manufacturing and Productivity (LMP).

Appendix A contains detail drawings of the die pin positioning system, and Appendix B contains program listings of pin height calculations for various geometries.

Variable Configuration Die Forming Machine

The Variable Configuration Die Forming Machine consists of two separate parts: the forming press and a positioning system. Most of the machine design was done by Rob Robinson [9] for his Masters' work. This chapter presents the assembled forming machine and explains its individual components. An explanation of the modes of operation is also included plus a description of the coordinate measurement machine used for part measurement.

2.1 Machine Layout

Figure 2.1 shows the actual set up of the Variable Configuration Die Forming Machine as it exists in the Laboratory for Manufacturing and Productivity. The die pin positioning system is in the foreground, while the horizontal forming press is in the background. Figure 2.2 shows a sketch the general layout of the Variable Configuration Die Forming Machine, the major components are labeled and will be presented in the rest of this chapter.

2.1.1 Horizontal Forming Press

The horizontal hydraulic forming press consists of the following components (See Figure 2.3):

- Variable Configurable Dies
- Blankholder
- Press End Plates

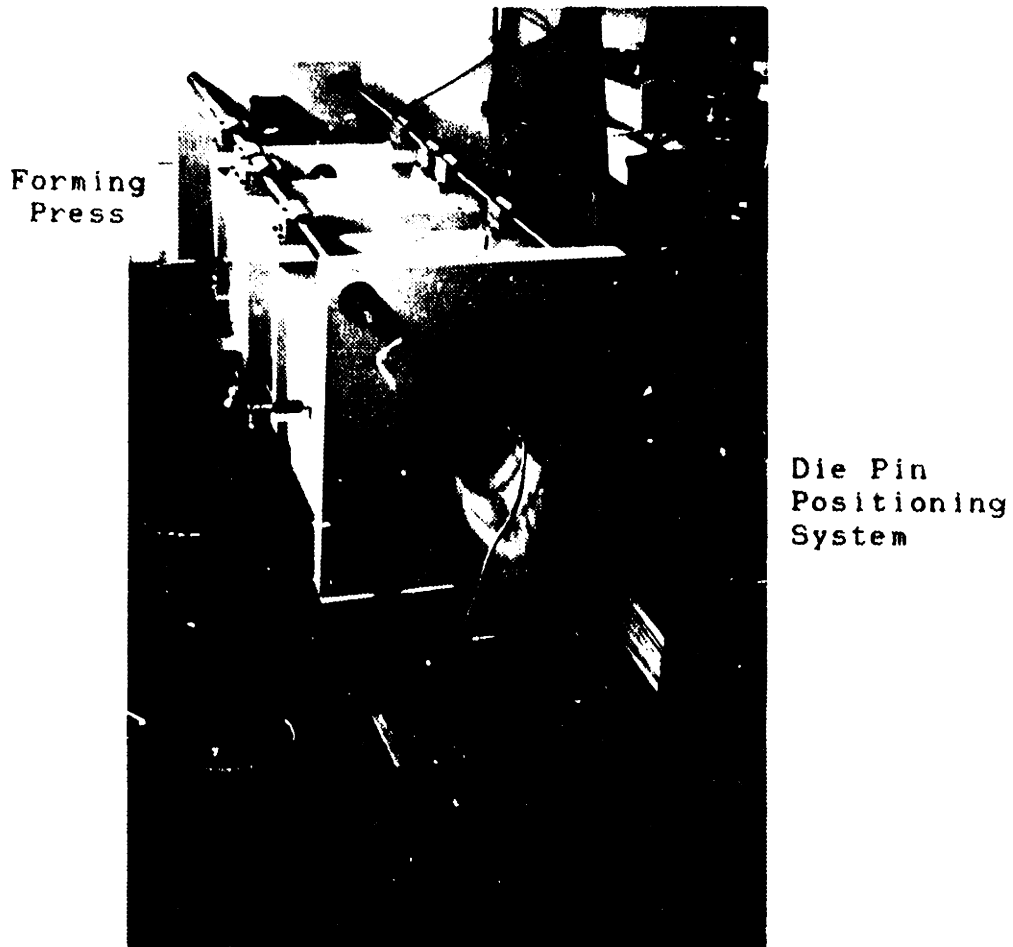


Figure 2.1 Variable Configuration Die Forming Machine

Tie Rods
Floating Cylinder Support Plate and Reference Block
Hydraulic Cylinders

The physical dimensions of the press are: 10'6" length, 38" height, and 33" width. The hydraulic cylinders (See Figure 2.4) have a 5" bore diameter which when operated at the designed system pressure of 3,000 psi. will produce a 58 ton (116,000 lb.) forming force. Each cylinder has a maximum stroke of 35 inches, although the actual forming

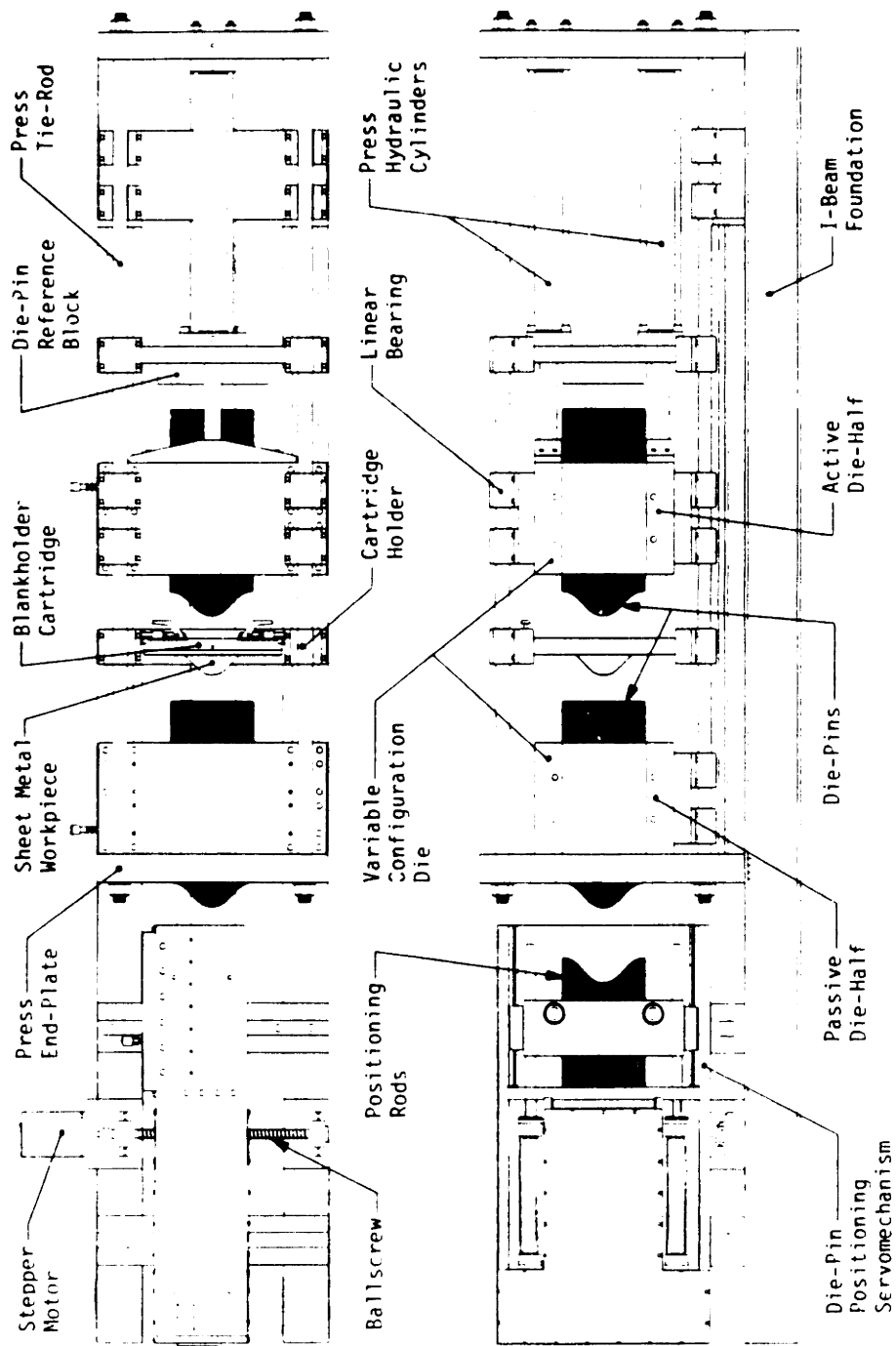


Figure 2.2 General Machine Layout: Major Components [9]

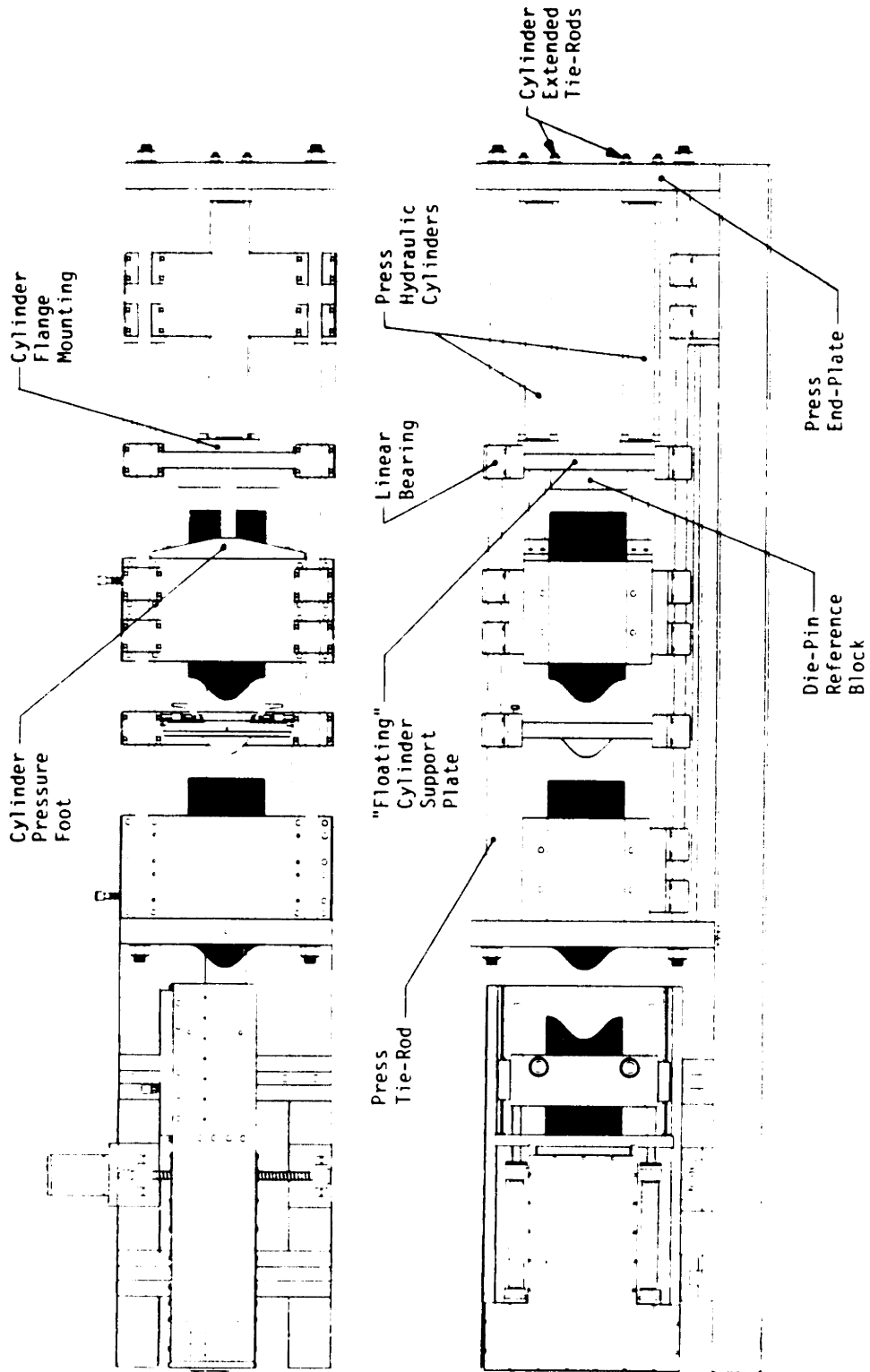


Figure 2.3 Horizontal Hydraulic Press: Component Breakdown [9]

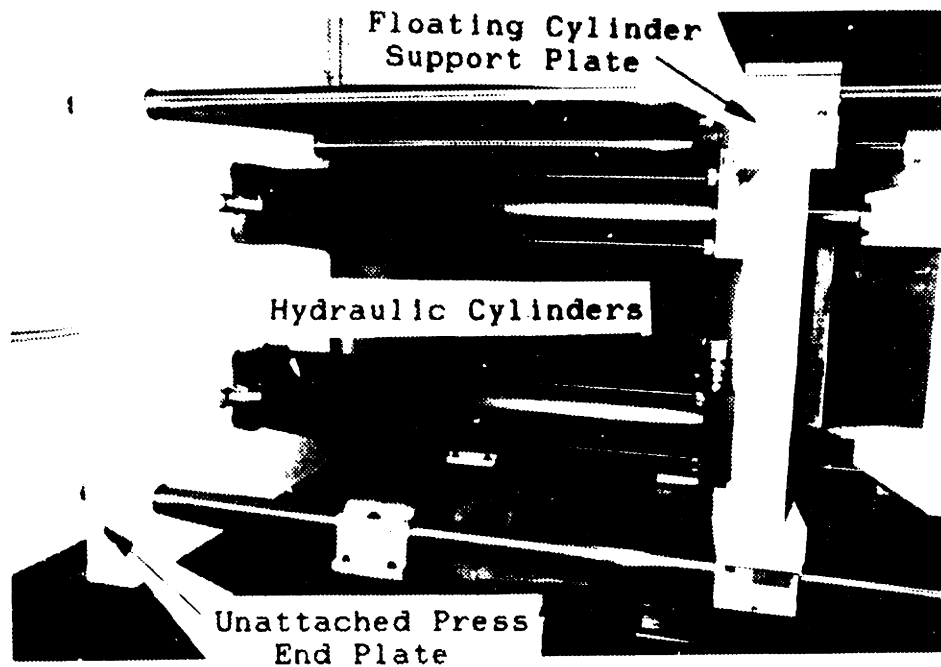


Figure 2.4 Hydraulic Cylinders

stroke will vary depending on part size, die pin geometries and modes of operation, the maximum formed part depth is 6 inches.

As shown in Figure 2.4, the cap (back) end of the cylinders are mounted to the unattached press end plate, while the head (front) ends are mounted to the floating cylinder support plate. The unattached press end plate helps reduce the chance of press bowing during forming by allowing the four tie rods to elastically stretch under load. The floating cylinder support plate is attached to the press structure through linear bearings on the tie rods, it not only supports the weight of the cylinders, it also allows for the cylinders to thermally expand, maintain alignment and increases the column strength rating of the cylinder piston rods over long forming strokes. The die pin reference block is mounted to the floating cylinder support plate. It is a precision

ground flat plate used during the Die Set Up Procedure to reset the active die pins to a common reference surface.

2.1.2 Variable Configuration Dies

The variable configuration dies are the flexible tooling that are the main thrust of this research project. The present set up consists of an active and passive die.

The active die is attached to the hydraulic cylinders and is mounted on linear bearings to be free to move during the forming strokes (See Figure 2.5). The passive die is mounted to the press end plate that is rigidly attached to the foundation (See Figure 2.6). The active and passive dies are both similar in construction and contain an array of die pins surrounded by a steel framework (See Figure 2.7).

The die pin array consists of spherically tipped pins made from 0.25 inch keystock, 26 inches long. The pins are arranged in 42 columns of 48 pins each, (2016 die-pin array), with a 0.030" thick sheet metal spacer between the columns giving approximately a 12" X 12" forming area. As demonstrated by Pasch [10], the spacers are used to decouple the columnar pin movement, since the die pin positioning system, to be discussed later, addresses one column at a time. The spacers are also designed to distribute the shearing load seen by the pins during forming to the die housing.

The active die pins are arranged to form the male die half while the passive die pins are arranged to form the female die half. Both sets of die pins are in exact alignment with each other. This allows the active die shape to be set up in the passive die and transferred to the active die pins. This process will be discussed in more detail in the forming procedure section of this chapter.

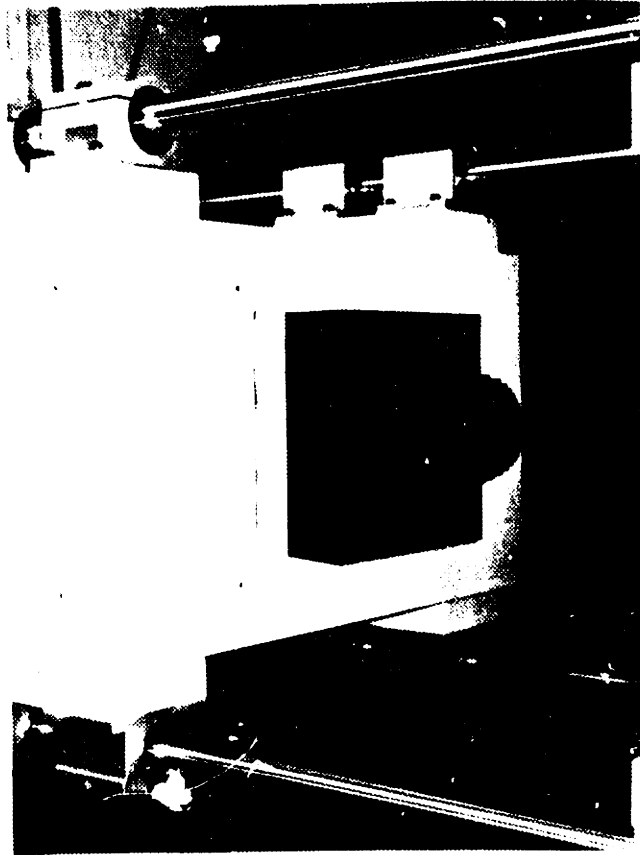


Figure 2.5 Active Die

The major components of each die housing consists of two hydraulic rams, a die pin clamping plate, top and bottom plates, and the two end blocks. The hydraulic rams are used to clamp the die pins, when set to their proper positions, to form a solid discrete die. Each ram is single acting with a spring return and has a 5/8" stroke. Under a maximum working pressure of 10,000 psi., the two rams can produce a maximum clamping force of 150 tons (300,000 lbs.), which creates a 6250 lb. clamping force to 48 rows of die pins.

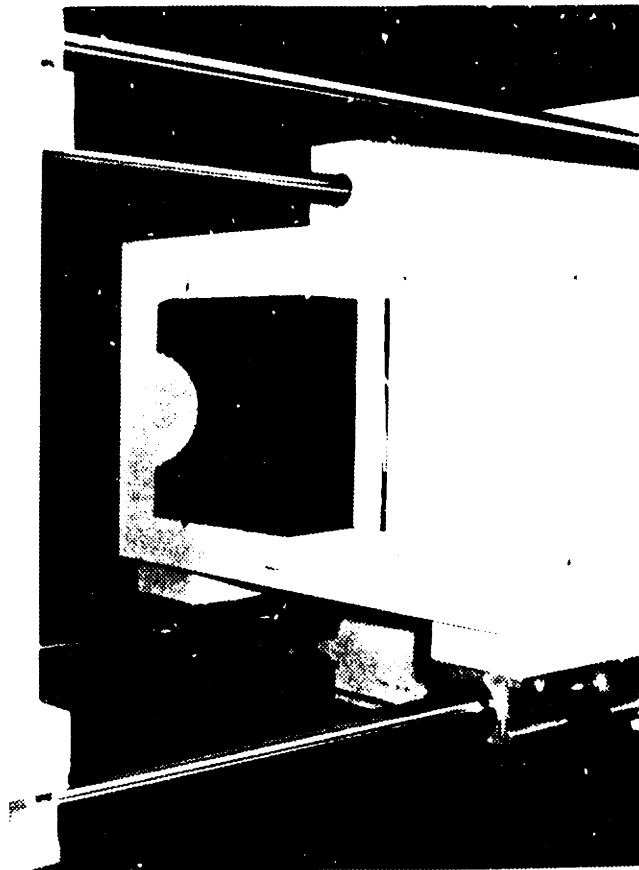


Figure 2.6 Passive Die

2.1.3 Blankholder

The blankholder is located between the active and passive die halves. It consists of two parts: a removable cartridge and a holder.

The cartridge holds the sheet metal in a fixed orientation and a constant clamping force is obtained through uniformly tightening bolts surrounding the die opening. The present blankholder cartridge has been designed to take advantage of the 12" X 12" forming surface of the present variable configuration dies. It has an opening of 12.5" X 12.5" with 24, 3/8" dia. socket head cap screws around the periphery for clamping (See Figure 2.8). Note that the cartridge holder is mounted to the press tie rods by four

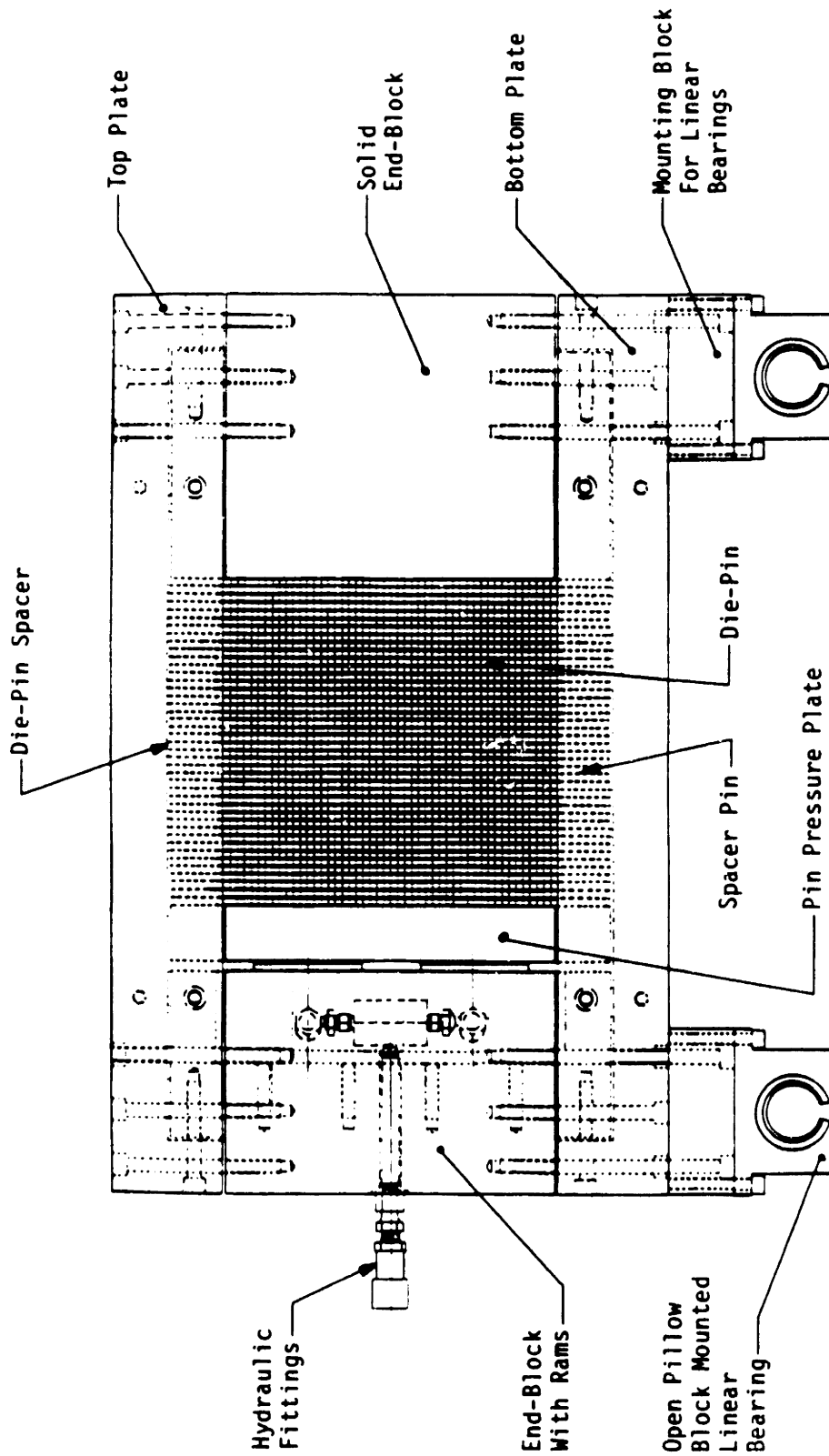


Figure 2.7 Active/Passive Die Framework

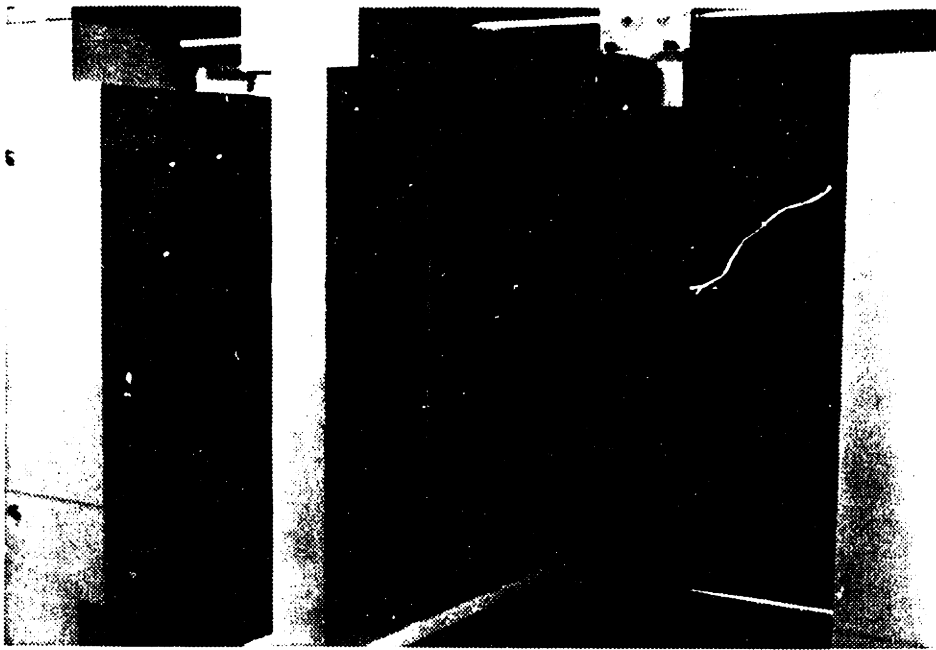


Figure 2.8 Blankholder

linear bearing to maintain alignment to the forming surface and allows the blankholder to float freely and not introduce any moments to the part during the forming sequence.

The cartridge was designed to be removable and is attached to the holder through eight linear bearing modules. This allows for in-process part shape measurement without unclamping the workpiece and repeatable workpiece orientation is maintained during the forming cycle.

To form different sized parts other than square based shapes a new cartridge would have to be designed with a corresponding new die opening.

Figure 2.9 shows the Variable Configuration Die set up consisting of the active die, blankholder and passive die.

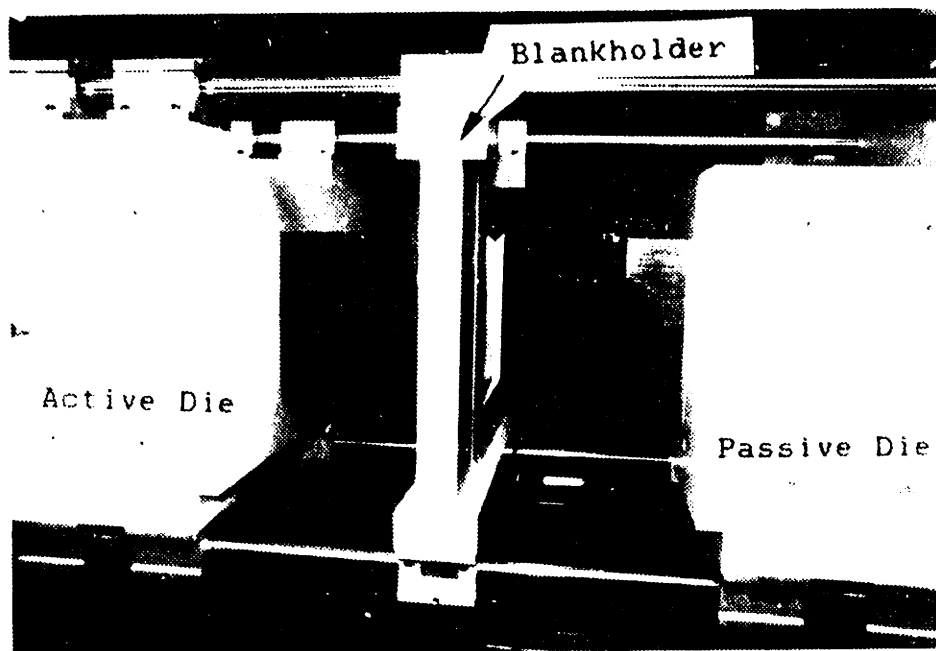


Figure 2.9 Active Die, Blankholder and Passive Die

2.1.4 Die Pin Positioning System

The die pin positioning system represents the second part of the Variable Configuration Die Forming Machine. It is located next to the rigidly attached press end plate (See Figure 2.10). The die pin positioning system serves to generate the die pin locations for both die halves. It is shown without the solenoid housing plate assembly (which at this time are still in fabrication). The missing parts make up the servo-controlled unit designed to automatically generate the die surface. Without the solenoid housing, the current positioning system is functional in that the positioning rods can be manually positioned. Given this limitation, experiments were chosen utilizing simple geometries that will still help characterize this new machine. In this section, information on the

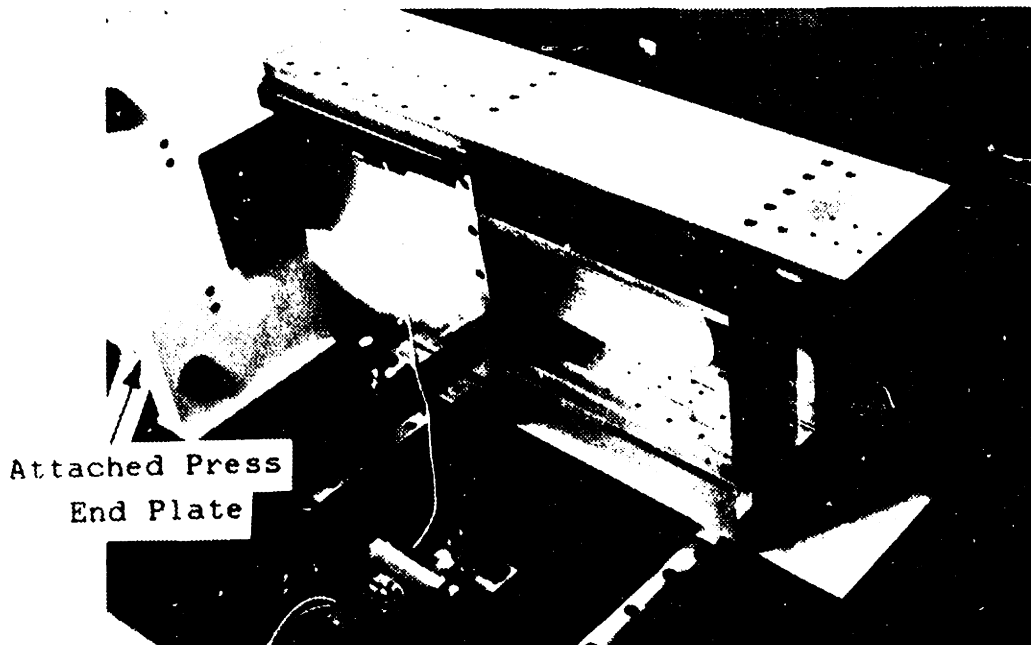


Figure 2.10 Die Pin Positioning System

complete die pin positioning system will be presented and whenever appropriate the actual arrangement will be discussed.

The die pin positioning system (shown in Figures 2.11 - 2.15) consists of a vertical column of 48 cylindrical positioning rods used to impress the die profile into the individual columns of the variable configuration die (VCD). The 48 pins are 39.7 inches in length, $7/32$ inches in diameter, and are aligned vertically in the positioner clamp to correspond to the 48 rows of pins in the VCD. The positioner clamp contains 3 hydraulic rams rated at 20 tons clamping force each at 10,000 psi. and a pressure plate used to hold the positioning rods once set. Axial motion is accomplished by mounting the positioner clamp assembly on linear roller ways and attaching two hydraulic cylinders, each with a 2.5" bore diameter and 15.5" stroke, acting in parallel. A linear

encoder attached to the positioning clamp enables position feedback measurements to + 0.0005 inch.

While the major purpose to the positioner clamp is to align and lock up the positioning rods, the positioning rods extend from the clamp back into the solenoid housing to be automatically positioned. The solenoid housing consists of four vertical steel plates, two are grooved to align the positioning rods while the other two are used to mount the bank of 48 solenoids which will assist in individually positioning the rods. Figure 2.14 shows a top view of the solenoid housing while Figure 2.15 shows the cross section view as seen along the length of the positioning rods. Note the heat sinks, air dividers and squirrel cage fan used to cool the housing. The four plates making up the solenoid housing are, at the time of this writing, being fabricated. The positioning rods are currently manually positioned with calipers and then locked into position with the positioner clamp. A more detailed description of the die pin positioning system can be found in Robinson [1] in Chapter 7, with Section 7.1.2 pertaining to the solenoid housing and Section 7.2 explaining the die pin positioning system operation.

The entire die pin positioning system is mounted on two linear roller way rails that permit translation perpendicular to the axis of the press. With a DC motor and 5 to 1 ballscrew assembly, it will increment laterally behind the VCD to address the individual die pin columns (See Figure 2.16). A rotary optical encoder will be attached to the motor for accurate positioning of the die pin positioning system.

Detailed drawings of the die pin positioning system components can be found in Appendix A, while drawings for the rest of the machine can be found in Robinson[1].

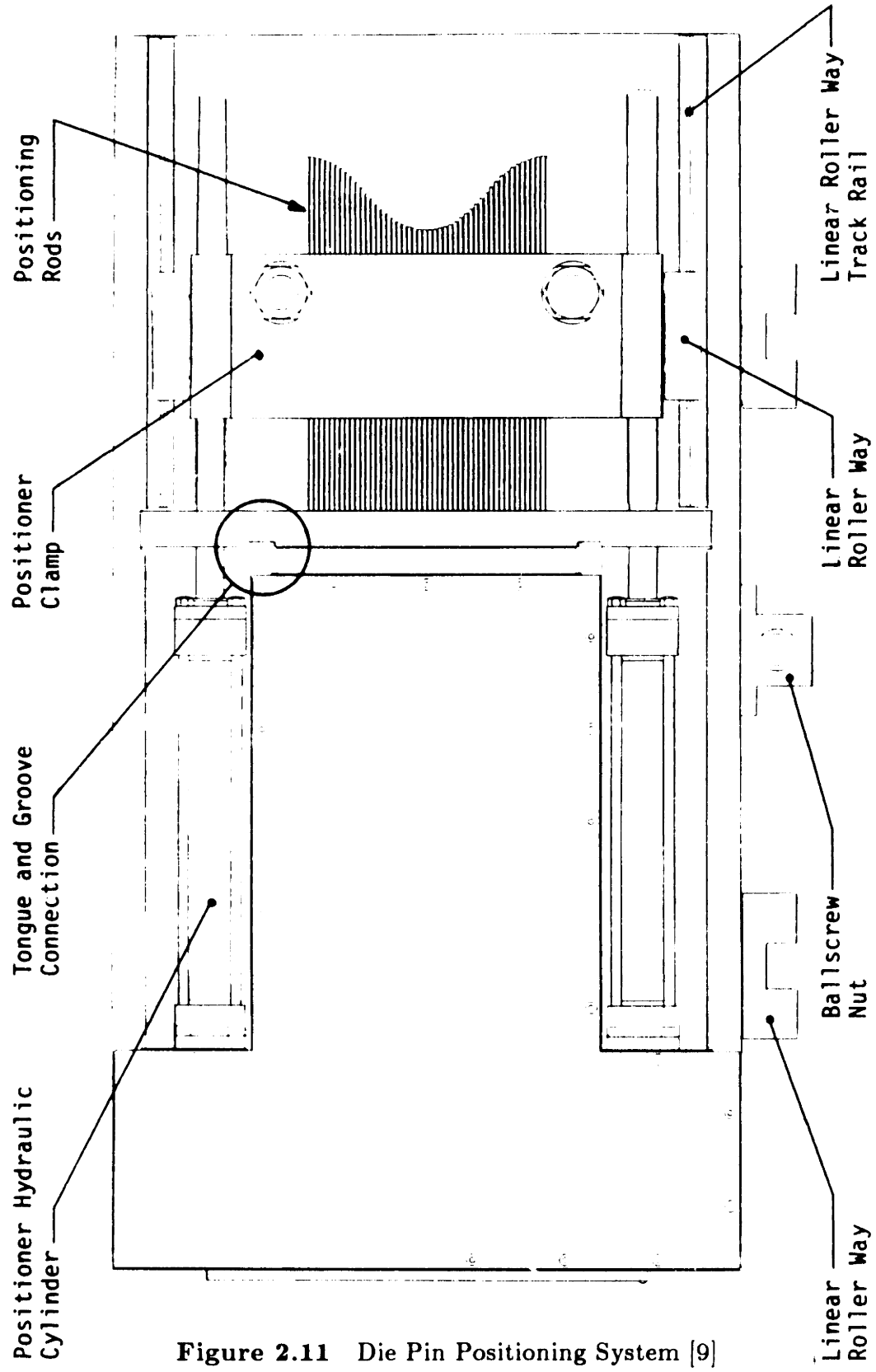


Figure 2.11 Die Pin Positioning System [9]

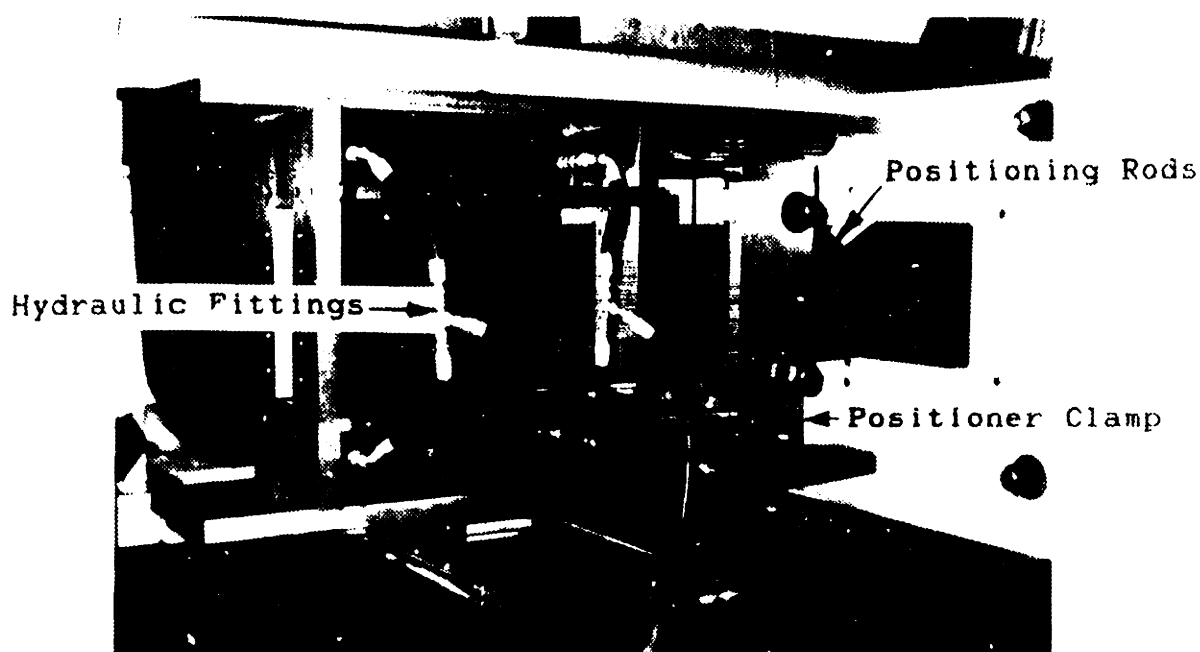


Figure 2.12 Die Pin Positioning System (Right Side View)

Figure 2.17 shows the entire Variable Configuration Die Forming Machine as it exists in the Laboratory for Manufacturing and Productivity at MIT, note the 2 ton gantry crane needed for assembly of this machine. Following are some statistics on this machine:

Overall length - 16'
Width - 33"
Height - 46"
Weight(approx.) - 4 tons
Number of bolts - 1000
Number of solenoids - 48
Number of positioning rods - 48
Number of hydraulic rams and cylinders - 11
Foundation - 3 ea. I-beams, W6 x 25 x 16'
Forming force @ 3000 psi. - 58 tons
Forming part size limitation - 12" x 12"
Forming depth - 6"

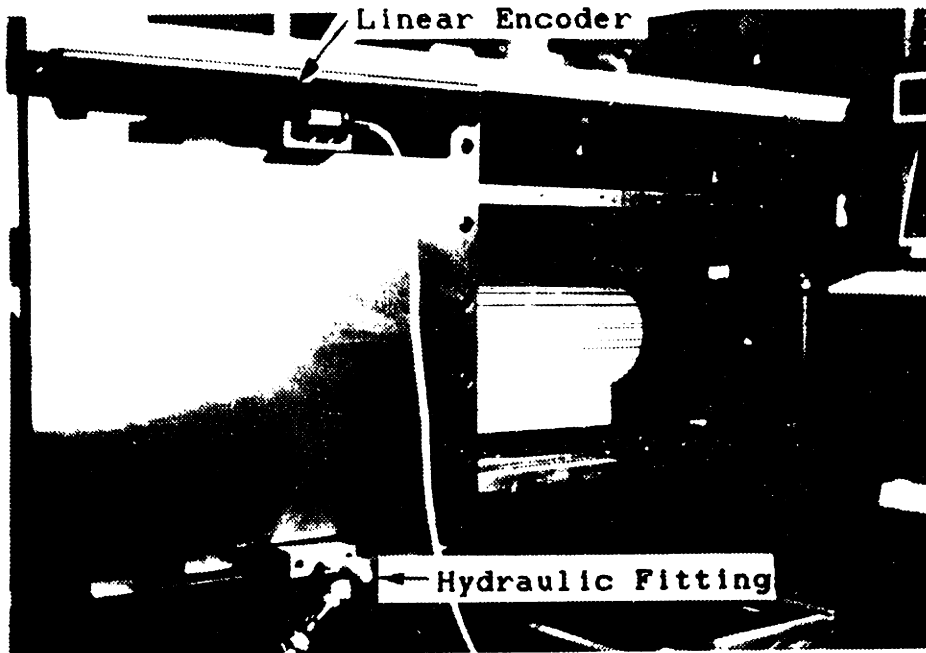


Figure 2.13 Die Pin Positioning System (Left Side View)

2.2 General Machine Operation

This section describes the basic operation of this machine, a procedure was developed explaining the set up of each die half surface to the forming of a part and its measurement with a coordinate measurement machine (CMM).

2.2.1 Discrete Die Set Up Procedure

Step 1. The active die pins are unclamped and the entire die is pulled back against the die pin reference block (See Figure 2.18). A linear encoder mounted to the active die relays the necessary position feedback measurement and the active die pins are shifted forward until a flat surface is formed and protrudes from the die front farther than the desired part depth (See Figure 2.19).

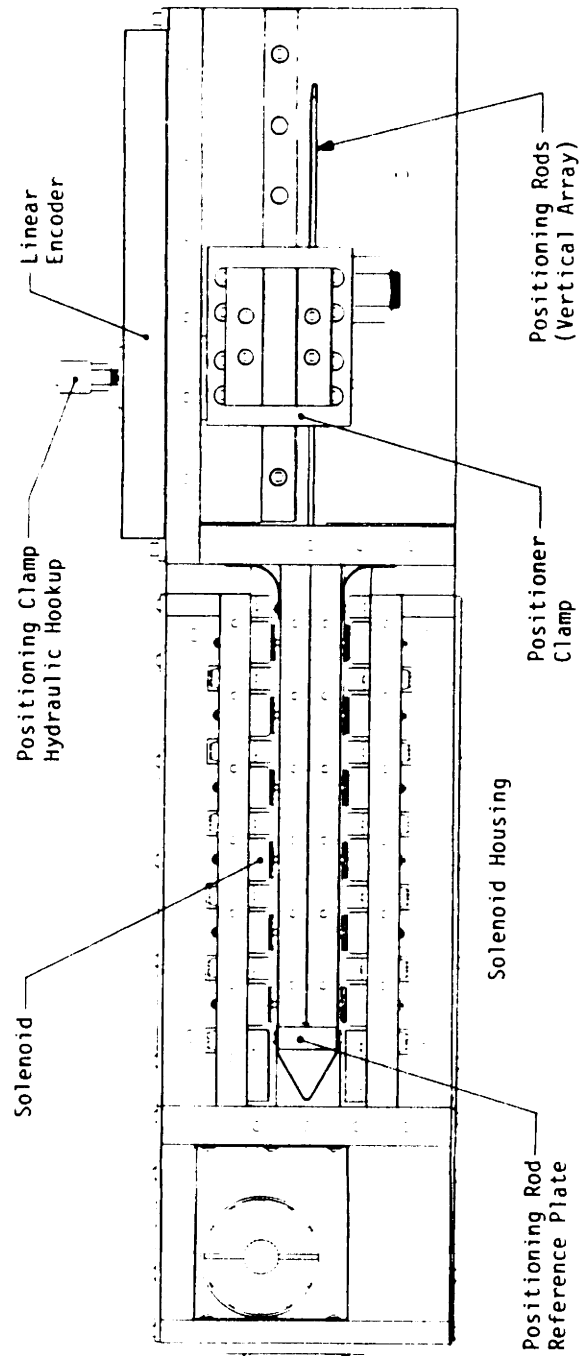


Figure 2.14 Die Pin Positioning System (Top View) [9]

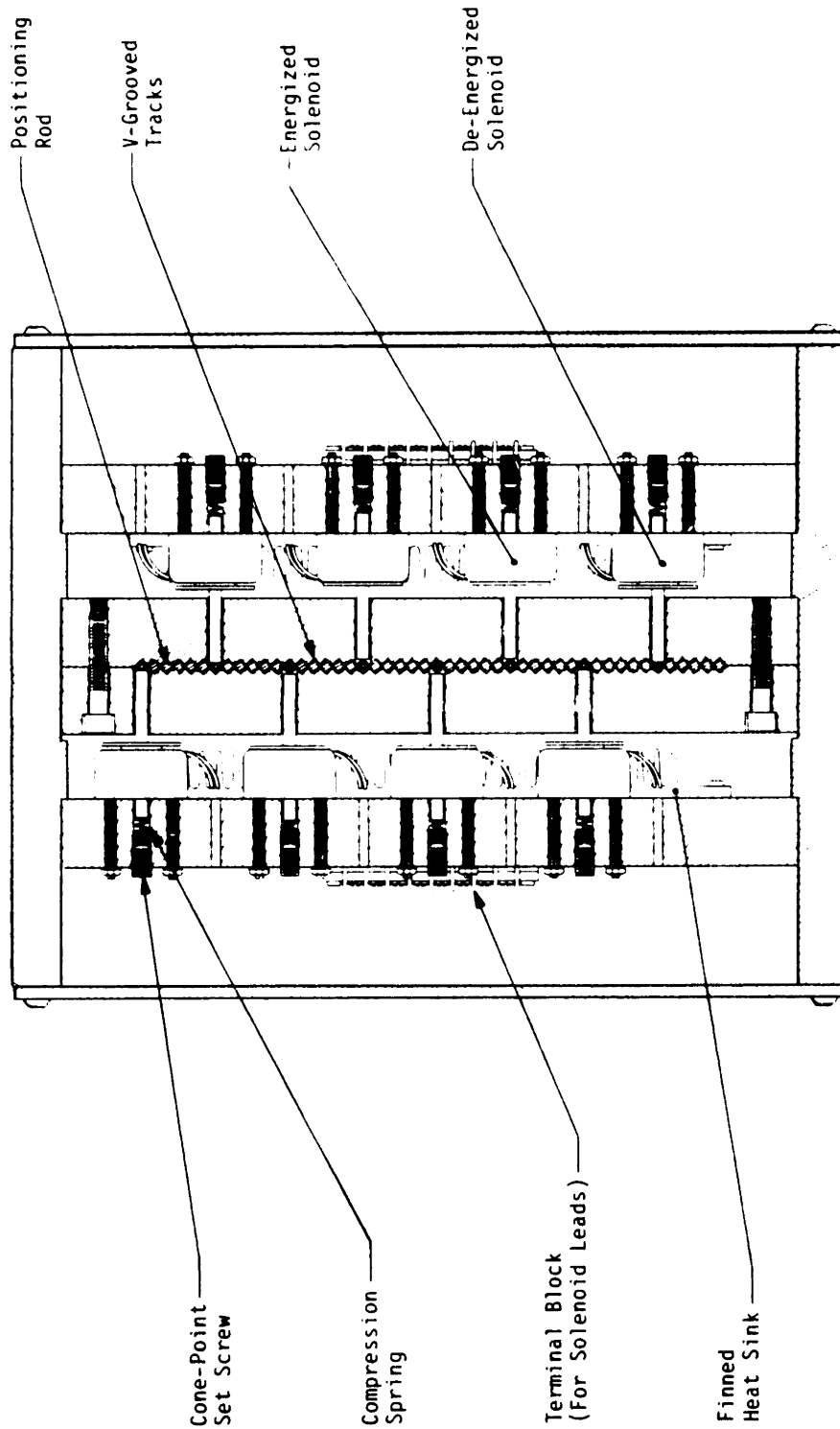


Figure 2.15 Solenoid Housing (Cross Section View, B-B) [9]

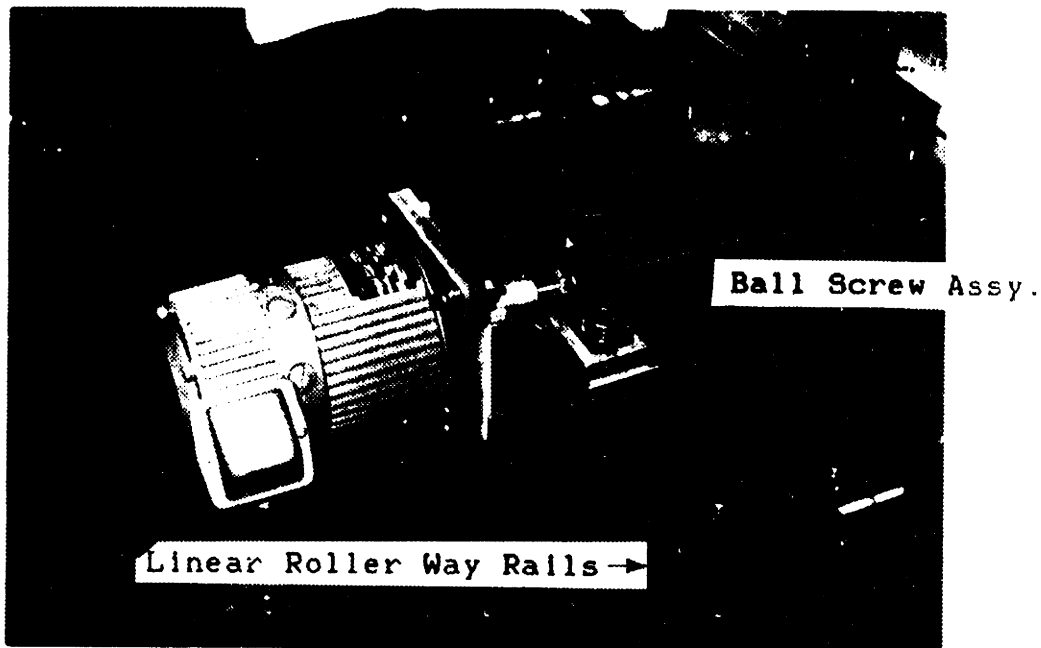


Figure 2.16 Motor, Mount and Linear Roller Way Configuration

Step 2. The active die pins are then clamped. The passive die pins are unclamped and the flat active die surface is pushed flush against the passive die pin using a steel plate between them to reduce pin splaying (See Figure 2.20).

Step 3. The passive die flat surface is pushed forward through the press end plate to just in front of the die pin positioning system. The active die is unclamped. The dies are now ready for their discrete surface development. Because of allowances for sheet metal thickness and rubber thickness, each die surface will be different. Also, due to the press physical arrangement, it's necessary to set the active die surface first, through the passive die. There are two ways to do this.

Set Up A

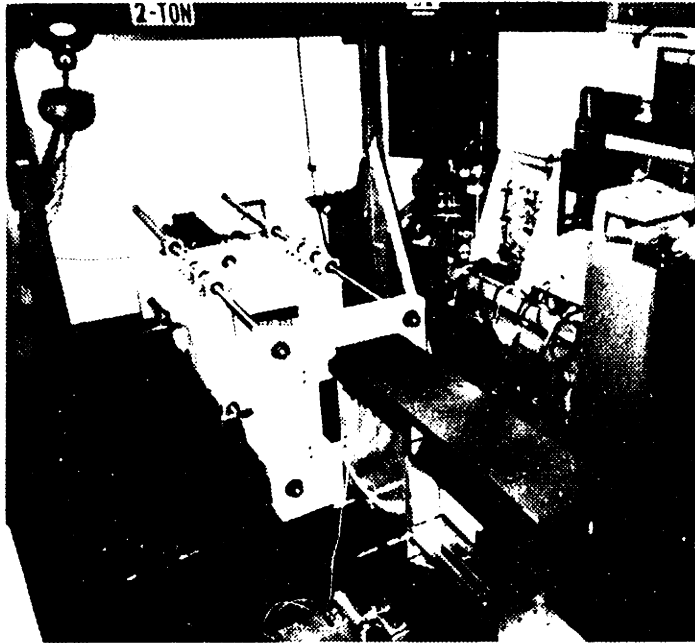


Figure 2.17 Variable Configuration Die Forming Machine

Step 4A. Align the active and passive dies (unclamped) in tip-to-tip registration. The positioning rods are set into the desired profile and imparted into a column of passive die pins and simultaneously into a column of active die pins.

Step 5A. Once set to the desired depth, the positioning rods are retracted and the die pin positioning system is incremented over to the next column of die pins. If needed, the positioning rods profile can be automatically reset to a new profile, locked into place and imparted into the new column. This process is repeated until the entire active die surface has be set.

Step 6A. The dies are separated and a flat steel plate is inserted between the two dies.

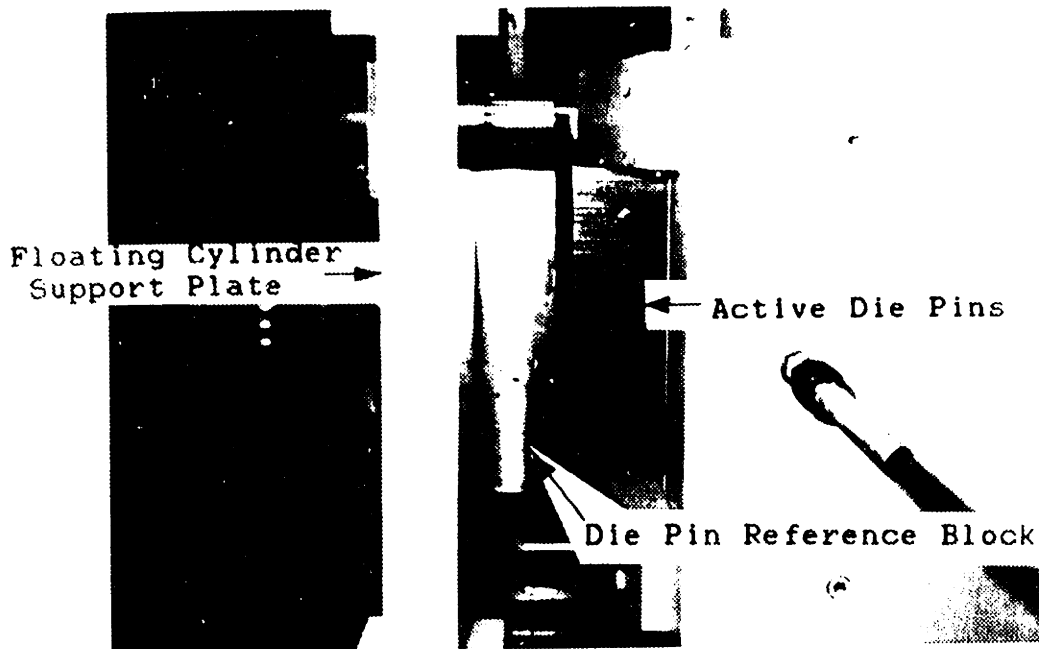


Figure 2.18 Active Die Pins Against Die Pin Reference Block

Step 7A. The active die pins are hydraulically clamped and pushed against the plate into the passive die pins to reset the passive die to its original flat surface in front of the die pin positioning system.

Step 8A. The passive die pins are positioned by the die pin positioning system as in Step 4A.

Set Up B

Step 4B. The active die is separated from the passive die by at least the desired formed part depth.

Step 5B. The die pin positioning system imparts the entire active die pin contour into the unclamped passive die.

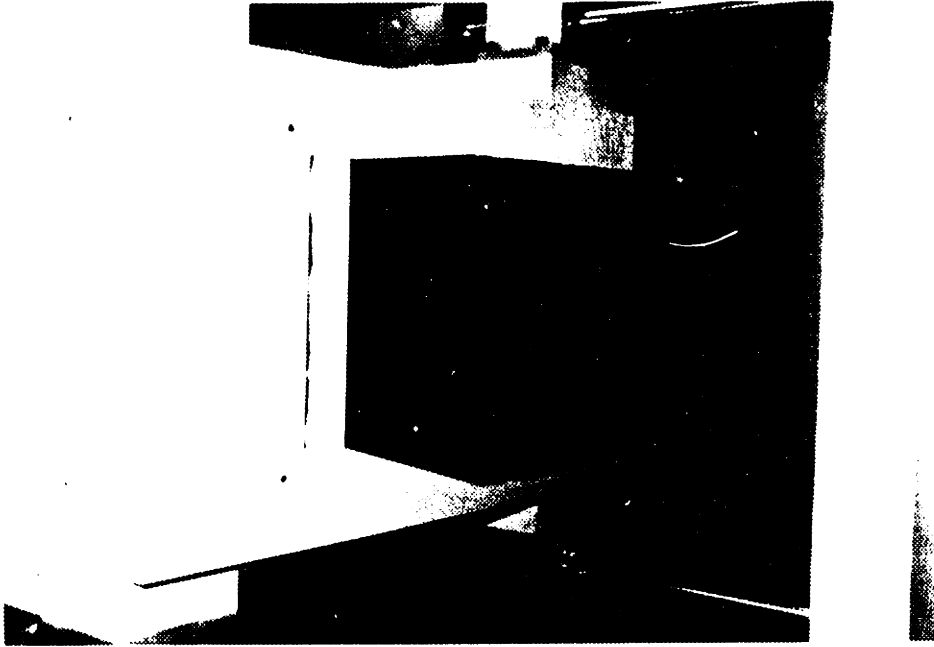


Figure 2.19 Active Die Pin Flat Surface

Step 6B. The passive die, with the active die pin contour, is clamped and the flat active die surface is pushed against the passive die, transferring its shape into the active die (See Figures 2.21, 2.22).

Step 7B. The active die with its desired die contour is clamped and the set up of the passive die follows that of Steps 6A-8A.

Criticisms of both methods.

In Set Up A, tip-to-tip registration is difficult since the die pins are spherically tipped. The pins tend to splay outwards, especially those on the die pin matrix outer edges, when trying to move the die pins. Figure 2.23 shows an example of a pin splaying. With Set Up B, the pins come together in a group and are more likely to support one another, reducing the chance to buckle. Both set up methods are victims of bent and

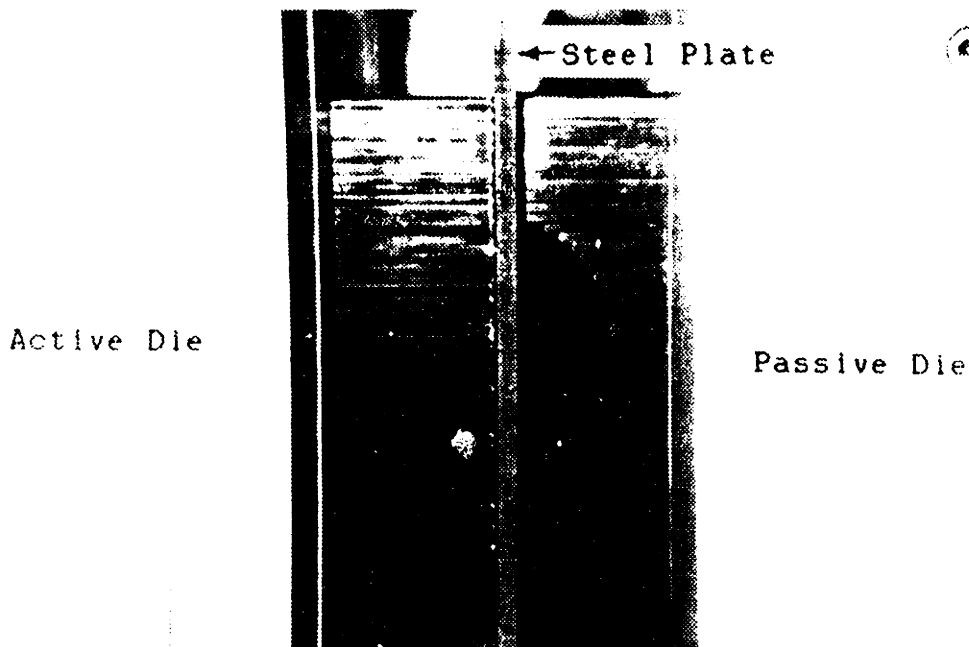


Figure 2.20 Resetting Passive Die

warped die pins which cause pins to stick and move together while being set up. Figure 2.24 shows die pins marked in white that moved during the forming operation. The pins were removed, found to be grossly warped, straightened and repositioned in the die. After subsequent forming tests, no movement was observed by these pins. More discussion of these problems will be made in Chapter 3, Design Modifications.

2.2.2 Positioning Rod Profile Set Up

A future goal of this project would be to have a CAD system incorporated with this machine. The operator could design a 3-D part and the CAD package would discretize that surface, figure out the desired pin locations and download this to the die pin positioning system controller to make the first set of discrete dies for that part.

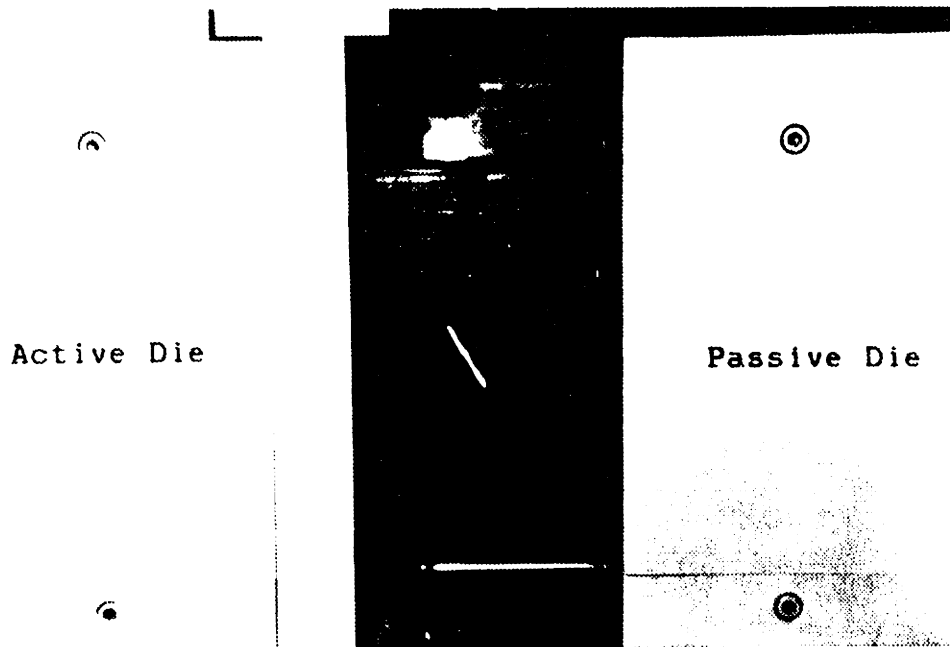


Figure 2.21 Transferring Active Die Surface with Passive Die (1)

The concept of contact points and force as related to the discrete surface plus the rubber pad effects and its distributed loading, poses some interesting problems. Webb [4] did some work on surface patch representation for the CAD interface problem and the use of closed loop control theory and part shape measurement seems to be a possible solution to the rubber pad effect.

Currently, the positioning rods must be positioned manually. The first experiments have been simple curves for 2-D bending analysis (See Figure 2-25). Programs, (Pin-height.pas, Height3d.pas, and Width3d.pas included in Appendix B), were written to calculate the positioning rod location for each passive and active die configuration. As mentioned earlier, these programs must calculate the positioning rod position by taking into account the material thickness and the compressed rubber thickness. This situation can be seen in Figure 2.26.

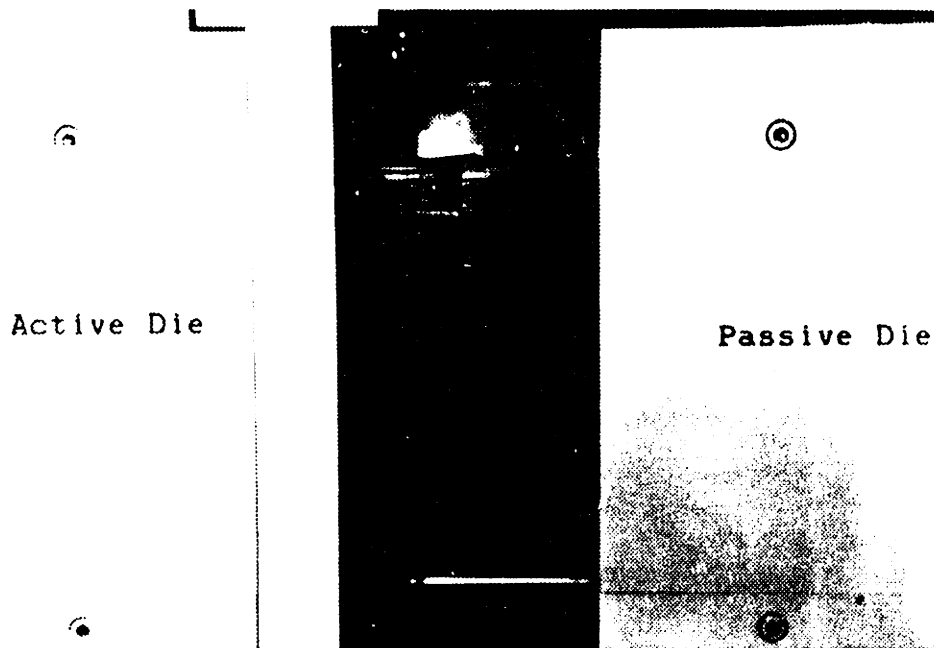


Figure 2.22 Transferring Active Die Surface with Passive Die (2)

From Webb [4], the rule of thumb on the rubber interpolating pad thickness should be on the order of the pin spacing, or 0.25 inch. The rubber will compress under load and it is necessary to find its compressed thickness that the metal sheet and the die pins will see. To find the compressed thickness, both die surfaces were reset flat, two 12" x 12" x 0.25" thick rubber pieces were attached, one on each side, to a sheet of forming material and set between the two die surfaces. The two die halves were brought together under full forming force and a linear encoder attached to the active die was used to help calculate the compressed rubber thickness. The average compressed rubber thickness was found to be 0.18 inches. This value is used in figuring out the pin locations and is basically a radius offset.

It is worthy to note, in Figure 2.26, the steep sides of the formed part and the low number of pins in this area versus the higher pin number in the center section.

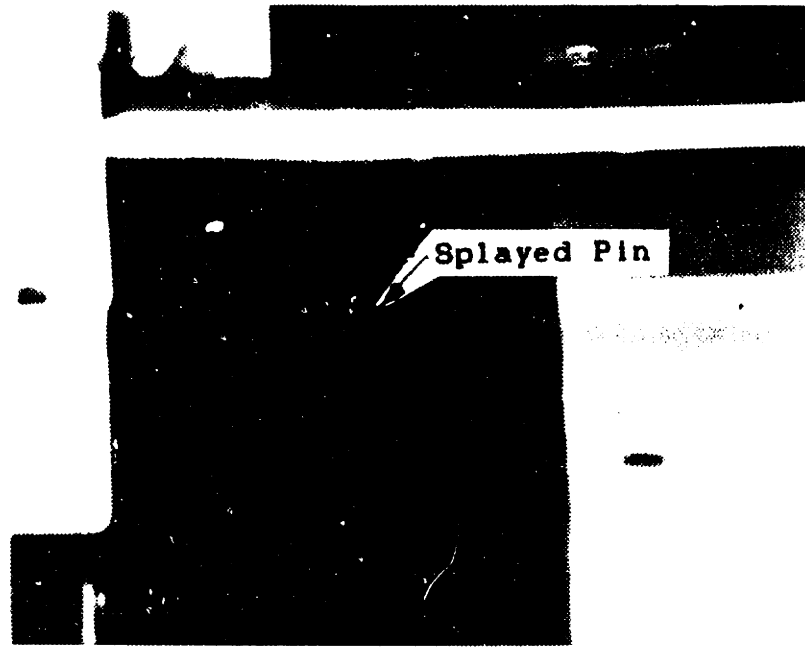


Figure 2.23 Splayed Pin

This is a limitation of a discrete die and its forming capabilities. Webb [8], did some work on the spatial frequency analysis of part and die shapes, and further work in this area as related to the discrete die will be beneficial. Also note that by using the rubber interpolating pads, the formed parts parting lines are not distinct as those from a continuous die. Some possible solutions might be some dedicated die pin arrangement with smaller more discrete die pins along the flange area or some sort of continuous die band to form the parting surface. These characteristics will be discussed in more detail in the following chapters.

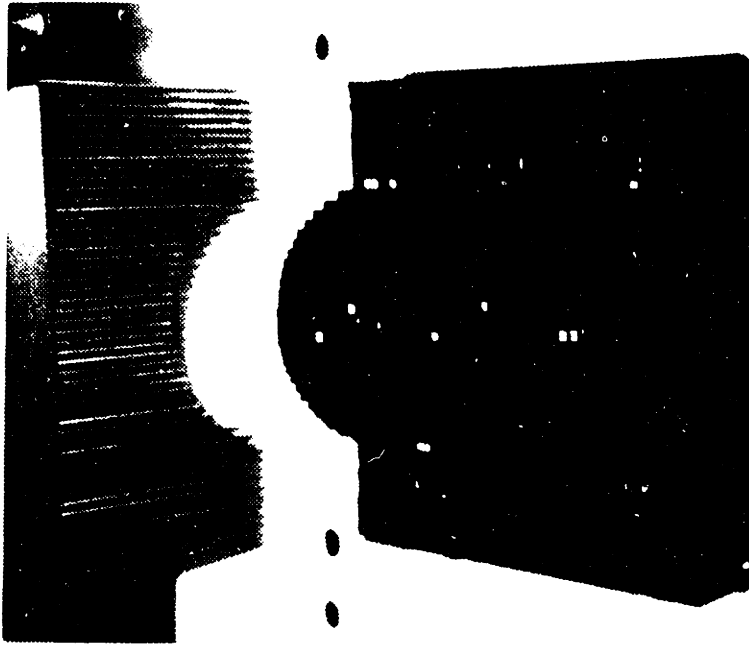


Figure 2.24 Pins Marked for Movement after Forming

2.2.3 Forming a Part

The material used for all experiments was S1010 LS steel, 0.036" thick, 12" x 17.7" for 2-D bending, and 17.7" x 17.7" for 3-D forming. The rolling direction was along the longest side for the 2-D experiments and perpendicular to the bending axis. The forming of a part will be explained with the 2-D bending experiment as an example.

Part lubrication came from wiping the packaging lubrication around to a consistent film on both sides of the part. Once lubricated, the part is placed into the blankholder. The sheet metal rests on the bottom bolts and is centered in the blankholder opening. The bolts are tightened down to a prescribed torque with a torque wrench to create the binding force. The rubber interpolating pads are placed on both sides of the sheet metal. The part is ready to be formed, the variable configuration die hydraulic rams are

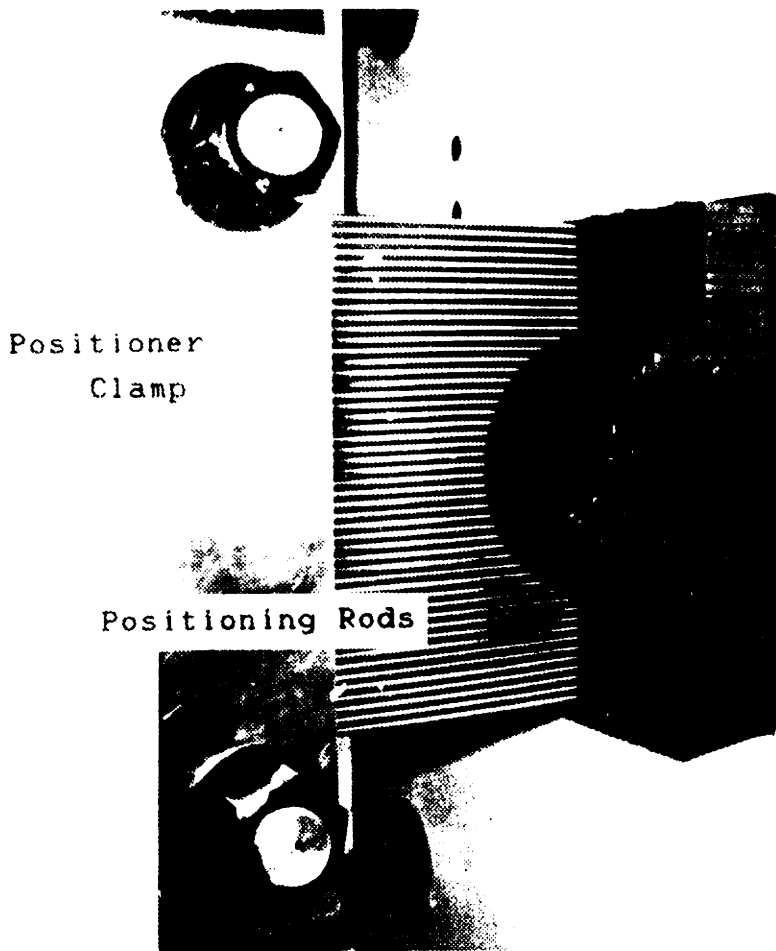


Figure 2.25 Positioning Rod Profile Set into Die Pins

activated, clamping the die pins to form two solid discrete dies, and the hydraulic press cylinders are activated to do the forming. One problem, that will be further discussed in Chapter 3, is that the rubber on the female die side tends to get stuck and flow is restricted during the forming sequence. This is a result of the rubber getting pinched between the sheet metal and the outer die pins that make up the parting surface. Once this happens the rubber begins to stretch and shear, losing its interpolating properties, and some pins come in direct contact with the sheet metal. One solution is to put as much of the rubber sheet into the female die cavity so the rubber will have enough to

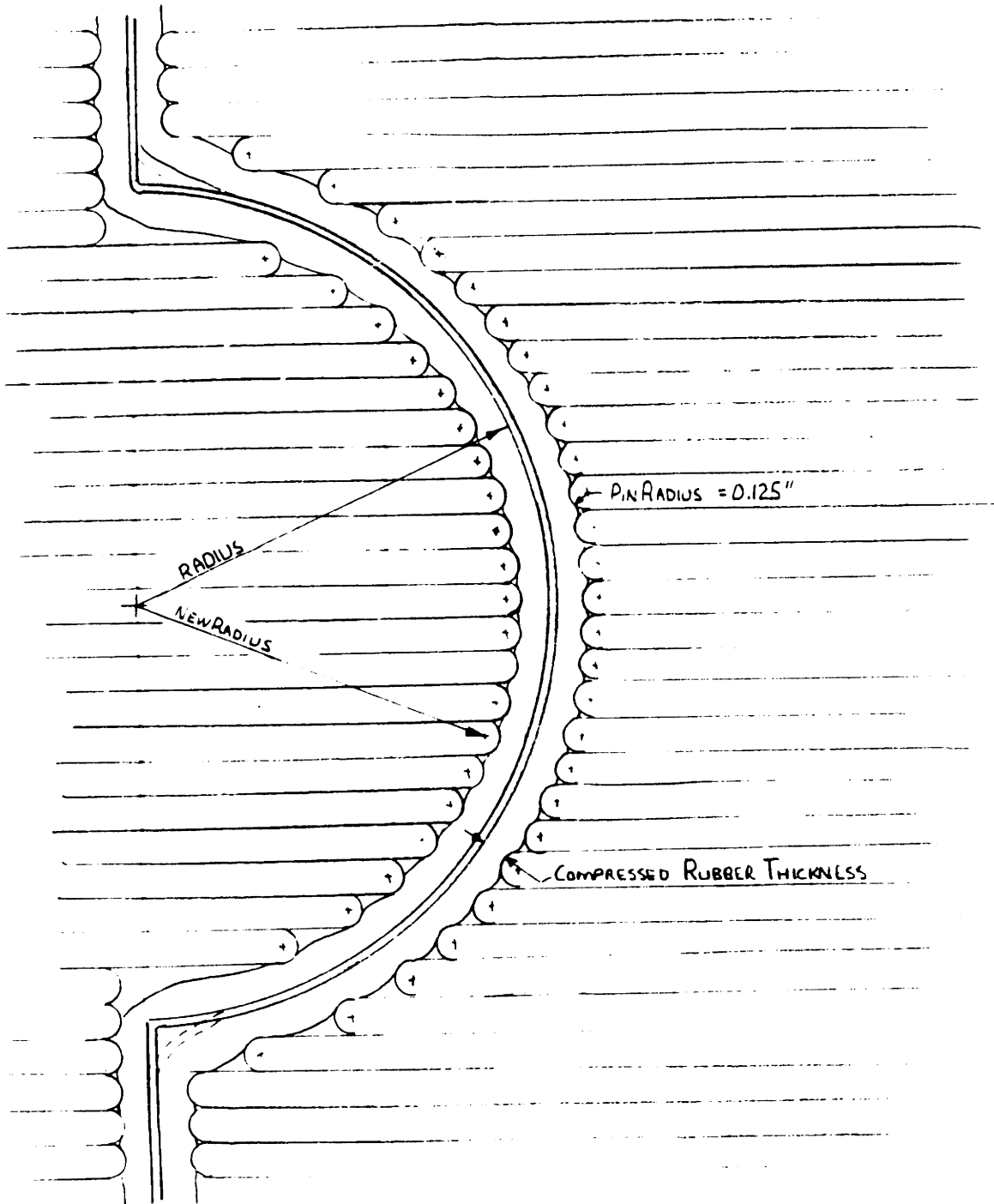


Figure 2.26 Example of Pin Height Calculation

Chapter 2: Variable Configuration Die Forming Machine

flow when it gets bound at the parting line. Figure 2.27 shows the blankholder with the metal inside it plus the rubber sheets in position. Figures 2.28 - 2.31 show a forming sequence.

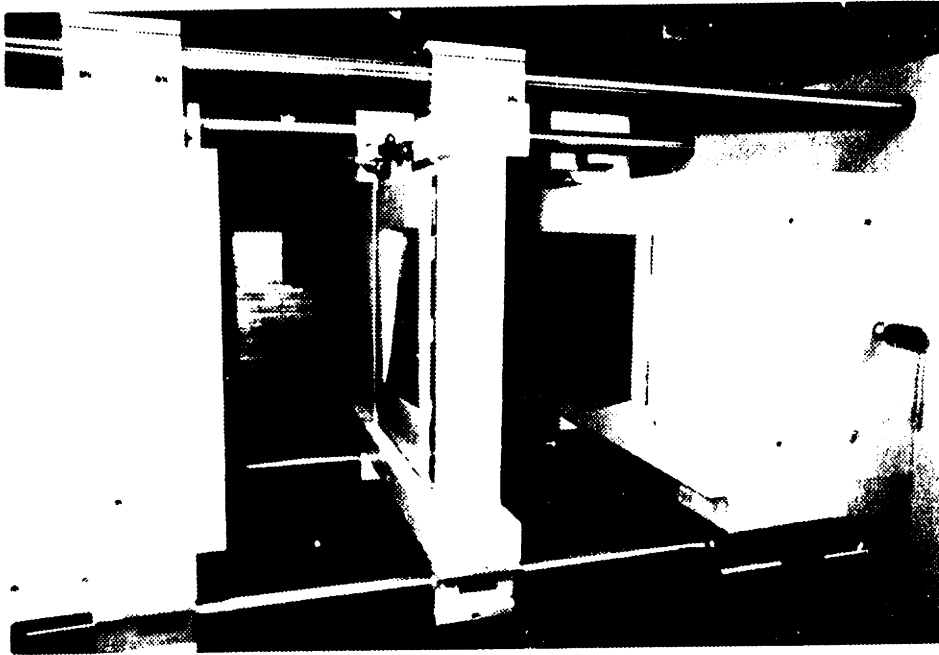
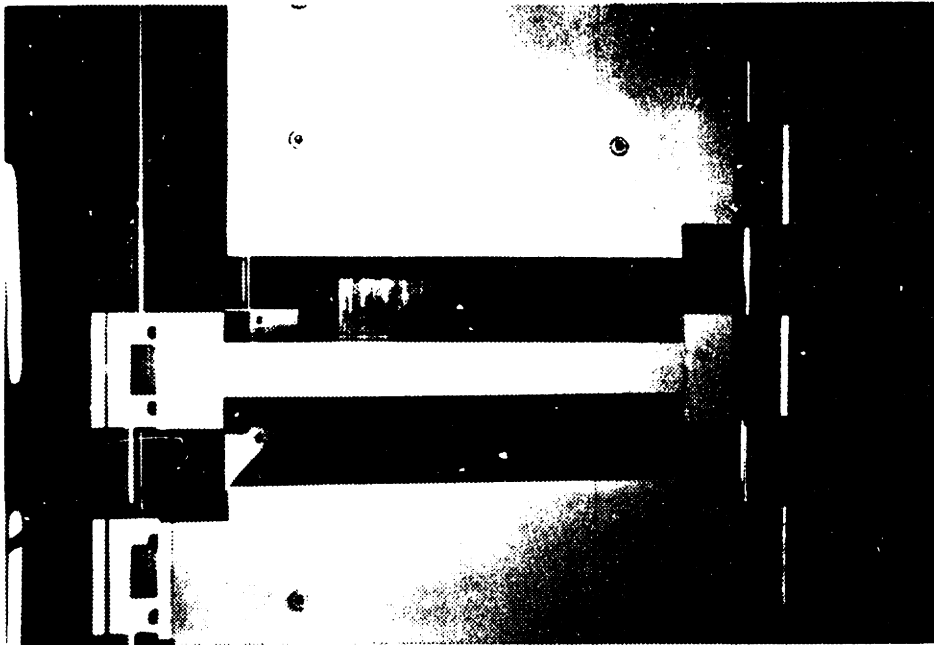


Figure 2.27 Blankholder with Sheet Metal (Ready to Form)

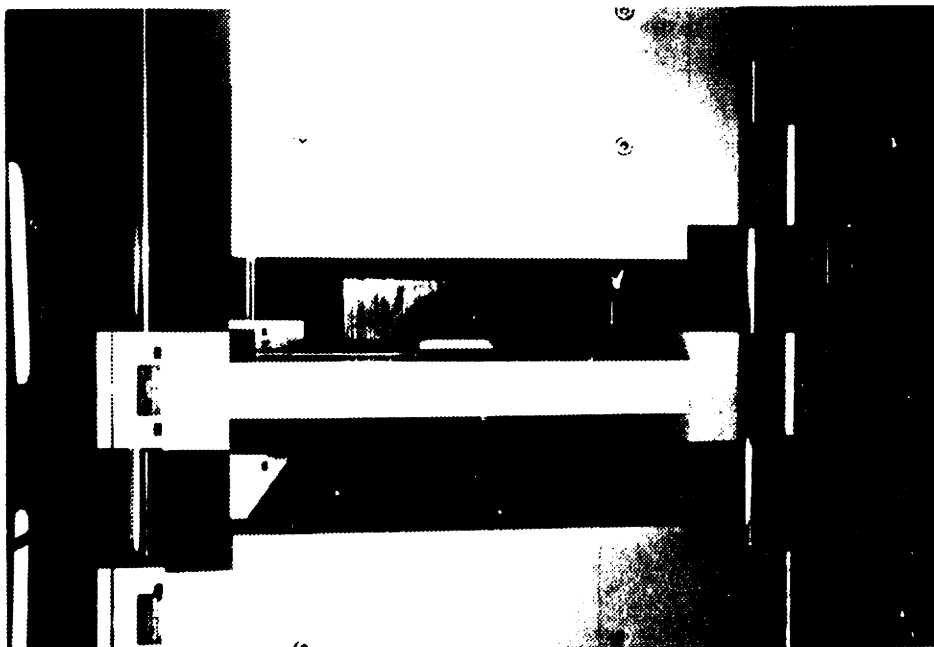
Once formed, the part is removed from the blankholder and readied for measurement. Part measurement is needed in order to use close-loop control and have a shape feedback measurement as part of the loop.

2.2.4 Measuring a Part

The Coordinate Measuring Machine (CMM) used for this project is a mix of components from a previous CMM and a Bridgeport milling machine upgraded with DC motors to power the feeds (See Figure 2.32). The part to be measured is put on the

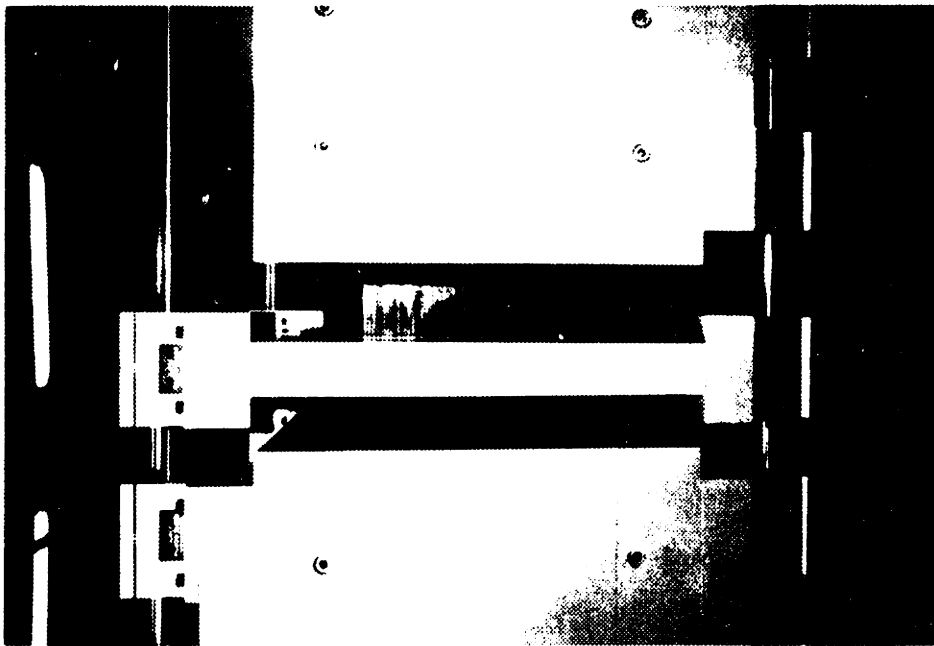


(2)

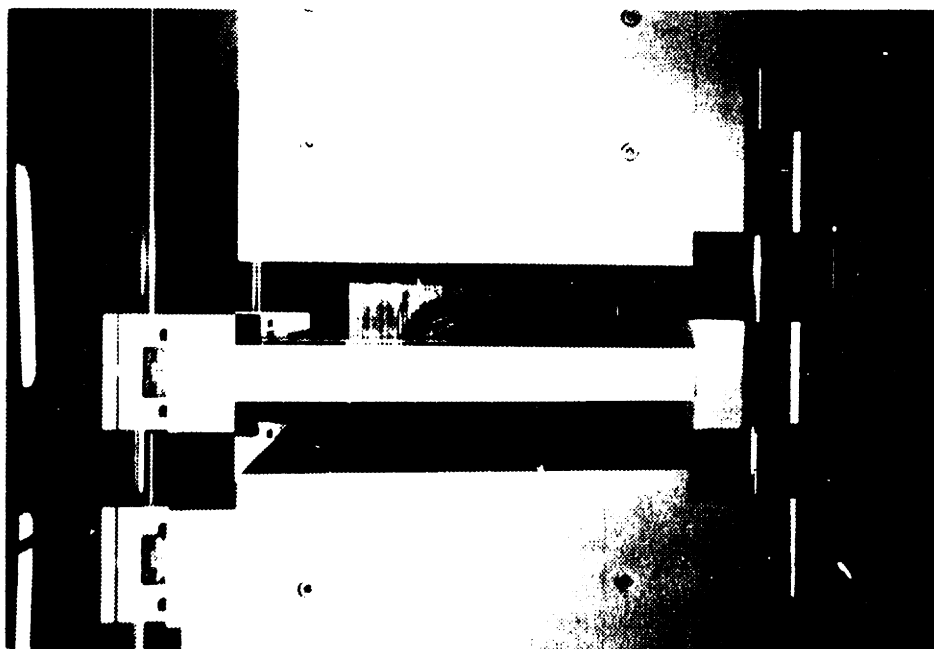


(1)

Figure 2.28 Forming Sequence (1,2)

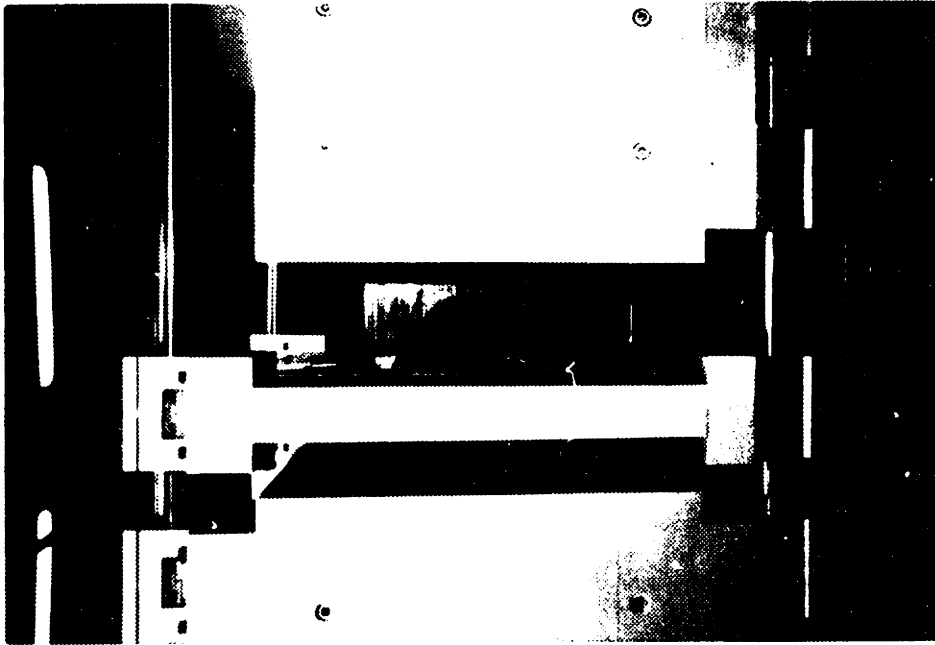


(4)



(3)

Figure 2.29 Forming Sequence (3,4)

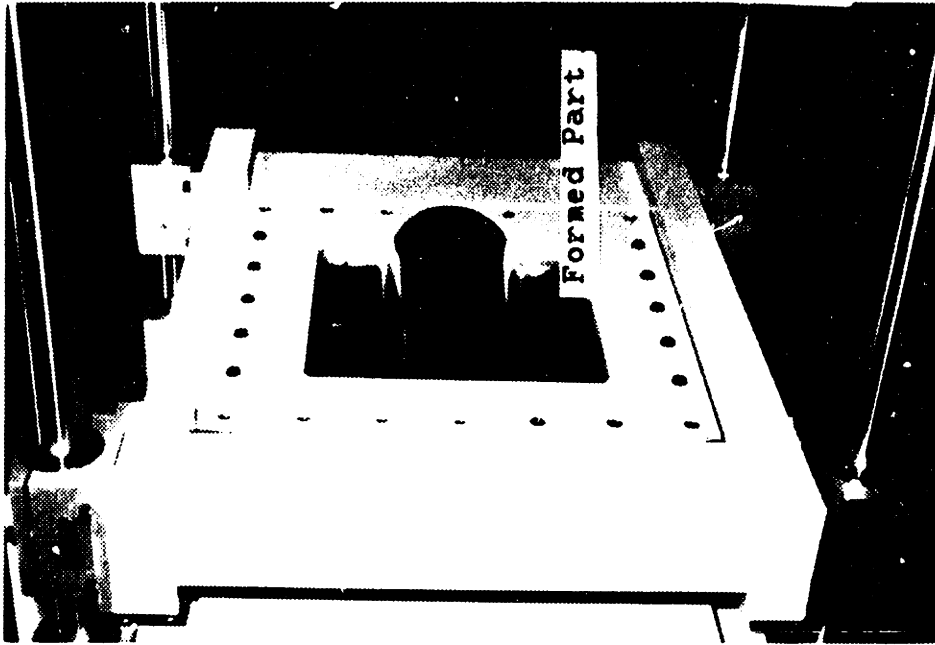


(6)

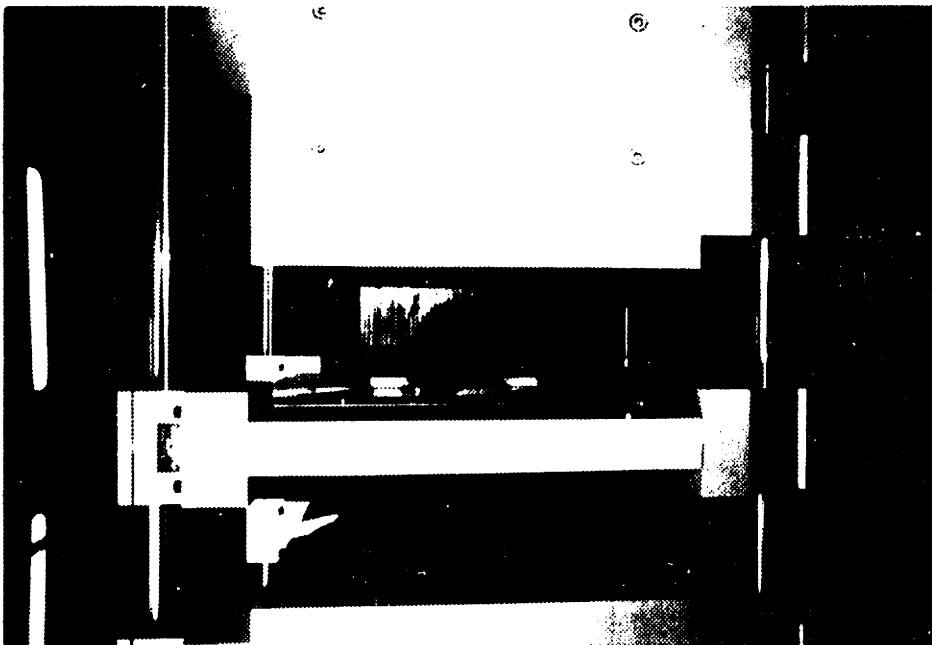


(5)

Figure 2.30 Forming Sequence (5,6)



(8)



(7)

Figure 2.31 Forming Sequence (7,8)

Chapter 2: Variable Configuration Die Forming Machine

CMM table and clamped into position. The program CMM1.pas controls the CMM, measures the part and stores the 3-D data array in an XYZ format.

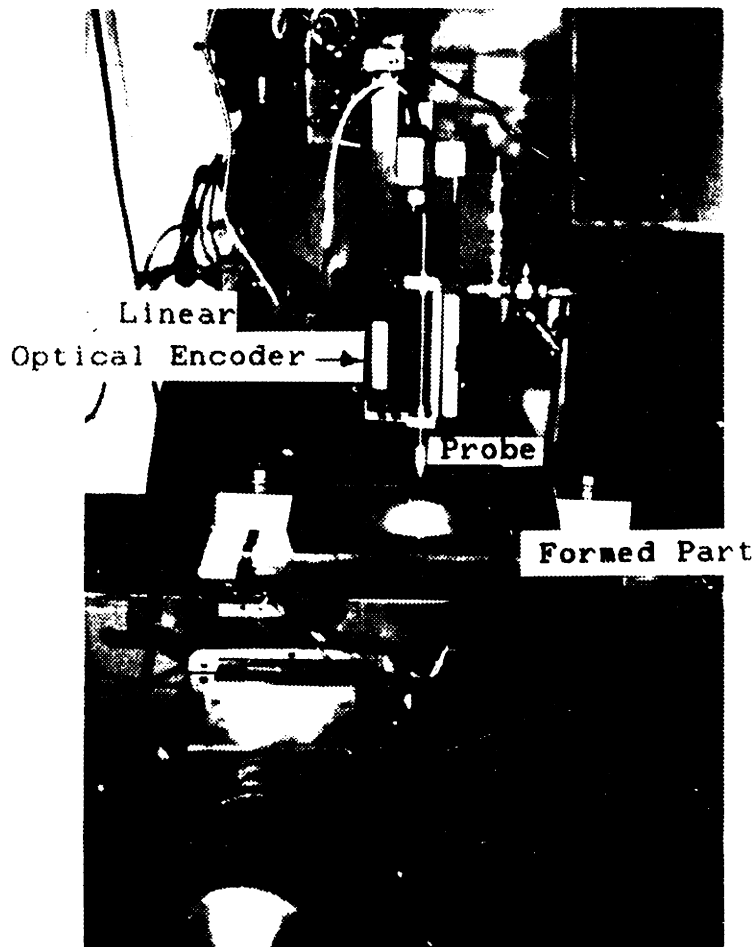


Figure 2.32 Coordinate Measurement Machine

The accuracy of the CMM is dictated by the linear encoder mounted to the measurement probe. The encoder's accuracy is $+0.0005$ inches. The true accuracy of the CMM lies in the degree of force the probe comes into contact with the part. Presently, the system is pneumatically operated with on-off solenoids, and the probe actually

Chapter 2: Variable Configuration Die Forming Machine

peens the workpiece as it contacts to measure the part. Future work on an upgrade of this CMM utilizing some sort of force controlled probe is pending.

An explanation of experiments and the data generated can be found in Chapter 4, Experiments.

2.3 Upgrade of Current System

The Variable Configuration Die Forming Machine is operable but not under optimum design conditions. The hydraulic set up used is currently rated at a maximum system pressure of 1500 psi. The VCD forming machine was designed to run at 3000 psi., so presently the forming force is approximately 30 tons (60,000 lbf.) instead of the designed 60 tons (120,000 lbf.). The desired set up utilizes a 30 GPM pump at 3000 psi. with solenoid valves controlling all the hydraulic cylinders and rams.

The four solenoid housing plates will be fabricated soon, giving the ability for computer controlled profile shape generation.

Design Modifications

The Variable Configuration Die Forming Machine is the product of over eight years of research and development, but only recently has there existed a full scale functional prototype. In initial tests, certain characteristics of the machine and forming processes were noted to be possible problems for future development. Design modifications were made to the machine in an effort to solve these problems. The following sections will describe these problems and the chosen modifications. Though some of the problems are strictly design problems and were solved by alternative designs, the interesting problems are those that are directly related to the nature of this new forming technique and are definite characteristics of this particular machine.

3.1 Positioner Clamp Assembly

The positioner clamp was designed to maintain positioning rod spacing and alignment plus provide two levels of clamping force during the two modes of operation. Figure 3.1 shows the first positioner clamp assembly. The two compression springs push the pressure plate against the positioning rod array for a continuous low-level clamping force of 2,944 lbs., while the three hydraulic rams provide a high-level clamping force of 20 tons (40,000 lbs.) each at 3000 psi. The positioning rod spacing and alignment is provided by V-grooved tracks milled into the clamp frame side plate.

Three problems were noted when the positioner clamp was assembled and installed in the die pin positioning system. The first problem was that the positioning rods, when

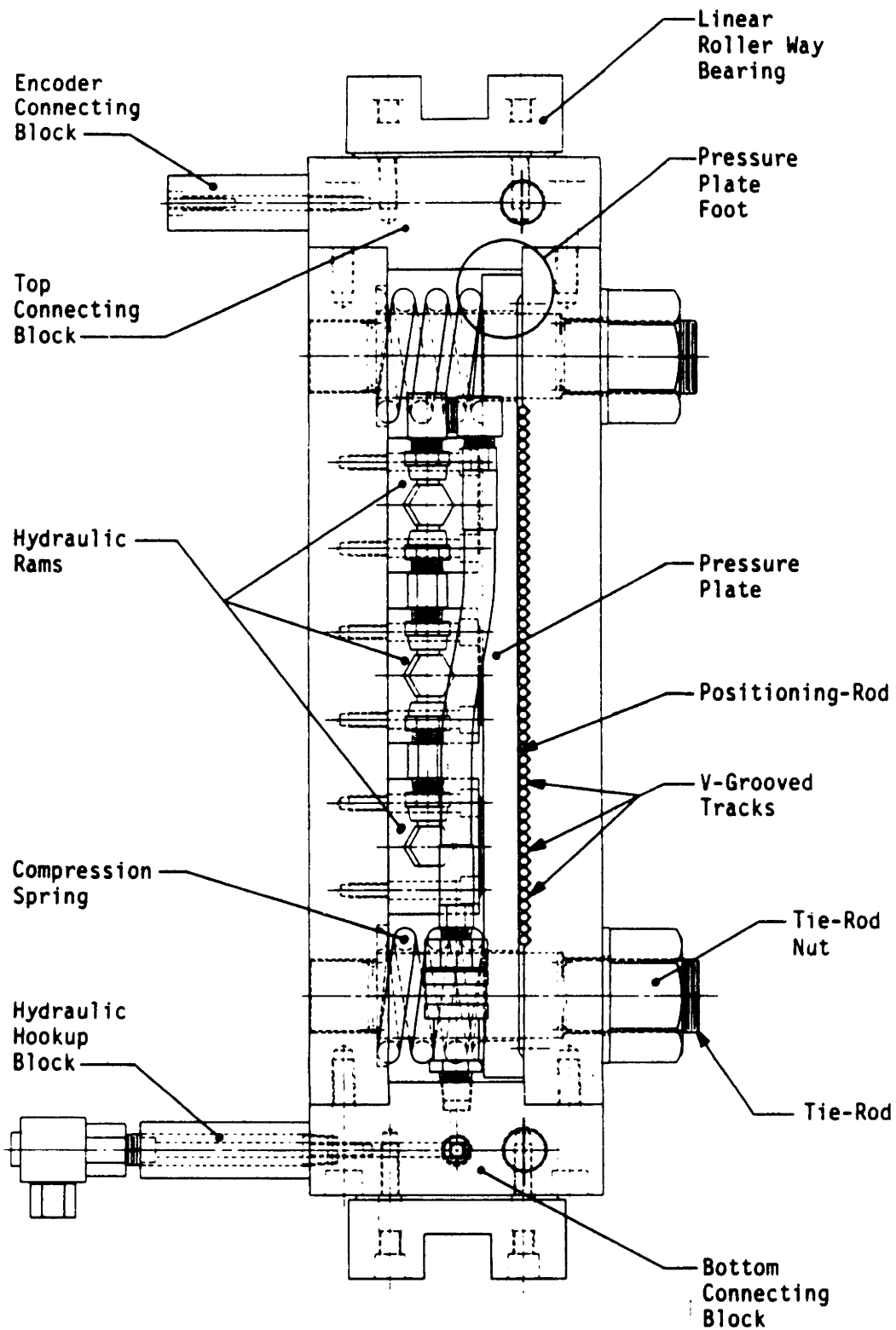


Figure 3.1 Positioner Clamp [9]

Chapter 3: Design Modifications

under the low-level clamping force from the compression springs, would not move easily as was needed during automatic positioning by the solenoid housing. Another problem observed was that once moving, the rods were shaved and burred by the sharp edges of the V-grooved and pressure plates. Shims were added under the pressure plate feet to give more clearance but proved to be unsuccessful. The third problem was that some positioning rods moved when transferring a profile into the passive die pin column while the clamp was under full pressure. This problem could be a result of unequal force distribution from machining flaws of the pressure plate or V-grooves to out-of-tolerance positioning rod diameters. It was decided to disassemble the positioner clamp, grind down the sharp edges of both pieces and then try possible solutions.

The positioner clamp hydraulic rams are single-acting, (hydraulic force in one direction, spring return in the other), when unclamped, the pressured plate will not retract due to the compression spring force. One solution, deemed not feasible, would be to redesign the positioner clamp using double-acting hydraulic cylinders with the pressure plate attached. Force control of the clamping force would then be possible. The next option was to look at the necessity of the compression spring force. With the compression springs removed, an approximate 1/16" space existed between the pressure plate and the retracted rams. A 1/16" thick rubber sheet was attached to the inside pressure plate surface that contacts the positioning rods (See Figure 3.2). When unclamped, the rubber compression due to clearance would provide the necessary force to keep the positioning rods in alignment and in the V-grooves. The force needed to reposition the rods was greatly reduced and found to be low enough for the solenoids during automatic positioning. Once clamped, the rubber distributes the clamping force over more positioning rod area, and with its low shear modulus, the shear force encountered

by the positioning rods will be transmitted to the V-groove plate. No positioning rod motion has been detected during profile transfer.

This design modification has greatly simplified the positioner clamp assembly. The condition of the rubber sheet must be regularly monitored and lubrication of the positioning rods and rubber is recommended.

3.2 Bevelled Tipped Positioning Rods

The original positioning rods called for a 0.030" x 45 degree cylindrical chamfer on the tips that address the passive die pins. The problem is that many die pins are bent and warped, causing improper vertical registration and alignment between the positioning rods and die pins. The solution chosen was to bevel the positioning rod tips, decreasing the tips contact area but increasing the chance to get proper registration. See Figure 3.3 for a sketch of the problem and solution. This reduction in tip contact area causes an increase in the positioning rods' bearing stress, but due to the low forces seen by the positioning rods during profile transfer, it was found to be acceptable.

The bent and warped die pins will show up in other problems discussed in this chapter and are truly characteristics peculiar to this forming machine. Some possible solutions are to purchase a new set of 4032 pins that are straight, a very expensive solution, or remove all the pins and straighten them, a very time and labor intensive solution. The bevelling solution addressed the positioning rod/die pin alignment problem quickly and effectively.

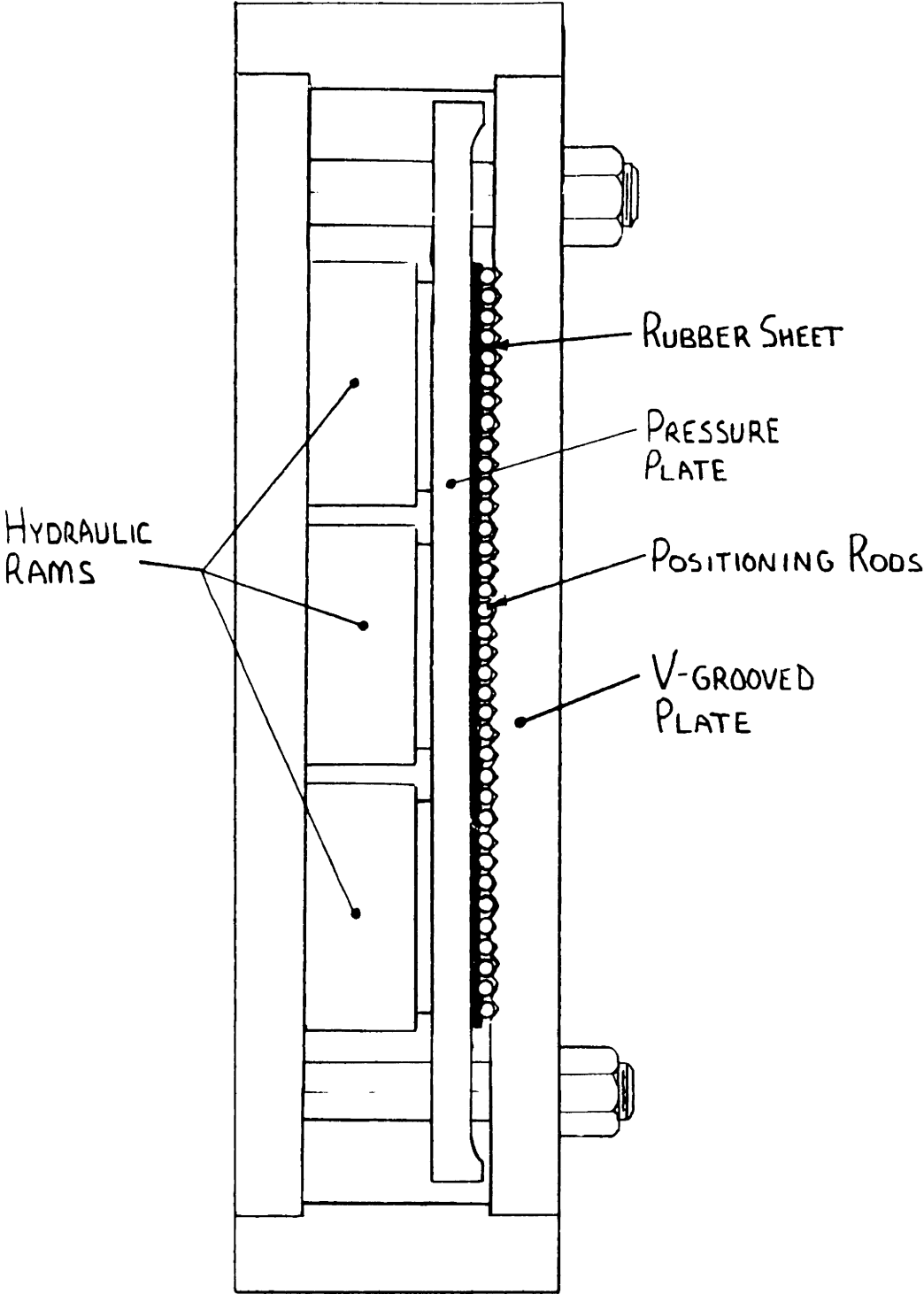


Figure 3.2 New Positioner Clamp Assembly

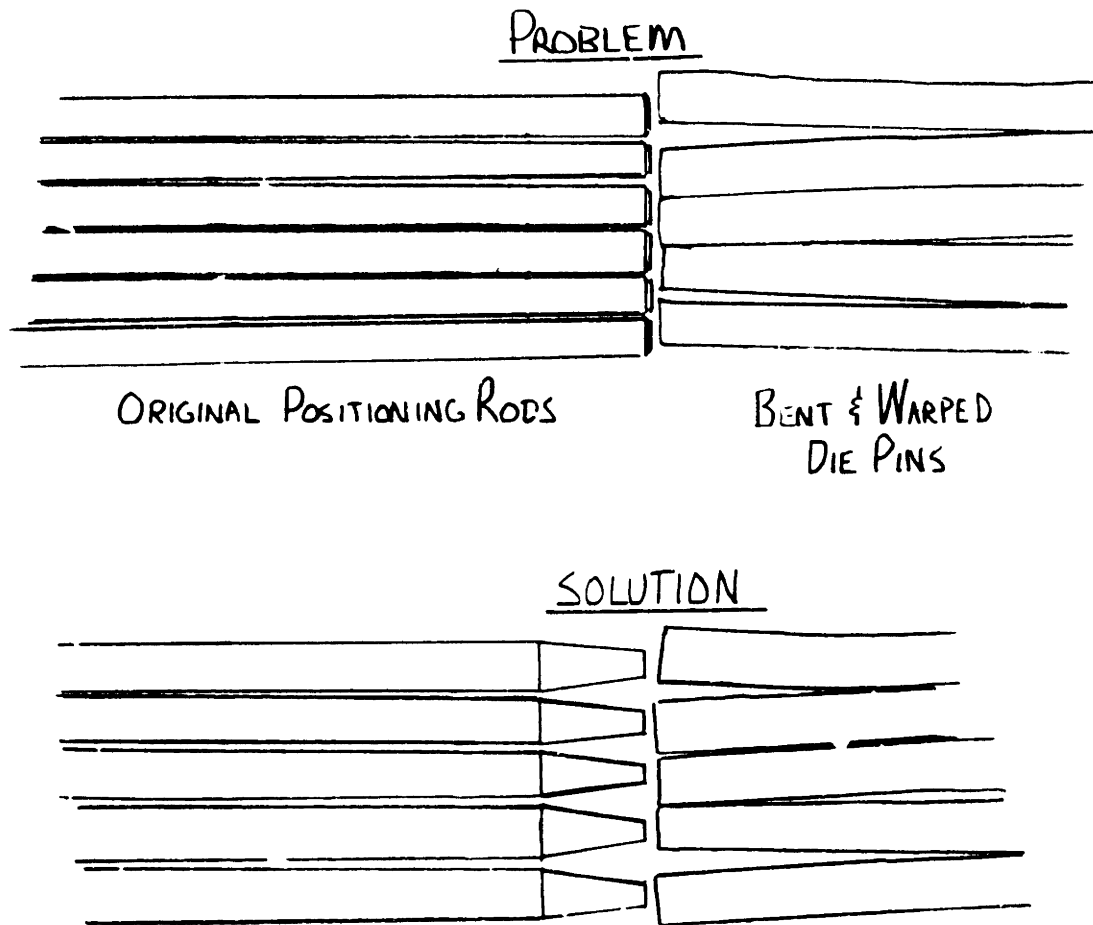


Figure 3.3 Bevelled Positioning Rod Tips

3.3 Bent and Warped Die Pins

This section deals with the overall problem of bent and warped die pins in both die halves. This problem has lead to trouble with pin alignment and registration as seen in the previous section. Another problem is pin placement and location when comparing the desired die surface representation to the actual die half surface. In the present die half configurations the die pins have room to laterally bend against each other, the actual pin locations during forming are then unknown and the concept of closed

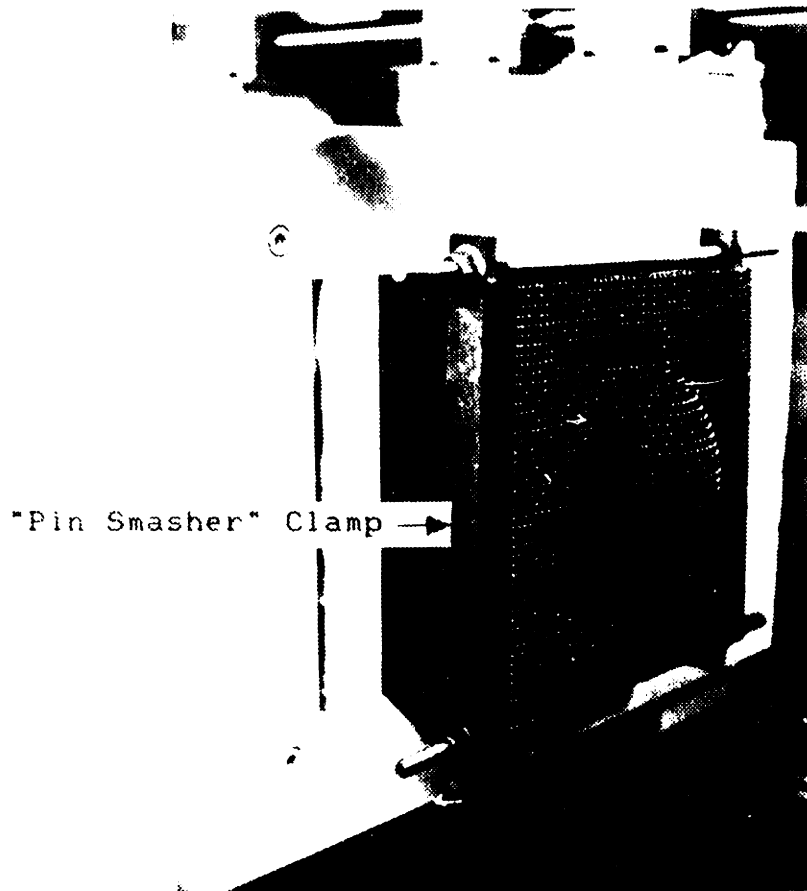
loop control and shape error measurement becomes prone to errors. What is needed is some way of insuring side-to-side die pin registration during the forming operation. With the proper profile depths transferred to the die halves by the die pin positioning system, and side-to-side pin registration, the locations of the die pins would be defined. A combination of two solutions will be described in the following sections.

3.3.1 "Pin Smasher"

The die pin arrays of the die halves consists of 42 columns of 48 die pins. The 48 die pins are stacked on top of each other, while the 42 columns are separated by a 0.030" thick sheet metal spacer. The die pins are made from 1/4" square keystock giving a forming surface height of 12" (48 pins x 1/4"), and a forming width of 11.73" (42 pins x 1/4" + 41 spacers x 0.030"). The spacer thickness allows the extended bent and warped die pins freedom to laterally contact surrounding pins causing misalignment.

A preliminary solution was to build a set of clamps to smash the pins together in the lateral direction to reduce the forming width by 1.23" (41 spacers x 0.030") to 10.5" (42 pins x 1/4"). This would remove all die pin spacer effects and all die pins would be in side-to-side registration. The clamps were made of steel flat stock and threaded tie rods to develop the clamping force (See Figure 3.4).

The initial die pin extensions from the forming sides of the die halves had been on the order of the part depth or a maximum depth of six inches. This created problems for the "pin smasher" to create enough force to clamp together the die pins, especially since the outside die pins had to be bent in 0.615" (1.23"/2) over this short six inch extension.



"Pin Smasher" Clamp →

Top View

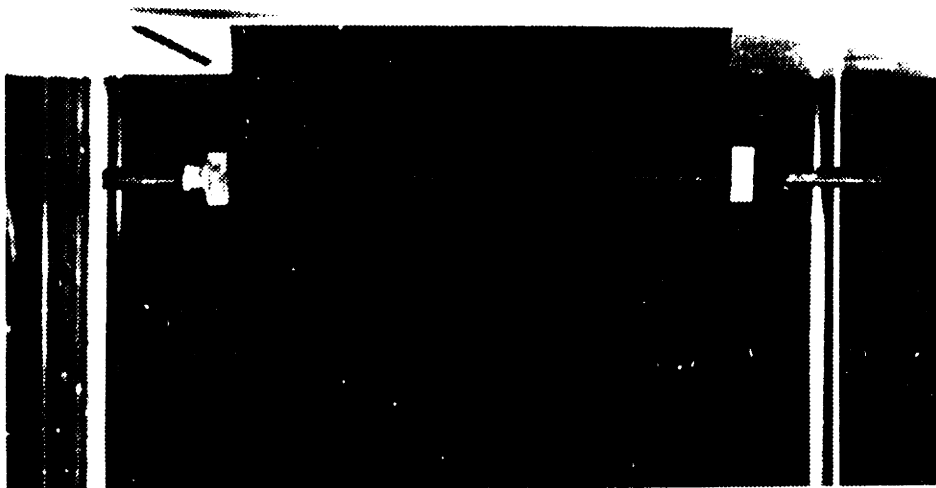


Figure 3.4 "Pin Smasher" Clamps

Chapter 3: Design Modifications

It was decided to extend the die pins as far out in front of the die halves as possible (approximately 10"). When unclamped by the pin smasher, the extended die pins gave the effect of two floppy die halves, another interesting characteristic of this machine. This extension would reduce the clamping force needed to bend the die pins inward, but will reduce the maximum forming depth due to initial machine design and the reduced hydraulic cylinder forming stroke. When clamped, the "pin smasher" could not generate enough force to clamp all the pins together. A forming width of 11" was reached (over half the pins are in side-to-side registration), although not the optimum 10.5", this width was used in experiments to determine the feasibility of a more permanent "pin smasher".

The first experiment used Set Up B, as describe in Section 2.2.1, Chapter 2. The active die surface was imparted on the passive die and the "pin smasher" clamps were used to insure tip-to-tip registration as this surface was transferred. The initial evaluation looked promising, only eight die pins (out of 2016) were obviously out of position in the active die once the shape was transferred. This can be accounted for by the bent and warped nature of these die pin upon removal. A future test using Set Up A will be conducted and will be described in more detail in the next section.

One problem noticed in the previous experiment was that the top and bottom rows of die pins tend to splay outward as in Figure 2.23. A clamp or restraint for the top and bottom die pins must also be incorporated in a permanent "pin smasher" addition. A permanent "pin smasher" has been designed and could be an attachment to the present blankholder with few revisions. The "pin smasher" attachment would use a bevelled plate to smash the die pins inward at the forming joint (See Figure 3.5).

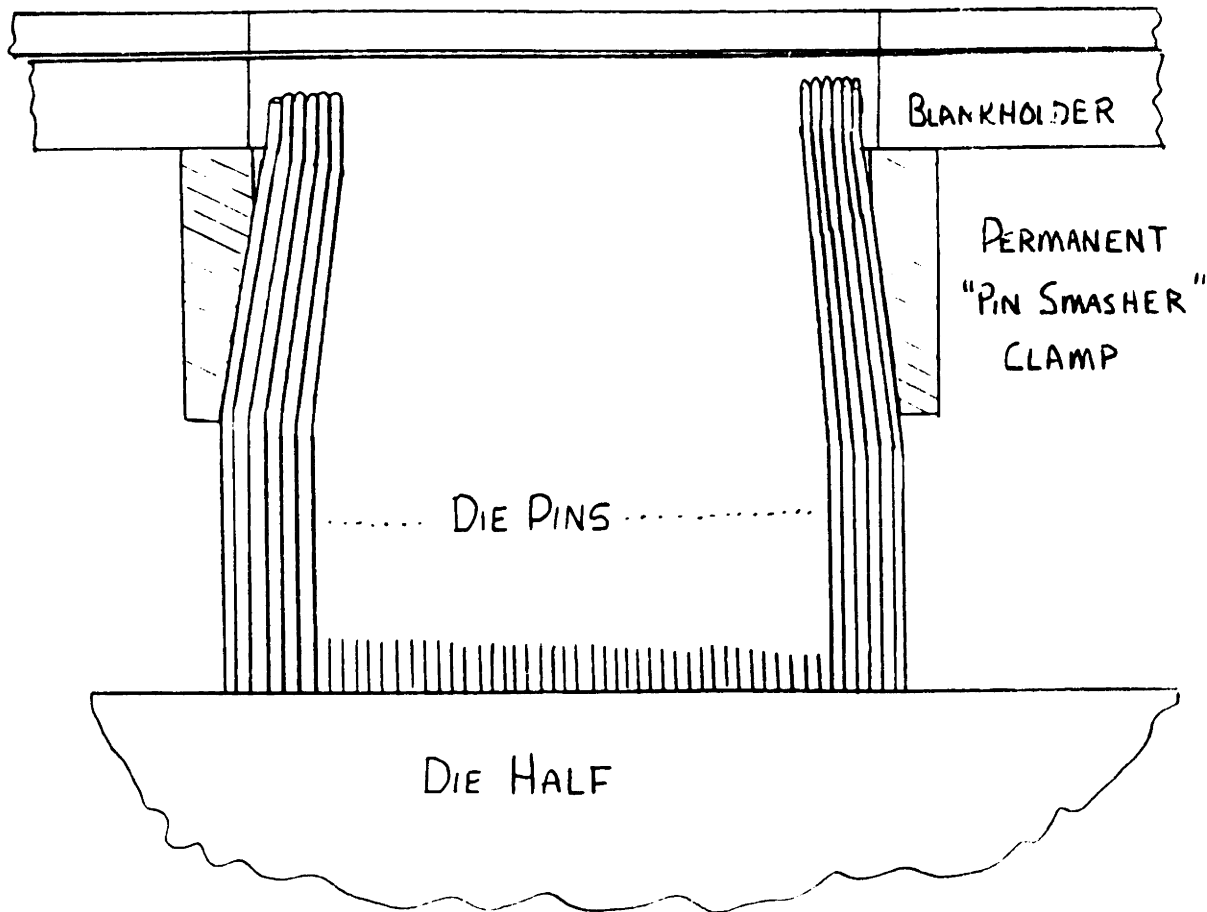


Figure 3.5 "Pin Smasher" Attachment to Blankholder

Since an 11" forming width was reached and not the optimum 10.5", another solution must be used before the "pin smasher" concept can be incorporated. The next section contains one such solution and when combined with the "pin smasher", might be workable solution to the bent and warped die pin problem.

3.3.2 Die Pin Spacers

The die pin spacers were designed to decouple the columnar die pin movement and help distribute the shear loading seen by the pins during forming to the top and bottom plates. The combined thickness of the 0.030" spacers is 1.23" (41 x thickness), if the thickness was reduced to 0.020", the combined thickness would be 0.82", and reduced to 0.010" spacers, the combined thickness would be 0.41". This 0.41" thickness would mean that the die pins would have to be bent in only 0.205", or less than a pin width, to reach the optimum width over the extended length using the "pin smasher". The thinner spacers would also conform better within the die halves to the bent and warped pins and help distribute the clamping force from the rams more evenly. The optimum working thickness has not been determined, the 0.030" thickness was determined more through supply availability and instinct, so the thickness limit has yet to be approached.

Another question that arose about the die pin spacers is how critical is the width dimension, does it distribute the shearing load to the top and bottom plates? The original die spacers were designed to fit snugly, (+0.001 width tolerance), within the top and bottom plate cavities. This tight fit would ensure the transferring of shearing forces seen by the die pins to the die framework. One experiment was devised to look into the shearing load seen by the spacers during forming. The active die half top plate was removed and three die spacers (original dimensions: 12" x 16" x 0.030") were removed from the center area of the die pins. (The active die surface was a hemispherical shape and the center die pin columns would see the largest forming forces.) The die pin spacers were replaced with shorter spacers, 11.5" x 16" x 0.030" in dimension and aligned flush with the active die front edge. If the die pin spacers do transfer the shearing load to the top and bottom plate, then when under load the

Chapter 3: Design Modifications

short spacers and surrounding pin columns should move back the 1/2" till the short spacers make contact with the active die back edge. The active die was reassembled and normal forming procedures were used to form a part. The center die pin columns did not move and removal of the active die top plate confirmed no motion of the short die pin spacers.

This experiment seems to answer some questions about the shearing load carried by the die spacers and how critical is the spacer width. The shearing load, if any, seems to be carried by the spacer pins that fill the gaps in the top and bottom plate cavities.

The next question to address is that of the die spacer thickness limit. Spacers with a 0.010" thickness were ordered to replace all the original spacers in both die halves. These spacers were also 11.5" wide, one, because of the previous experiment and two, for replacement ease. With the thinner die pin spacers, three die pin columns were added giving a new forming width of 11.69" (45 die pin columns x 1/4" + 44 die spacers x 0.010"). In conjunction with the "pin smasher" the new compressed forming width of the die pin matrices becomes 11.25".

In the first experiment, the 0.010" die pin spacers were installed in the active die half. Three hemispherical parts were formed using the blankholder to generate the full forming force on the die pins. No motion of the die pins or die pin spacers was detected upon removal of the top plate. In the next experiment, the passive die half was hydraulically clamped and the active die, with the 0.010" die pin spacers, was brought against it, transferring the passive die shape to the active die half and moving all the active die pins back four inches. No motion of the die pin spacers was observed upon removal of the top plate. The center die pin spacer was removed and no

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tearing or excessive wear was observed. Based on these results, the passive die half was disassembled and the 0.010" were installed plus the additional three die pin columns.

The combination of the "pin smasher" and the thinner die pin spacers is a solution to the bent and warped die pin problem. This combination not only assures the proper die pin location and registration during forming, it also increased the forming area to 11.25" x 12". Isolated problems with the bent and warped die pins will continued to occur and will be handled accordingly. During the transferring of a column shape from the positioning system to the active die half, some die pins tend to stick together causing a incorrect die shape. Again, the best solution would be to obtain straight die pins, but for the now, the pins are marked, removed, straightened and replaced back into the die.

An experiment to try Set Up A, tip-to-tip registration of active and passive die pins and the transfer of individual column shapes, was tried with the combination of the "pin smasher" and thinner die pin spacers. The "pin smasher" clamps were tightened on both die halves to obtain the 11.25" forming width. Both dies were unclamped hydraulically and the die pin positioning system was setup to transfer a shape. Tip-to-tip die pin registration was not possible with these temporary "pin smasher" clamps, the die pins would contact their tips and then slide into the gaps. Tip-to-tip registration would be possible with a permanent "pin smasher" attached to the blankholder that fully surrounded the die pin arrays. The pins would not be able to splay outward and would be forced into tip-to-tip registration. The current "pin smasher" clamps also tend to bow when generating high clamping forces because of their initial design, the permanent "pin smasher" would solve this problem. Set Up B is recommended when

using the temporary “pin smasher” clamps, an evaluation of Set Up A is recommended when the permanent “pin smasher” assembly is made.

3.4 Rubber Flow During Part Formation

The rubber interpolating pads are used to transform the discrete nature of the dies and distribute their inherent discontinuous loading of the sheet to form continuous smooth part surfaces. As discussed in Chapter 2, Section 2.2.3, during the forming operation the rubber on the female side tends to bind at the parting surface die pins. Once bound, the rubber will not be able to flow as the sheet metal is formed into the female die cavity. The rubber shears at this boundary resulting in die pin-to-sheet metal contact with limited smoothness and interpolation between die pin contact points.

One solution is to allow as much rubber possible into the female die cavity. This can be seen in Figure 2.27 and works well for 2-D bending experiments, though if too much rubber is in the female die cavity, the excess will have no place to flow, bunch up and create a deformed part. The real problem is creating 3-D parts where its not possible to put the rubber sheet into the female die cavity. One solution is to form a part in steps to different depths with a repositioning of the rubber sheet at each step change. Another possible solution is to include in the pin height calculation programs some type of variable rubber thickness allowance along the parting line edge based on some factor like geometry, forming depth, or steepness of formed part.

This rubber effect and flow problem is another characteristic peculiar to this machine and is worthy of investigation. Continued work will be done on this problem as this project proceeds.

3.5 Blankholder Revisions

The present blankholder, shown in Figure 2.8, was designed for use when forming square based parts. It will be necessary design and build new blankholders configured to different shape based parts. The blankholder shape becomes important when trying to draw parts, where the binding force and its area are important. When stretch forming parts this isn't a problem, the binding force level is high enough for no draw in to occur. A blankholder for circular parts, with a 12" diameter opening, was designed and can be found in Appendix A, drawings P-18 and P-19.

One problem noticed when doing the 2-D bending experiments was the opening of the binding surface at the sheet metal joint as the binding force bolts were torqued down. This splitting open resulted from the blankholder plate cocking on the sheet metal edges. A quick solution was to install 0.036" thick shims, (same as sheet thickness), below the bottom bolts and above the top bolts. This helps distribute the binding force along the whole flange area.

This leads to the discussion creating a known binding force for the forming operation. Presently, the blankholder's 24 bolts are torqued down to a prescribed torque using a torque wrench. The torque wrench is a normal industrial wrench with an accuracy probably around +10 percent. One solution would be to use compression springs with known stiffnesses and by measuring the compressed displacement the binding force could be calculated. This would be a more accurate solution but could have space and clearance problems with the passive die. Another solution would be to use Belleville washers which compress once a designed force is met, and can be stacked in series to get the desired binding force. One final solution would be to use a hydraulic clamping

system that can be under force control. Fenn [11] has found that force control is possible for the drawing process using some general shape measurements and closed loop control. This option has been considered for future investigation.

One final topic dealing with the blankholder is the feasibility of measuring a formed part in the blankholder. The author feels that this type of measurement will not add any significant information and is not practical. An experiment will be described in the next chapter where a part was measured in the blankholder, removed and measured, and a part was formed with no blankholder at all. The data from these three parts were compared and discussed.

Basically a part held in the blankholder is constrained and has not completely sprungback. There can be no definite relationship between this arbitrary constrained state and the free state of a part removed from the blankholder. Springback has been studied by Hardt et al. [3], [6], and [7] within the LMP and can be calculated and accounted for in certain applications. In this case, the true part formed is the one removed from the blankholder and measured. Using this measurement in the closed loop shape error strategy, the measured part will converge quicker to the desired part.

3.6 Force Control on CMM

The current coordinate measurement machine (CMM) uses a pneumatic cylinder and on-off solenoids to position the measurement probe. This probe is mechanically linked to an optical linear encoder, making it a very accurate system, but the probe contacts the part with so much force it actually dents the material. When measuring a steep part, the high force will cause the probe to hit and slide down the part, deflecting

the probe. The CMM accuracy is then subject to question. The current policy is to clamp the part as tightly down as possible and reduce the measurement probe travel to a minimum. Future work has been discussed about some type of force controlled probe system or some type of optical measuring device.

3.7 Summary

The design modifications in this chapter fell into three areas: those of strictly alternate designs, those that addressed the machine characteristics, and those that were pending further work but were of the first two types.

The alternative design solutions were implemented quickly and greatly simplified certain aspects of this machine. The compression spring removal and the addition of the rubber sheets in the positioner clamp has eased the positioning rod movement, eliminated all burring and shaving of positioning rods, and has increased the clamping force distributed to the positioning rods during profile transfer. The bevelled positioning rod tips has virtually eliminated the position rod/die pin registration problem.

The most interesting modifications were a result of the machines peculiar characteristics. The fact that bent and warped pins are a intricate part of this machine and how the "pin smasher" and die spacer thickness addressed this problem is commendable. With the side-to-side registration and the pin location definition, more accurately defined parts can be made. Plus the known die pin locations correlated with the CMM measurements will definitely enhance the closed loop shape error effectiveness. The use of the rubber interpolating pads has added a whole new dimension to this forming process. The rubber exhibits characteristics similar to those in rubber-pad forming. It

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can take many different shapes, but wears out quickly and definition may be less sharp (as in the parting line area). The important feature and problem is that it must flow with the material to utilize its interpolating properties.

These and other modifications will be made as this machine is continually used and experiments are preformed to characterize this machine.

Initial Forming Experiments

The initial forming experiments were developed to help characterize the variable configuration die forming machine along with the design modifications. These experiments investigate various properties peculiar to this machine, from discrete surface formation and rubber pad effects, to general properties like springback and measurement procedures. This characterization is needed in order to apply a closed loop shape control strategy to the variable configuration die forming machine. No attempt was made to implement a closed loop shape control strategy.

The experiments can be divided into two types of shapes: 2-D bending and 3-D stretch forming. The forming experiments used simple geometries for the die shapes owing to the present manual operation of the machine. The set up of these geometries will be described in the following section.

4.1 2-D Forming Experiments

The 2-D forming experiments consisted of setting up the variable configuration dies with simple bending shapes to look into the following topics: 1) optimum forming conditions, 2) part shape repeatability and 3) part shape measurement procedures. The set up for each test will be described, noting changes in testing conditions, then graphs will be used to show the experimental outcomes.

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The desired shape of the 2-D forming experiments was a half-cylinder with a 3.0 inch radius (See Figures 2.25 and 2.26, Chapter Two). The program PinHeight.pas was used to calculate the die pin locations for the active and passive dies. The material used for all experiments was S1010 LS steel, 0.036" thick, 12" x 17.7" in dimension. The rolling direction was along the longest side and perpendicular to the bending axis. For more information on the procedure to form a part, see Section 2.2.3.

4.1.1 Optimum Forming Conditions and Part Shape Repeatability

The optimum forming condition is that which results in a part that draws evenly from both the top and the bottom of the blankholder. In most experiments, the part drew exclusively from either the top or the bottom binder. In the following experiments, the amount of binding force and the order in which it is applied was varied to obtain the optimum forming condition.

TEST JU04-1: The top and bottom binder bolts were tightened to 45 ft. lbs. torque. The rubber interpolating pad on the female die half side was positioned inside the passive die cavity (Chapter Three, Design Modifications, Section 3.4). Result: All the draw-in observed occurred from the bottom binder. (The bottom binder corresponds to the right side of all future graphs presented in this chapter, the top corresponds to the left side.)

TEST JU04-2: This experiment attempted to force draw-in from the top by tightening down the bottom binder bolts to 45 ft.lbs. torque first. It was observed in Test Ju04-1 that the side tightened down first would not draw-in during the forming cycle. This could be attributed to the cocking of the blankholder plates on the sheet metal edges (Chapter Three, Design Modifications, Section 3.5). (Tightening down first or last

Chapter 4: Initial Forming Experiments

describes the order in which the five binder bolts of each binder, top or bottom, are tightened to the prescribed torques before the other set of binder bolts are tightened). The top binder bolts were tightened last to 45 ft.lbs. torque. Result: All the material drew in from the top binder, as predicted. The order in which the binding force is applied has an effect on draw-in, with similar binding forces, the binder tightened first will hold the part flange better. A bolt tightening procedure must be developed for forming experiments.

TEST JU04-3: This experiment attempted to force draw-in by varying the binding force magnitudes of both binders. The top binder bolts were tightened first to 25 ft.lbs. torque. The bottom binder were tightened last to 45 ft.lbs. torque. Result: All material drew in from the top binder. A large magnitude difference of binder force has a stronger influence on draw-in than the order of application.

TEST JU04-4: This experiment further investigate the results observed in Test JU04-3. The top binder bolts were tightened first to 45 ft.lbs. torque. The bottom binder bolts were tightened last to 55 ft. lbs. torque. Result: The part drew in 1/2 inch from the top binder and almost 2 inches from the bottom binder. This supports the stronger influence of order-of-application as the magnitude difference is decreased. The part drew to a deeper part than previous tests as indicated by stretching in the center part region.

Figure 4.1 shows Tests JU04-1 through JU04-4 plotted together in comparison to the desired 3.0 inch radius shape. Note the vertical and horizontal scales, the desired shape curve labelled in Figure 4.1 is the representation of a 3.0 inch radius half-circle. The data has been manipulated so that the highest point of each test is

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plotted underneath one another. Test JU04-4 formed the deepest part. The higher binder force in Test JU04-4 caused higher strains perpendicular to the bending axis, resulting in more plastic deformation. Figure 4.2 superimposes Tests JU04-1 through JU04-3 (JU04-4 was not included because it underwent stretching.) Note the similarity in the shapes of Tests JU04-1 through JU04-3, even though these parts had different binding conditions and drew in exclusively from either the top or bottom binder.

Conclusion from Tests JU04: The optimum forming condition, defined as equal draw-in from top and bottom binders, has yet to be found. The forming of a part with the variable configuration dies is very repeatable, even under varied binding force conditions. Deeper parts can be formed if stretching occurs.

The objective of Tests JU09 is to approach the optimum forming condition by varying the order and magnitude of the binding force in the higher, 45 - 50 ft.lb. torque range. This range will also tend to cause stretching and form deeper parts.

TEST JU09-1: The top binder bolts were tightened first to 45 ft.lbs. torque. The bottom binder bolts were tightened last to 50 ft.lbs. torque. Result: The draw-in observed was 1/2 inch from the bottom binder and almost 2 inches from the top. This draw-in characteristic is a reversal from Test JU04-4, but appears logical. The following tests will work from the results of Test JU09-1 and vary the binding force in an attempt to find the optimum forming condition.

TEST JU09-2: The top binder bolts were tightened last to 48 ft.lbs. torque. The bottom binder bolts were tightened first to 50 ft.lbs. torque. Result: The draw observed was 1/4" from the top and almost 2 1/4" from the bottom binder. This shows the effect of

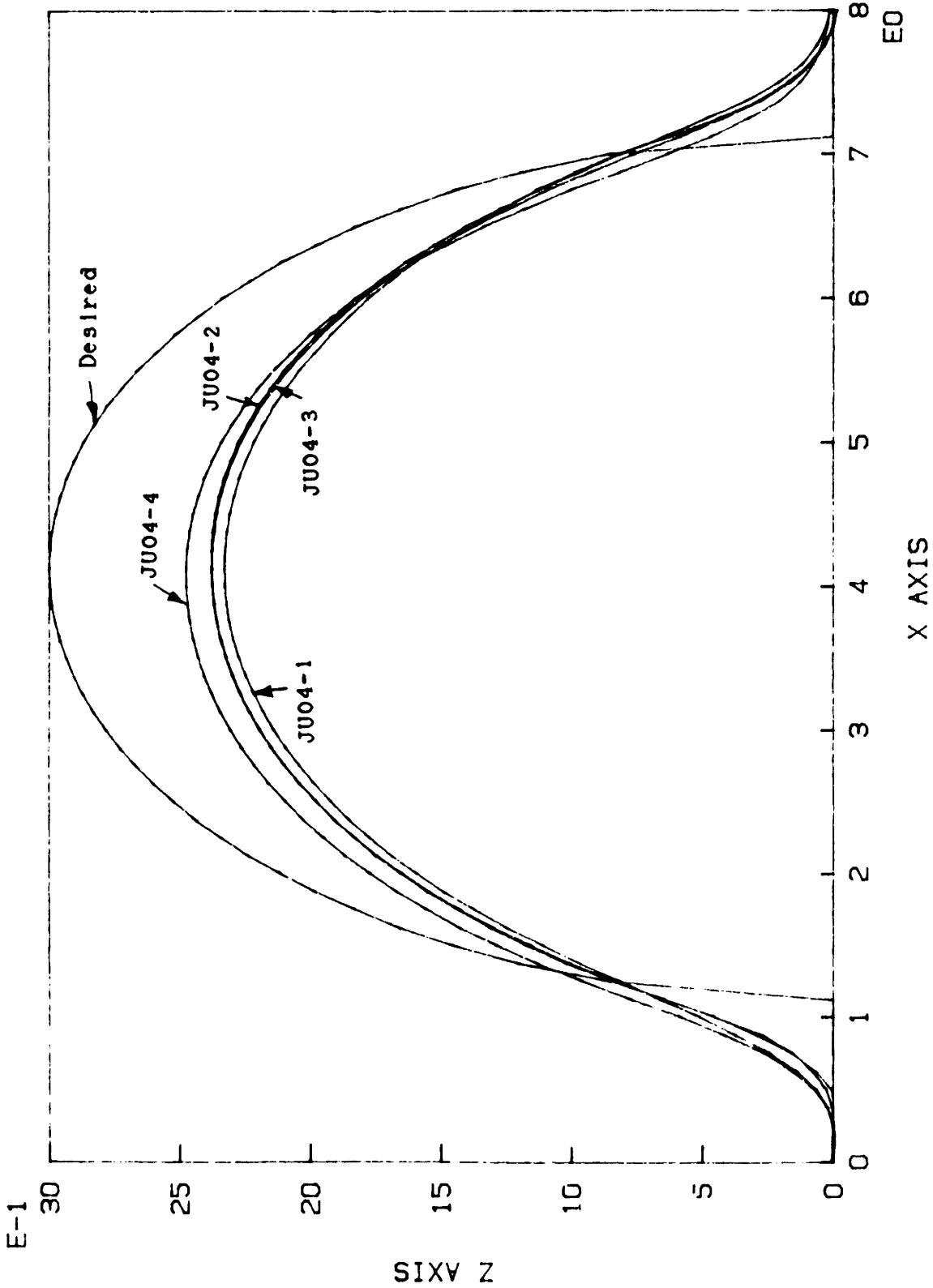


Figure 4.1 Tests JU04 Comparison

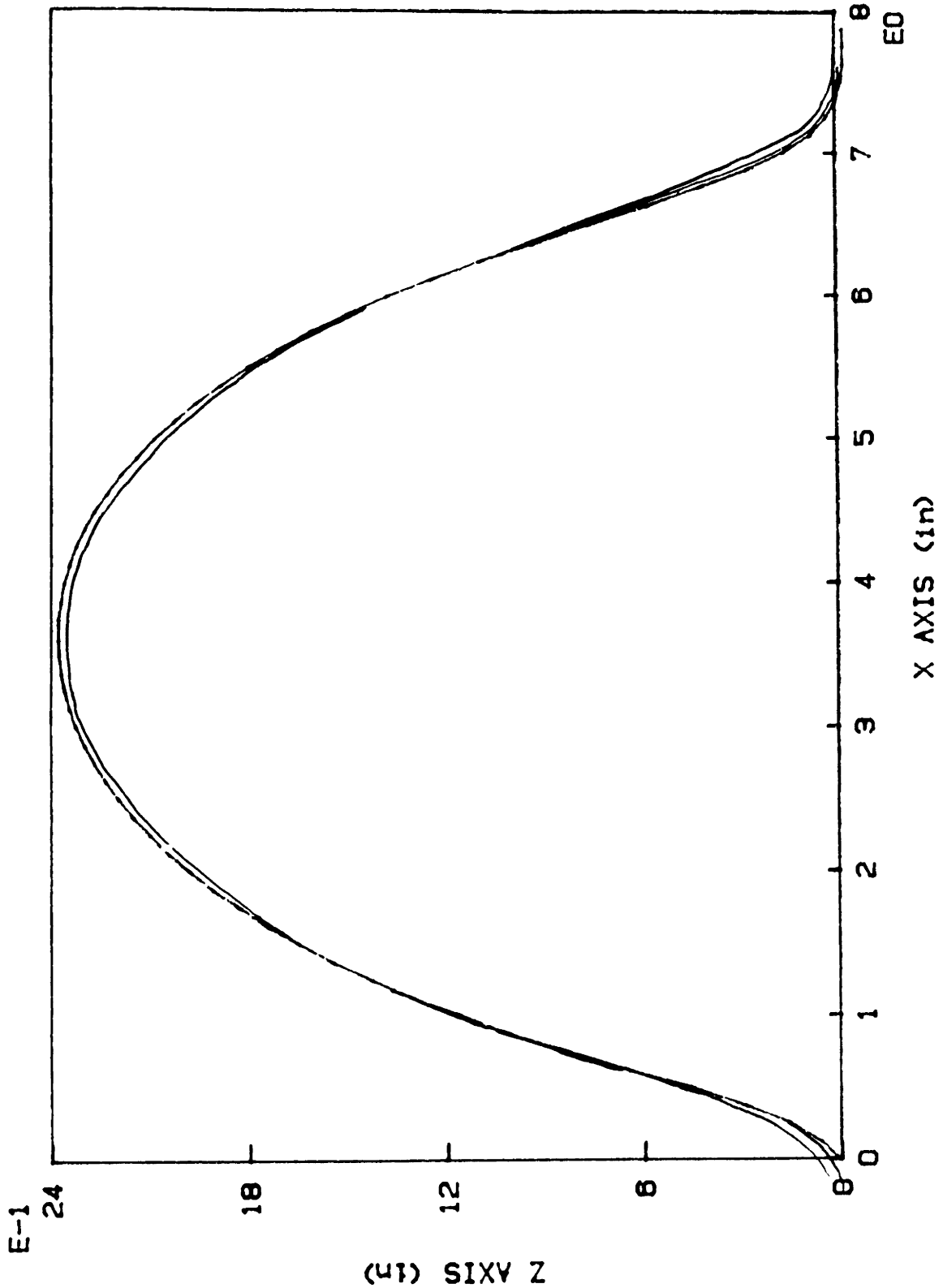


Figure 4.2 Tests JU04 Superimposed

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binding force application order when the magnitude difference is small. The optimum forming condition must lie somewhere between Test JU09-1 and Test JU09- 2.

TEST JU09-3: This experiment will attempt to approach the optimum forming condition by starting from Test JU09-1 conditions. The top binder bolts were tightened first to 47 ft.lbs. torque. The bottom binder bolts were tightened last to 50 ft.lbs. torque. Result: Most of the draw-in observed occurred from the bottom binder, this is a reversal from Test JU09-1.

TEST JU09-4: The top binder bolts were tightened first to 46 ft.lbs. torque. The bottom binder bolts were tightened last to 50 ft.lbs. torque. Result: Most of the draw-in observed occurred from the bottom binder. This result signifies that the optimum forming condition is not purely a function of binding force, and other factors are involved. Other factors could be part lubrication, surface condition, thickness variation, and surface conditions of binding force plates.

Figure 4.3 shows Test JU09-1 through Test JU09-4 plotted together in comparison with the desired 3 inch radius part. The data has been manipulated so that the highest point of each test is plotted underneath each other. Though a optimum forming condition as a function strictly of binder force was not found, it is worthy to note the repeatability of forming a part with the variable configuration dies. The horizontal scale for Tests JU09 was increased to 12 inches by measuring the part with the CMM over the increased length. (The plots from Test JU04 would plot approximately the same on this different horizontal scale.) With the increased horizontal scale, the degree of springback can be seen.

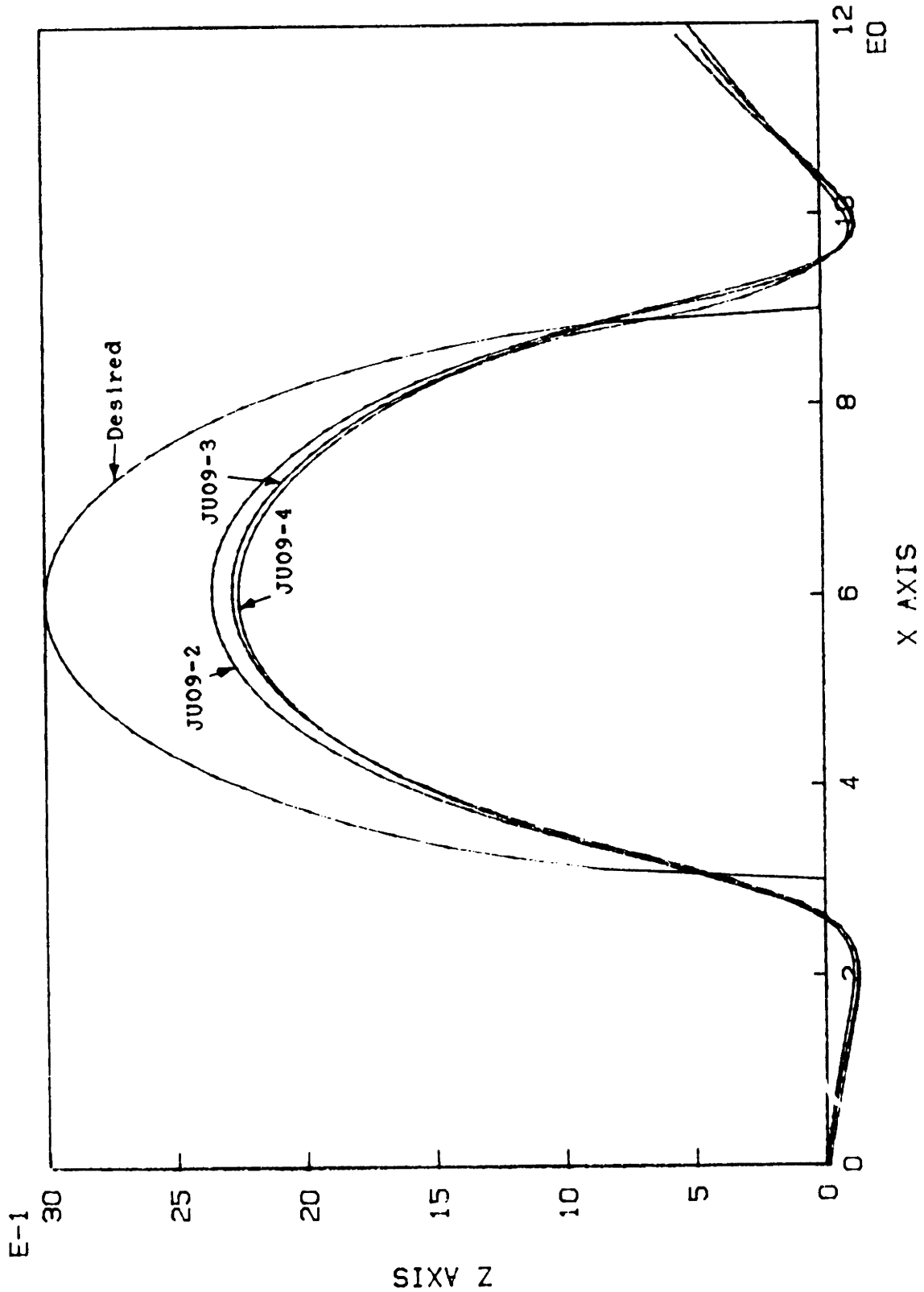


Figure 4.3 Tests JU09 Comparison

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Conclusion of Tests JU09: An optimum forming condition was not found and it is not strictly a function of binder force. Other factors such as lubrication, part surface conditions, thickness variations, and binding force surface conditions contribute to the outcome. The draw-in characteristics appear to be functions of stick friction, once one side begins to draw-in, the effective binding force is reduced and the whole side draws in. Future work will be conducted to investigate these factors. However, forming parts with the variable configuration dies is very repeatable, even with different draw-in characteristics. Figure 4.4 superimposes Tests JU09 to show this repeatability. Part shape repeatability will be very important when closed loop shape control theory is applied to this new forming process.

An interesting observation from both Figures 4.1 and 4.3 is the gross error between the formed parts and the desired part shape at the parting surface. Unlike regular die forming, there does not exist a sharp edge to form a distinct parting line. With the variable configuration dies, the sharp corner is defined by the die pin size and the compressibility of the rubber (See Figure 4.5). As noted by Webb [8],[12], the rubber acts as a "low pass shape filter". The sharp edge of the desired shape parting line would have a high frequency component in the spatial frequency domain and would be filtered out by the rubber. Webb worked on a spatial frequency based transfer function identification algorithm and suggested an improved method for spatial sampling. Instead of measuring displacement normal to a sampling plane, a part shape would be measured relative to a desired part shape. The sampling would occur normal to and evenly spaced along the arc length of the desired part (See Figure 4.6). The combination of the algorithm and sampling method would not only recognize higher frequency components of the steep sides, but an increased controller action would focus on that

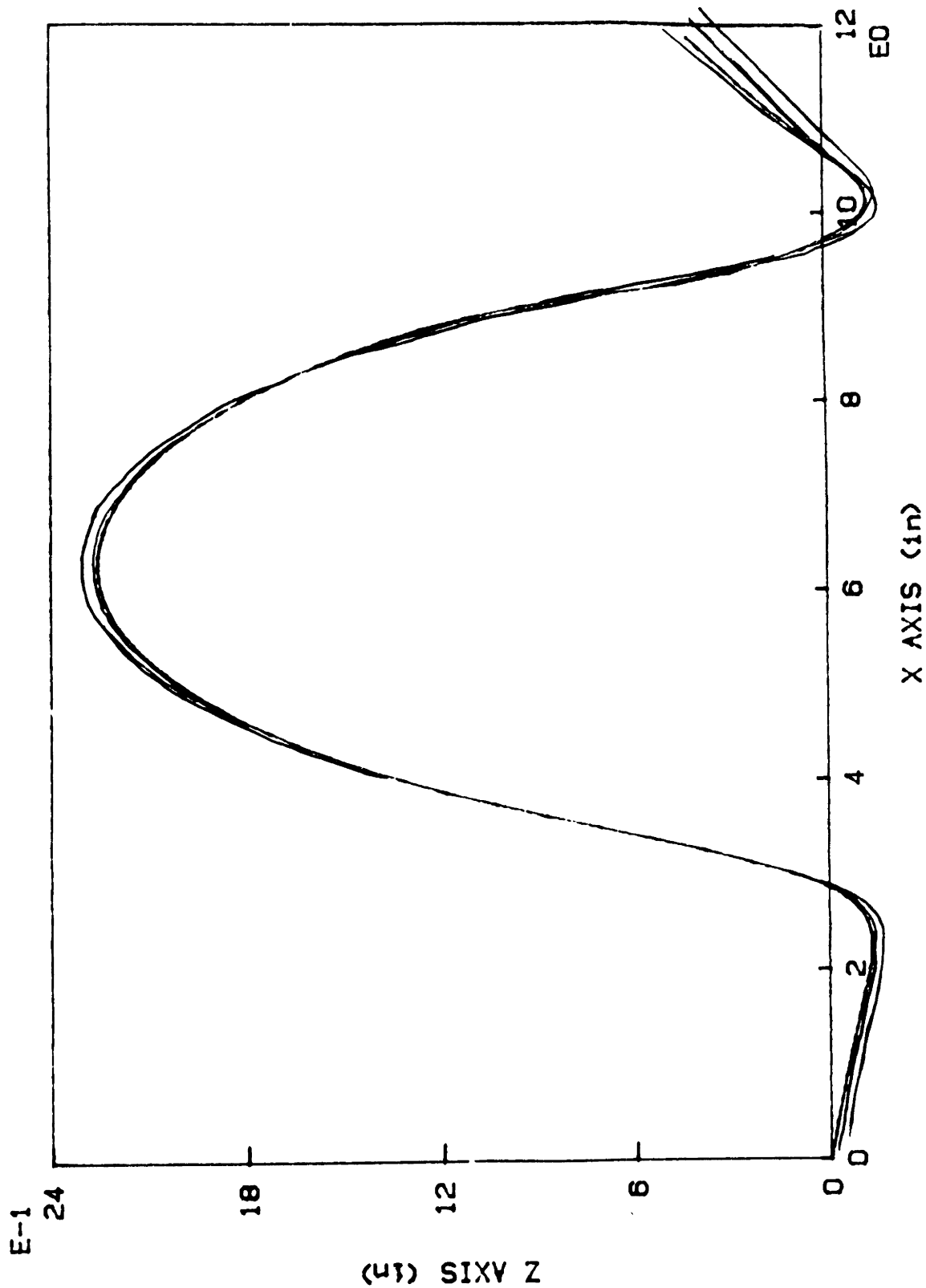


Figure 4.4 Tests JU09 Superimposed

area. An empirical solution would be to move the die pins in the parting line area to force increased deformation. This is shown in Figure 4.5 and Test JY27-1 of the 3-D experiments in the next section will investigate this solution. Other solutions might contain a dedicated die pin arrangement with smaller more discrete die pins along this parting line area or some sort of continuous die band to form the parting surface.

4.1.2 Measurement Procedures

This section investigates procedures for measuring a formed part. The parts in the earlier tests, once formed, were removed from the blankholder and positioned in the CMM to be measured. A earlier suggested procedure proposed that the blankholder cartridge, with the formed part still bound, be removed from the press and located in a fixture attached to the CMM for in-process measurement without unclamping the part. The present blankholder design is a result of this procedure.

The following tests used the same desired part shape, (3.0 inch radius half circle), and material from the previous experiments. The experiments will investigate the effects of using the blankholder and whether part measurement should be made with or without the blankholder.

TESTS JU17-1 through JU17-3: No binder force was used (no blankholder) so the part was subject to simple bending. Result: The formed parts observed were shallower than in previous experiments. Figure 4.7 shows these curves superimposed on Test JU17-1, note how similar these parts are, the error is in the flange area as a result of springback and the discrete nature of the parting line. Most of the shape error between the parts can be attributed to improper orientation of the blank before forming. Test JU17-2 was chosen to represent this method of forming when comparing to the following tests.

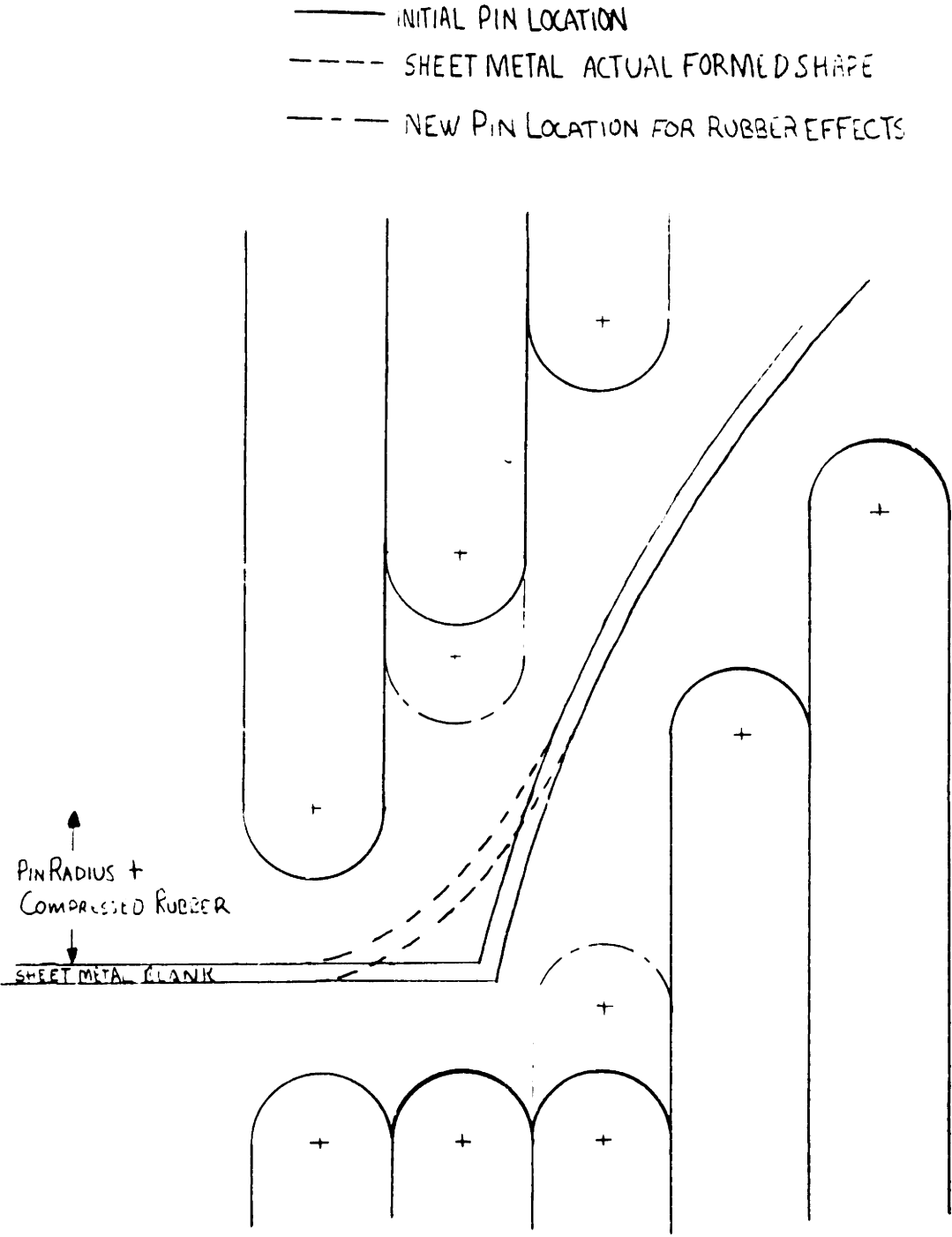


Figure 4.5 Discrete Parting Line

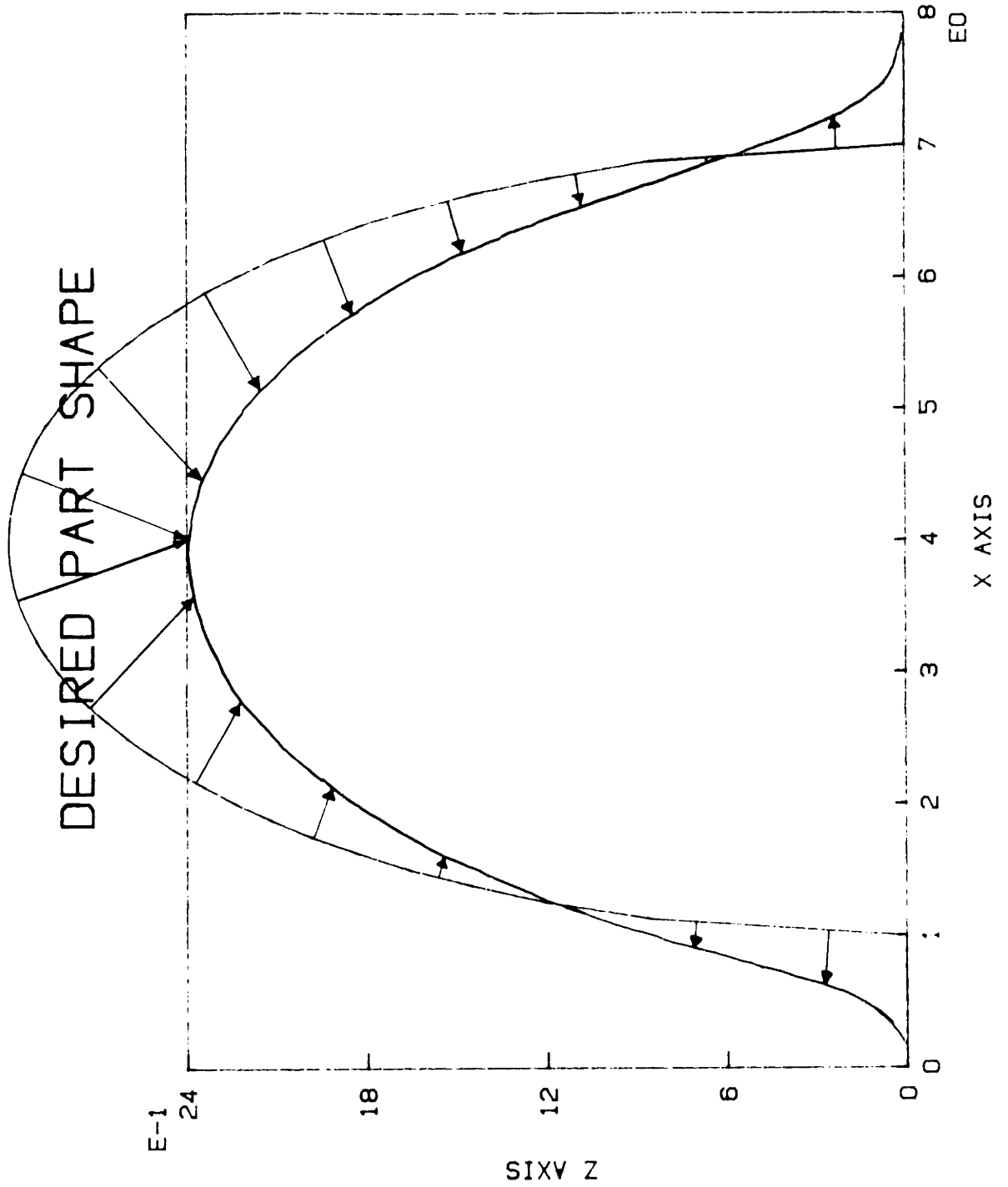
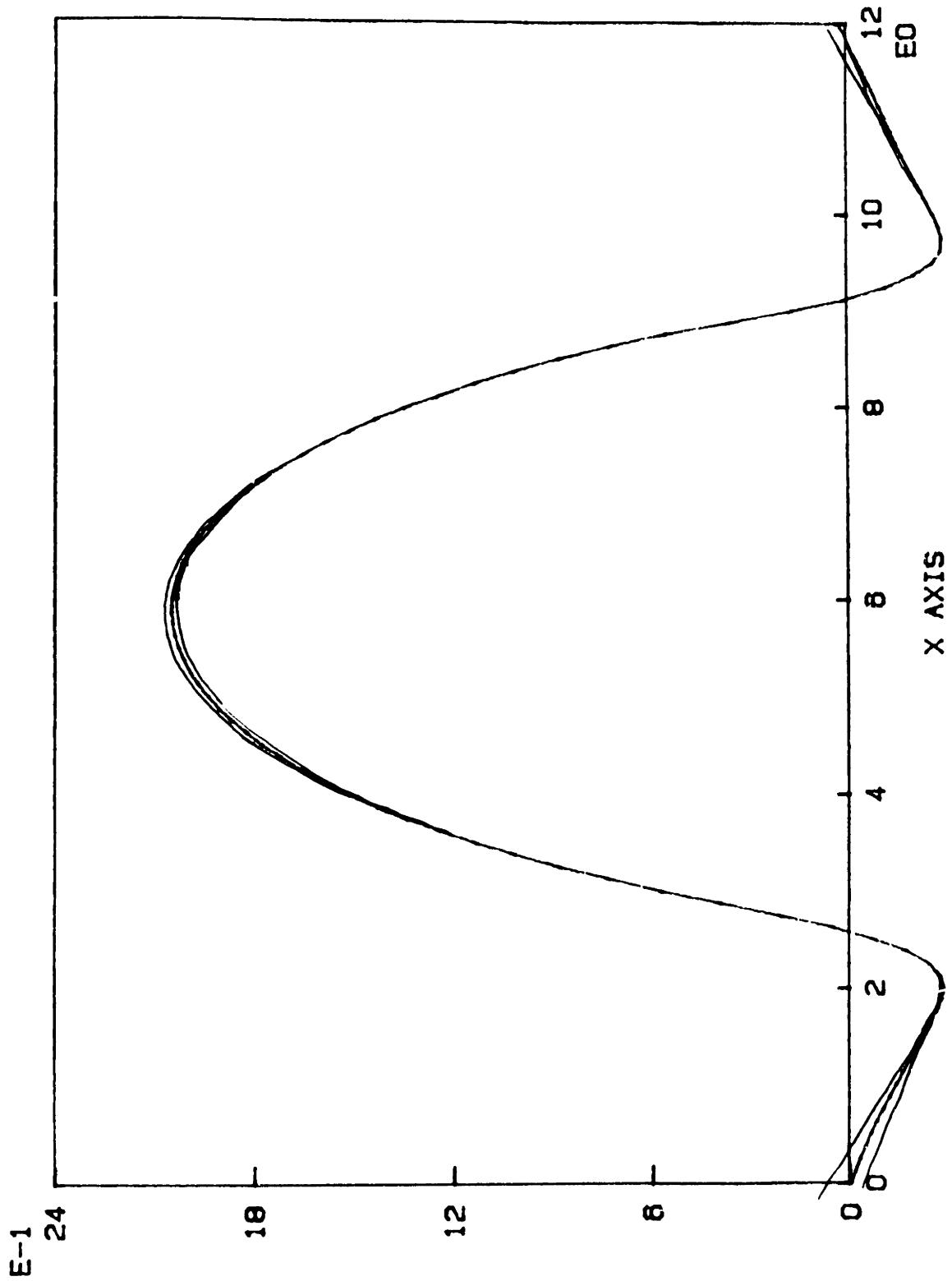


Figure 4.6 Spatial Sampling Scheme



SIXV Z
Figure 4.7 Tests JU17 Superimposed

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TEST JU17-4B: The blankholder was used and the top and bottom binder bolts were tightened to 45 ft.lbs. torque. The blankholder and formed part were removed from the press and measured by the CMM.

TEST JU17-4: The part formed in Test JU17-4B was removed from the blankholder and remeasured by the CMM.

Figure 4.8 shows a comparison of the three tests. As expected, the part measured in the blankholder (JU17-4B) formed the deepest part. This makes sense because the part is in a constrained state and is allowed very little springback. Once removed from the blankholder (JU17-4) the part springs back to a similar shape as in the other experiments. The part formed without the blankholder is the shallowest part because no stretching or resistance to flow is applied and the part bends freely.

The results clearly show that the constrained state of the part measured in the blankholder does not give the proper representation of the resultant part. The use of the constrained data in the control theory would cause the resultant formed part to converge to a different desired part shape because of springback. Measuring the part in the blankholder has some good aspects since it gives a repeatable orientation of the part relative to the CMM but with the current CMM, it is not physically possible to measure any part held in the blankholder without clearance problems.

The recommended part measuring procedure becomes: Remove the formed part from the blankholder and use the CMM to measure the part. This data will be used in a closed loop shape control strategy to calculate the error between the desired shape and the resultant shape. Once the controller makes the necessary changes to the die

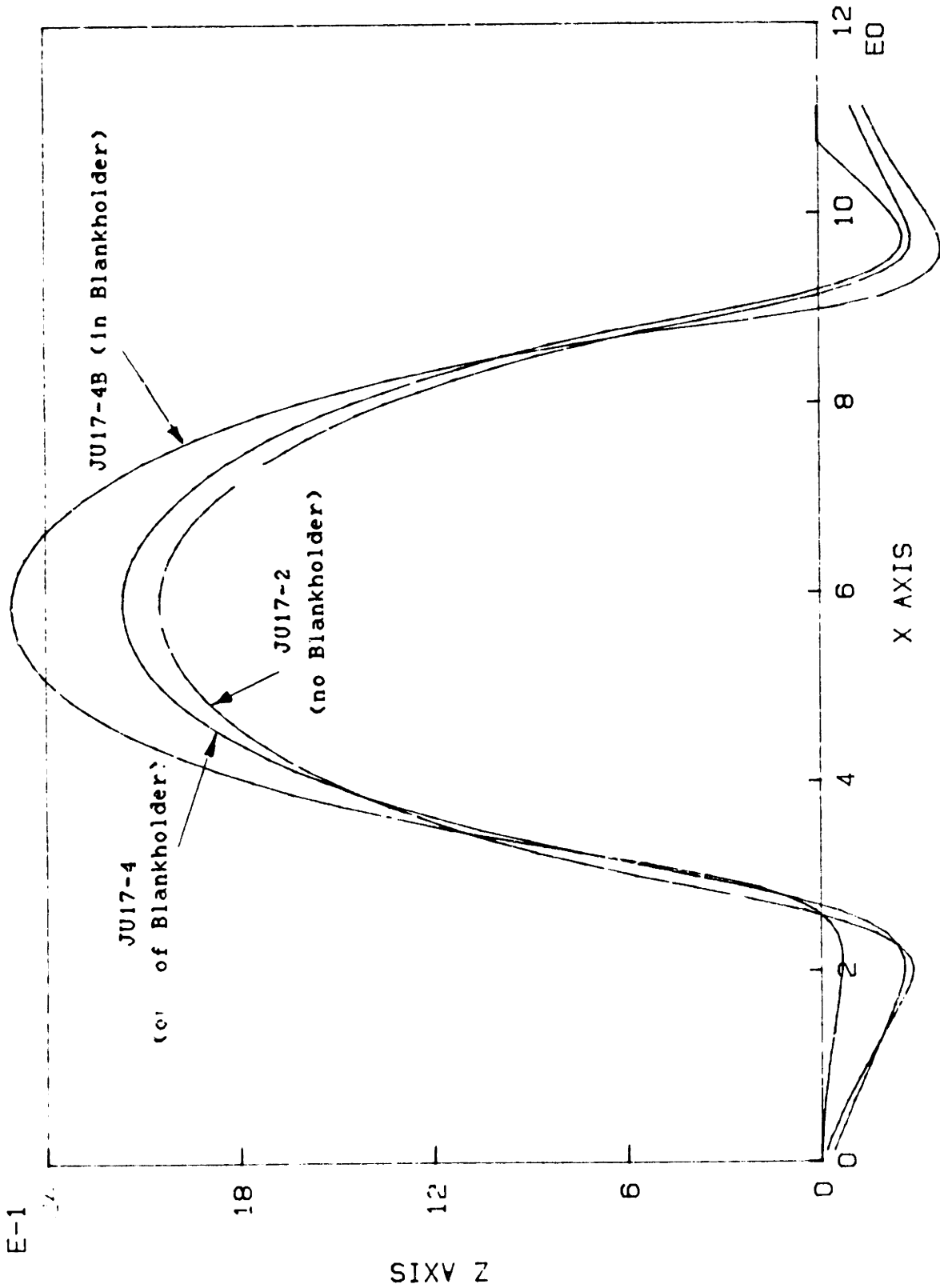


Figure 4.8 Tests JU17 Comparison

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halves, a new blank is inserted in the blankholder and formed. This process repeats until the resultant shape converges to the desired shape. Webb [4] has shown that springback of doubly curved sheet metal parts can be adaptively compensated for by a flexible die system (an early prototype of the variable configuration die) with closed loop control.

4.1.3 Summary

The initial 2-D forming experiments have provided some interesting characteristics of the variable configuration die forming machine. An effort was made to find an optimum forming condition that would cause a part to draw in equally from the top and bottom binders. This optimum forming condition was not found because the drawing characteristics appear to be more than a function of binding force. Other factors such as lubrication, surface quality, thickness and binder plate surface quality appear to be important. Continued work in the area is recommended. Despite this, the parts formed were found to be repeatable when under similar forming conditions. Increasing the binding force to induce stretching resulted in more plastic deformation and deeper formed parts. The recommended procedure for measuring a part is to remove it from the blankholder and measure it in its sprungback shape.

4.2 3-D Forming Experiments

The 3-D forming experiments were designed to increase the complexity of parts formed with the variable configuration die forming machine. The following topics will be investigated: 1) part shape repeatability, 2) rubber effects, and 3) design modification enhancement. The set up for each test will be described, noting changes between tests, and graphs will be used to show the experimental outcomes.

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The desired shape for the 3-D forming experiments resembles a hemisphere that is stretched in one direction. A cross section at the long axis can be described by a 4.0 inch radius half circle with a 2.0 inch chord offset removed. A cross section at the short axis reveals a 3.0 inch radius half circle with a chord offset of 1.0 inch removed (See Figure 4.9). Note that by removing the offset, part of the steep sides encountered with the 2-D experiments is removed. Figure 4.10 shows a 3-D representation of the desired part shape. The programs, Height3d.pas and Width3d.pas were used to calculate the die pin locations for the active and passive dies.

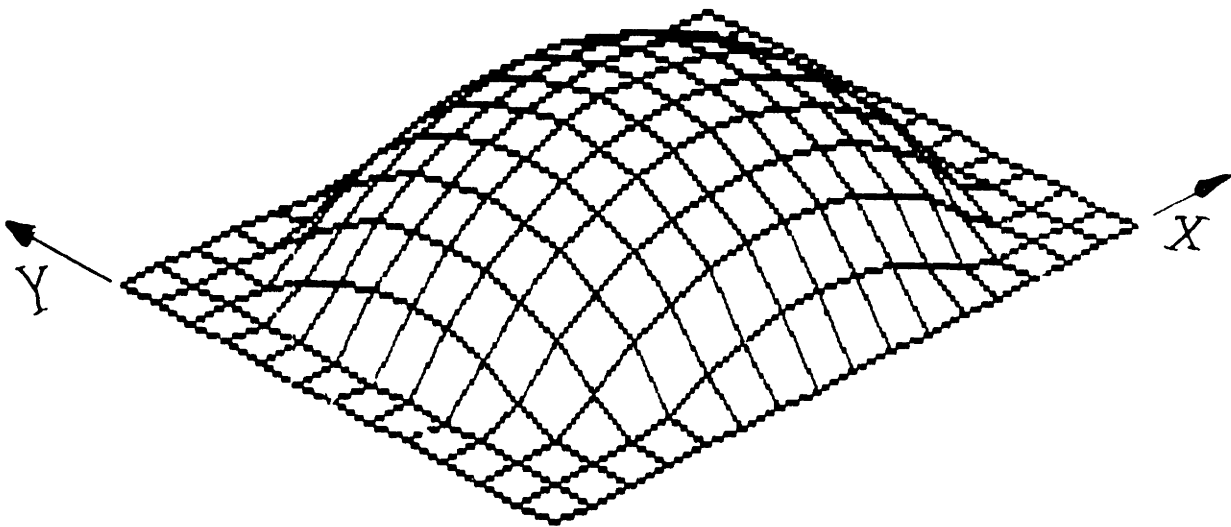


Figure 4.10 3-D Desired Part Shape

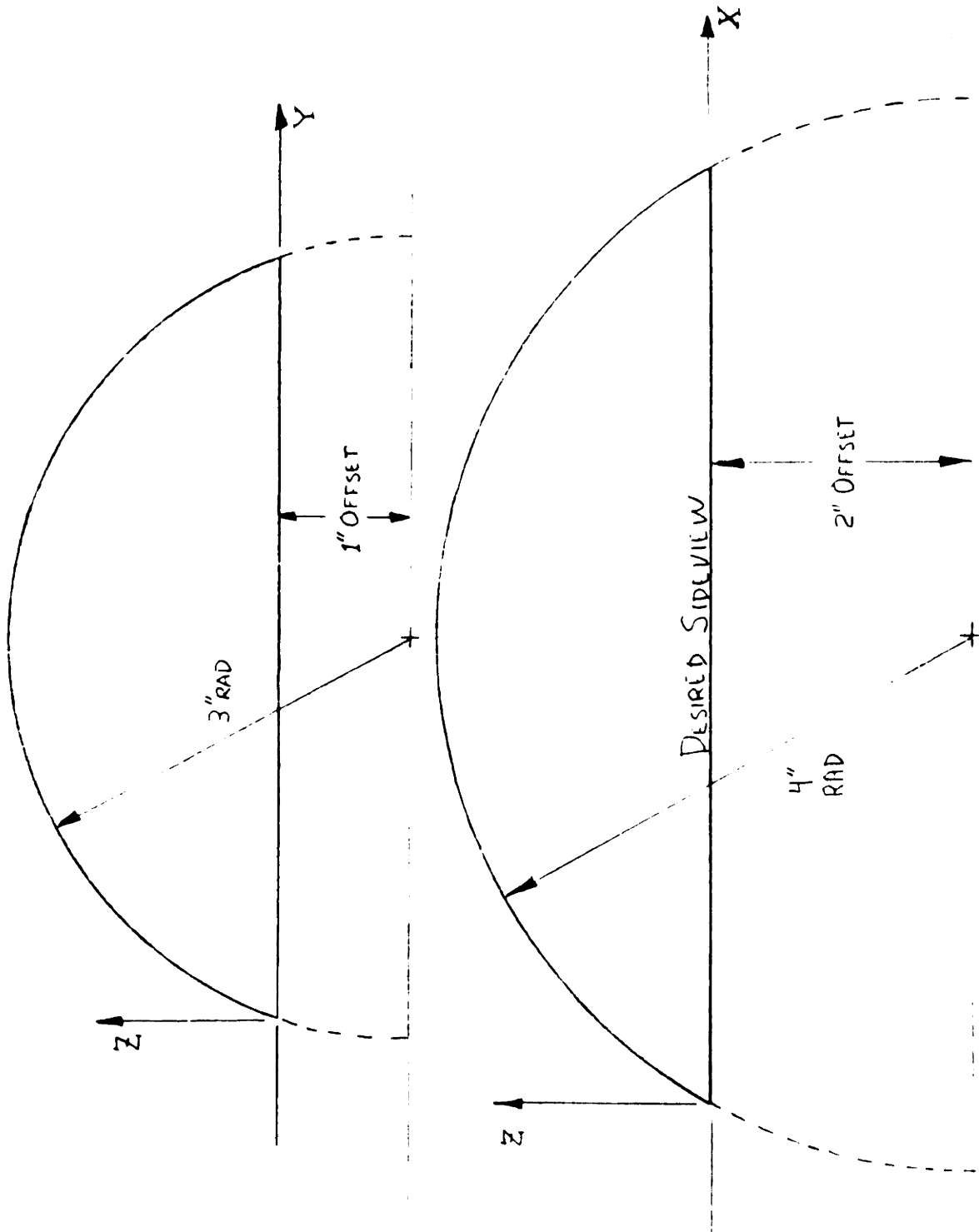


Figure 4.9 Cross Sections of Desired 3-D Part Shapes

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The blank material used in all experiments was S1010 LS steel, 0.036" thick, 17.7" x 17.7" in dimension. The rolling direction was along the long axis of the desired part or parallel to the X axis in Figure 4.10. Since no optimum forming condition was found in the previous section, the binder bolts will be tightened down to 45 ft.lbs. torque and the bolt tightening sequence used alternated between top - bottom - left side - right side until all 24 blankholder bolts are fastened. The importance of some design modifications mentioned in Chapter Three can be seen when forming 3-D parts. The combination of the "pin smasher" and thinner die spacers results in a forming area of 11.25" x 12.0" and assured proper pin registration and location during the forming cycle. The active die shape was formed using Set Up B, the active die shape was set into the passive die by the positioning system and then the whole shape was transferred to the active die.

TEST JY18-1: New rubber interpolating pads were used on both sides of blank. The "pin smasher" clamps were used to get a 11.25 inch forming width for each die half. The location of the blank in the blankholder was marked before forming for a die pin location reference to be used by the CMM, and the binder bolts were tightened to 45 ft.lbs. torque. Once formed, the part was removed from the blankholder for measurement with an effort to have the measured points correspond to the die pin centerline locations. A 9.0" x 9.0" measurement grid with 1/4" increments encompassing the formed part was used on all 3-D experiments. Once measured, Test JY18-1 was compared to the desired part shape and an error data file was developed. Figure 4.11 shows a cross section plot along the longest axis of the part. This error plot has similar characteristics to the 2-D comparison plots shown in the previous section. Figure 4.12 is a plot of the error between these two curves. The largest error occurs at the parting line because of

springback and the discrete nature and rubber effects at the parting line. Figure 4.13 shows a 3-D error plot of the whole part. Options discussed in the previous section to combat this parting line error must be investigated in future research.

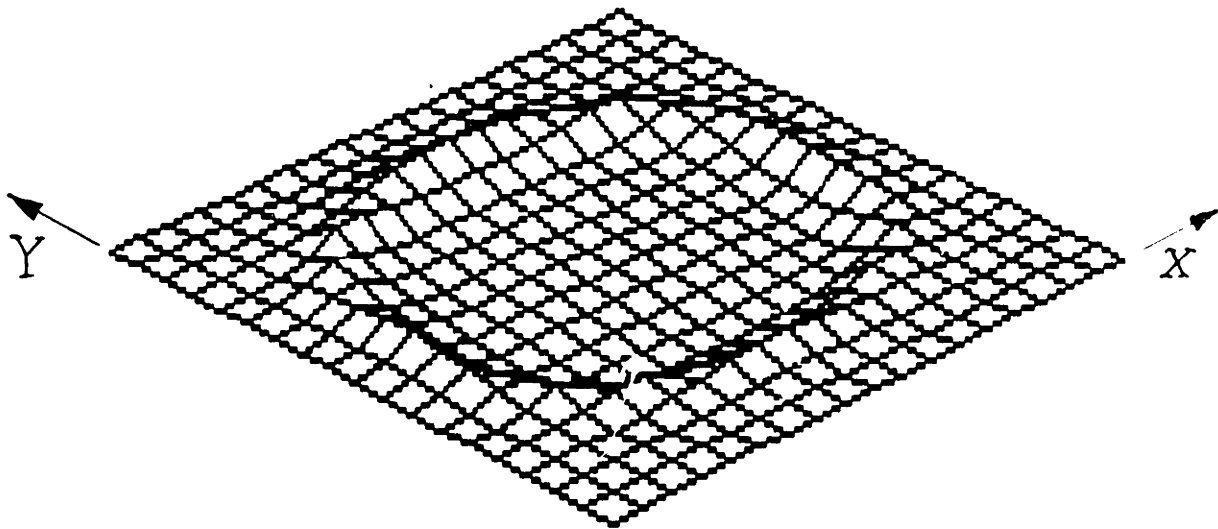


Figure 4.13 3-D Error Surface Plot Between JY18-1 and Desired Part

TEST JY20-1: This experiment attempted to repeat Test JY18-1 by using the same forming conditions except worn rubber interpolating pads were used instead of new ones. When forming 3-D parts, the rubber on the passive (female) die side tends to bind at the parting line and is restricted to flow causing shearing and tearing of the pads. This experiment was designed to try to see this rubber effect.

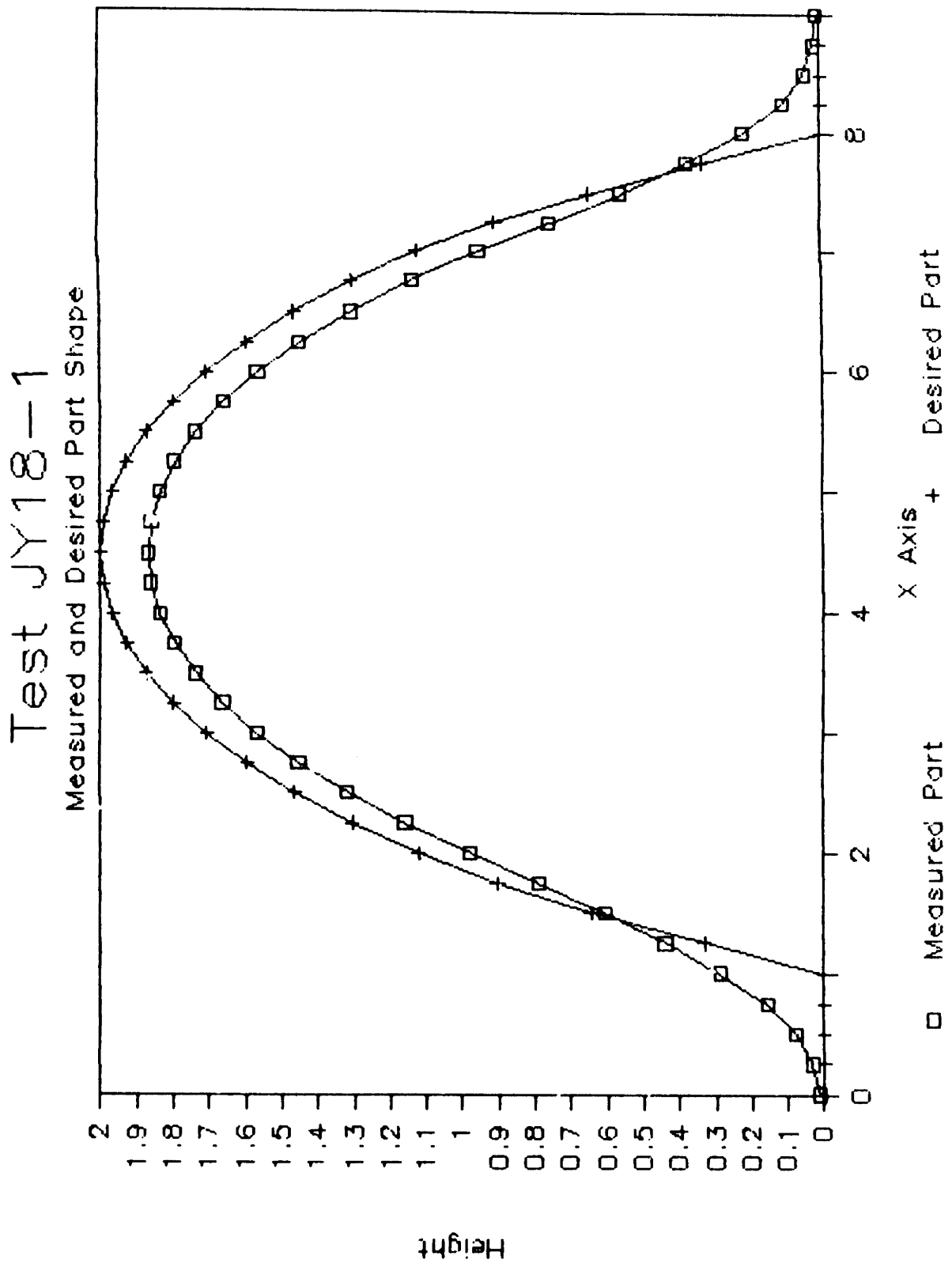


Figure 4.11 Test JY18-1 and Desired Part Shape Comparison

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TEST JY20-2: This experiment attempted to repeat Test JY18-1 by using the same forming conditions. The test will investigate part shape repeatability in 3-D forming.

TEST JY20-3: This experiment did not use the "pin smasher" clamps to control the forming width, all other forming conditions were the same as in Test JU18-1. This test will investigate the effect the "pin smasher" has on the resultant part shape. Pin registration and location is not guaranteed without the "pin smasher", and a outer forming width of 11.39 inches of the die halves was observed.

TEST JY21-1: This experiment attempted to repeat Test JY18-1 by using the same forming conditions. This test will investigate if die pin movement contributes to part shape errors. The location of an active die pin was measured before and after the forming cycle.

TEST JY27-1: This experiment will attempt to make a more distinct parting line. The active and passive die pins in the parting line regions were moved, from their calculated positions, to force deformation in this area. The forming conditions used were that of Test JY18-1.

Test Results Between JY20-2 and JY18-1: The purpose of this comparison was to check on part shape repeatability. Figure 4.14 shows a 3-D error plot between Test JY20-2 and JY18-1. Both tests used new rubber interpolating pads, 45 ft.lbs. torque, and the "pin smasher". The error shown in Figure 4.14 has been multiplied by 20 in order for it to be seen. Figure 4.15 shows a cross section of this error plot along the longest axis of the part (parallel to X axis at Y = 4.5). The two data arrays were centered under the highest point that occurred at X = 4.5, Y = 4.5. The error plots suggests the need for

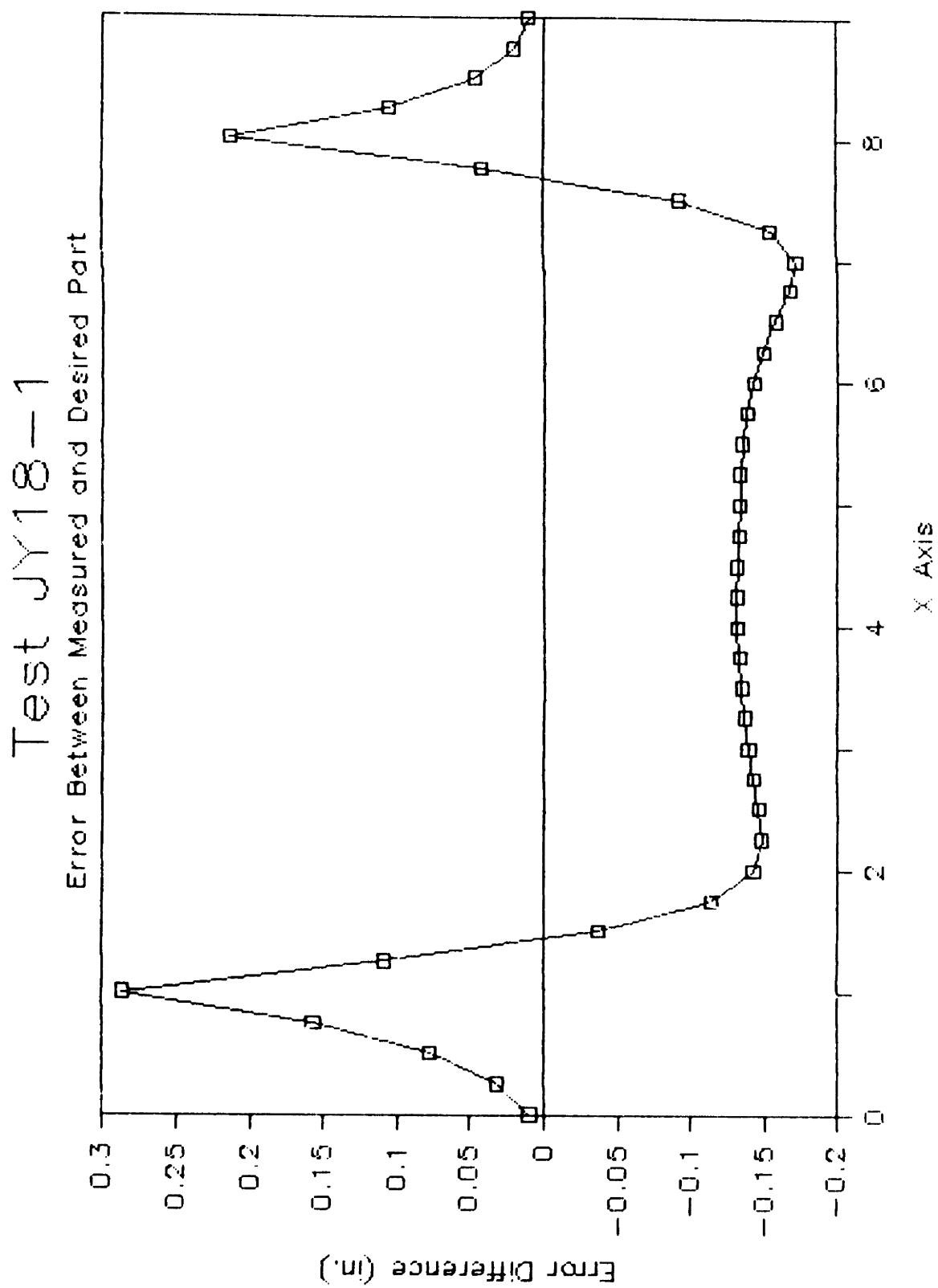


Figure 4.12 Cross Section Error Between JY18-1 and Desired Part

measurement data array translation in the Y direction to get the minimum shape error. Translation of the data arrays was tried but larger errors were obtained than in Figure 4.15. The largest difference between the two shapes was 0.06 inches and this occurred in the steep sloped areas of the part. In the steep sloped areas, any lateral translation can result in large differences in measured values. This test suggests the repeatability of forming a 3-D part shape, though a discussion on part shape representation and optimization of minimized error is needed and can be found in the next section.

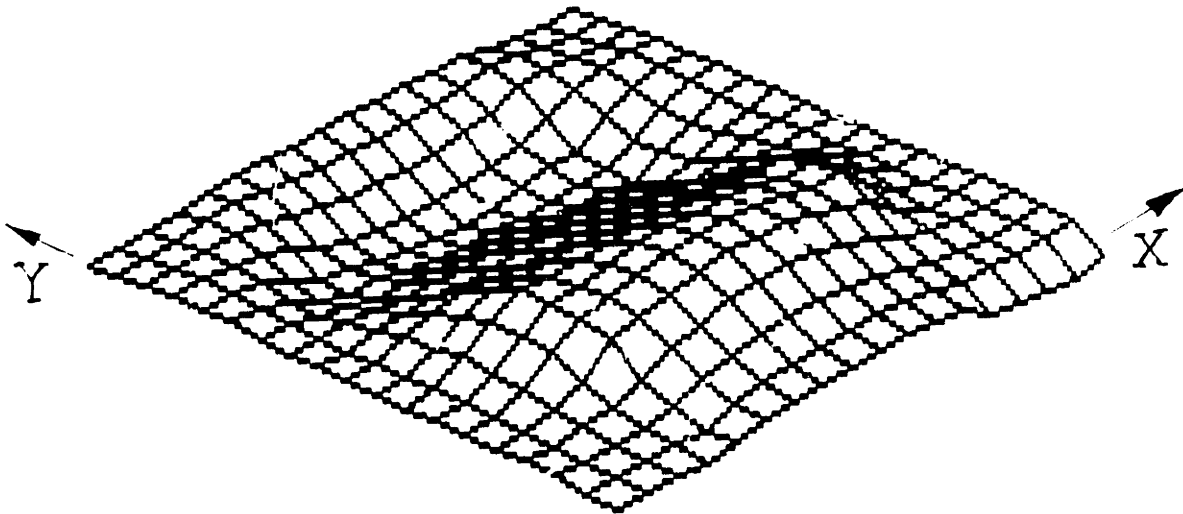


Figure 4.14 3-D Error Surface Plot Between JY20-2 and JY18-1

Test Results Between JY21-1 and JY18-1: The purpose of this comparison was to check on part shape repeatability and more importantly to see if a die pin moved during the forming cycle. Identical forming conditions were used in both tests. Before forming,

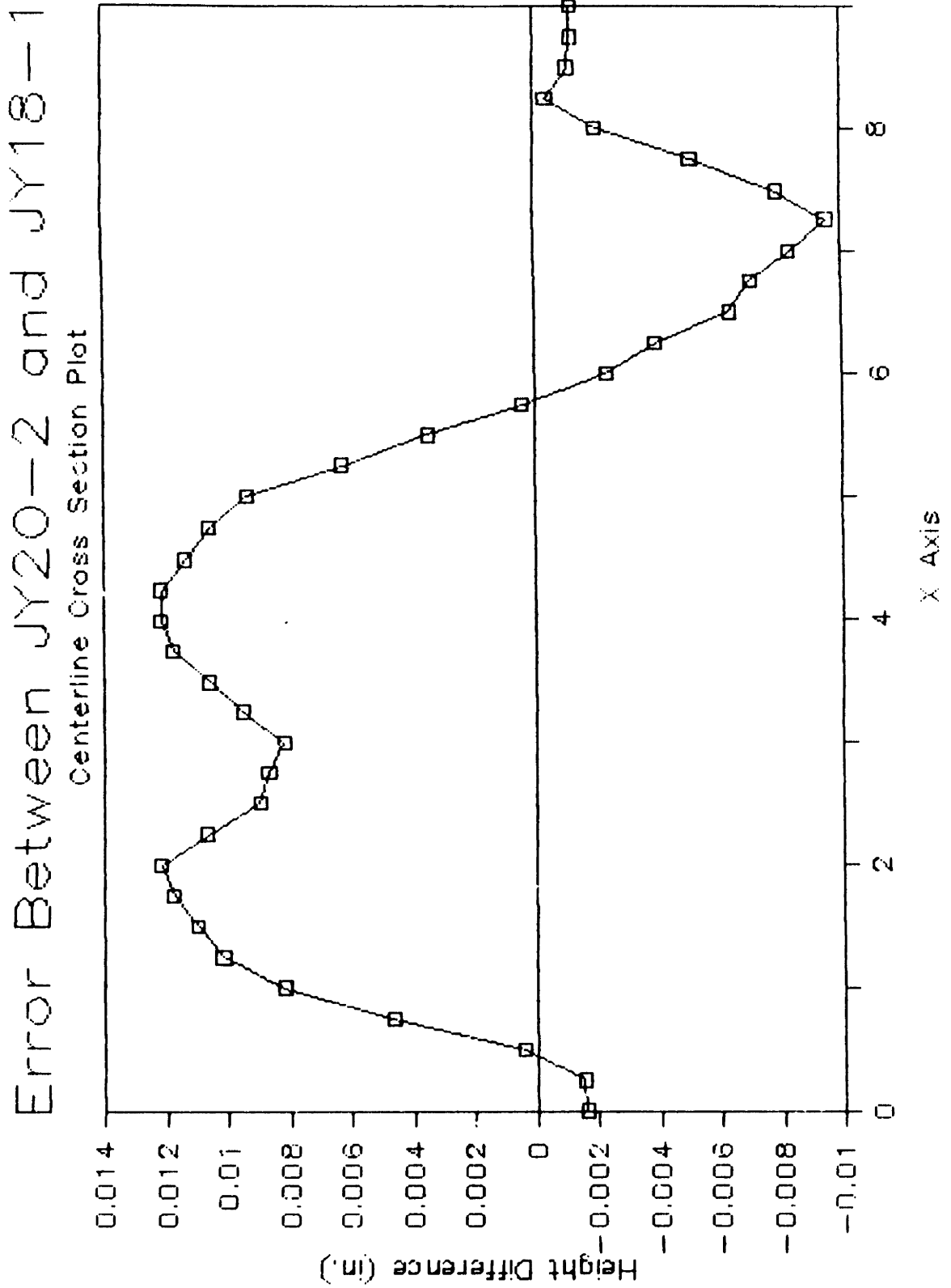


Figure 4.15 Cross Section Error Between JY20-2 and JY18-1

the location of an active die pin was measured with a depth caliper from a reference plane from the back of the die. After forming, the die pin location was remeasured. The location of the die pin did not change during the forming cycle, therefore any error found between this part and JY18-1 is not physically a function of the machine, but could be attributed to measurement errors. Figure 4.16 shows the 3-D error plot magnified by 20X. Figure 4.17 shows the cross section along $Y = 4.5$, parallel to the X axis. Once again this error might be a non optimal error reduction solution. The test suggests the repeatability of forming a part with the largest error occurring in the steep sloped region of the parts.

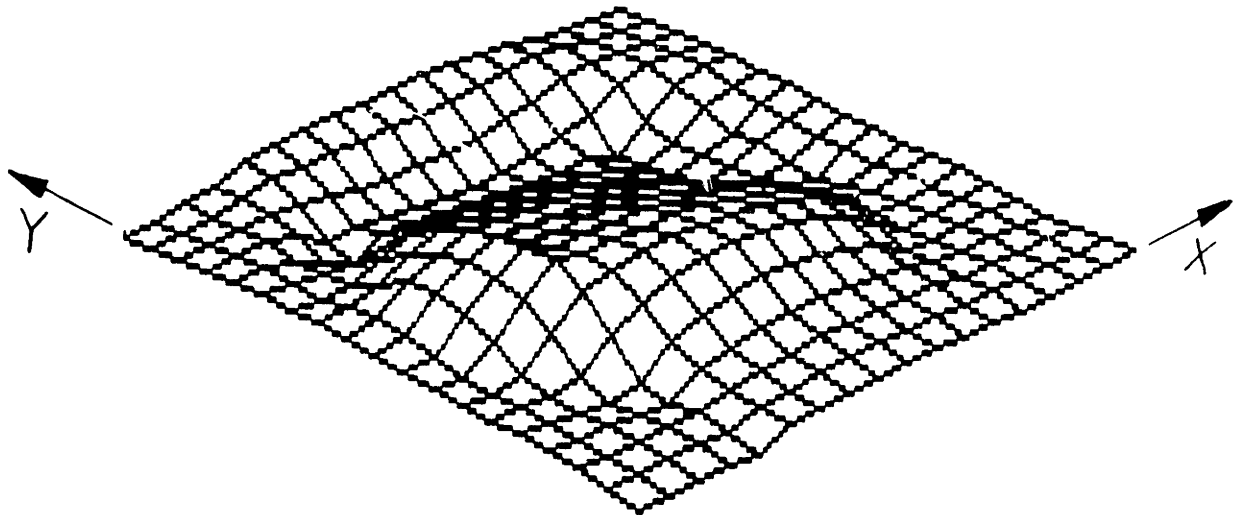


Figure 4.16 3-D Error Surface Plot Between JY21-1 and JY18-1

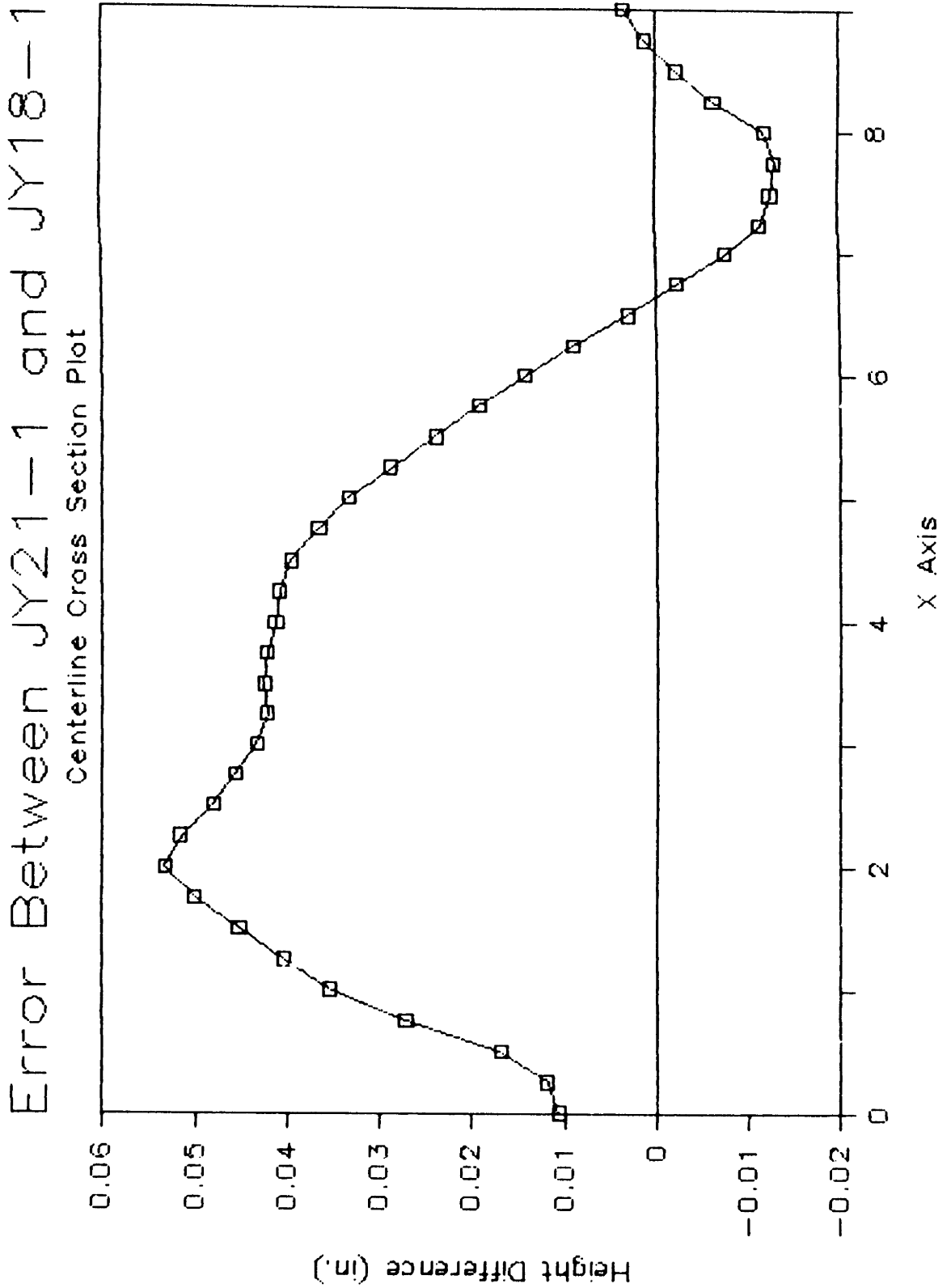


Figure 4.17 Cross Section Error Between JY21-1 and JY18-1

Test Results Between JY20-2 and JY20-1: The purpose of this comparison was to look into the effect of used rubber interpolating pads on resultant part shapes. Figure 4.18 shows the 3-D error plot while Figure 4.19 shows the cross section along $Y = 4.5$, parallel to the X axis. Figure 4.19 shows symmetric minimal error which signifies a possible translation error in centering the two data files. The data was translated but larger errors were obtained than in Figure 4.19. The test does not directly show the effect of the used rubber, but both plots show the largest errors occurring in the parting line/steepest sloped region of the parts. In a previous experiment where a steeper part was formed, the rubber interpolating pads used were torn from being bound in the passive die from an earlier experiment. The torn pads lost their ability to interpolate between contact points and the resulting part formed was deformed through actual die pin contact to the sheet metal.

Test Results Between JY20-3 and JY20-2: The purpose of this comparison was to investigate the importance of the "pin smasher" when forming parts. The purpose of the "pin smasher" is to remove the effects of the die pin spacers by laterally clamping the die pins to insure pin registration. Test JY20-3 did not use the "pin smasher" and a forming width of approximately 11.7 inches of the die halves were observed. The temporary "pin smasher" clamp was used in Test JY20-2 to get a forming width of 11.25 inches. Figure 4.20 shows the 3-D error plot while Figure 4.21 shows the cross section along $Y = 4.5$, parallel to the X axis. Though it looks like it might have some translation problems, the error is positive which signifies that the resultant part shape without the "pin smasher" is larger. The larger resultant part shape can be attributed to the die pins freedom to move laterally. The actual die pin tip locations during form-

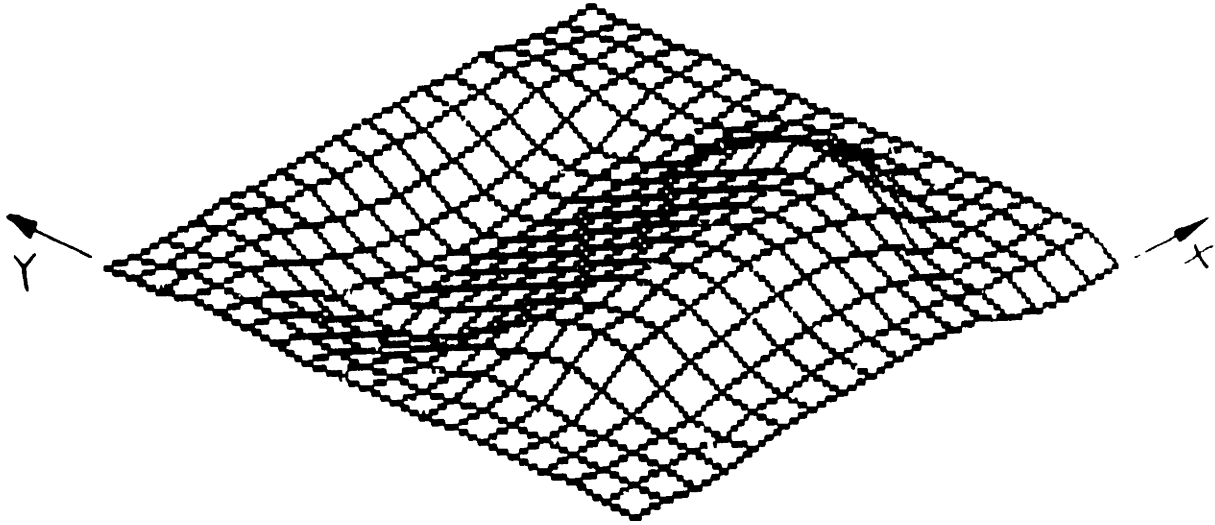


Figure 4.18 3-D Error Surface Plot Between JY20-2 and JY20-1

ing were unknown, and any attempt to implement closed loop shape control based on these pin locations would be prone to error.

Test Results Between JY27-1 and JY18-1: The purpose of this comparison was to investigate the effect of changing the parting line region of a part to force deformation. No attempt was made to calculate the proper die pin movement, the die pins were moved through judgement of the experimenter. As discussed in the previous section, the spatial frequency based transfer function identification algorithm by Webb would recognize the higher spatial frequency components of this parting line region and focus on this area. The limiting factor with the current die pin matrix configuration is the possibility of creating shear points in this region. Forming with this current machine,

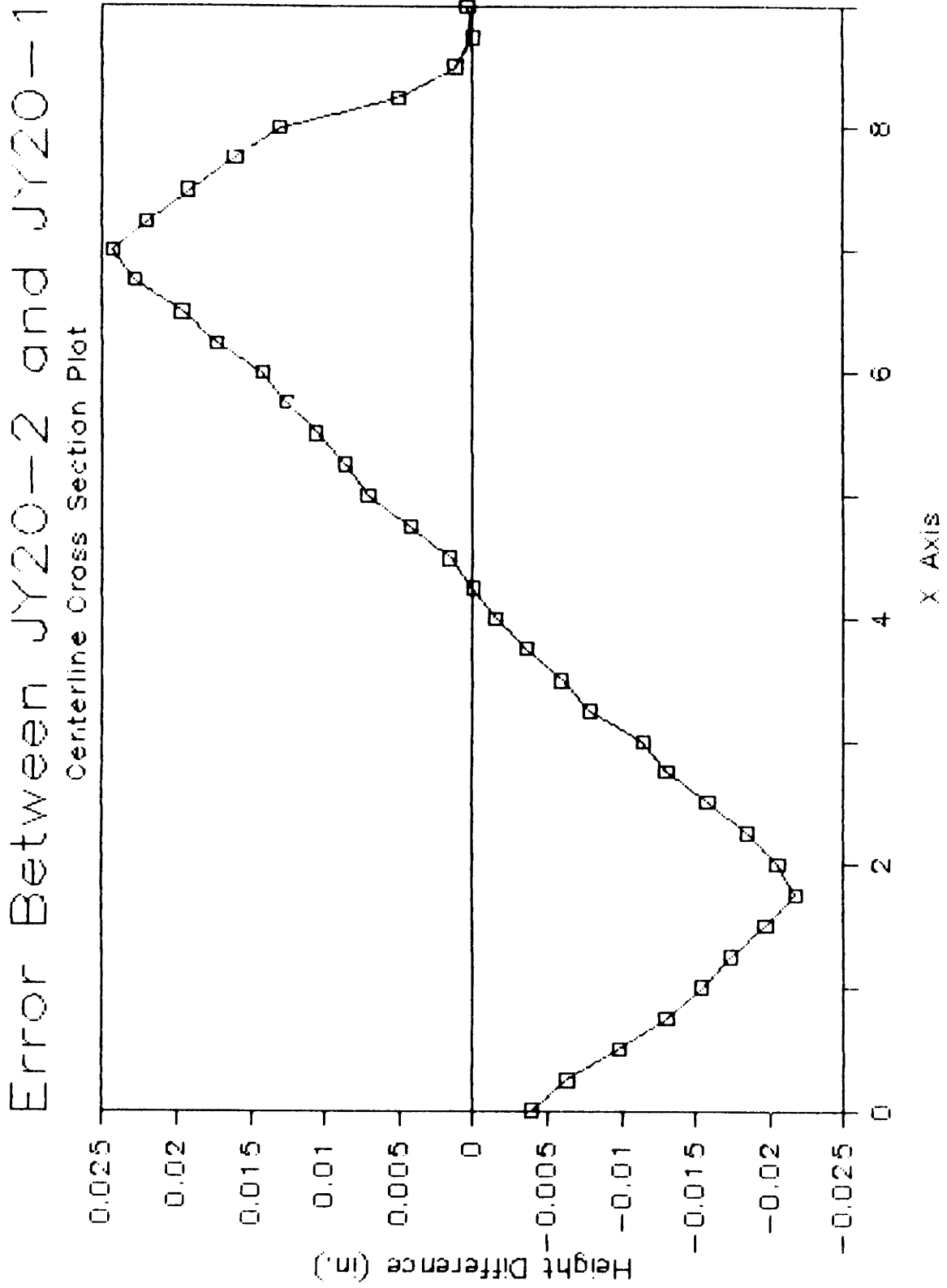


Figure 4.19 Cross Section Error Between JY20-2 and JY20-1

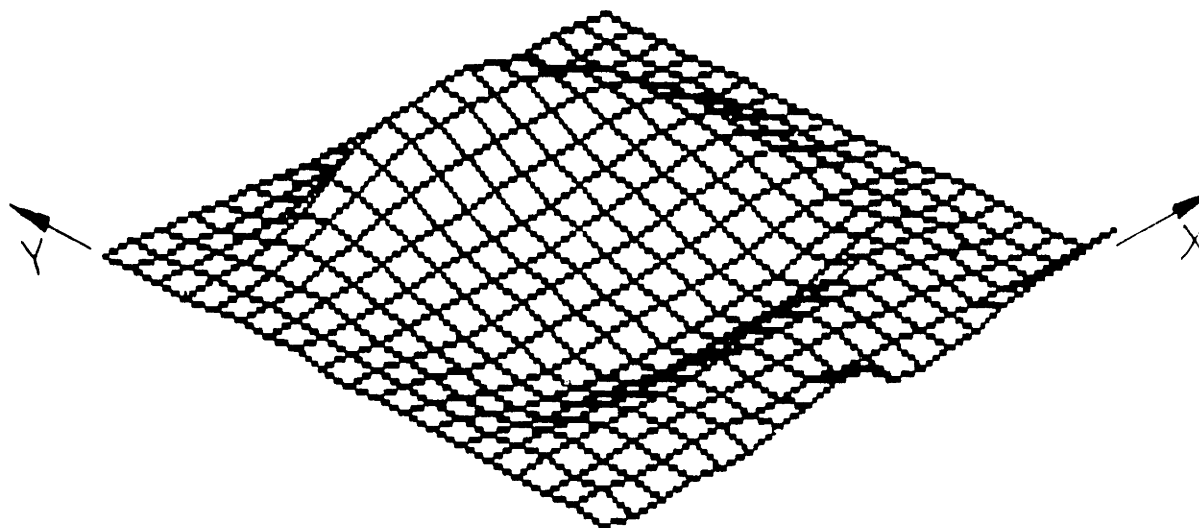


Figure 4.20 3-D Error Surface Plot Between JY20-3 and JY20-2

the frequency limitation becomes one die pin width to avoid this shear condition. The forming conditions were the same as in Test JY18-1. Figure 4.22 shows a comparison between Test JY27-1 and the desired part shape. A slight translation is apparent, but less error is observed in the parting line region. Figure 4.23 shows the error plot of these curves, note the difference between this plot and Figure 4.11, less error is observed. Figures 4.22 and 4.23 also show that a deeper part was drawn. This would be the result of increased stretching in the center area because of the decrease in clearance and resulting increase in binding conditions in the parting line region. Figures 4.24 and 4.25 show the comparison between Test JY27-1 and Test JY18-1. These figures confirm the previous observations that the parting line region in Test JY27-1 is closer to the desired than Test JY18-1, and the Test JY27-1 formed a deeper part.

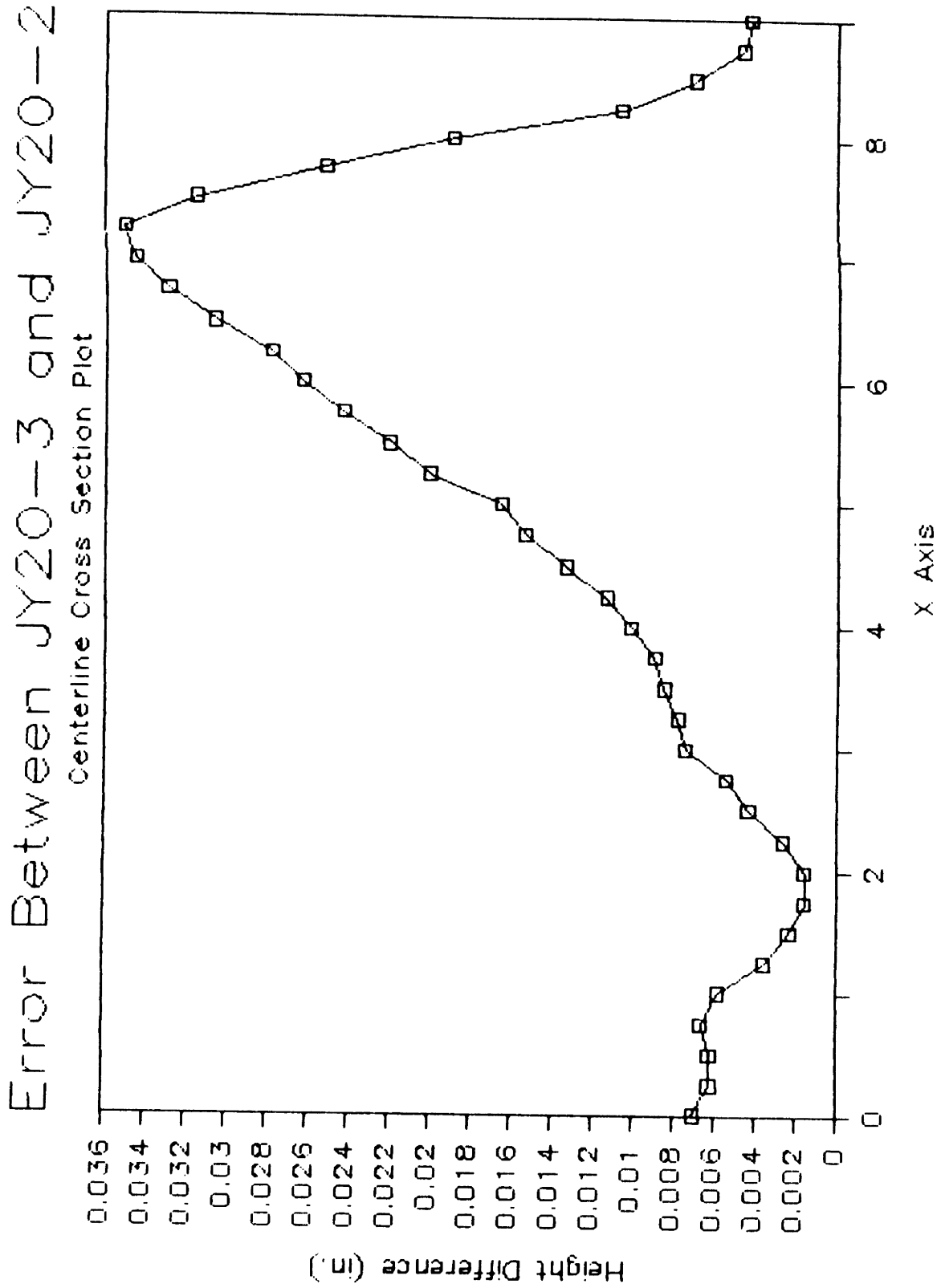


Figure 4.21 Cross Section Error Between JY20-3 and JY20-2

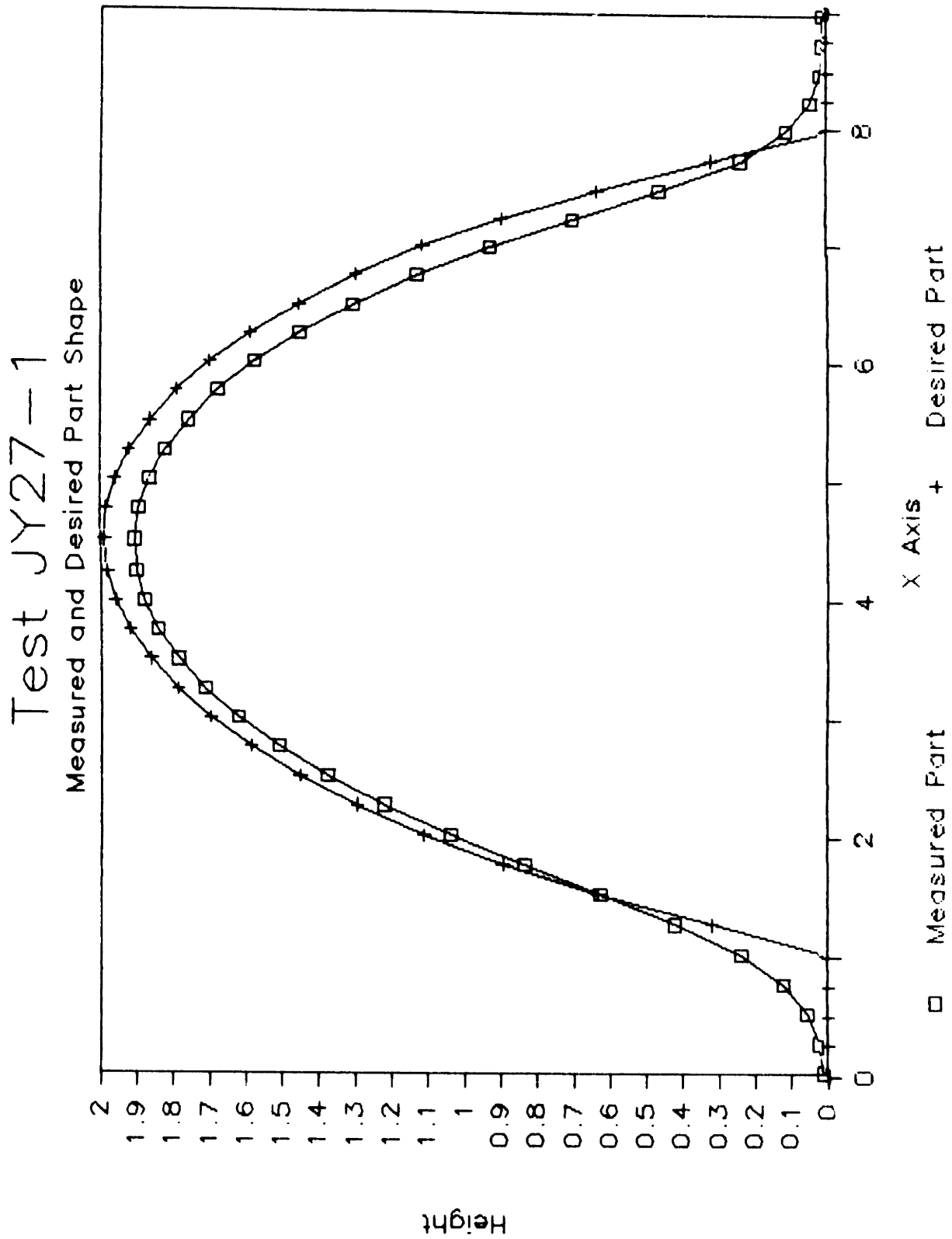


Figure 4.22 Test JY27-1 and Desired Part Shape Comparison

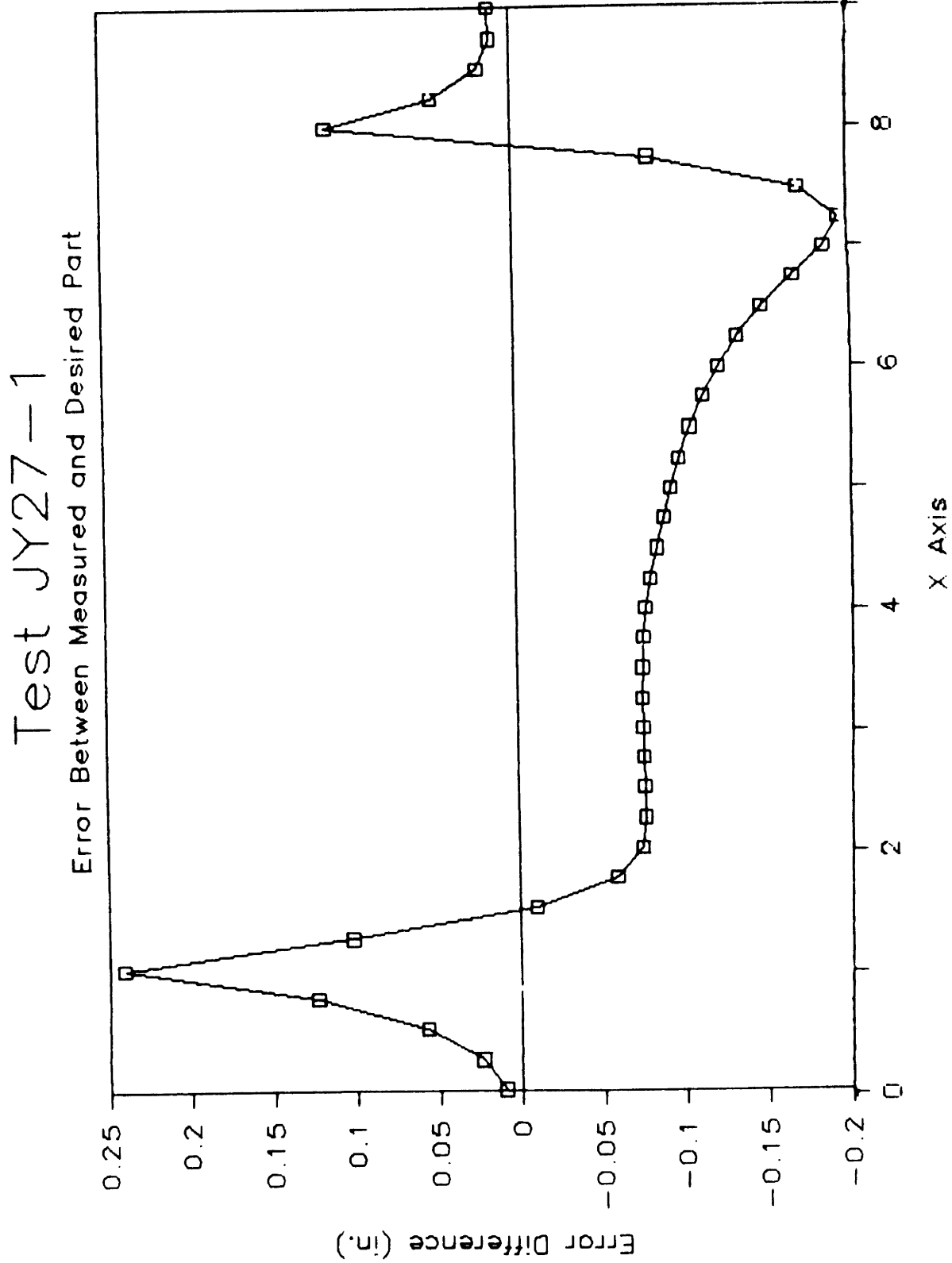


Figure 4.23 Cross Section Error Between JY27-1 and Desired

Comparison JY27-1 and JY18-1

Centerline Cross Section Plot

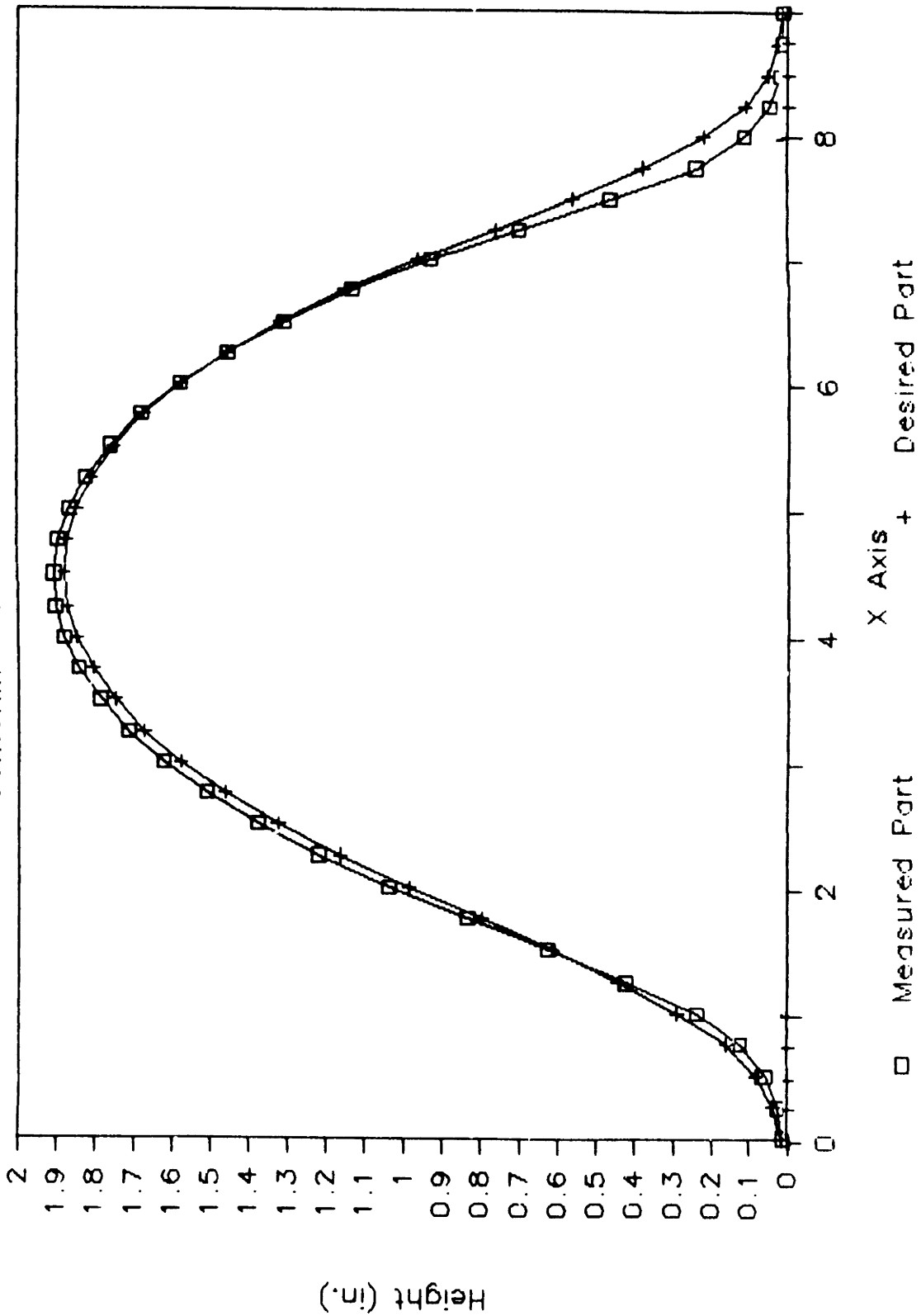


Figure 4.24 JY18-1 and JY27-1 Shape Comparison

Error Between Test JY18-1 and JY27-1

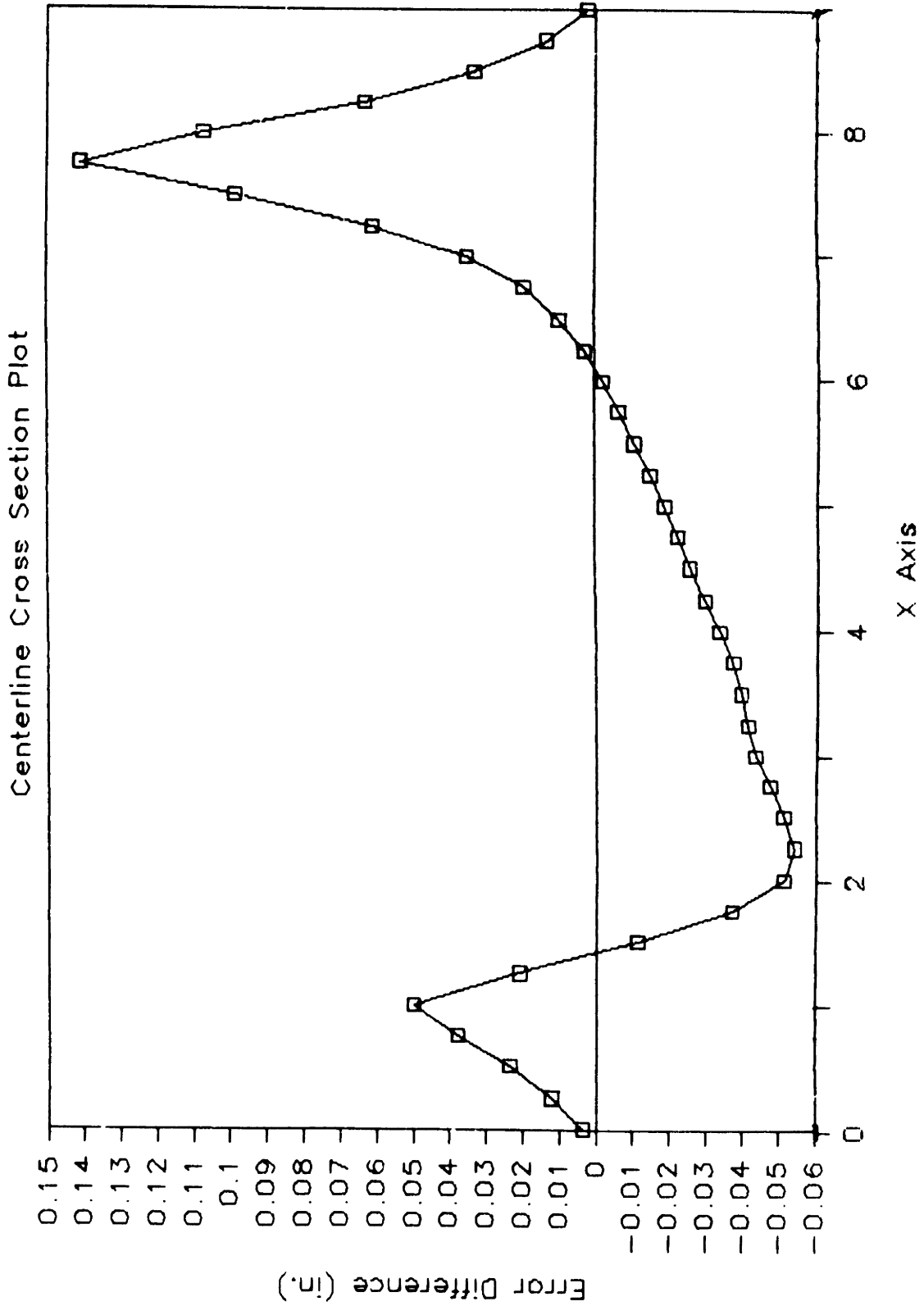


Figure 4.25 Cross Section Error Between JY18-1 and JY27-1

4.2.1 Summary

The results of the 3-D forming experiments were not as conclusive as the 2-D experiments. The forming of 3-D part shapes appears to be repeatable, although errors in the measurement stage tend to cloud this result. Die pin motion was monitored before and after a forming cycle. The die pin did not move, suggesting that any part shape error is not a function of the physical machine. The effect of using worn rubber interpolating pads on the resultant part shapes was found to be inconclusive, although in earlier, undocumented tests with used rubber interpolators, it was found that the die pins tore the rubber and directly contacted the part causing local deformations. The "pin smasher" assures the proper pin registration and location during forming, and without it it becomes an indeterminate problem of pin location, and the repeatability of a formed part is not guaranteed. Finally, by moving die pins in the parting line region to compensate for the discrete nature of the die pin matrix and the rubber pad effects, a more distinct parting line was formed. This action simulates the implementation of a spatial frequency based transfer function identification algorithm and the focus of the controller to the higher spatial frequency components of the parting line.

4.3 Error Observation

There are many possible contributors to the errors observed in the forming experiments. An obvious error possibility exists in the manual set up of the positioning rods in the die pin positioning system. The error could be in actual set up of the positioning rods to the desired shape or the positioning of the die pins with the positioner clamp to incorrect forming depths.

Chapter 4: Initial Forming Experiments

The bent and warped condition of the die pins causes errors when the die pins are positioned by the positioning rods. When each column of die pins is being positioned, if a die pin is bent and warped and laterally contacts adjacent pins it could pull a die pin along as it is being positioned. This will cause in die pins in the next column to be in a overextended position and cause a incorrect die shape. The solution to this problem would be to acquire a new set of straight die pins.

Error could occur in the transferring of the active die shape from the passive die to the active die (Set Up B procedure) through improper tip-to-tip die pin registration. The use of the temporary "pin smasher" clamps reduces this error but some bowing of the clamps has been observed. The installation of the permanent "pin smasher" to the blankholder would insure die pin alignment and registration, eliminating this error.

The rubber interpolating pads are a unique feature of this forming process. Closed loop shape control theory should compensate for the effect of the rubber. Webb [12] used neoprene as a disturbance in evaluating the spatial frequency based transfer function identification algorithm. The algorithm was able to compensate for the neoprene and implementation of this algorithm is essential in utilizing the flexible forming properties of the VCD. One problem is that the rubber is subjected to high shearing forces during a forming cycle and in certain die configurations, the rubber tends to bind and tear. If torn, the rubber loses its interpolating properties and the resultant part can be deformed through actual die pin contact causing dimpling. The condition of the rubber interpolating pads must be continually monitored and any repositioning of the pads to reduce binding points should be done whenever possible.

Chapter 4: Initial Forming Experiments

One important characteristic of this machine is that once the die pins are positioned and hydraulically clamped for forming, the die pins do not move during the forming cycles. The system pressure of 3,000 psi. must be maintained to assure this proper clamping. Other than the errors discussed earlier, the machine does not add any errors to the resultant part shape formed.

Numerous error possibilities exist in the measurement phase of the experiments. Some errors can be attributed to the physical set up of the CMM. Consistent clamping can not be obtained because the flange area is slightly buckled, so any relative measurements from the sheet metal edges would be useless. The CMM makes relative measurements from an initial zeroing of the encoders, so the height measurements for each part are a function of this arbitrary datum. The position of the measurement probe is controlled by a pneumatic system with two on-off solenoids. The probe contacts the part with considerable force, actually peening the part, and depending on the its stiffness, the part will deflect and an erroneous height measurement will be taken. The probe also lacks some lateral stiffness and in combination with the high contact force will slide down the steeper sloped part regions. Future development of a force controlled CMM is being pursued and will reduce these errors.

With the relative height measurements from the CMM, there needs to be some way to define the shape as a surface such that two surfaces could be compared to find the minimized shape error. This problem arose in the question of data translation in both the 2-D and 3-D error plots of the experiments. In both cases, the tests were compared by centering the data around the highest points found, which does not guarantee finding the minimal shape error. Webb [4] investigated surface patches to relate back to die pin locations. These patches would be analogous in three dimensions

Chapter 4: Initial Forming Experiments

to the cubic splines in two dimensions. Using surface patches would also work well with the eventual implementation of a CAD system to describe the part shapes. Continued work in part shape representation is necessary for the implementation of the closed loop shape control theory.

Conclusions and Recommendations

5.1 Conclusions

A new forming technique has been implemented in the assembly of the variable configuration die forming machine. Though presently not fully automated, 2-D and 3-D forming experiments were conducted to characterize the forming properties of the machine. One important result found was the ability of the machine to repeatedly form the same part shapes under varied forming conditions (i.e. varied binder force magnitudes and order of application). This property is important for the implementation of a closed-loop shape control strategy to this machine.

Along with the property of repeatability, other unique properties of this forming process were observed. Rubber interpolating pads are used to interpolate between the contact points of the die pins and form smooth parts. These rubber pads work very well, but care must be taken to make sure the pads do not bind or tear, in which the interpolating property is lost. The most interesting area is around the parting line where the discrete nature of the die pins and the rubber pad effects can be seen by not forming distinct parting lines. An experiment was performed simulating the implementation of a spatial frequency based control algorithm where increased controller action would focus on the high frequency component of the parting line. Extra die pin movement occurred within the parting lines area, forcing deformation, and a better, more distinct parting line was formed.

Chapter 5: Conclusions and Recommendations

Another characteristic of this machine that has caused many problems is the bent and warped nature of the die pins. The bent die pins will stick to other die pins resulting in inaccurate die set up. The new positioner clamp and the bevelled positioning rod tips have simplified the positioning system and have removed the bent and warped die pin effects during profile transfer. The implementation of the "pin smasher" clamps and thinner die pin sheet spacers combination has resulted in more accurate die shapes with proper die pin registration and known die pin location. This modification has greatly increased part shape repeatability.

A measurement procedure has been developed to aid in the convergence of the measured part to the desired part when utilizing a closed-loop shape control strategy. It was found that a part should be measured when removed from the blankholder and in an unconstrained state. The earlier method of in-process measurement while held in the blankholder was found to give an improper representation of the true state of the part.

Though design modifications have removed many possibilities for shape errors, there still exist many places where errors can occur. However, one important property noted is that once the die pins are positioned and hydraulically locked into place, *they do not move under forming loads*, so no shape errors occur because of physical properties of the machine. Shape errors can occur in the inaccurate set up of the dies and in the measurement practices currently used.

5.2 Recommendations

The first recommendation is to install the solenoid housing plates into the die pin positioning system, once fabricated. The completion of the die pin positioning system enables the implementation of a closed-loop shape control strategy.

Some physical additions to the machine would be to obtain a new set of straight die pins and install a permanent "pin smasher" clamp to the present blankholder. The bent and warped die pins have caused many problems during die set up. Though many of the design modifications have taken care of these problems, other problems will continue to appear. The installation of a permanent "pin smasher" clamp is needed to eliminate the die pin sheet spacer thickness effects and ensure pin-to-pin registration during die shape transfer.

The present direction of the project should be to implement Webb's [12] spatial frequency transfer function identification algorithm. To implement this, work must be done on the shape descriptor. The discrete measurement data points from the CMM must be transformed to define a continuous part surface and this must be related back to correspond to die pin locations for die set up. The implementation of the spatial sampling scheme will tie together the shape descriptor work and control work. The shape descriptor work will also help to interface the CAD system by converting the CAD part design to the actual die pin locations accounting for rubber thickness and contact points.

Another suggestion is to implement the real-time binder force control done by Fenn [11] to respond to changes in lubrication, blank thickness, blank size and other material

Chapter 5: Conclusions and Recommendations

properties. A hydraulic clamping system would replace the present blankholder. Space limitations might be a problem, but small hydraulic rams could be used to get the binder force control needed. An upgrade of the present hydraulic system would be recommended to increase to design pressure of 3,000 psi.

The current measurement practices need to be revised. Most problems are a result of the current CMM. The high contact force on the part from the probe during measuring causes the part to deflect giving erroneous measurements. The revision of the current set up to some sort of force controlled probe would greatly increase the accuracy of the machine.

Even under its current state of manual operation, the variable configuration die forming machine has exhibited many desirable properties such as quick die shape changes for die prototype tryout, its ability to handle low batch production needs and its use to investigate experimental forming techniques. Some forming techniques to be investigated with the current machine set up are: 1) a forming process similar to hydroforming, where the active (male) die shape is locked solid at system pressure while the passive die pins are positioned to form a flat surface. The passive die pins would be under a lower hydraulic pressure, to be determined experimentally, and contact the sheet metal with a rubber interpolating pad between them. During the forming cycle the die pins of the passive die would be able to move, but while under some hydraulic force. This would give continuous support to the sheet metal as it is being deformed to the active die shape. The amount of pressure to the passive die pins could be varied and some correlation between the hydraulic pressure and shape error could be found. 2) use the machine to form advanced thermoplastic composites. The composites industry is also plagued by the expense, lag time, and inflexibility of traditional machined dies.

Chapter 5: Conclusions and Recommendations

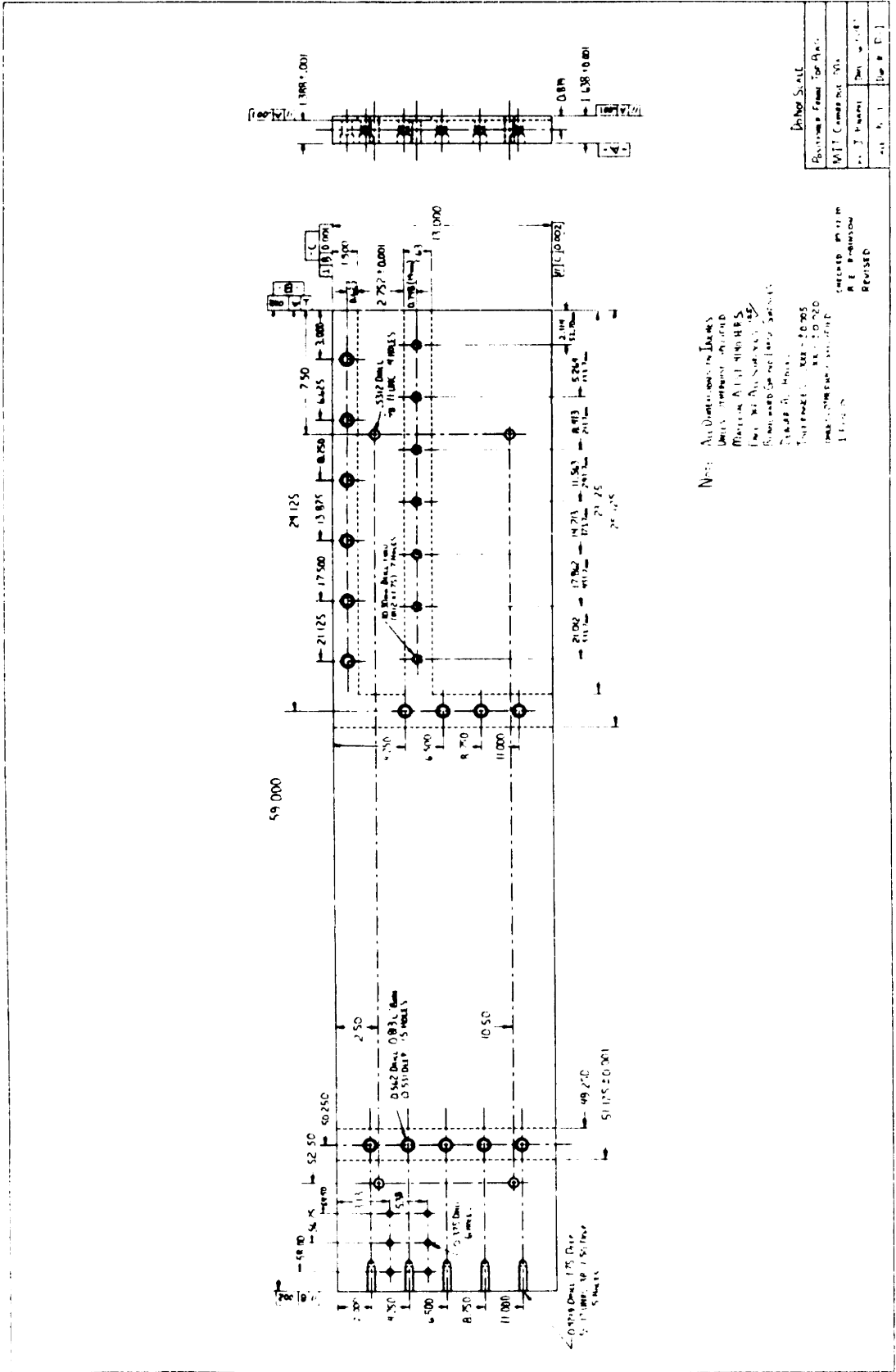
The machine could form sheet metal dies for single autoclave and diaphragm forming, or for matched die stamping. The sheet metal dies would need to be able to handle forming pressures of 100-300 psi. to remove the voids during consolidation of the composites. The sheet metal dies offer low thermal masses and die shapes could be quickly changed with the variable configuration dies. This work would be in conjunction with the Composites and Polymer Processing Program within the LMP.

REFERENCES

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3. Hardt, D. E., Olsen, B. A., Allison, B. T., and Pasch, K., "Sheet Metal Forming with Discrete Die Surfaces", *Proc. 9th North American Manufacturing Research Conference*, 1981, pp. 140- 145.
4. Webb, R. D., "Adaptive Control of a Flexible Die System for Forming Sheet Metal Parts", Sc.M. thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, September, 1981.
5. Stelson, K. A., Gossard, D. C., "An Adaptive Pressbrake Control Using an Elastic-Plastic Material Model", *Journal of Engineering for Industry*, Vol. 104, Nov. 1982, pp. 289-293.
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8. Webb, R. D., and Hardt, D. E., "Spatial Frequency Based Closed-Loop Control of a Sheet Metal Process", *Sensing and Control of Manufacturing Processes and Robots*, ASME Special Publication, Nov., 1984.
9. Robinson, R. E., "Design of a Automated Variable Configuration Die and Press for Sheet Metal Forming", Sc.M. thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, February, 1987.
10. Pasch, K., "The Design of a Discrete Die Surface Fixture for Sheet Metal Forming", Bachelor thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, June, 1981.
11. Fenn, R., and Hardt, D. E., "Real-Time Sheet Metal Forming Stability Control", to be submitted to *ASME Journal of Engineering for Industry*, 1988.
12. Webb, R. D., "Spatial Frequency Based Closed-Loop Control of Sheet Metal Forming", Ph.D. thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, May, 1987.

Appendix A
Die Pin Positioning System Drawings

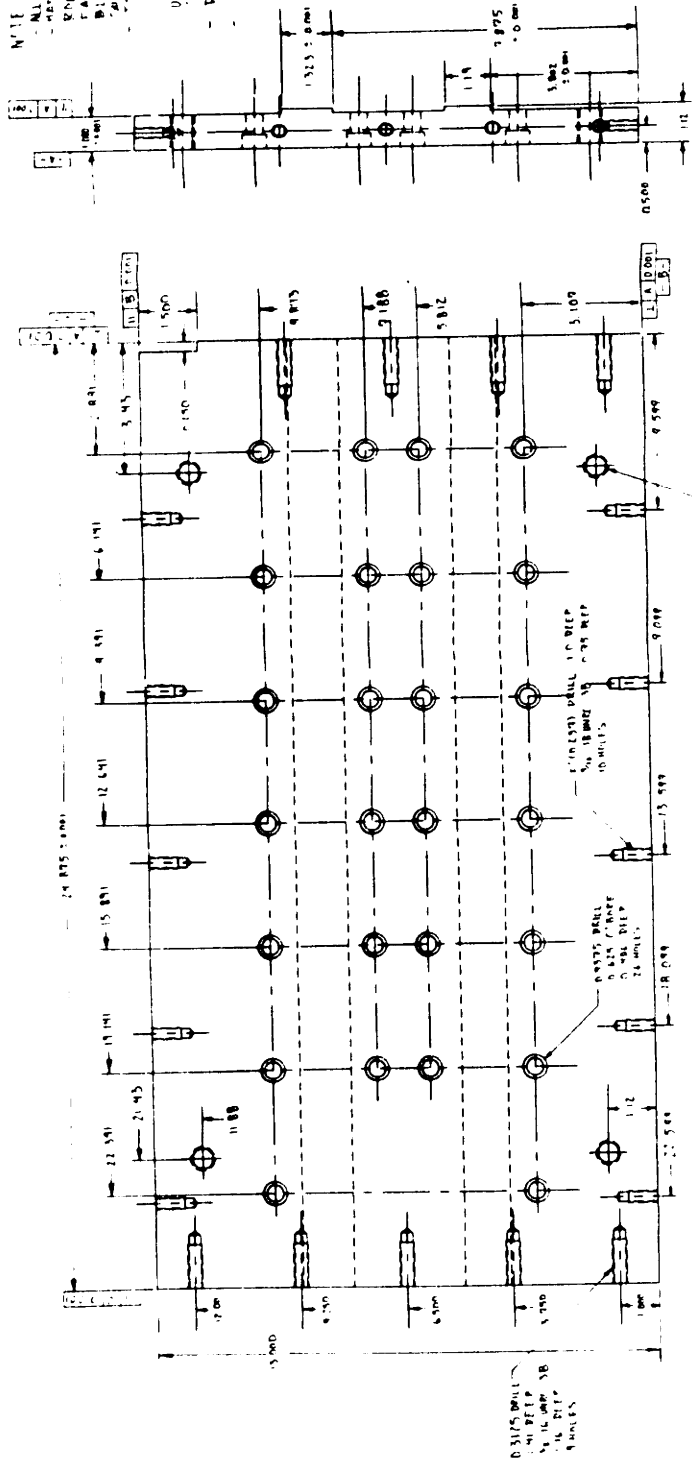
Appendix A: Die Pin Positioning System Drawings



Appendix A: Die Pin Positioning System Drawings

NOTE

- ALL DIMENSIONS IN MM UNLESS SPECIFIED OTHERWISE
- ALL DIMENSIONS TO CENTER UNLESS SPECIFIED OTHERWISE
- ALL DIMENSIONS TO CENTER UNLESS SPECIFIED OTHERWISE
- DEBURR ALL HOLES
- 1 Pcs/D

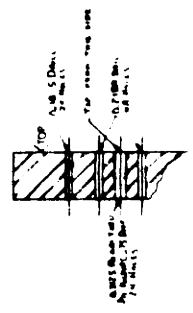


Drawing Scale	
System	1:1
Part	1:1
Rev	1
Date	01/01/00

Checked: 07/12/10
 R.F. Robinson
 REVISED

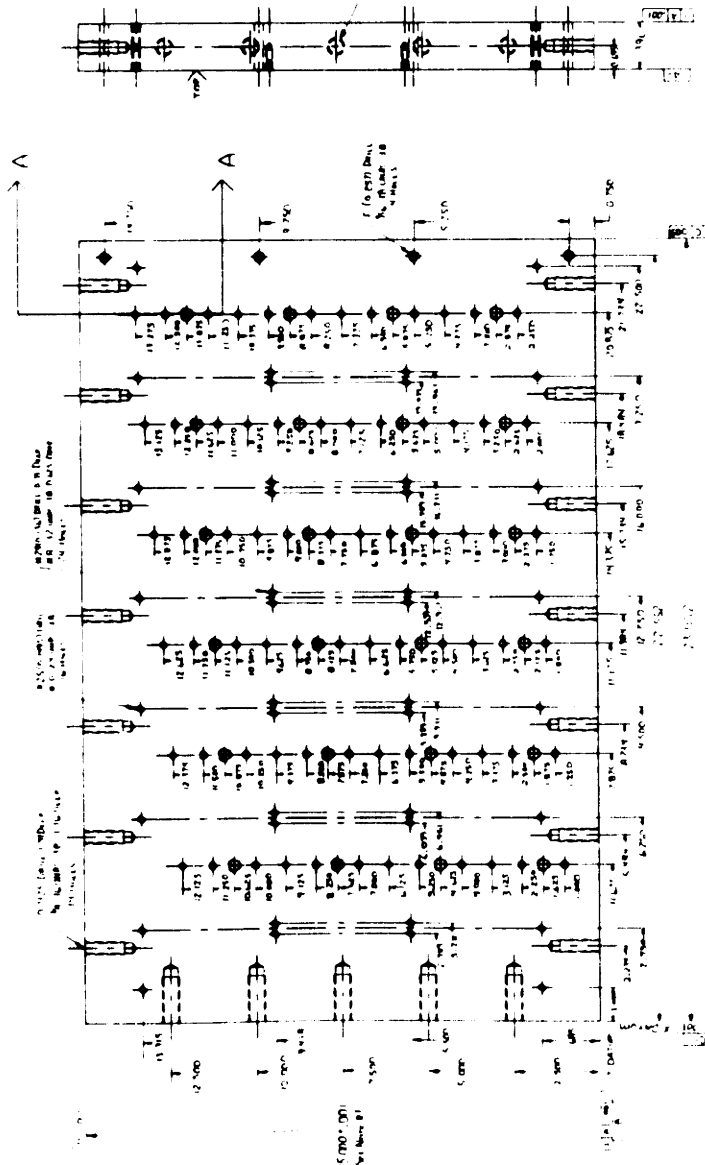
Appendix A: Die Pin Positioning System Drawings

SECTION AA



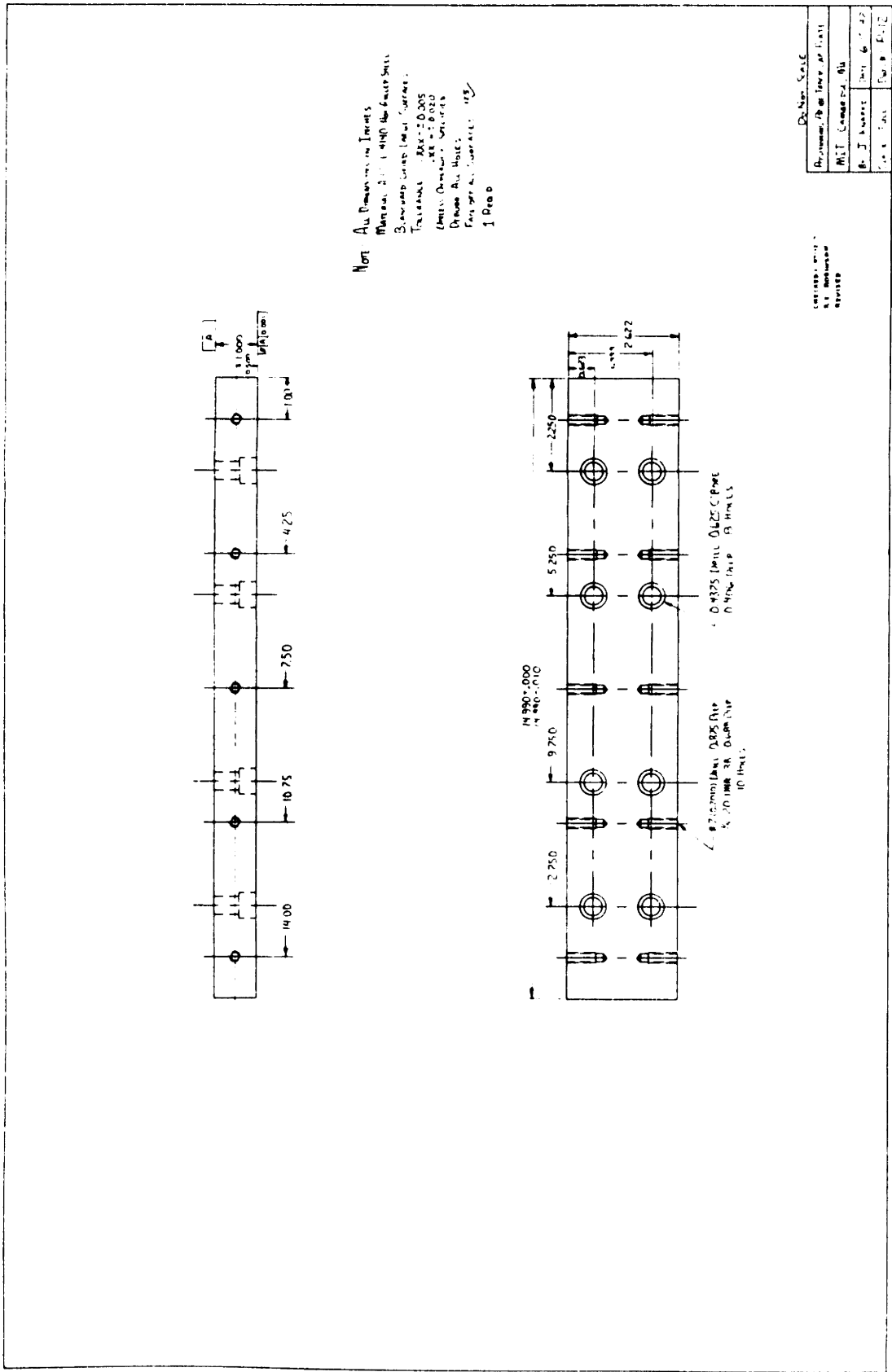
- Note
- 1) Max. Minus 15 mils on length with dimension P P ID (P II)
 - 2) Dimension of Pin to be used
 - 3) All Dimensions in Inches
 - 4) Material: A151-7140 HRS
 - 5) Face of All Surfaces
 - 6) Placement on Lathe Faces
 - 7) Drawn as Shown
 8. Tolerance: ±0.005
 9. Units: Dimension in inches
 10. P. Rao

20 Nov 1952	
Rear Section Assembly Plate	
WLT Cambridge, MA	
By: J. Moore	Draw: L. J. Rao
Scale: 1" = 1"	Sheet: 8 of 9



Checked by: W. R. Robinson
 Revised

Appendix A: Die Pin Positioning System Drawings

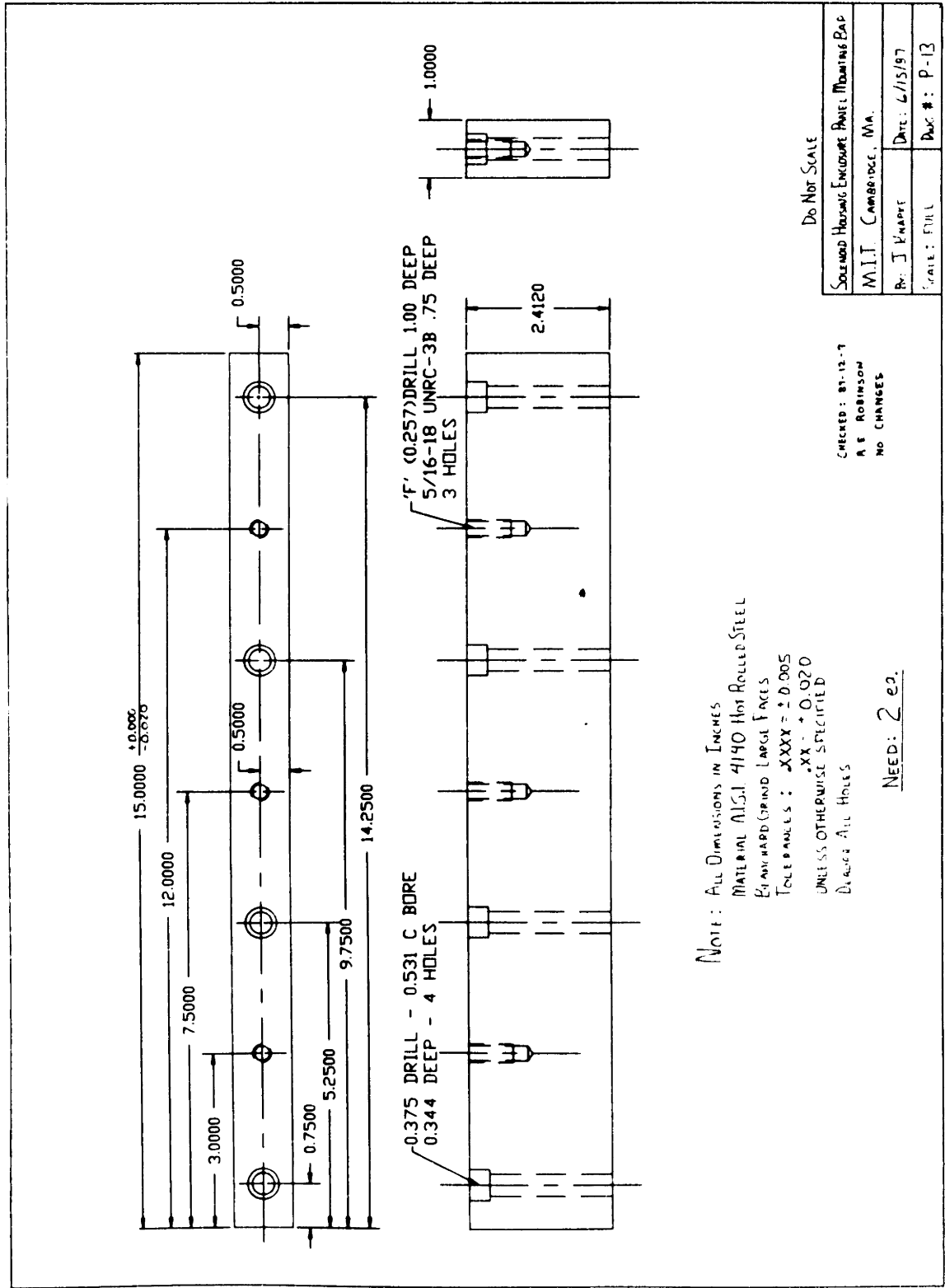


Note: All Dimensions in Inches
 Material: 316L Stainless Steel
 Standard Class: Low Temperature
 Tolerances: ASME Y14.5-2005
 Finish: Chromate Conversion
 Drawing: All Holes
 Fasteners: Torqued: 15
 1 Pin 0

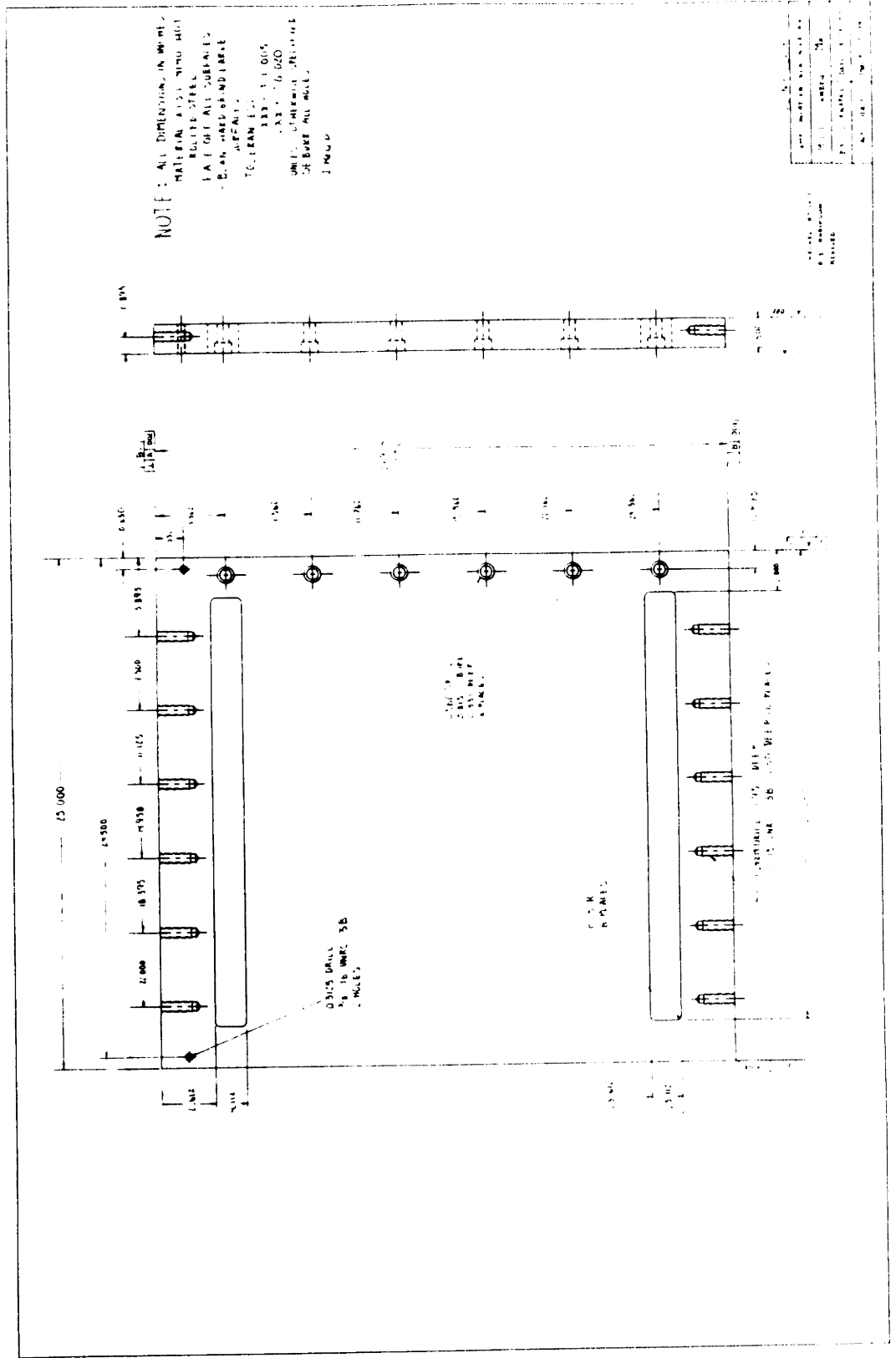
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As Shown	As Shown
MIT	Cambridge, MA
Rev. 1	June 6, 2012
Rev. 2	June 12, 2012

REVISIONS
 NUMBER
 REVISION

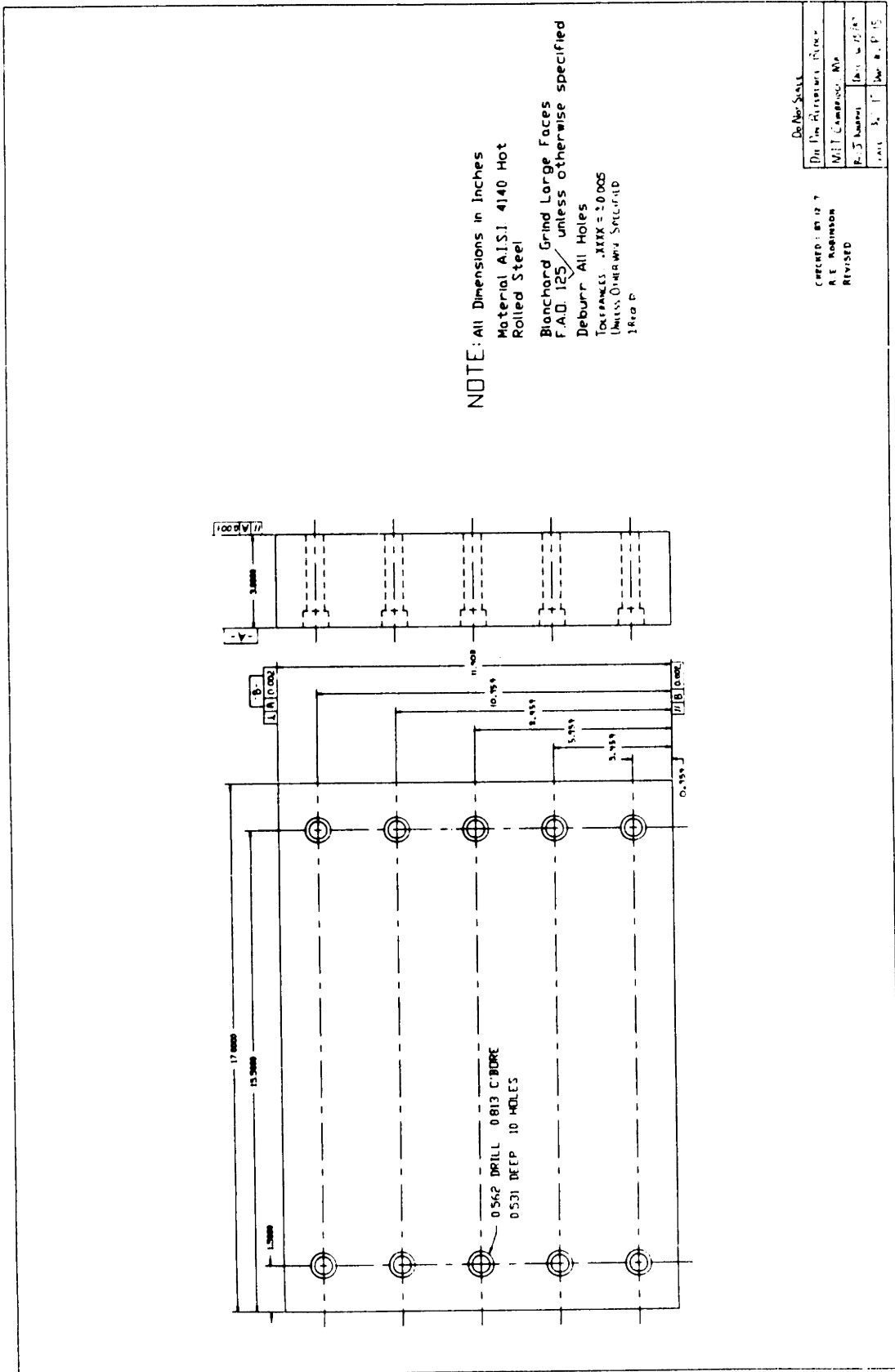
Appendix A: Die Pin Positioning System Drawings



Appendix A: Die Pin Positioning System Drawings



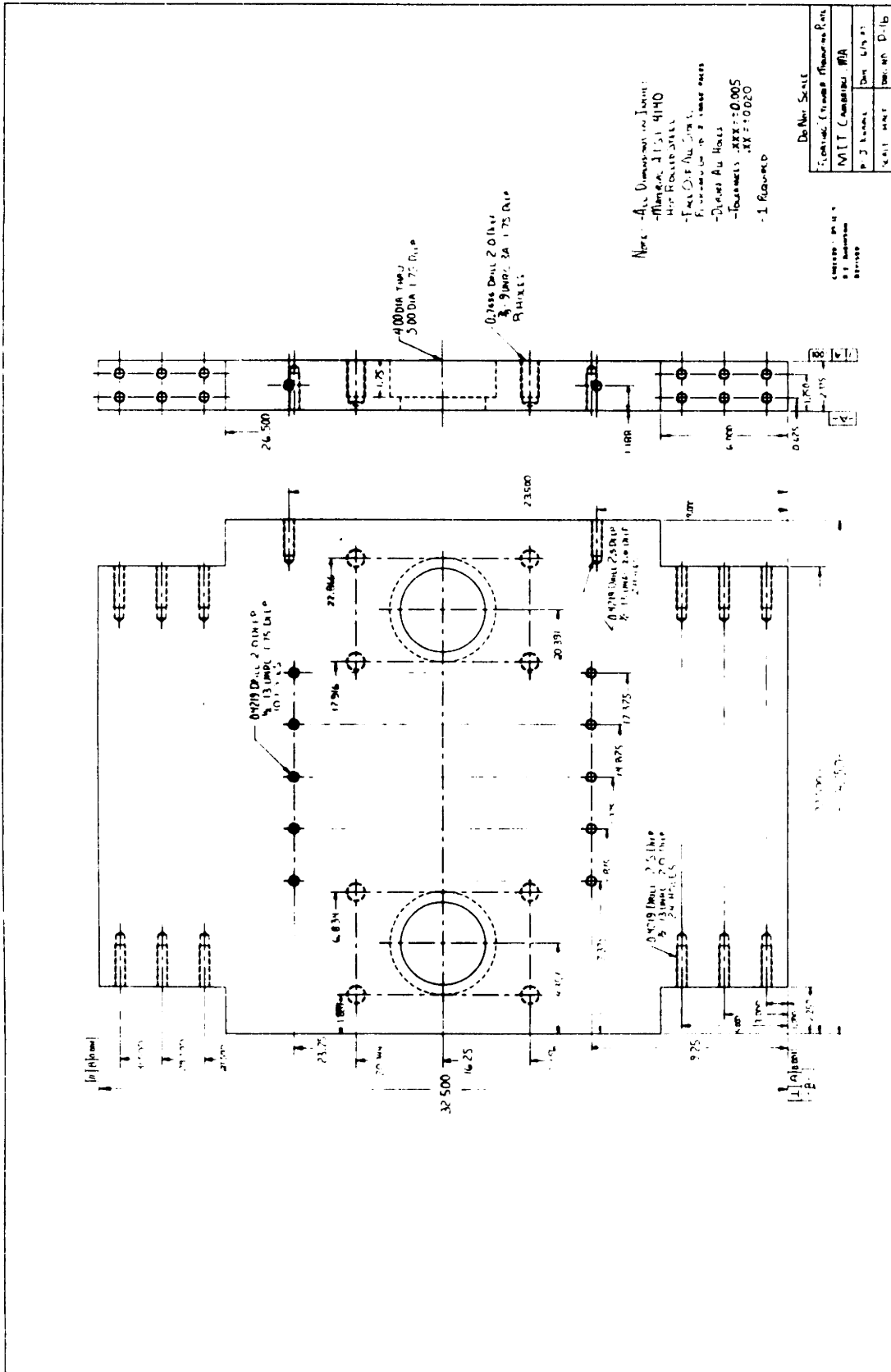
Appendix A: Die Pin Positioning System Drawings



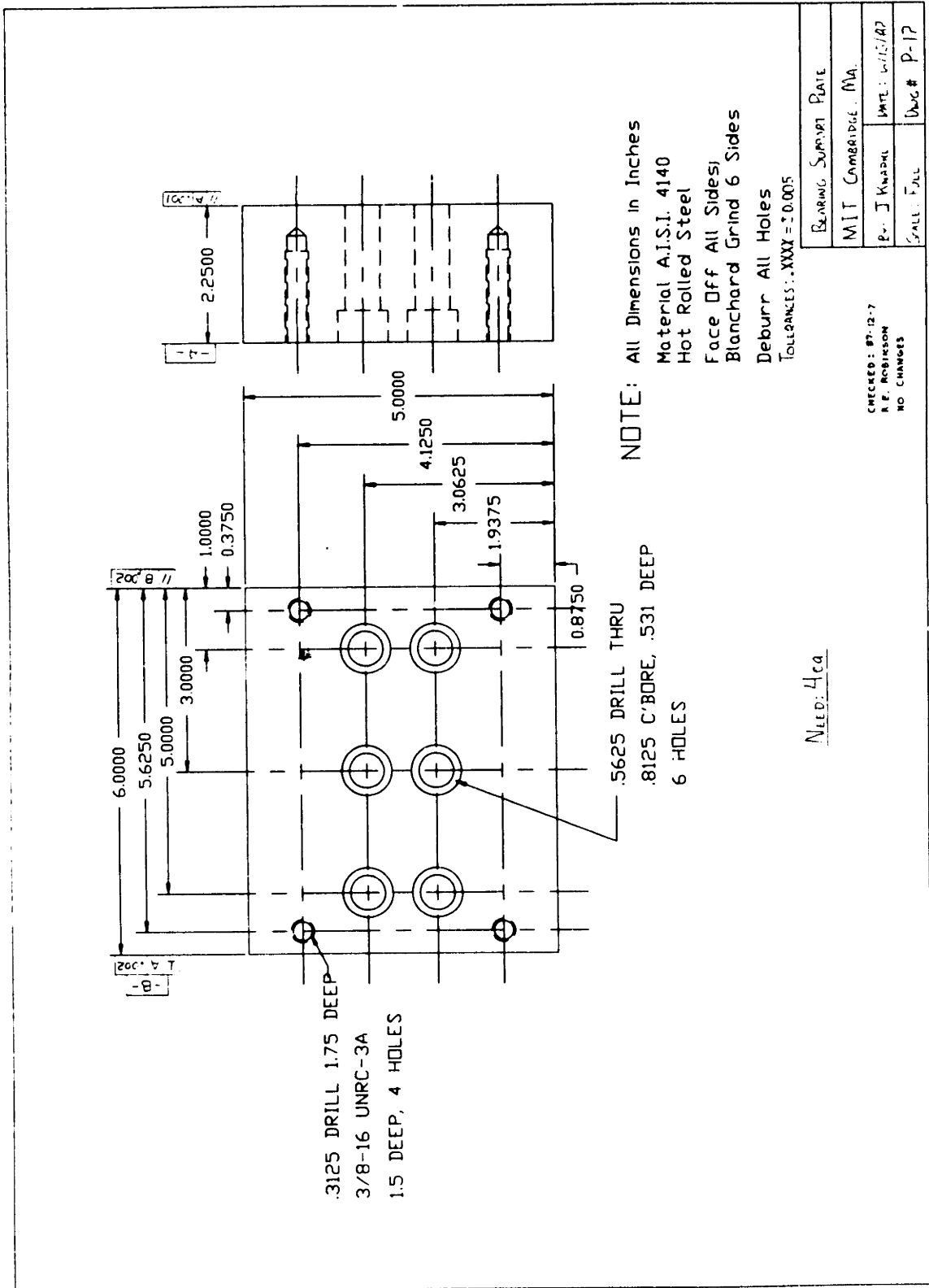
Die Pin	
Dr. J. H. Robinson	Dr. J. H. Robinson
M.I.T. Cambridge, Mass.	M.I.T. Cambridge, Mass.
R. S. Nelson	Rev. 10/15/47
1947	Rev. 8.1.15

CHECKED BY 12 7
 A. E. ROBINSON
 REVISED

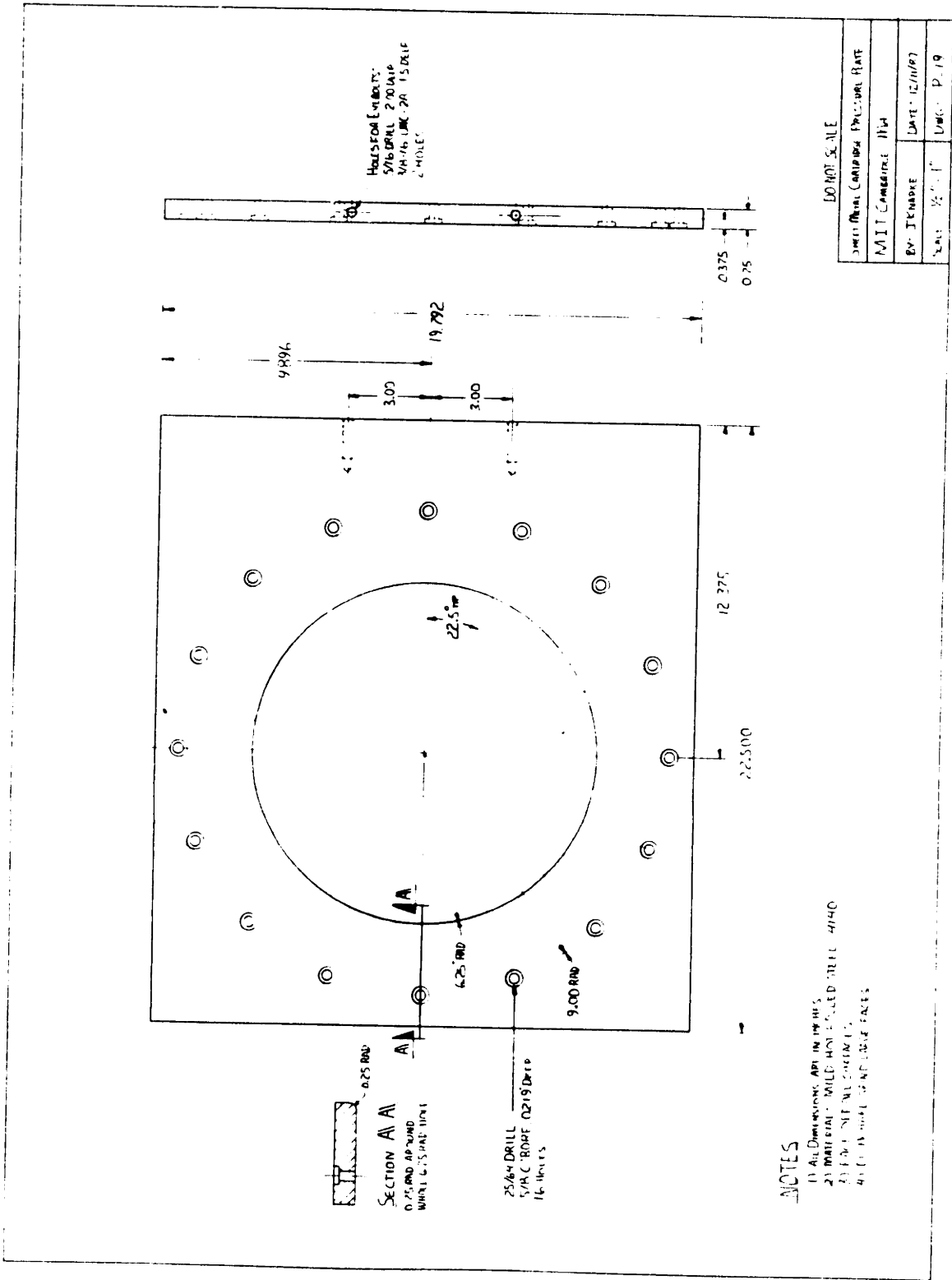
Appendix A: Die Pin Positioning System Drawings



Appendix A: Die Pin Positioning System Drawings



Appendix A: Die Pin Positioning System Drawings



- NOTES
- 1) ALL DIMENSIONS ARE IN INCHES
 - 2) MATERIAL - MILD-STEEL 1018
 - 3) FINISH - MILL
 - 4) 16 HOLES - SPACED EQUALLY

Appendix B

Program Listings

```
Program PinHeight;
{ Program for Symmetric Shapes}
{ No chord offset, strictly hemispheres, intial step of 0.125"}

{$U+}

Const
  PinRadius = 0.125;
  MetalThickness = 0.036;
Type
  ActiveHeightArray =Array[0..100] of Real;
  PassiveHeightArray =Array[0..100] of Real;
  PositionActive =Array[0..100] of Real;
  PositionPassive =Array[0..100] of Real;
Var
  Count,I,J,Interval,Intervl :Integer;
  Radius,Step,RubberThickness,StartPinA,NRadThick :Real;
  StartPinP,Thickness,NewRadius,Thick,RubberPinRad :Real;
  Active :ActiveHeightArray;
  Passive :PassiveHeightArray;
  PosA :PositionActive;
  PosP :PositionPassive;
  Pname :String[20];
  Prog :Text;

Begin
  Write('Enter New File Name: ');Readln(Pname);

  Write('Enter Radius of Desired Part: ');
  Readln(Radius);
  Write('Enter Compressed Rubber Thickness: ');
  Readln(RubberThickness);
  ClrScr;

  Writeln('Radius of Desired Part',Radius:5:2,' in.');
```

Appendix B: Program Listings

```
Writeln('Compressed Rubber Thickness of',RubberThickness:5:2,' in.');
```



```
Thick:=(PinRadius + RubberThickness + MetalThickness);  
NewRadius:=Radius - Thick;  
Interval:=Round(NewRadius * 4);  
Count := 2*Interval;  
StartPinA := (48 - Count)/2 + 1;  
Writeln('First Pin for Active Die is down ',StartPinA:3:1,' pins.');
```



```
Writeln('Pinheights and locations for the Active Die');
```



```
Step := 0.125;  
for I:=(Interval + 1) to 2*Interval do  
  begin  
    Active[I]:=8.0 - (Sqrt(Sqr(NewRadius) - Sqr(Step)) + Thick);  
    Step := Step + 0.25;  
  end;
```



```
I := 2*Interval;  
for J := 1 to Interval do  
  begin  
    Active[J] := Active[I];  
    I := I - 1;  
  end;
```



```
Step := 0.125;  
for I := 1 to 2*Interval do  
  begin  
    PosA[I]:=Step;  
    Step := Step + 0.25;  
    Writeln(Active[I]:10:4,#9,PosA[I]:10:3);  
  end;
```



```
Thickness:=(2 * (RubberPinRad) + MetalThickness);  
Intervl:=Round((NewRadius + Thickness)*4);  
NRadThick:=(NewRadius + Thickness);  
RubberPinRad:= (RubberThickness + PinRadius);
```



```
Count := 2*Intervl;  
StartPinP := (48 - Count)/2 + 1;  
Writeln('First Pin for Passive Die is down ',StartPinP:3:1,' pins.');
```

Appendix B: Program Listings

```
Writeln('Pinheights and locations for the Passive Die');

Step := 0.125;
for I:=(Intervl + 1) to 2*Intervl do
  begin
    Passive[I]:=8.0-(Sqrt(Sqr(NRadThick)-Sqr(Step))-RubberPinRad);
    Step := Step + 0.25;
  end;

I := 2*Intervl;
for J := 1 to Intervl do
  begin
    Passive[J] := Passive[I];
    I := I - 1;
  end;

Step := 0.125;
for I := 1 to 2*Intervl do
  begin
    PosP[I]:=Step;
    Step := Step +0.25;
    Writeln(Passive[I]:10:4,#9,PosP[I]:10:3);
  end;

Assign(Prog,Pname);
Rewrite(Prog);
Writeln(Prog,'Filename:',Pname);
Writeln(Prog,'Radius of Desired Part',Radius:5:2,' in. ');
Writeln(Prog,'Compressed Rubber Thickness of',RubberThickness:5:2,' in. ');

Writeln(Prog,'First Pin for Active Die is down ',StartPinA:3:1,' pins. ');

Writeln(Prog,'Pinheights and locations for the Active Die');

  For I:=1 to 2*Interval do
    Writeln(Prog,Active[I]:10:4,#9,PosA[I]:10:3);

Writeln(Prog,'First Pin for Passive Die is down ',StartPinP:3:1,' pins. ');
Writeln(Prog,'Pinheights and locations for the Passive Die');

  For I:=1 to 2*Intervl do
```

Appendix B: Program Listings

```
Writeln(Prog,Passive[I]:10:4,#9,PosP[I]:10:3);
```

```
close(prog);
```

```
end.
```

Appendix B: Program Listings

```
Program Height3d;
{ Program for Part Shape used for }
{ Tests JY18-1 to JY21-1 }
{ Program will calculate the Positioning Rods locations }

{$U+}

Const
    PinRadius = 0.125;
    MetalThickness = 0.036;
Type
    DataArray = Array[0..100] of Real;

Var
    Count, I, J, Interval, Intervl : Integer;
    Radius, Step, RubberThickness, StartPinA, Offset : Real;
    StartPinP, Depth, Thickness, NewRadius, Thick, Thick2, NRadThick : Real;
    Pname : String[20];
    Prog : Text;
    Active, Passive, PosA, PosP : DataArray;

Begin
    Write('Enter New File Name: ');
    Readln(Pname);
    Write('Enter Radius of Desired Part: ');
    Readln(Radius);
    Write('Enter Chord Offset: ');
    Readln(Offset);
    Write('Enter Compressed Rubber Thickness: ');
    Readln(RubberThickness);
    Write('Enter Set Up Depth: ');
    Readln(Depth);

    ClrScr;

    Writeln('Calculation Program used: Height3d.pas');
    Writeln('Filename', Pname);
    Writeln('Radius of Desired Part', Radius:5:2, ' in. ');
    Writeln('Chord Offset', Offset:5:2, ' in. ');
```

Appendix B: Program Listings

```
Writeln('Compressed Rubber Thickness of ',RubberThickness:5:2,' in. ');
Writeln('Set Up Depth',Depth:5:2,' in. ');

Thick:=(PinRadius + RubberThickness + MetalThickness);
Thick2:=(PinRadius + RubberThickness);
NewRadius:=Radius - Thick;
Interval:=Round(NewRadius * 4);
Count := 2*Interval;
StartPinA := (48 - Count)/2 + 1;
Writeln('First Pin for Active Die is down ',StartPinA:3:1,' pins. ');
Writeln('Pinheights and locations for the Active Die');

Step := 0.125;
for I:=(Interval + 1) to 2*Interval do
  begin
    Active[I]:=Depth-(Sqrt(Sqr(NewRadius)-Sqr(Step))-Offset+Thick2);
    Step := Step + 0.25;
  end;

I := 2*Interval;
for J := 1 to Interval do
  begin
    Active[J] := Active[I];
    I := I - 1;
  end;

Step := 0.125;
for I := 1 to 2*Interval do
  begin
    PosA[I]:=Step;
    Step := Step + 0.25;
    Writeln(Active[I]:10:4,#9,PosA[I]:10:3);
  end;

Thickness:=(2 * (RubberThickness + PinRadius) + MetalThickness);
NRadThick:= (NewRadius + Thickness);
Intervl:=Round((NRadThick)*4);
Count := 2*Intervl;
StartPinP := (48 - Count)/2 + 1;
Writeln('First Pin for Passive Die is down ',StartPinP:3:1,' pins. ');
```

Appendix B: Program Listings

```
Writeln('Pinheights and locations for the Passive Die');

Step := 0.125;
for I:=(Intervl + 1) to 2*Intervl do
  begin
    Passive[I]:=-Depth-(Sqrt(Sqr(NRadThick)-Sqr(Step))-Offset-Thick2);
    Step := Step + 0.25;
  end;

I := 2*Intervl;
for J := 1 to Intervl do
  begin
    Passive[J] := Passive[I];
    I := I - 1;
  end;

Step := 0.125;
for I := 1 to 2*Intervl do
  begin
    PosP[I]:=Step;
    Step := Step +0.25;
    Writeln(Passive[I]:10:4,#9,PosP[I]:10:3);
  end;

Assign(Prog,Pname);
Rewrite(Prog);
Writeln(Prog,'Calculation Program used: Height3d.pas');
Writeln(Prog,'Filename:',Pname);
Writeln(Prog,'Radius of Desired Part',Radius:5:2,' in. ');
Writeln(Prog,'Chord Offset',Offset:5:2,' in. ');
Writeln(Prog,'Compressed Rubber Thickness of',RubberThickness:5:2,' in. ');
Writeln(Prog,'Set Up Depth',Depth:5:2,' in. ');

Writeln(Prog,'First Pin for Active Die is down ',StartPinA:3:1,' pins. ');

Writeln(Prog,'Pinheights and locations for the Active Die');

For I:=1 to 2*Interval do
  Writeln(Prog,Active[I]:10:4,#9,PosA[I]:10:3);

Writeln(Prog,'First Pin for Passive Die is down ',StartPinP:3:1,' pins. ');
```

Appendix B: Program Listings

```
Writeln(Prog,'Pinheights and locations for the Passive Die');
```

```
  For I:=1 to 2*Intervl do
```

```
    Writeln(Prog,Passive[I]:10:4,#9,PosP[I]:10:3);
```

```
close(prog);
```

```
end.
```


Appendix B: Program Listings

```
Program Width3d;
{ Program for Part Shape used in }
{ Tests JY18-1 to JY27-1 }
{ Program will calculate Positioning Rod locations }

{$U+}

Const
    PinRadius = 0.125;
    MetalThickness = 0.036;
Type
    dataArray = Array[0..100] of Real;

Var
    Count, I, J, Interval, Intervl : Integer;
    Radius, Step, RubberThickness, StartPinA, Offset, RThick2 : Real;
    StartPinP, Depth, Thickness, NewRadius, Thick, Thick2 : Real;
    Pname      : String[20];
    Prog       : Text;
    Active, Passive, PosA, PosP : dataArray;

Begin
    Write('Enter New File Name: ');
    Readln(Pname);
    Write('Enter Radius of Desired Part: ');
    Readln(Radius);
    Write('Enter Chord Offset: ');
    Readln(Offset);
    Write('Enter Compressed Rubber Thickness: ');
    Readln(RubberThickness);
    Write('Enter Set Up Depth: ');
    Readln(Depth);

    ClrScr;

    Writeln('Calculation Program used: Width3d.pas');
    Writeln('Filename', Pname);
    Writeln('Radius of Desired Part', Radius:5:2, ' in. ');
    Writeln('Chord Offset', Offset:5:2, ' in. ');
```

Appendix B: Program Listings

```
Writeln('Compressed Rubber Thickness of ',RubberThickness:5:2,' in. ');
Writeln('Set Up Depth',Depth:5:2,' in. ');

Thick:=(PinRadius + RubberThickness + MetalThickness);
Thick2:=(PinRadius + RubberThickness);
NewRadius:=Radius - Thick;
Interval:=Round(NewRadius * 4);
Count := 2*Interval;
StartPinA := (45 - Count)/2 + 1;
Writeln('First Pin for Active Die is over ',StartPinA:3:1,' pins. ');
Writeln('Pinheights and locations for the Active Die');

Step := 0.125;
for I:=(Interval + 1) to 2*Interval do
begin
    Active[I]:=Depth-(Sqrt(Sqr(NewRadius)-Sqr(Step))-Offset+Thick2);
    Step := Step + 0.25;
end;

I := 2*Interval;
for J := 1 to Interval do
begin
    Active[J] := Active[I];
    I := I - 1;
end;

Step := 0.125;
for I := 1 to 2*Interval do
begin
    PosA[I]:=Step;
    Step := Step + 0.25;
    Writeln(Active[I]:10:4,#9,PosA[I]:10:3);
end;

Thickness:=(2 * (RubberThickness + PinRadius) + MetalThickness);
Intervl:=Round((NewRadius + Thickness)*4);
RThick2:= (Radius + Thick2);
Count := 2*Intervl;
StartPinP := (45 - Count)/2 + 1;
Writeln('First Pin for Passive Die is over ',StartPinP:3:1,' pins. ');
```

Appendix B: Program Listings

```
Writeln('Pinheights and locations for the Passive Die');

Step := 0.125;
for I:=(Intervl + 1) to 2*Intervl do
  begin
    Passive[I]:=Depth-(Sqrt(Sqr(RThick2)-Sqr(Step))-Offset-Thick2);
    Step := Step + 0.25;
  end;

I := 2*Intervl;
for J := 1 to Intervl do
  begin
    Passive[J] := Passive[I];
    I := I - 1;
  end;

Step := 0.125;
for I := 1 to 2*Intervl do
  begin
    PosP[I]:=Step;
    Step := Step +0.25;
    Writeln(Passive[I]:10:4,#9,PosP[I]:10:3);
  end;

Assign(Prog,Pname);
Rewrite(Prog);
Writeln(Prog,'Calculation Program used: Width3d.pas');
Writeln(Prog,'Filename:',Pname);
Writeln(Prog,'Radius of Desired Part',Radius:5:2,' in. ');
Writeln(Prog,'Chord Offset',Offset:5:2,' in. ');
Writeln(Prog,'Compressed Rubber Thickness of',RubberThickness:5:2,' in. ');
Writeln(Prog,'Set Up Depth',Depth:5:2,' in. ');

Writeln(Prog,'First Pin for Active Die is over ',StartPinA:3:1,' pins. ');

Writeln(Prog,'Pinheights and locations for the Active Die');

For I:=1 to 2*Interval do
  Writeln(Prog,Active[I]:10:4,#9,PosA[I]:10:3);

Writeln(Prog,'First Pin for Passive Die is over ',StartPinP:3:1,' pins. ');
```

Appendix B: Program Listings

```
Writeln(Prog,'Pinheights and locations for the Passive Die');
```

```
  For I:=1 to 2*Intervl do
```

```
    Writeln(Prog,Passive[I]:10:4,#9,PosP[I]:10:3);
```

```
close(prog);
```

```
end.
```