INVESTIGATION OF THE SHOVEL FORMING PROCESS RELATED TO THE MANUFACTURE OF TAPERED METAL POLES

By

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TABLE OF CONTENTS

Chapter Page

I. INTRODUCTION 1

- Objective 1

II. BACKGROUND 3

- Process Overview 3
- Literature Survey 5
  - Patent Search 6
  - Other Forming Processes 8
- Previous Work 11

III. EXPERIMENTAL APPARATUS 15

- Test Machine 15
  - Forming Die Design 17
- Data Acquisition System 18
  - System Calibration 19
- Experimental Test Samples 23
  - Sample "Preforming" 24

Chapter Page

IV. EXPERIMENTAL RESULTS 27

- Visual Observations 28
- Lubrication Experiments 33
- Force Requirement Experiments 36

V. BENDING FORCE MODELS 38

- Classical Bending Models 38
- Empirical Forming Model 43
  - Force vs. Thickness Relationship 44
  - Force vs. Die Diameter Relationship 47
  - Other Contributing Factors 48
  - Assembly of "Shovel" Forming Model 49
- Evaluation of Forming Model 54
- Practical Form of Forming Model 56

VI. CONCLUSION AND RECOMMENDATIONS 59

- Summary 59
- Process Viability 60
- Lubrication and Friction Effects 60
- "Shovel" Forming Force Model 62
- Conclusion 63

BIBLIOGRAPHY 64

APPENDICES 66

APPENDIX A – EXPERIMENTAL "SHOVEL" PRESS MACHINE DRAWINGS 67

APPENDIX B – FORCE VS. DIE DISPLACEMENT PLOTS 71

LIST OF TABLES

Table Page

1. Load Cell Calibration Data 21

2. String Potentiometer Calibration Data 21

3. Initial Test Blank Width 24

4. "Preform" Die Radius 25

5. Pure Bending Model Sample Calculation Parameters 40

6. Average Maximum Force Values 45

7. Test Blank Material Mechanical Properties 49

8. Initial Empirical Force Model Calculations 51

9. Comparison of Experimental Results and Initial Forming Model 51

10. Comparison of Experimental Results and Improved Forming Model 54

11. Error Analysis for Improved Forming Model 55

LIST OF FIGURES

Figure Page

1. Stages of the "Shovel" Forming Process 4
2. "Shovel" Forming Process Schematic 5
3. UOE Tube Manufacturing Process Schematic 6
4. UOE Seam Formation Process Schematic 7
5. V and Wiper Bending Operations 9
6. Bead Forming Schematic 10
7. Chada's Small "Preforming" Press 12
8. "Shovel" Machine Test Press 16
9. Forming Die 18
10. Data Acquisition System Diagram 19
11. Load Cell #1 Calibration Curve 22
12. Load Cell #2 Calibration Curve 22

Figure Page

13. Test Sample "Preforming" ... 26

14. Test Blank Prior to Forming ... 29

15. Initial Die Contact with Test Blank ... 30

16. Two-point Die Contact with Test Blank ... 31

17. Full Die Contact with Test Blank ... 32

18. Finished Test Blank ... 33

19. Lubrication Comparison Plot – Mineral Oil & No Lubricant ... 34

20. Lubrication Comparison Plot – Grease & No Lubricant ... 35

21. Force vs. Die Displacement Plot - 5.46" Shovel & 0.25" Material ... 36

22. Bending Model Diagram ... 39

23. Force vs. Blank Material Thickness Plot ... 46

24. Force vs. Die Diameter Plot ... 47

LIST OF FORMULAS

Formula Page

1. V and Wiper Bending Formula 9
2. "Preform" Mandrel Size Formula 13
3. Blank Width Formula 13
4. Engineering Strain Due to Bending Formula 13
5. Elastic Pure Bending Stress Formula 39
6. Modified Elastic Pure Bending Stress Formula 40
7. Force Formula for Pure Bending 40
8. Sample Force Calculation for Pure Bending 41
9. Pure Plastic Bending Formula 42
10. Modified Pure Plastic Bending Formula 42
11. Force Formula for Pure Plastic Bending 42
12. Sample Calculation for Pure Plastic Bending 43

Formula Page

13. Ultimate Strength – Brinell Hardness Relationship 49

14. Preliminary Empirical Force Model for Straight Tube Section 50

15. Empirical Force Model for Straight Tube Section 53

16. Force Integral for Tapered Tube Section 57

17. Tapered Die Diameter – Length Relationship 57

18. Modified Force Integral for Tapered Tube Section 57

19. Empirical Force Model for Tapered Tube Section 57

20. Sample Force Calculation for Tapered Tube Section 58

CHAPTER I

INTRODUCTION

Tapered metal poles are a part of every urban landscape. Every individual can view tapered metal poles in most lit parking lots, at intersections controlled by traffic signals and even at many athletic stadiums. Even though these products go largely unnoticed, they play a part in everyday life for many people.

For several years research has been conducted at Oklahoma State University (OSU) with an eye towards improving and possibly revolutionizing the manufacture of tapered metal tubes. The work conducted at OSU has evolved and produced a unique forming process called "shoveling", which is the forming of a tube through the use of two semi-circular sliding dies. Up to this time, research at OSU has proven that the "shovel" forming process does work when forming tubes of eleven gage (0.12") sheet steel. However, little is known about how and why the "shovel" process works.

Objective

The purpose of this study is to develop an understanding of the underlying mechanics of the "shovel" forming process. This study of the "shovel" forming process includes a thorough literature search, extensive experimental work and the development of forming relationships using experimental data.

This investigation focuses upon some specific issues concerning the "shovel" forming process. First of which is the possibility of using the "shovel" forming process for manufacturing tubes of materials of thickness greater than 0.12". However, perhaps the most important questions concern the amount of force required to perform "shovel" forming. Therefore, a great deal of the experimental work performed during this investigation is aimed at developing relationships suitable for the estimation of forming forces. Finally, it is hoped that the work presented in this report will add significantly to the Tapered Tube Research Team's effort to develop a revolutionary method for manufacturing tapered tubes.

CHAPTER II

BACKGROUND

Tapered metal tubes have been used for lighting, traffic signals and other applications for many years. These tubes, commonly made of steel, range in size from 10 to 100 feet in length and have diameters ranging from 2½ inches to several feet. The standard taper for these tubes is 0.14 inches per foot of length. The research conducted at OSU has been focused on the development of an improved process capable producing tapered tubes which will meet or exceed the specifications described by the American Society for Testing and Materials (ASTM) A595 - 93.

Process Overview

The tapered tube forming process developed at OSU begins with a trapezoidal blank. The initial forming process is known as "preforming", which is the bending of the longitudinal edges to the final desired curvature. Through experimentation, it has been determined that each blank edge must be formed to minimum of 60° of curvature in order for the "shovel" process to work properly. The "shovel" process then forms the blank into the final circular shape through the use of two sliding semicircular dies. A schematic of the different stages, which a tube blank goes through during the OSU tube forming process, is presented below in Figure 1. Stage 1 is the trapezoidal blank prior to any forming, and, Stage 2 depicts an end view of the tube blank after the "preforming" process. Finally, Stage 3 depicts the final shape of the blank, which is ready for welding of its longitudinal seam.

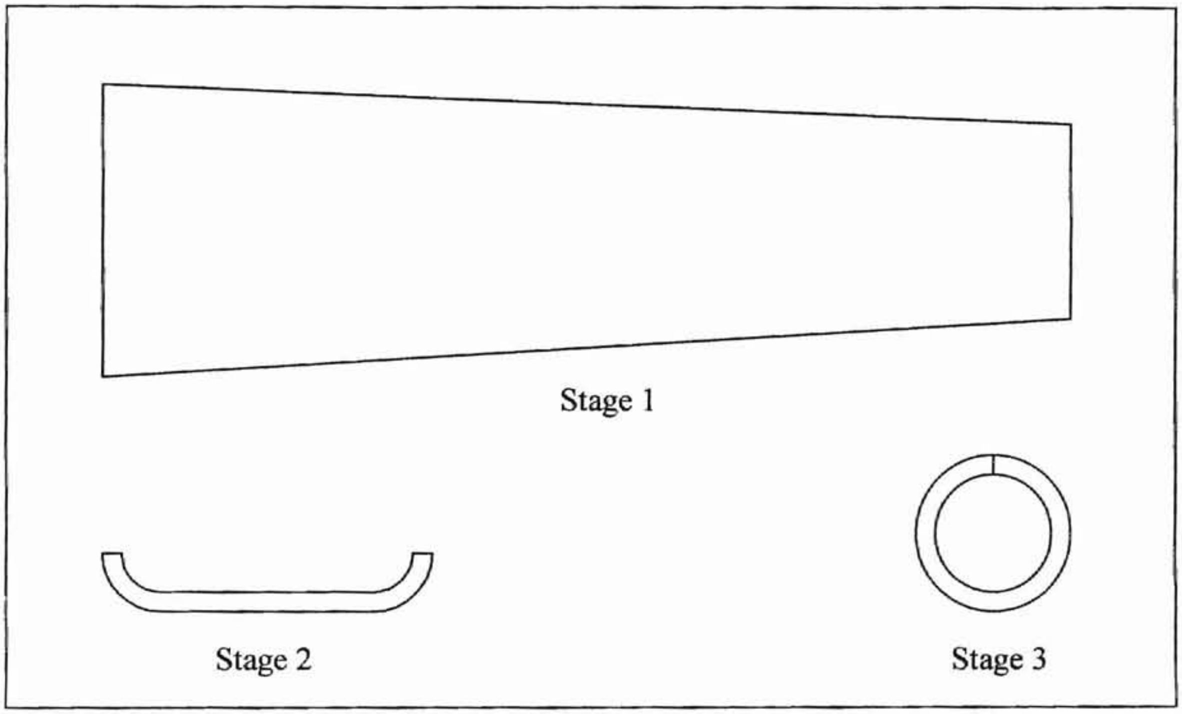

Figure 1: Stages of the "Shovel" Forming Process

The "shovel" process received its name from its similarities to the blade of a snowplow. The material enters the upset semicircular die at the bottom and is "shoveled" around the circumference of the die until it reaches the apex, similar to the manner in which snow is moved by a snowplow. Figure 2 is a simple schematic demonstrating the "shovel" forming process.

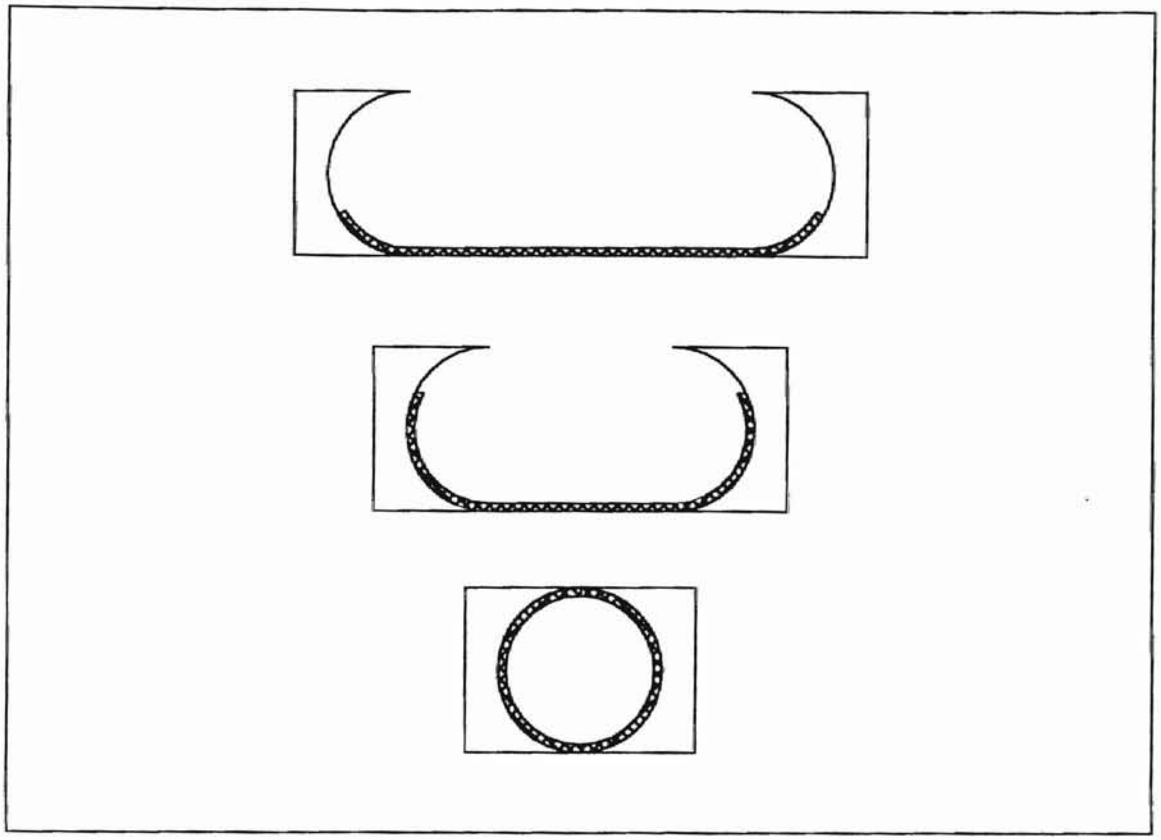

Figure 2: "Shovel" Forming Process Schematic

Literature Survey

The literature survey of work pertaining to metal forming and tube manufacturing led to some very interesting discoveries, but most importantly it verified the uniqueness of the tube manufacturing process developed at OSU. The search included United States patents, books and literature published in technical journals. There can be no denying that a great deal of research has been performed in the area of metal forming. However, it was quickly learned that much of this work has been of an empirical nature and very few physical models have been developed for many processes.

Patent Search

A search of U.S. patents revealed a few of the current methods of manufacturing tapered tubes. The most similar to the process developed at OSU is what is referred to as the UOE process and is described by the 1990 United States Patent 4,971,239, obtained by Ameron, Inc. Below in Figure 3 is a schematic from the patent covering the UOE tube manufacturing process.

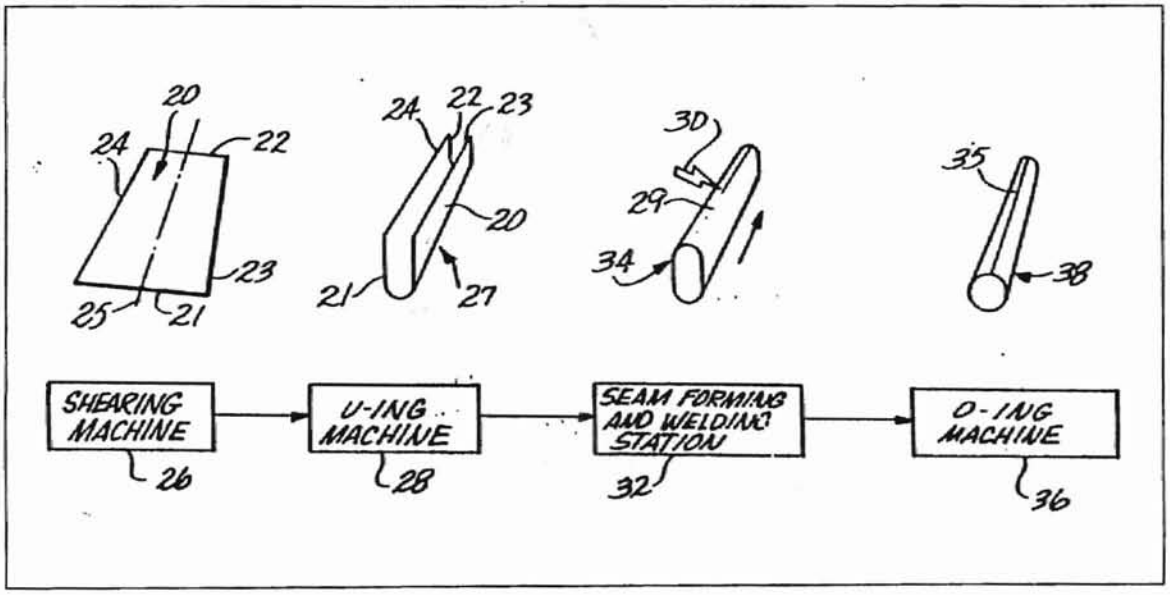

Figure 3: UOE Tube Manufacturing Process Schematic

As can be seen, the process begins with a sheared trapezoidal blank. The blank is then formed into a "U" shape by what is referred to as the "U-ing" machine. "U-ing" is followed by the seam forming stage of the process. This stage of the UOE process is particularly interesting because it uses what could be described as a vertical "shovel" operation. Figure 4 is a reproduction of a drawing included in U.S. Patent 4,971,239 depicting the UOE seam formation stage. The similarities to the "shovel" process developed by OSU are quite evident. However, the UOE seam forming process is performed completely in the vertical direction and it is used to form the edges of the tube blank. Alternatively, the OSU "shovel" process forms the center of the tube blank and not the edges, which are done during the "preforming" operation.

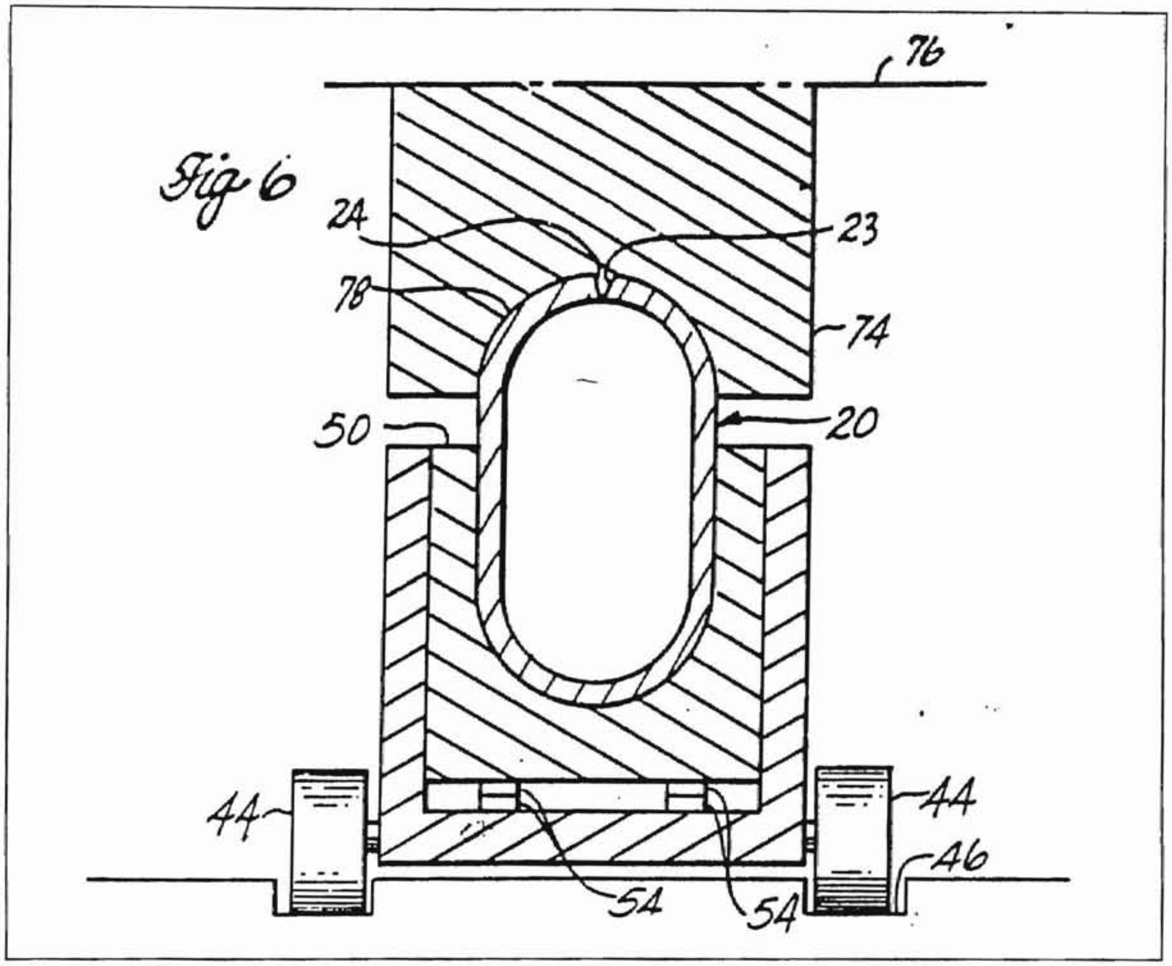

Figure 4: UOE Seam Formation Process Schematic

Finally, the UOE process is the most similar tube manufacturing process to that developed at OSU, and therefore, it garnered the most interest during research into other tube manufacturing processes. Unfortunately, information concerning the forming mechanics of the process is not available in the patent or any other published literature.

Therefore, the UOE process provides little more than some interesting background information on other methods for the manufacture of tapered tubes.

The other tube manufacturing processes discovered by the U.S. patent search were based mainly on roll forming and press break operations for both tapered and straight tube sections. Even though a tube is the end result of these processes, they are dissimilar enough to OSU's method that their value to this research is limited.

Other Forming Processes

Metal forming in various forms has existed for millennia and today there are many processes used to create metal objects with both simple and complex shapes. In order to investigate the "shovel" process properly, it is important to have an awareness of these processes. Work performed by researchers regarding these other metal forming processes could lend a solid basis for analyzing any experimental results obtained during this investigation of the "shovel" process.

Rolling, wiper bending, press brake bending, beading, flanging and hemming are all processes commonly used to form metal and in particular sheet metal. There has been a great deal of research conducted, which investigates many of these processes and with improved techniques utilizing finite element methods, the mathematical models are becoming more accurate and complex. These new and improved mathematical models of forming processes are of great interest to researchers. However, industry still relies upon experience and the models developed many years ago for most of these processes. A prime example of one such model used to calculate bending forces is found in Kalpakjian and applies to both common V die as well as wiper bending. Figure 5 is a drawing from his text, which depicts these processes.

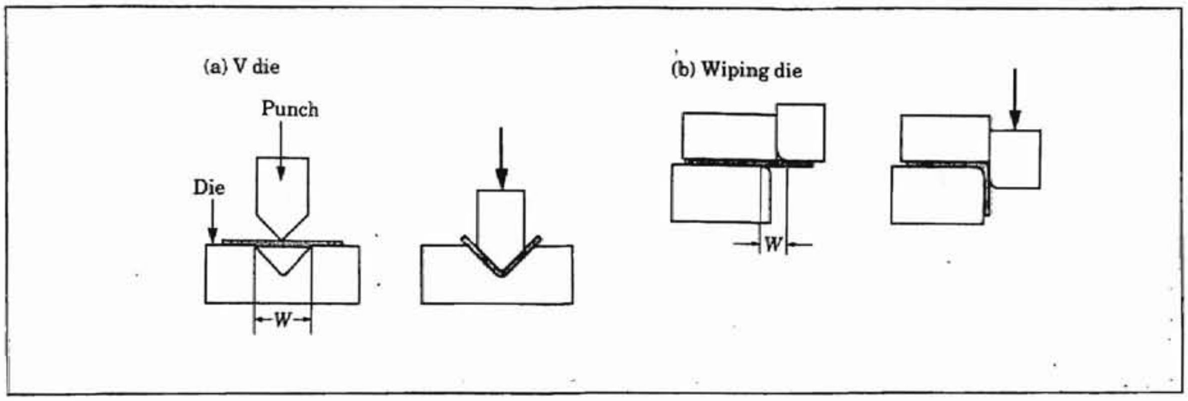

Figure 5: V and Wiper Bending Operations

The bending force model for these types of bending is

$$F = \frac{S_u t^2 l}{W} \tag{1}$$

where

F = Force (lbs.),
l = Length of Bend (in.),
t = Material Thickness (in.),
W = Width of Die Opening (in.), and
S_u = Ultimate Strength of Material (ksi).

A majority of the models found, during research into general forming processes resemble Equation 1. In many instances, the models contain many of the same components as Equation 1, but with the addition of some constant multiplier.

Beading was by far the most similar forming process to "shovel" forming which was encountered during the literature search. Below in Figure 6 is a schematic, from Kalpakjian, presenting two separate bead forming processes.

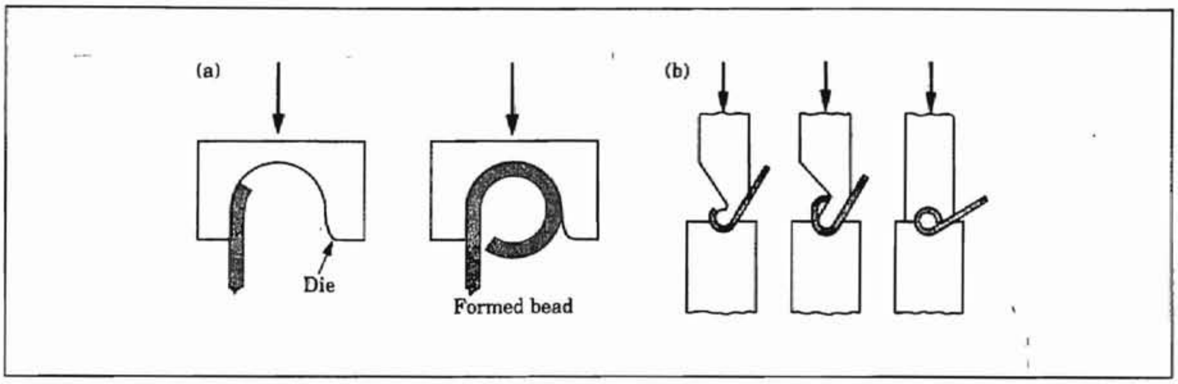

Figure 6: Bead Forming Schematic

The similarities between the bead forming process using a single die and OSU's "shovel" process are very apparent. In fact, the two processes are almost identical, except, beading is used to produce bends of significantly smaller radius in light gage material. However, this process has garnered not much more than short references in manufacturing texts and handbooks. The search for literature while investigating the beading process ended with very little success. This process has been performed successfully for many years by industry, which has evidently made this process unattractive to researchers.

The tapered tube forming process developed at OSU is unique in many respects. There has certainly been a great deal of work performed on the topic of metal forming. However, it seems that Oklahoma State's forming operations are either new and unique or that similar processes have been ignored by researchers. For this reason, the work of

Chada, Adair and Hoberock & Inda is depended upon heavily as a basis for the investigation presented in this report.

Previous Work

As stated previously, the process developed at Oklahoma State is unusual, and, there has been little or no published work on similar processes. Therefore, before beginning research into the forces required to "shovel" form tubes, certain assumptions based on previous work by the Tapered Tube Research Team had to be made.

First, the basic design of the full-scale "shovel" press, built for previous experiments, would be the model for any test press, which would be built. Secondly, Chada performed extensive research into "preforming", the process that precedes "shovel" forming. The assumption made regarding Chada's work was that the test blanks must be "preformed" to the extent and in the manner prescribed by his work. Chada's work included the construction of a small "preforming" press, which he used while investigating the "preforming" process. His "preforming" press was utilized to prepare the samples for each experiment presented in this report. Chada's press is shown in Figure 7.

Figure 7: Chada's Small "Preforming" Press

Previous investigation of the "preforming' process has yielded two important relationships, which were utilized extensively during the investigation of the "shovel" process. The first of which addressed the diameter of the forming mandrel used in "preforming", such as the one pictured above in Figure 7. Each mandrel must be sized according to the desired final bend radius, thickness and estimated springback of the test material. This meant that every combination of material thickness and shovel die required a correctly sized mandrel. In all, nine "preform" mandrels were fabricated for this particular project. The formula developed by Adair and verified by Chada for the radius of the "preform" mandrel is

$$R_p = \frac{R_d}{1 + \frac{3YR_d}{Et}} \tag{2}$$

where

R_p = Radius of Preform Mandrel (in.),
R_d = Desired Bend Radius (in.),
Y = Yield Stress of Material (ksi),
E = Modulus of Elasticity (ksi), and
t = Material Thickness (in.).

The second formula, which served as an important basis for the investigation of the "shovel" process, was the formula developed by Adair for calculating the initial width of tube blanks. Adair's formula for initial blank width is

$$L_o = \frac{\pi D}{\frac{t}{D-t} + 1} \tag{3}$$

where

L_o = Initial Blank Width (in.),
D = Final Bend Diameter (in.), and
t = Material Thickness (in.).

This formula finds its basis in the standard relationship for engineering strain due to bending

$$\varepsilon = \frac{t}{2r} \tag{4}$$

where

ε = Strain of Outer Fibers,

t = Material Thickness (in.), and

r = Bend Radius (in.).

Of course, the use of Adair's formula (3) for determining the dimensions for a full-sized tapered tube blank would require two calculations, one for each end diameter.

Finally, the research performed by colleagues and predecessors has contributed greatly to the work presented in this report. The uniqueness of the tube forming process, developed at OSU, and lack published work regarding similar forming processes has made it necessary to rely primarily upon their work as the basis for this investigation.

CHAPTER III

EXPERIMENTAL APPARATUS

The centerpiece of the experimental apparatus used in this study of the "shovel" forming process is a small press built especially for this investigation. This test machine equipped with load cells, string potentiometers and a computer data acquisition system allowed for the collection of data critical for the development of the resulting forming force model. Of course, as with any measurement system, such things as calibration, experimental uncertainty and sample preparation are of great importance and each of these items will be addressed.

Test Machine

The "shovel" machine test press was built around a large I-beam, which served two purposes. First, the I-beam serves as a simple frame that required no fabrication and provides good rigidity. Secondly, the flange of the I-beam provides a ready-made slider guide. The press is powered by two 5 inch diameter hydraulic rams connected in a parallel circuit supplied by a 2000 psi two-stage pump. These rams are rated for pressures up to 2100 psi and a maximum force output of approximately 41,000 lbs. The remainder of the press is constructed of low carbon steel plate. The "shovel" machine test press is shown below in Figure 8. Please note, detailed machine drawings of the test machine are included in Appendix A of this report.

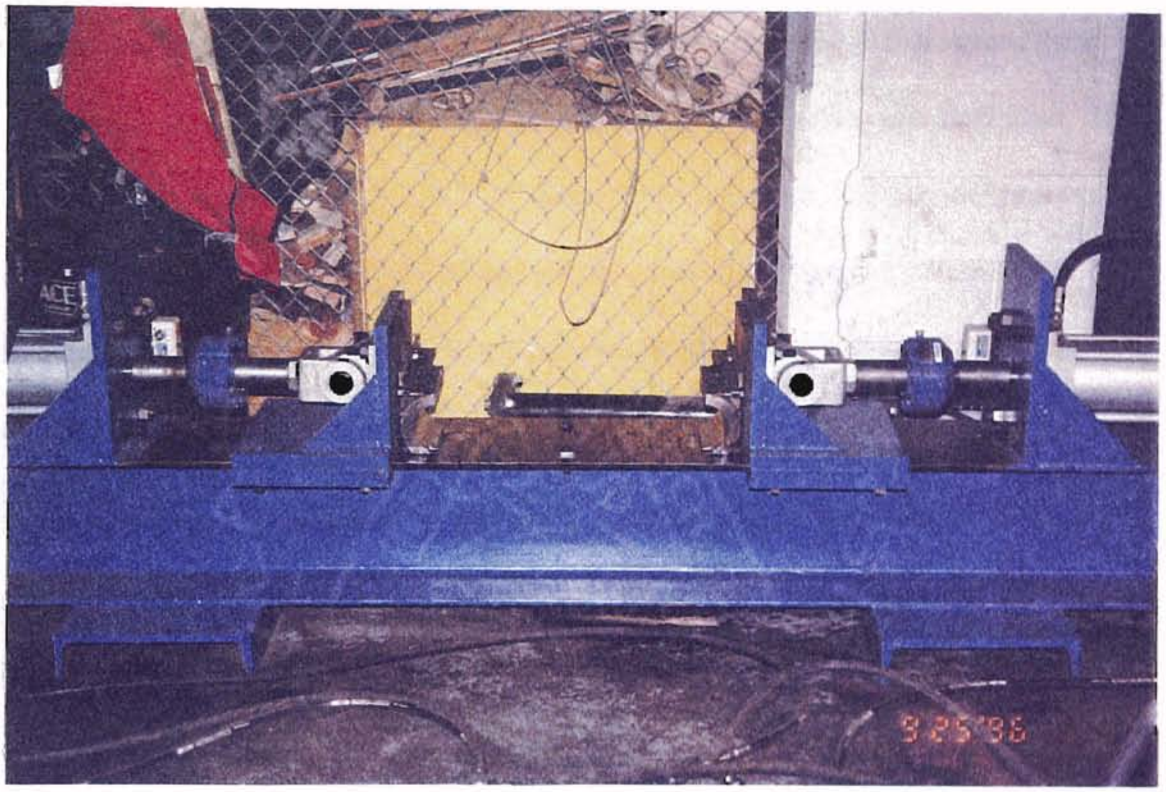

Figure 8: "Shovel" Machine Test Press

Operation of the machine is really quite simple. The test blanks are loaded into the machine and held in place by two small bolts. The bolts were used on this test machine, in the interest of simplicity, in lieu of the hydraulic clamps, which have been successfully utilized on the twenty-foot "shovel" machine used by previous researchers. Then the operator must simply hand actuate the control lever located on the hydraulic valve to close the dies. Once forming is completed the operator retracts the dies by reversing the valve lever.

Forming Die Design

Perhaps the most important components of the test machine are the forming dies. Simplicity in both fabrication and use was of the utmost importance during the design of the dies and the test machine itself. For the experiments presented in this report, three dies of various diameters were constructed using thick-walled tubing and steel plate. It should be noted that the dies constructed for this investigation of the "shovel" process were not tapered. The fabrication of tapered dies would have entailed a tremendous amount of additional work, which would not necessarily have aided the efforts to develop a model of the forming process.

Figure 9 is a photograph of one of the dies used during this research. As can be seen, the thick-walled tubing has been split in half and welded to the mounting plate with the aid of some small angle iron. In fact, all of the dies fabricated for this investigation were constructed in this manner.

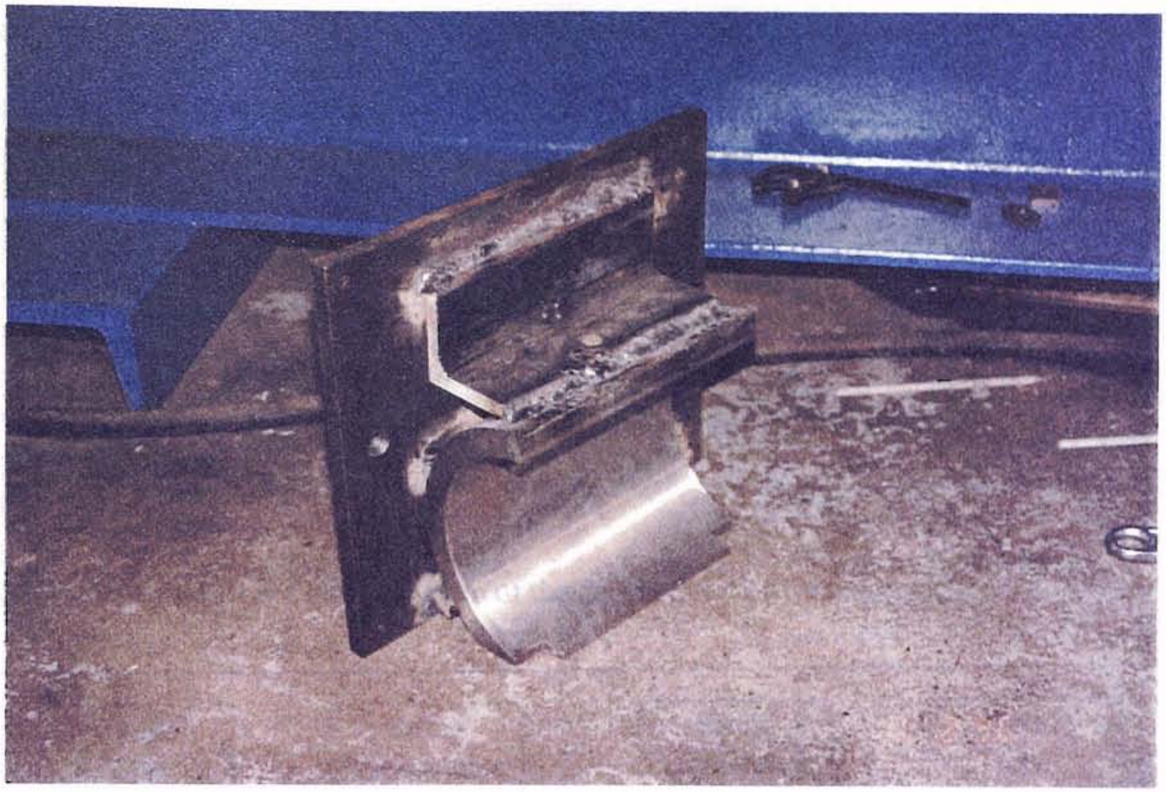

Figure 9: Forming Die

One of the main benefits of fabricating the test forming dies in this manner was the simplicity. This theme is even carried into the installation and removal of the dies, because, each die is held in position by only two bolts. This simple mounting system allows the changing of forming dies in just minutes.

Data Acquisition System

The primary components of the data acquisition system used during this investigation of the "shovel" process were the load cells and string potentiometers used to measure the force and die displacements during each experiment. The load cells and string potentiometers were read using an 8 bit A/D computer board which was installed in an ordinary personal computer. Below is a complete list of components used in the collection of data for this investigation.

- 486/66 Personal Computer with Lablog II Data Acquisition Software
- Computer Boards, Inc. Model CIO-DAS08 Computer Board
- 2 Interface Model 1220AF Load Cells
- 2 Measurements Group, Inc. Model P-3500 Digital Strain Indicators
- 2 Magnetek Rayelco Linear Motion Transducers Model P-50A
- Hewlitt Packard DC Power Supply

Below in Figure 10 is a block diagram of the data acquisition system.

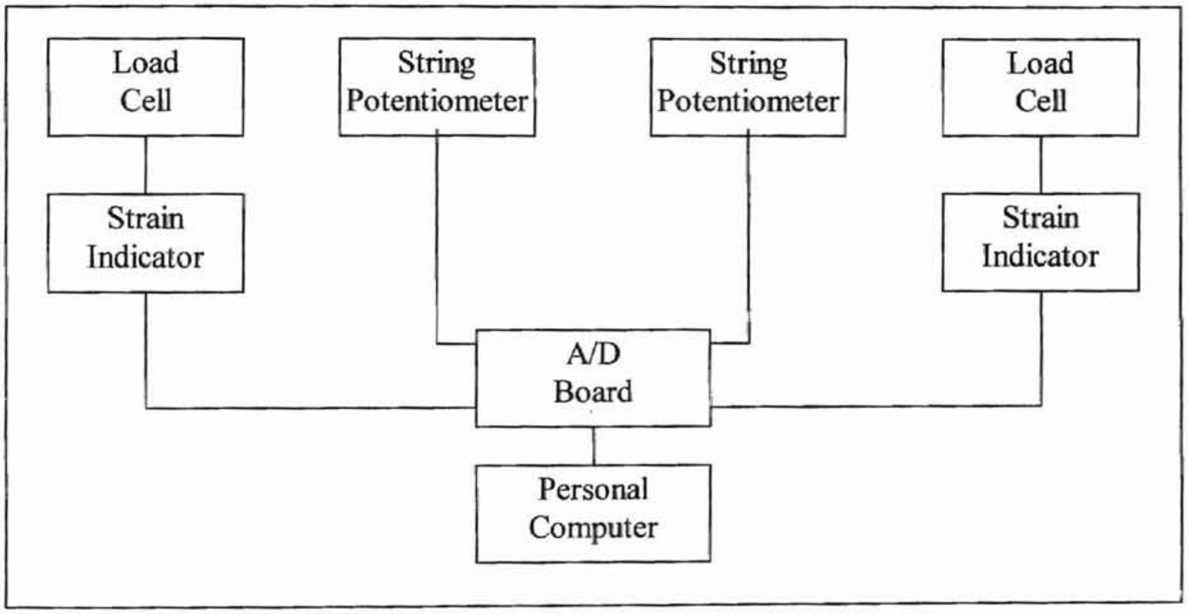

Figure 10: Data Acquisition System Diagram

System Calibration

As is the case with any experimentation, the collected data is only as good as the calibration of the measuring instruments. The calibration of the system used in this experimental setup included individual calibration checks of the load cells and string potentiometers and then a calibration of the entire system.

The most important instruments used in the collection of data during this investigation were the Interface load cells, which are rated up to 25,000 lbs. The calibration certifications provided by the manufacturer included output voltages (mV/V), static error bands (% Full Scale) and shunt calibration output (lbs.). In order verify that each load cell was working correctly after installation, a shunt calibration was performed. This was done by inserting a 30 KΩ resistor across one leg of the measurement bridge. For what was referred to as Load Cell #1, the output for the shunt calibration should have been 17,031 lbs., assuming the use of a resistor with an error band of 0.01%. Instead, a resistor with an error band of 1% was used for the shunt calibration. The resulting output from the shunt calibration was 16,950 lbs. This value allowed for the conclusion that the load cell was working correctly and still in calibration. Next, a shunt calibration was performed on what was referred to as Load Cell #2 and a similar result was achieved. At this time, it should be noted that the data presented in this report was recorded from only one side of the "shovel" machine for the sake of consistency. The data obtained from what was referred to as Load Cell #2 contained some unknown noise, which was never identified. Although the data obtained from this load cell did coincide with the data obtained from the other, it was best to use this data as a sort of control to continually verify that the load cells were working properly and in agreement.

Following in Table 1, the critical data concerning load cell calibration and accuracy is shown.

Table 1: Load Cell Calibration Data

	Load Cell #1	Load Cell #2
Output (mV/V)	4.204	4.185
Static Error Band (%FS)	±0.0170	±0.0170
Shunt Calibration (lbs.)	17,031	17,384
Measured Shunt Calibration (lbs.)	16,950	17,422

The next step was to check the calibration of the string potentiometers. This was done using a scale and an ordinary voltmeter. The Magnetek string potentiometers used have a range of 50 inches and an error band of 0.03% of full scale. The calibration of each potentiometer was checked from 0 to 50 inches in increments of 10 inches and every data point fell within the prescribed 0.03% error band. Below in Table 2, the critical data concerning the calibration of the string potentiometers is shown.

Table 2: String Potentiometer Calibration Data

	String Potentiometer #1	String Potentiometer #2
Sensitivity (mV/V/in)	19.866	19.882
Static Error Band (%FS)	±0.03	±0.03

The final task regarding the data acquisition system was an overall calibration. As previously stated, digital strain indicators were used to create the bridge circuits recommended by the load cell manufacturer. Using an adjusted gage factor, it is possible for the strain indicators to display a load cell's output in pounds. If the strain indicators were capable of digital output, there would be no problem. However, the only output from the strain indicators is an analog signal, which is not the same as the voltage input from the load cell. Therefore, it was necessary to calibrate the strain indicator's output voltage versus the digitally displayed pounds reading. Figures 11 and 12 are the calibration curves developed for each load cell.

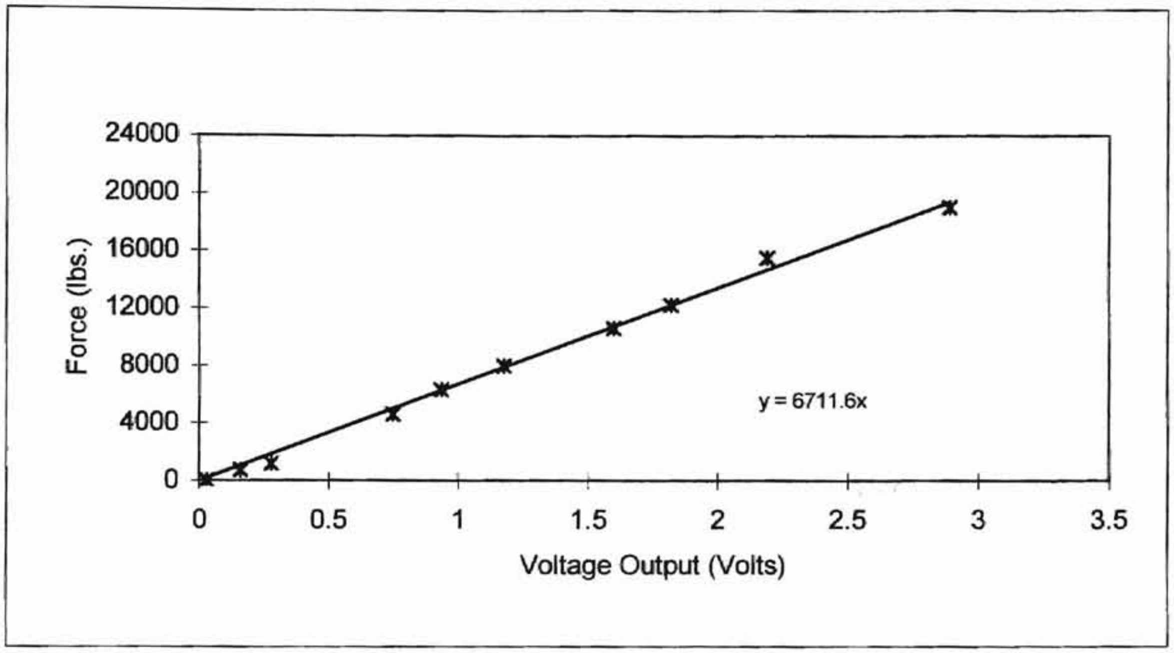

Figure 11: Load Cell #1 Calibration Curve

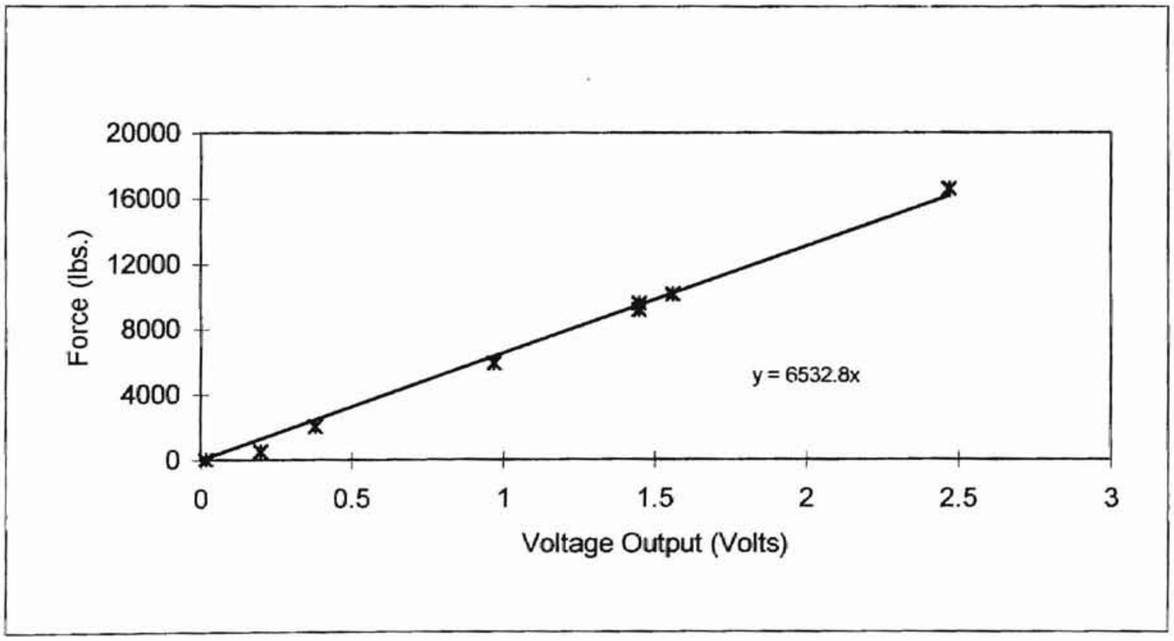

Figure 12: Load Cell #2 Calibration Curve

The primary question concerning any measured values is of course the accuracy of those measurements. The load cells and string potentiometers used in this experimental setup are high-quality instruments with small error bands. The calibration of each instrument was checked and each proved to be working well.

The A/D board, unfortunately, introduced a great deal of uncertainty to the experimental data recorded during this investigation. The A/D board used to collect the data presented in this report was an 8-bit board with a set range of -5 to 5 Volts. This translates into a resolution of 39 mV or 262 lbs. per division, which is certainly not ideal. However, when the resulting data is examined, this rather large uncertainty does not jeopardize the validity of this study.

Experimental Test Samples

The preparation of test coupons, for use with the "shovel" machine, required cutting the coupons to size, drilling holes for clamping and "preforming". All of the coupons used during this study were made of low carbon steel obtained from a local steel supplier. Unfortunately, the supplier was unable to provide complete data sheets indicating the mechanical properties of the individual heats, which in turn introduced more uncertainty to these experiments. However, this did not particularly hinder the development of the model, which resulted from this study.

Each test coupon or blank was cut to size using a common lay-down saw and had length of 8 inches. The width of each blank depends upon the thickness of material and final diameter desired. Adair's research yielded Equation 3, which can be used to calculate the initial width of a blank.

$$L_o = \frac{\pi D}{\frac{t}{D-t}+1} \qquad (3)$$

Using Equation 3, the initial blank width for each set of samples used in this study may be generated. Table 3 presents the calculated initial blank widths for each combination of material thickness and "shovel" die diameter used during this investigation.

Table 3: Initial Test Blank Width

Material Thickness (in.)	Shovel Die Diameter (in.)	Initial Blank Width (in.)
0.125	3.82	11.61
0.125	5.46	16.76
0.125	6.24	19.21
0.188	3.82	11.41
0.188	5.46	16.56
0.188	6.24	19.01
0.25	3.82	11.22
0.25	5.46	16.37
0.25	6.24	18.82

Sample "Preforming"

The most critical aspect of sample preparation is "preforming". Previous research has shown that in order for the "shovel" process to work correctly, each blank edge must have at least 60° of curvature after the "preforming" process. During experiments conducted previously, researchers observed that blanks with less than the prescribed 60°

curvature would buckle in the "shovel" press, instead of forming as intended. Therefore, achieving proper blank "preforming" was crucial to this investigation.

Both Adair and Chada researched the "preforming" process, and, their work was used as a prescription for this portion of sample preparation. As stated previously, for each combination of material thickness and "shovel" die diameter, a specially sized "preform" mandrel must be machined. Adair's formula (2) for "preform" mandrel sizing was used to generate Table 4.

Table 4: "Preform" Die Radius

Material Thickness (in.)	Forming Die Diameter (in.)	"Preform" Die Radius (in.)
0.125	3.82	1.782
0.125	5.46	2.476
0.125	6.24	2.793
0.188	3.82	1.835
0.188	5.46	2.580
0.188	6.24	2.925
0.25	3.82	1.859
0.25	5.46	2.627
0.25	6.24	2.986

Figure 13 is a photograph of the "preforming" of two test samples. The particular samples shown in Figure 13 are 0.25" material and the forming mandrel has radius of 1.859".

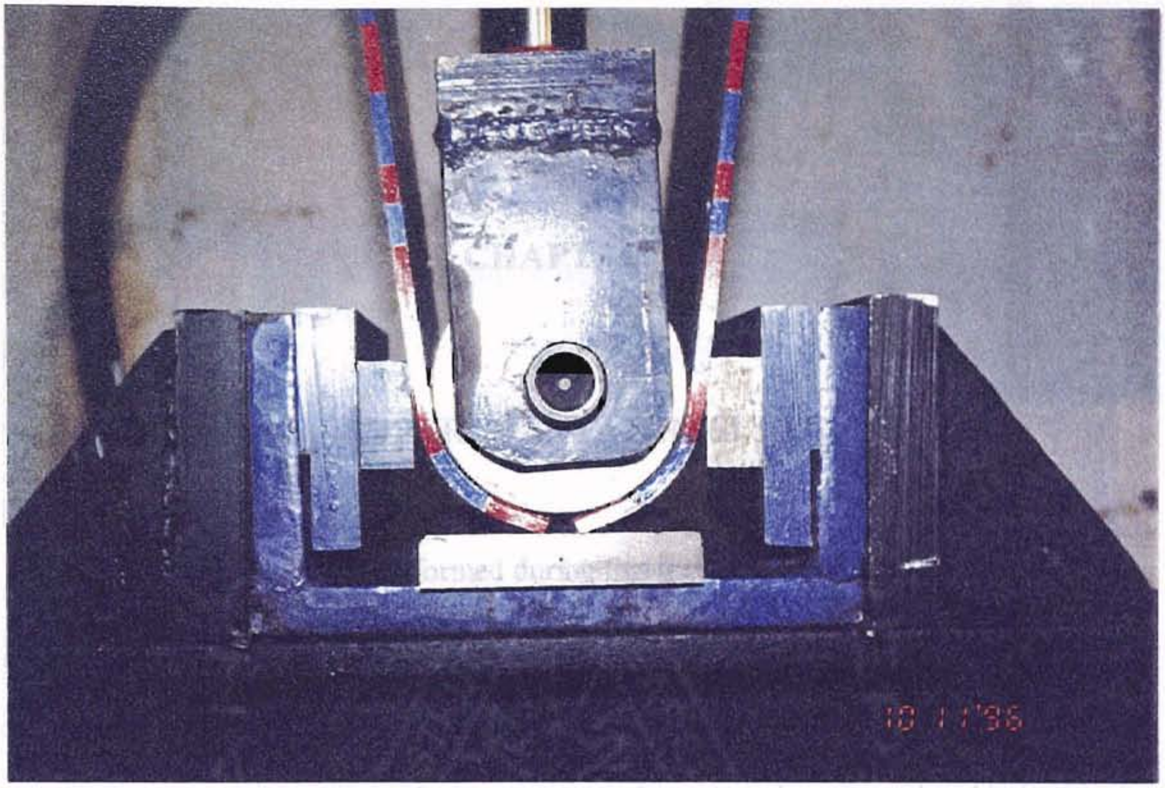

Figure 13: Test Sample "Preforming"

As can be seen, the "preforming" process forms the edges of two blanks at one time. Of course, then both blanks must then be rotated in order to form the opposite edges. Once the "preforming" process is completed the result is two blanks ready for "shovel" forming.

Visual Observations

In an attempt to gain understanding of the mechanics involved in the "shovel" forming operation, two experiments were performed using specially painted samples and documented with series of photographs. What is meant by specially painted, is that prior to "preforming", the edge of each sample was painted with a 1" alternating red-blue pattern. The painting of the blank edges helped greatly when it came time to compare successive photographs in each series. The 1" reference marks made it possible to distinguish which sections were being formed and at what die displacement throughout the forming process. The following photographs displayed in Figures 14-18 were chosen to illustrate the significant points of interest which were discovered as a result of these experiments.

Figure 14, shown on the following page, is a photograph of a painted test blank which has been clamped into the "shovel" press with the dies fully retracted and is ready for forming. One point of interest here is the clamping system used on the test machine. As can be seen, two bolts are used to hold each blank in place, and, the blank rests atop two small aluminum blocks. These aluminum blocks were used merely to elevate the blank so as to match the bottom edge of the forming dies and to keep the blank centered between the die halves. Throughout the development of the "shovel" press, the question of the type of clamping and even the need for clamping has been addressed numerous times. Early prototypes of the "shovel" press used no clamping mechanism, thus allowing the tube blank to float. However, this system was eventually abandoned because of various problems, including uneven forming and difficulty in controlling the forming dies. In the end, it became apparent that the best solution was to clamp the tube blank down in the center and attempt to form both halves simultaneously. Therefore, when building the test "shovel" press, instead of building an elaborate pneumatic or hydraulic clamping system, holes were drilled in each test specimen and the clamping was performed using bolts.

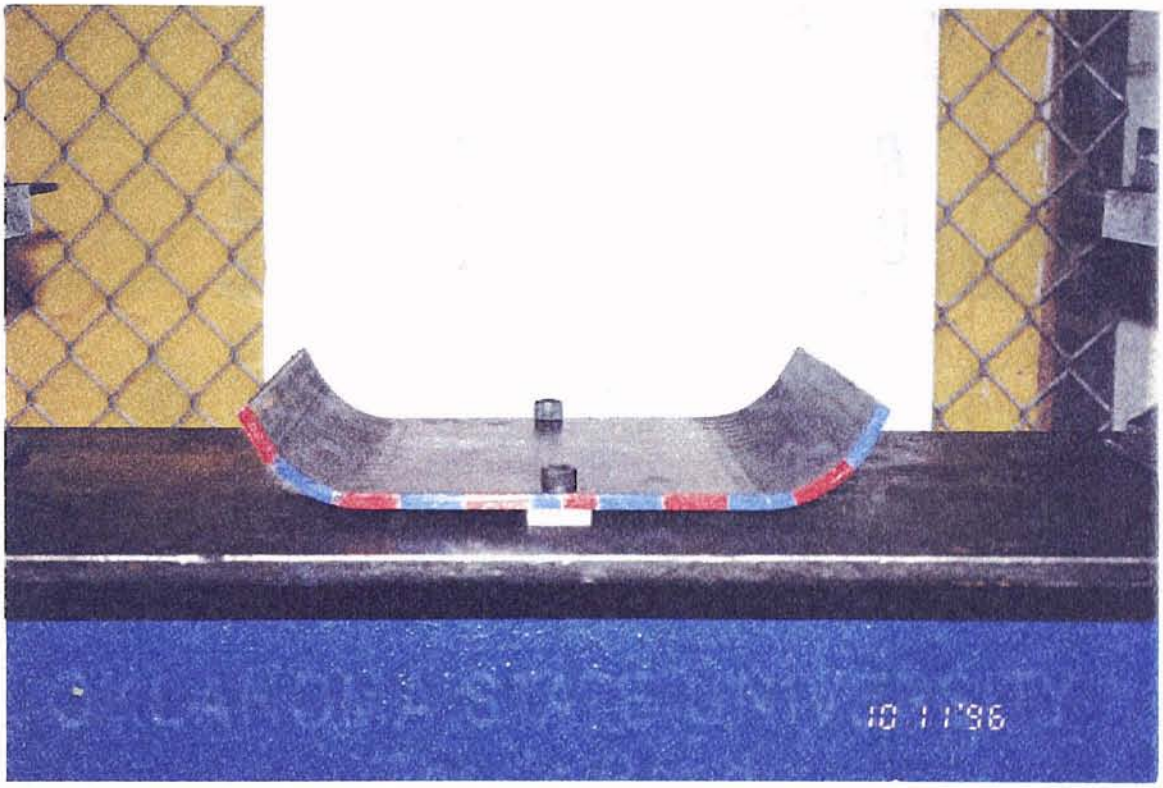

Figure 14: Test Blank Prior to Forming

The second point of interest shown in Figure 14 is the straightness of the inner portions of the blank. As one can see, the areas not deformed by the "preforming" process are parallel to the frame of the test press, which is not the case in Figure 15.

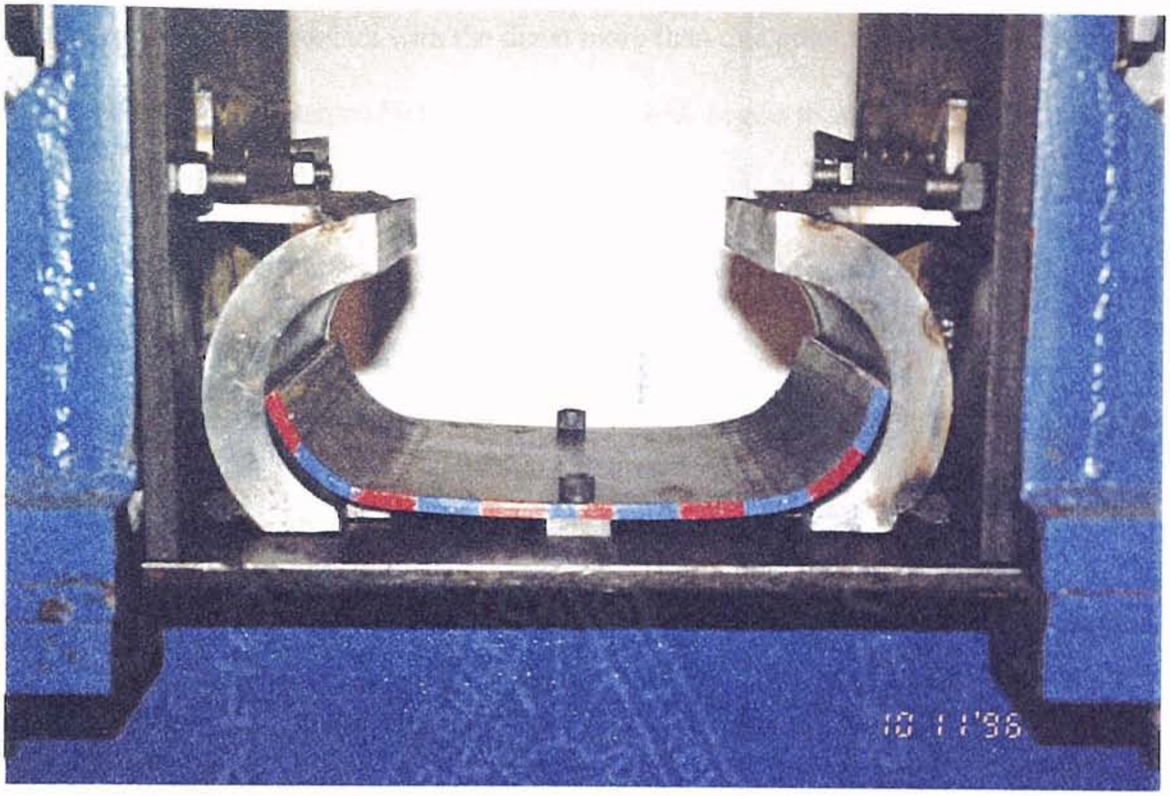

Figure 15: Initial Die Contact with Test Blank

Figure 15 shows a significant observation concerning the behavior of the test blank during "shovel" forming. Pictured, in Figure 15, is the point at which the forming dies initially make contact with the blank. It should be noticed that the edges of the blank rise and the inner portions of the blank are no longer parallel to the test press frame. The interior portion of the test blank is deformed into a slight "V" shape with the restraint bolts acting as the base of the "V". It should be noted that this is not the first observance of this phenomenon. Parkinson observed the same during his research into the "shovel" forming of 20' long tapered blanks. Also, each die makes contact with the blank at only one location, which is approximately 45° from the horizontal. From the initial 45° contact points, the blank edges continue to rise and act as the only contact between forming dies and blank until approximately the 60° mark is reached. At this point, each side of the blank begins to make contact with the die at more than one point. This is clearly shown by the photograph presented by Figure 16. The blank begins to make contact at the bottom of each die as well as maintaining contact at the blank edges. However, possibly the most important observation from Figure 16 is the disappearance of the "V" shape, which was pointed out during the discussion of Figure 15.

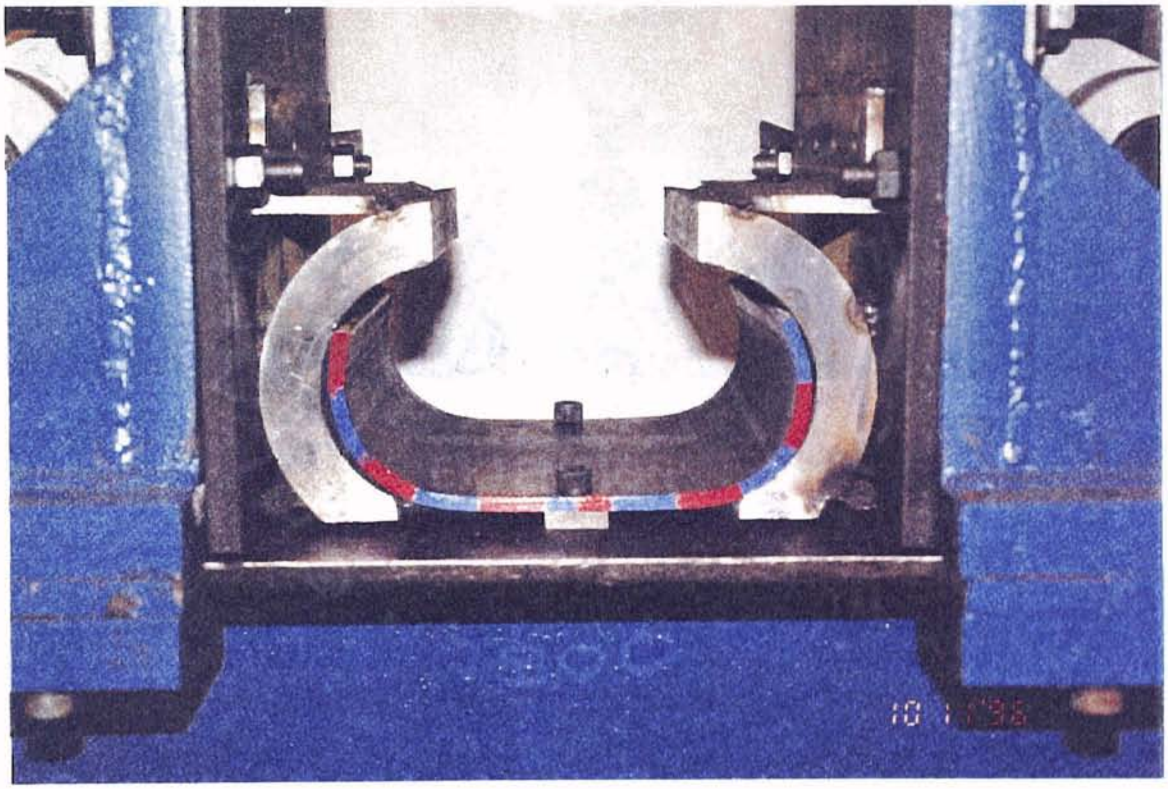

Figure 16: Two-point Die Contact with Test Blank

From this point on, the area of contact between the blank and dies increases until almost the entire blank is in contact with the forming dies. Figure 17, a photograph taken just prior to the completion of forming, which shows quite clearly that the blank is in contact with almost the entire circumference of each die.

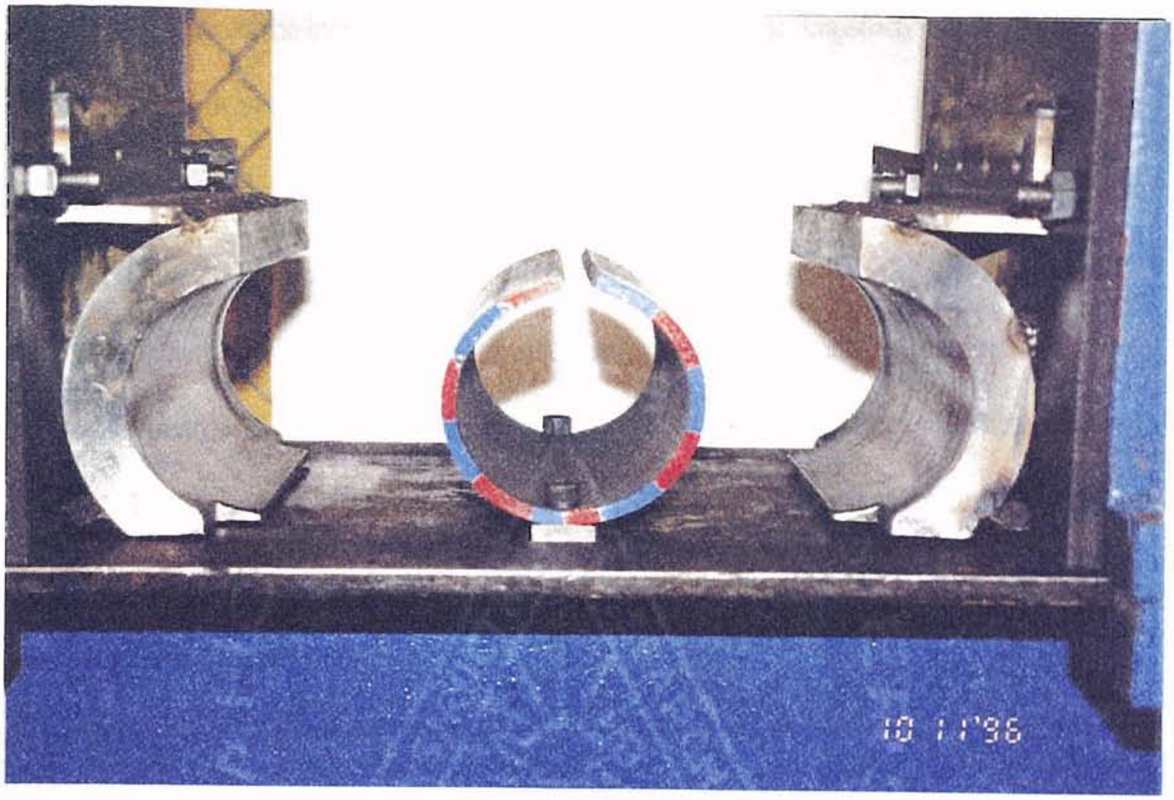

Figure 18: Finished Test Blank

Finally, it should be obvious that the operation of the "shovel" press is quite simple. However, it is also apparent that the underlying forming process is very complex.

Lubrication Experiments

Lubrication of forming dies is extremely important in many metal forming operations. Thus far, little attention has been paid to this topic in OSU's research into the manufacture of tapered tubes. All of the tube forming work performed by Parkinson used mineral oil as the die lubricant. The reason for this choice of lubricant was made only because the process was found to work satisfactorily while using it as a lubricant. In contrast, the bulk of the experimental work performed during this study of the "shovel" forming process was done without lubrication of the forming dies.

Using the 3.82" diameter "shovel" dies and 0.25" thick test blanks, experiments were run using no lubricant, mineral oil and GIA aircraft grease. Intuitively, one would expect the force required to form a tube using no lubrication would be greater than when lubrication was used. In general, this was found to be true but possibly not the extent to which one might expect. Below in Figure 19 is a graph which presents the results of four experiments and makes it possible to compare the non-lubricated cases to the ones performed using mineral oil.

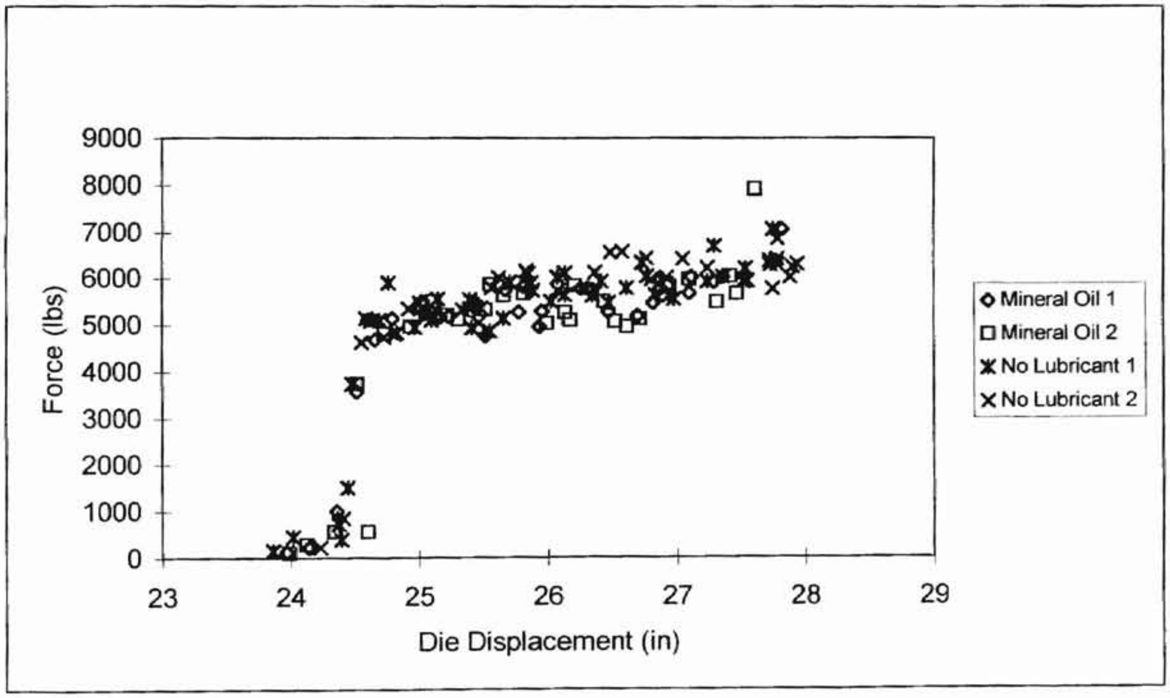

Figure 19: Lubrication Comparison Plot - Mineral Oil & No Lubricant

Figure 19 is interesting for two reasons. First, it is apparent that dry forming does require more force than forming with mineral oil as one would expect. However, the difference between the curves is not dramatic and the force requirements of the two lubricants vary on the order of 10% at maximum. Figure 20 is a plot similar to Figure 19, which allows for the comparison of the no lubricant case to the use of grease. Again it is obvious that slightly greater force is required when no lubrication is used. However, as was the case when compared to mineral oil lubrication the difference between dry forming and lubricating with grease is at best on the order of 10%.

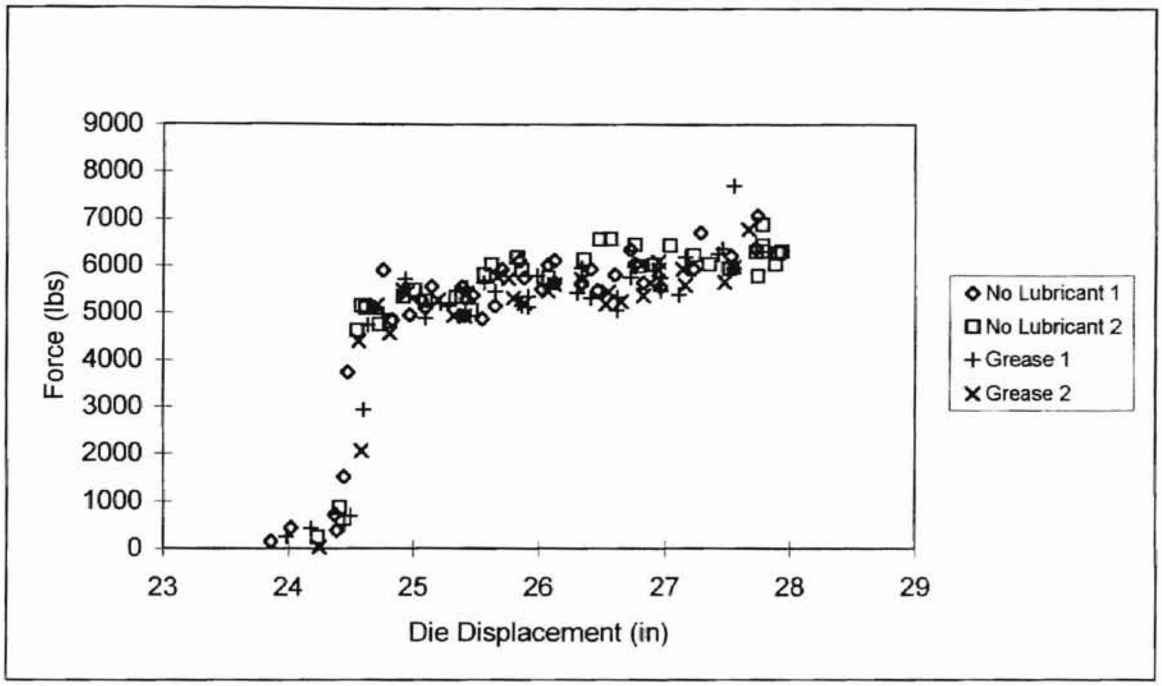

Figure 20: Lubrication Comparison Plot - Grease & No Lubricant

Finally, the conclusion, which can be drawn from these die lubrication experiments, is that lubrication does not greatly affect the amount of force required to form a blank. However, it would not be prudent to conclude, from this limited number of experiments, that die-blank friction is completely insignificant.

Force Requirement Experiments

The centerpiece of this investigation into the "shovel" forming process is the experiments performed using combinations of various diameter forming dies and material thickness'. As previously stated, "shovel" dies of 3.82, 5.46 and 6.24 inches in diameter were used to form blank material of 0.125, 0.188 and 0.25 inches. For each of the die and material thickness combinations, four tests were performed. Below in Figure 21, the results for 0.25" material formed by the 5.46" diameter "shovel" die are presented.

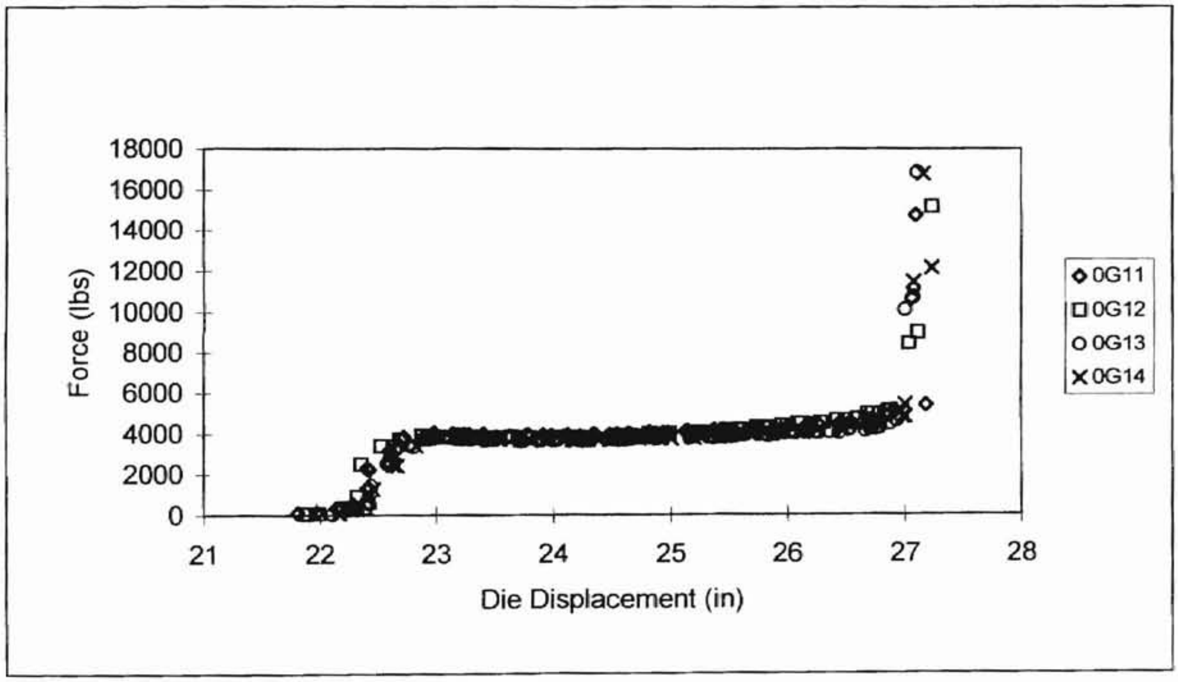

Figure 21: Force vs. Die Displacement Plot - 5.46" Shovel & 0.25" Material

The results presented in Figure 21 are representative of nearly all of the experiments performed during this study. To avoid any confusion, it should be pointed out that the legend on the right side of Figure 21 contains references to a personal labeling system. All of the samples used for this set of experiments were prepared identically, and therefore, the labels were merely used for sample identification purposes.

The first observation, which can be made upon viewing Figure 21, is that the results are similar, which speaks well for the experimental apparatus and the repeatability of these experiments. Secondly, there are certain aspects of the curves themselves, which are common to each set of experimental data gathered during this study. First, notice the sudden increase in force from near zero to approximately 4000 lbs., which occurs around the 22.5" die displacement mark. Of course, this feature of each curve corresponds to the point at which the die begins to make contact with the blank. Next, each curve exhibits a plateau, which actually contains a slightly positive slope. This positive slope continues until the time when the two dies make contact at the center of the machine. This occurrence is distinguishable on each plot because the force reading spikes dramatically. Finally, the plots presented in Figure 21 represent only one of the nine sets of data collected during this investigation. A complete set of plots for each data set is included in Appendix B.

CHAPTER V

BENDING FORCE MODELS

Thus far it has been demonstrated that "shovel" forming is an extremely complicated process which involves plastic deformation, friction effects and variable points of contact. Attempts to use elastic beam equations and idealized plastic-elastic bending models failed to predict force requirements to any reasonable degree. Hence, it was necessary to develop a forming model based on the data gathered during this investigation. The literature survey performed for this study showed that empirical models are commonly used in the practice of metal forming. Although empirical models do not provide much insight into the underlying mechanics of a forming process, in practical terms they are every bit as useful.

Classical Bending Models

The initial attempts to create a model, which could predict the force required to bend a blank, were founded in classical beam equations. The first model tried was for a beam subjected to pure bending

$$\sigma = \frac{Mc}{I} \tag{5}$$

where

σ = Stress (psi),
M = Moment (lbs.-in.),
c = Distance to fiber (in.), and
I = Second Moment of Inertia (in.^{4}).

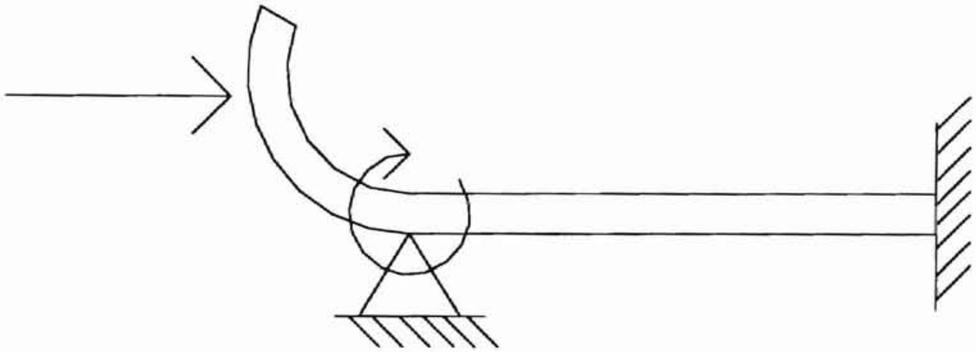

Figure 22: Bending Model Diagram

Figure 22 shows the simplified free body diagram for the initial attempt to model the "shovel" forming process. This model assumes a point load located at the center of the forming die which results in a bending moment at the intersection of the curved and straight portions of the blank, which is also the initial location of die-blank contact.

However, it only took a few calculations to come to the realization that this model was either too simple or merely incorrect. Shown below is a sample calculation, which was used to compare results obtained during one set of forming experiments to the predicted results using Equation 5. But, first some manipulation of the equation must be performed.

$$\sigma = \frac{Mc}{I} = \frac{Frc}{I} \tag{6}$$

As can be seen the moment term (M) of the equation has been replaced by the components of a moment, a force (F) and moment arm (r). This substitution makes it possible to solve directly for the force required to initiate forming. Rearranging the equation gives the expression shown below.

$$F = \frac{\sigma I}{rc} \tag{7}$$

The sample calculation attempts to compare the predicted force found using the pure elastic bending model to the experimental results found using 0.125" material and the 3.82" diameter forming die. Table 5 shows the values of the known parameters for this experimental case.

Table 5: Pure Bending Model Sample Calculation Parameters

Yield Strength (σ)	50 ksi
Second Moment of Inertia (I)	0.001302 in.^{4}
Moment Arm (r)	1.91 in.
Distance to Outer Fiber (c)	0.0625 in.

A few of the parameters presented in Table 5 deserve some additional explanation. As stated previously, no data sheets detailing exact material properties were available from the steel supplier. The manufacturers guaranteed that the steel purchased for test material met or exceeded ASTM A-36. Which states that the material must have a minimum yield strength of 36 ksi and a tensile strength in the range of 58-80 ksi. Therefore, it is necessary to estimate the yield strength for the sample calculation. A certainly generous estimate of 50 ksi is used.

The second parameter, requiring further explanation, is the value of 1.91" used for the moment arm. In the previous chapter some photographs of the "shovel" forming operation were presented. At that time the location of contact points were discussed in detail. It was noted that forming was initiated when the blank edge was located at approximately 45° from the horizontal. This position corresponds to an approximate moment arm of one-half the diameter of the forming die. Hence, this was the justification for the use of a value of 1.91" for the moment arm.

Now, inserting the known values into the expression yields the following result.

$$F = \frac{\sigma I}{rc} = \frac{(50ksi)(0.001302in.^4)}{(1.91in.)(0.0625in.)} = 545lbs. \tag{8}$$

The average measured force for experiments using the same set of parameters was 1086 lbs., which is approximately twice the value predicted by the elastic pure bending model. Calculations using this model for all experimental cases yielded similarly unsatisfactory results.

One might initially believe that an elastic bending model could not possibly predict the forming force for such a forming operation. However in actuality, the strains imparted in the test blanks during these experiments were at most seven percent at the outer fiber. In fact, the strain at the outer fiber for the particular experiment depicted in the sample calculation above, is approximately 3 percent. Considering the amount of plastic deformation is small for such gradual bends, it is not completely implausible that an elastic bending model could predict "shoveling" force.

The second model investigated was the one presented by Johnson & Mellor concerning the moment required to make a section fully plastic when subjected to pure bending. According to them, the moment can be expressed as shown by Equation 9.

$$M = \frac{bh^2 Y}{4} \tag{9}$$

where

M = Moment (lbs.-in.),
b = Base (in.),
h = Height (in.), and
Y = Yield Strength (ksi).

This model again assumes the same arrangement as shown in Figure 22, where the applied force results in a moment at the base of the die. Again using the experimental data from the 1.91" radius forming die and 0.125" material experiments as was done in the previous example calculation, an estimated force value can be found.

$$Y = \frac{4M}{bh^2} \tag{10}$$

Making the same substitution for the moment term (M) and rearranging the equation gives the following expression.

$$F = \frac{Ybh^2}{4r} \tag{11}$$

Now, inserting the same values used in the previous example yields the following result.

$$F = \frac{(50ksi)(8in.)(0.125in)^2}{4(1.91in.)} = 818lbs. \tag{12}$$

Again the experimental result for this case was 1086 lbs. This model is certainly closer to the experimental result than the elastic pure bending model. Interestingly, the completely plastic model more closely predicts the experimental result. However, considering the truly small amounts of plastic deformation imparted to the blank during "shovel" forming it is really not reasonable to think this more accurate result is anything more than chance.

After considering the above bending models, it was apparent that predicting the force required to "shovel" form various blanks would not be so simple. Finally, there is one factor, which these models have overlooked that may contribute to the amount of force required to form a particular blank. This factor is the amount of friction induced in the slide mechanism of the "shovel" machine itself. The location of the load cells between the hydraulic rams and sliders means that the recorded force data could include frictional forces caused by contact between slider and machine frame. For all of these reasons, an attempt to create a model through analysis of the experimental data was made, and, the results of that endeavor are presented in the next section.

Empirical Forming Model

Thus far it has been shown that "shovel" forming is very a complicated process which is not easily modeled using classical beam formulas. In fact, the series of photographs exhibited in Chapter IV give rise to the argument that the forming dynamics may actually change throughout the process. If the "shovel" forming process actually involves more than one mode of deformation, separate models would be needed for each individual mode.

In addition, the magnitude of the friction force in the slide mechanism of the forming machine, which must be overcome, cannot currently be distinguished from the forces required to actually bend the blank material. Instead, any model developed will be able to predict the amount of force required to form a blank under certain conditions using the current design of the "shovel" machine. For all these reasons, it became necessary to develop a model from the experimental data acquired during this investigation.

When beginning the development of the empirical forming model derived from the experimental data gathered during this investigation, there were no preconceptions regarding the form of the model. Because, the underlying forming mechanics could not be described successfully by classical beam formulas and the literature search uncovered few clues to what the model could look like, the development of the model was started completely from scratch.

Force vs. Thickness Relationship

The first relationship investigated while formulating the empirical model was how the forming force varies with blank thickness. During the discussion of Figure 21, presented in Chapter IV, it was pointed out that the maximum force during actual forming occurs just prior to the meeting of forming dies, where the force readings spike severely.

Below in Table 6, the average maximum experimental value for each combination of die size and blank thickness is presented.

Table 6: Average Maximum Force Values

Material Thickness (in.)	Forming Die Diameter (in.)	Avg. Maximum Force (lbs.)
0.125	3.82	1377
0.125	5.46	906
0.125	6.24	738
0.188	3.82	2782
0.188	5.46	2532
0.188	6.24	1672
0.25	3.82	5806
0.25	5.46	4356
0.25	6.24	3639

From the data provided in Table 6, it is possible to develop a curve for the each forming die, which can be used to estimate the effect of blank thickness. Figure 23 is the resulting plot.

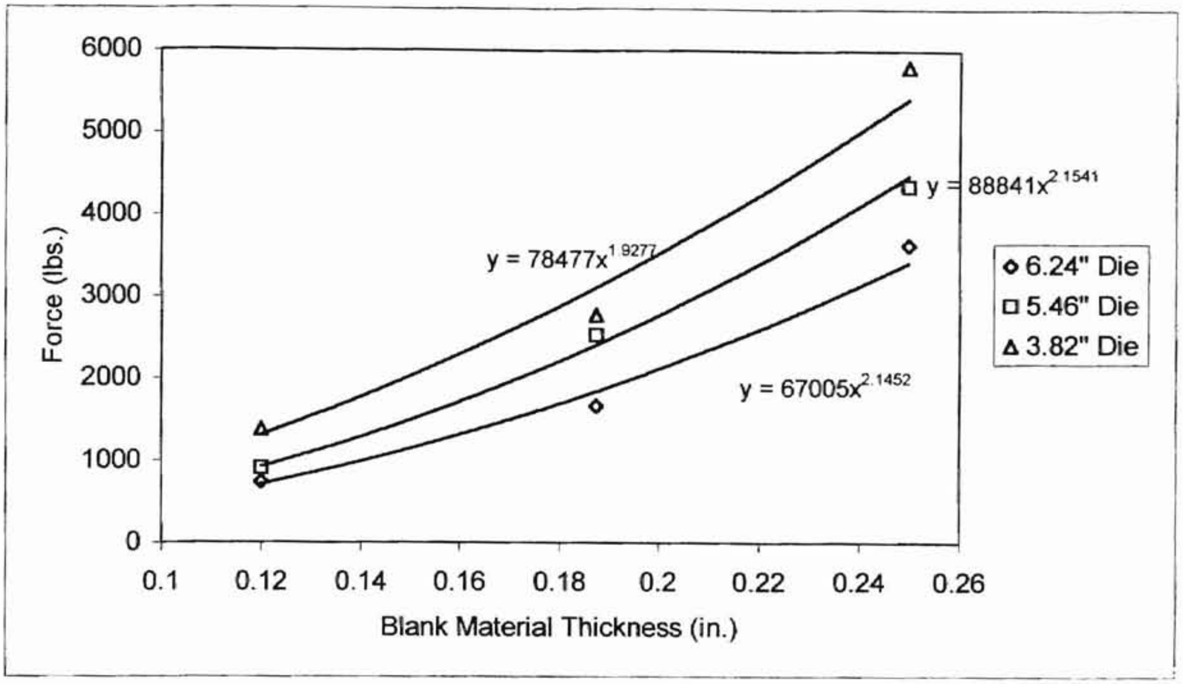

Figure 23: Force vs. Blank Material Thickness Plot

There are some obvious conclusions that can be drawn from an examination of Figure 23. First, it is clear that the force increases as material thickness increases for each forming die. However, the exact relationship is not extremely apparent, and, it turns out that power curves best fit the data. Notice that the force seems to vary approximately with the square of the thickness. The average exponent for the three curves is 2.07, and in fact, this result is not completely surprising. Formula 1, which was presented in Chapter II and is shown again below, is used for the prediction of force requirements for "V" and wiper bending operations.

$$F = \frac{S_u t^2 l}{W} \tag{1}$$

One will notice that this formula includes a thickness-squared term. Therefore, it does not seem unlikely that the force requirement for "shovel" forming is also dependent upon the thickness raised to a power of two. Finally, it is also apparent from Figure 23 that force also increases as forming die diameter decreases when material thickness is held constant, and, this relationship is explored in the next section.

Force vs. Die Diameter Relationship

The relationship between force and die diameter was another parameter, which could easily be explored using the data gathered during the experimentation phase of this investigation. From the plot shown in Figure 23, it was obvious that if blank material thickness is held constant the force required to "shovel" form a blank increases as die diameter decreases. Figure 24 is a plot of the relationship between force and die diameter for three blank material sizes.

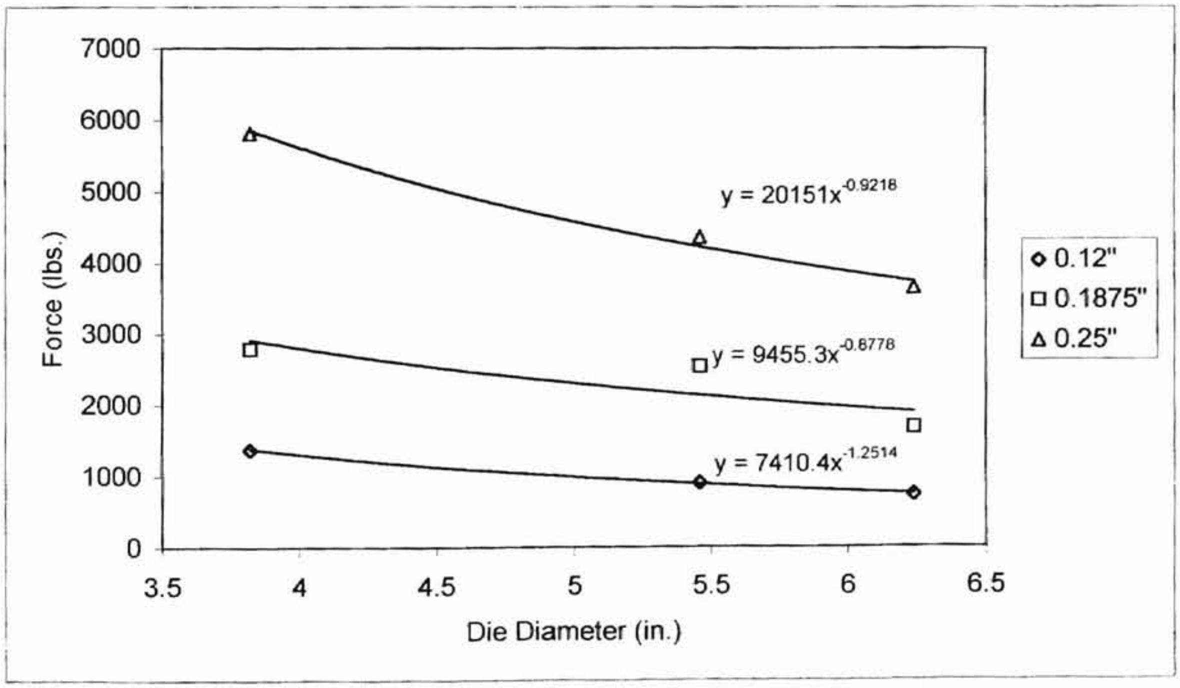

Figure 24: Force vs. Die Diameter Plot

Again, power curves have been fit to the data series shown in Figure 24. From this plot it seems evident that the force required to "shovel" form a blank is inversely proportional to die diameter. In fact, if one averages the exponents of the three curves shown in Figure 24, the result is -1.02. Again, considering the forming force formula for "V" and wiper bending, the forming force is inversely proportional to the die opening width. In those processes, the die opening width controls the final bend radius. Therefore, it is reasonable to conclude that the "shovel" die diameter affects the forming force in a similar manner.

Other Contributing Factors

Up to this point, two relationships concerning how material thickness and die size affect the required force in the "shovel" forming operation have been developed. The first two relationships found seem to indicate that the form of the forming force model is similar to the model for wiper bending. Therefore, it is sensible to continue on this path when determining the other factors, which affect the amount of force required for "shovel" forming.

As in any forming operation, the mechanical properties of the material affect the amount of force required to perform the operation. As previously mentioned, the exact mechanical properties of the test blank material were not available from the steel supplier. However, the model for wiper and "V" bending uses the ultimate strength of the material as opposed to yield strength in its calculation of forming force. Therefore, with the model for wiper bending in mind, the ultimate strength for the three materials was estimated using the time-tested relationship between Brinell hardness and ultimate strength for steels. This relationship is

$$S_u = \frac{H_B}{2} \tag{13}$$

where

S_u = Ultimate Strength (ksi), and
H_B = Brinell Hardness.

Below in Table 7, the results of the surface hardness tests are presented along with the corresponding estimation of the ultimate strength of the materials.

Table 7: Test Blank Material Mechanical Properties

Material Thickness (in.)	Brinell Hardness	Ultimate Strength (ksi)
0.125	127	63.5
0.188	138	69.0
0.25	143	71.5

The final factor, which can easily be related to the required forming force, is the blank length. For all of the experiments performed for this study the blank length was eight inches, and, it should be obvious that the amount of force required to form any size of blank will be directly proportional to the length of the blank. Therefore, the final form of the "shovel" forming force model will include the longitudinal length of the blank.

Assembly of "Shovel" Forming Model

After evaluating how force is dependent upon both die diameter and blank material thickness, it appeared that a force model for "shovel" forming would be similar in form to the model for wiper and "V" bending. Assembling the relationships developed in the previous sections, the initial attempt at a "shovel" forming model looks like Equation 14, shown below.

$$F = \frac{S_u t^2 l}{D} \tag{14}$$

where

F = Force (lbs.),
S_u = Ultimate Strength (ksi),
t = Material Thickness (in.),
l = Blank Length (in.), and
D = Die Diameter (in.).

Now that all of the easily obtainable relationships and parameters have been gathered into a single expression, the questions to be answered are whether the model is complete and can it accurately predict the amount of force required to perform "shovel" forming. Table 8 shows the results of calculations using the proposed force model for the nine experimental cases.

Table 8: Initial Empirical Force Model Calculations

Material Thickness (in.)	Blank Length (in.)	Die Diameter (in.)	Ultimate Strength (ksi)	Predicted Force (lbs.)
0.125	8.0	3.82	63.5	2075
0.125	8.0	5.46	63.5	1451
0.125	8.0	6.24	63.5	1270
0.188	8.0	3.82	69.0	5107
0.188	8.0	5.46	69.0	3573
0.188	8.0	6.24	69.0	3127
0.25	8.0	3.82	71.5	9385
0.25	8.0	5.46	71.5	6566
0.25	8.0	6.24	71.5	5745

Table 9 presents a comparison of the average experimental results to the calculated predicted forces shown in Table 8.

Table 9: Comparison of Experimental Results and Initial Forming Model

Material Thickness (in.)	Die Diameter (in.)	Measured Force (lbs)	Calculated Force (lbs)	Ratio (Meas./Calc.)
0.125	3.82	1377	2075	0.66
0.125	5.46	906	1451	0.62
0.125	6.24	738	1270	0.58
0.188	3.82	2782	5107	0.54
0.188	5.46	2532	3573	0.70
0.188	6.24	1672	3127	0.53
0.25	3.82	5806	9385	0.61
0.25	5.46	4356	6566	0.66
0.25	6.24	3639	5745	0.63

Table 9 displays some significant findings concerning the proposed forming model. First of all, it is obvious that the proposed model does not to any reasonable degree concur with the experimental results. The proposed model overestimates the required forming force, which leads to the conclusion that the model is either incorrect or incomplete.

The evidence behind the relationships on which the current model has been based seems substantial. The analysis of the experimental data certainly suggests that any model of "shovel" forming will resemble the model for "V" and wiper bending. Based on this belief, it obvious that the initial forming model requires some alterations or additions.

Table 9 includes a column, which presents the ratio of experimentally measured force to the force predicted by the initial forming model. One will notice that these values are all within a range of 0.53 to 0.70, which gives the indication that they are all related in some manner. Examining these values more closely, there does not seem to be any relationship associated with die size or blank thickness. Therefore, there are two possibilities for the differences between the experimental results and the values predicted by forming model in its initial form. The first possibility is that friction has not been accounted for in the initial forming model. However, the minimal reduction in forming force found with the use of lubrication seems to indicate that friction between the blank and forming die may not be significant.

The second possibility is that instead of ultimate strength, the yield strength of the blank material should be used in the forming model. The "V" and wiper bending forming operations are primarily used to create bends of 90° or greater. Therefore, for these forming operations, the strains in the blank material are far greater than the strains created during "shovel" forming. "V" and wiper bending involve a large amount of plastic deformation and therefore the use of ultimate strength in the forming model is very reasonable. However, considering the small strains involved in the "shovel" forming process it seems it may be appropriate to use the yield strength in lieu of ultimate strength.

ASTM A-36 states that the minimum yield strength must be 36 ksi and the ultimate strength range from 58-80 ksi. It is probably safe to assume that most inexpensive low carbon steel will have a yield strength near the minimum of 36 ksi and an ultimate strength towards the lower end of the possible range. The reason this is interesting is that the ratio of the minimum possible yield strength (36 ksi) to the minimum tensile strength (58 ksi) is a value of 0.62, which is precisely the average of the ratios presented in Table 9. Therefore, it appears that a good estimate of the yield strength of the test blank material may be the ultimate strength multiplied by 0.62. All of this seems to indicate that the force model may be improved by simply using the blank material's yield strength in place of ultimate strength. Therefore, the model in its improved form is

$$F = \frac{S_y t^2 l}{D} \tag{15}$$

where

F = Force (lbs.),
S_y = Yield Strength (ksi),
t = Material Thickness (in.),
l = Blank Length (in.), and
D = Die Diameter (in.).

Evaluation of Forming Model

After assembling all of the pieces of information available from the experimental data into a single expression, the final step is to evaluate the accuracy of the forming model. Table 10 presents values calculated using the improved forming model and a comparison of these values to the actual experimental results. Of course, these new calculated force values are simply the old values, presented in Tables 8 and 9, multiplied by the constant 0.62 in accordance with the approximate relationship found between yield and tensile strength.

Table 10: Comparison of Experimental Results and Improved Forming Model

Material Thickness (in.)	Die Diameter (in.)	Measured Force (lbs.)	Calculated Force (lbs.)	Difference (Calc. – Meas.)
0.125	3.82	1377	1284	-93
0.125	5.46	906	899	-7
0.125	6.24	738	786	48
0.188	3.82	2782	3162	380
0.188	5.46	2532	2212	-320
0.188	6.24	1672	1936	264
0.25	3.82	5806	5810	4
0.25	5.46	4356	4065	-291
0.25	6.24	3639	3557	-82

The first conclusion, which can be drawn from these new results, is that the model is much improved by using yield strength as opposed to tensile strength. The results ranged from an overestimation of 380 lbs. to an underestimation of 320 lbs. Interestingly, the two extremes occurred for the same material thickness, 0.188". Perhaps a better measure of the accuracy of the new model would be an investigation of the percent error from the measured force. The results of this analysis are presented below in Table 11.

Table 11: Error Analysis for Improved Forming Model

Material Thickness (in.)	Die Diameter (in.)	Percent Error (Diff./Meas.*100)
0.125	3.82	6.8
0.125	5.46	0.8
0.125	6.24	6.5
0.188	3.82	13.7
0.188	5.46	12.6
0.188	6.24	15.8
0.25	3.82	0.1
0.25	5.46	6.7
0.25	6.24	2.3

The results presented in Table 11 range from outstanding to less than ideal. As can be seen, the worst estimates of the actual force came from the cases using 0.188" thick material. The cause of this is not clearly evident. The obvious reason for the greater disparities between measured and predicted forces is that the ratios calculated for these cases in Table 9 were the farthest from the mean, 0.62. Notice in Table 10 that the force model overestimated the forming force for the 3.82" and 6.24" dies, while the forming force was underestimated for the 5.46" forming die.

Considering that the worst estimate calculated using the improved force model is only off by 15.8%, this model can not be discounted. Finally, even a minimum accuracy of roughly 16% will aid greatly in the design of future "shovel" machines by reducing the amount of over-design, especially, in the area of hydraulic power requirements.

Practical Form of Forming Model

The forming model presented in the previous sections was developed under the assumption that the diameter of the final product was constant. This assumption simplified the analysis and most importantly it simplified the fabrication of the forming dies for the test "shovel" machine. However, the ultimate goal of this research is aimed at improving the manufacture of tapered tubes. Therefore, it is important to transform the forming model, developed in the previous sections, into a form, which can be used to estimate the required force for a full-sized tapered tube.

Beginning with the final form of the model for a straight tube,

$$F = \frac{S_y t^2 l}{D}, \tag{15}$$

the only unknown in the relationship will be F, the forming force. Yield strength, blank thickness and blank length should all be known when designing a "shovel" press. The difficulty, which arises from the use of the model in the current form, is that the die diameter is not constant. Therefore, the force model for a tapered tube must take into account the variable diameter. In order to evaluate the forming force for a tapered tube, it is necessary to integrate the model over the entire length of the blank.

$$F = \int_{l_1}^{l_2} \frac{S_y t^2}{D} dl \tag{16}$$

However, Equation 16 still does not deal with the problem of a variable diameter. The simplest approach for handling this difficulty is to express the variable die diameter as a function of length and degree of taper, as shown by Equation 17.

$$D = D_1 + Tl \tag{17}$$

where

D_1 = Minimum Die Diameter (in.),
T = Degree of Taper (in./in.), and
l = Linear Distance from Minimum Die Diameter (in.).

Making this substitution for die diameter in Equation 16 yields the following expression.

$$F = \int_{l_1}^{l_2} \frac{S_y t^2}{D_1 + Tl}\, dl \tag{18}$$

Performing the integral gives Equation 19.

$$F = \frac{S_y t^2}{T} \ln\left(\frac{D_1 + Tl_2}{D_1 + Tl_1}\right) \tag{19}$$

Equation 19 is the complete force model for a tapered tube forming press. The model can be used for any die diameter and any degree of taper. It should be noted that this equation should only be used for cases involving a taper. For cases involving straight tubes, the original force model should be utilized. Equation 19 will estimate the forming force required for one entire side of a tapered tube. Please note that if a single hydraulic pump is to be used to drive both sides of a "shovel" press, then the value calculated using Equation 19 must be doubled in order to account for both sides of the press.

Below is a sample calculation using the tapered tube forming model for a blank with end diameters of 4.0" and 6.8", measuring twenty feet in length. The material used in the sample calculation is 0.125" sheet steel with an estimated yield strength of 39.37 ksi.

$$F = \frac{S_y t^2}{T} \ln\left(\frac{D_1 + Tl_2}{D_1 + Tl_1}\right) \tag{20}$$

$$F = \frac{(39{,}370\,psi)(0.125in.)^2}{0.01167in./in.} \ln\left(\frac{4in. + (0.01167in./in.)(240in.)}{4in. + (0.01167in./in.)(0in.)}\right)$$

$$F = 27{,}979lbs$$

As can be seen, the predicted forming force is 27,979 lbs. for one side of the tube blank.

The parameters used in the example shown above were not chosen arbitrarily. The parameters duplicate the ones used by Parkinson during his forming experiments. In fact, the 0.125" blank material used during this investigation came from excess material from Parkinson's work. Parkinson performed his experiments using the twenty foot "shovel" machine built by OSU tapered tube researchers. Also, he acquired force and die displacement data exactly as was done in the experiments performed for this investigation.

The results of a comparison between Parkinson's experimental data and the value calculated using the forming model developed during this investigation are very encouraging. The force measured by Parkinson during his experiments averaged approximately 28,000 lbs. Considering that the force model predicted a value of 27,979 lbs., the model's performance for this set of parameters can only be characterized as excellent.

CHAPTER VI

CONCLUSION AND RECOMMENDATIONS

Summary

At the beginning of this research, the mechanics behind the "shovel" forming process were very much a mystery. This research has shed a great deal of light on the process. However, there are still aspects of "shovel" forming, which require further investigation. This study began with a survey of literature pertaining to metal forming research. However, it was quickly learned that the "shovel" forming process is unique and similar processes have garnered little attention from researchers.

Predecessors laid the groundwork for many of the advances presented in this report. The work of Adair, Chada and others proved invaluable, particularly in the areas of sample "preforming" and design of the small "shovel" machine fabricated for this study. Of the contributions this study has made to OSU's tapered tube research, the most significant is the force model developed using the experimental data collected during this project. Proving the viability of the process for use with materials of thickness up to 0.25" and the study of the effects of lubrication, have also furthered knowledge about the "shovel" process greatly. However, the work presented in this report should only be thought of as the first significant steps taken towards a complete understanding of the "shovel" forming process.

Process Viability

All previous tapered tube research at OSU has focused on the forming of 11 gage (0.12") material. Therefore, many observers wondered whether the process could be used to form thicker material. It was believed that the process would work with any material thickness as long as enough force could be generated. The work performed during this investigation supports this earlier assumption. The experimental "shovel" press handled the set of experiments performed using 0.25" blank material and the 3.82" die with ease. Therefore, it appears that the thickness of possible blank material is limited only by the amount of strain the particular material can withstand. Meaning, that a blank of any thickness can be formed using the "shovel" process as long as the final diameter is greater than the minimum bend diameter for a particular material.

Lubrication and Friction Effects

The effect of friction and lubrication is the facet of "shovel" forming that is currently the least understood. For this reason, future researchers will definitely have an interest in these topics. However, the work performed during this investigation seems to indicate that contributions from friction between die and blank may not be significant. The limited number of lubrication experiments, using mineral and grease, showed only marginal reductions in required forming forces over dry forming. In fact, the benefits of those lubricants were at most a 10% reduction in forming force.

In addition, some concern about friction in the shovel machine's slider mechanism has been raised. Initial indications are that friction in the slider mechanism is not a major contributor to the amount of force required to form a blank. The model developed during this investigation has been shown to be accurate to approximately 16% and it contains no terms dealing with friction. Therefore, it would be incorrect to conclude that friction has no bearing on the forming force. However, the analysis of the experimental data and consequent development of the forming model seems to indicate that the majority of force supplied by the hydraulic rams goes directly into forming. Finally, initial indications are that friction in the slider mechanism and that due to blank-die contact are not significant contributors to the total force required for "shovel" forming, however, further research into both should not be discouraged.

Although members of industry have expressed concerns about the use of any lubricants in the "shovel" forming process, future experiments investigating the use of solid film lubricants such as molybdenum disulfide should be considered. The reason for the concerns surrounding lubrication is that the formed tube would have to be cleaned prior to subsequent manufacturing processes. Therefore, it will have to be shown that the benefits of lubrication in reduced forces would outweigh the added time and cost of additional manufacturing operations, and at this time, that does not seem likely. However, any future work, which could precisely quantify the effects of friction, could only add to the accuracy of the model developed during this investigation.

"Shovel" Forming Force Model

The development of the "shovel" forming model will greatly benefit researchers as work continues toward the development of industrial production "shovel" machines. The model allows a designer to accurately predict force requirements for "shovel" machines capable of forming tapered tubes of any size. As was shown by the sample calculation in the previous chapter, the model is extremely simple to use. Which will make the task of sizing hydraulic pumps, rams and frame components for new "shovel" machines very easy.

It should be remembered that there are actually two forms of the "shovel" forming model. One form can be used for tapered tubes and the other for straight tubes. The model for a tapered tube "shovel" machine is Equation 19, shown below.

$$F = \frac{S_y t^2}{T} \ln\left(\frac{D_1 + Tl_2}{D_1 + Tl_1}\right) \tag{19}$$

While, the straight tube form of the model is given by Equation 15.

$$F = \frac{S_y t^2 l}{D} \tag{15}$$

It would be desirable to have only one model for both cases. However, Equation 19 will not allow a value of zero to be used for degree of taper (T), as is the case for a straight tube. Therefore, when performing calculations using the model, one must make certain that the appropriate form of the model is being used.

As has been discussed, the model still contains some unknown parameters, namely friction forces. Current indications are that friction forces contribute minimally to the overall force requirements. The model's agreement with the experimental results of this study and Parkinson's work, showed that the current form of the model can be expected to produce accurate force estimates for "shovel" forming, even without giving consideration to friction. However, until the frictional forces are quantified, the forming model may still have room for refinement. Although in a practical sense, the model is complete and ready for use as a design tool.

Conclusion

This study has produced some significant advances in the understanding of the "shovel" forming process and also raised a number of questions. The test "shovel" machine built for this study performed extremely well and could be used for almost any future research regarding the "shovel" forming process. Of course, the largest development, presented in this report, is the force model. This force model will simplify and make more efficient the design of future "shovel" forming presses. Although, the model can not truly be considered complete until the friction effects are completely understood, the model could be used in its current form for the design of a full-scale industrial "shovel" machine.

Finally, the "shovel" forming process is just a single aspect of the tapered tube manufacturing process developed at Oklahoma State University, which will someday prove itself a viable alternative to current manufacturing techniques.

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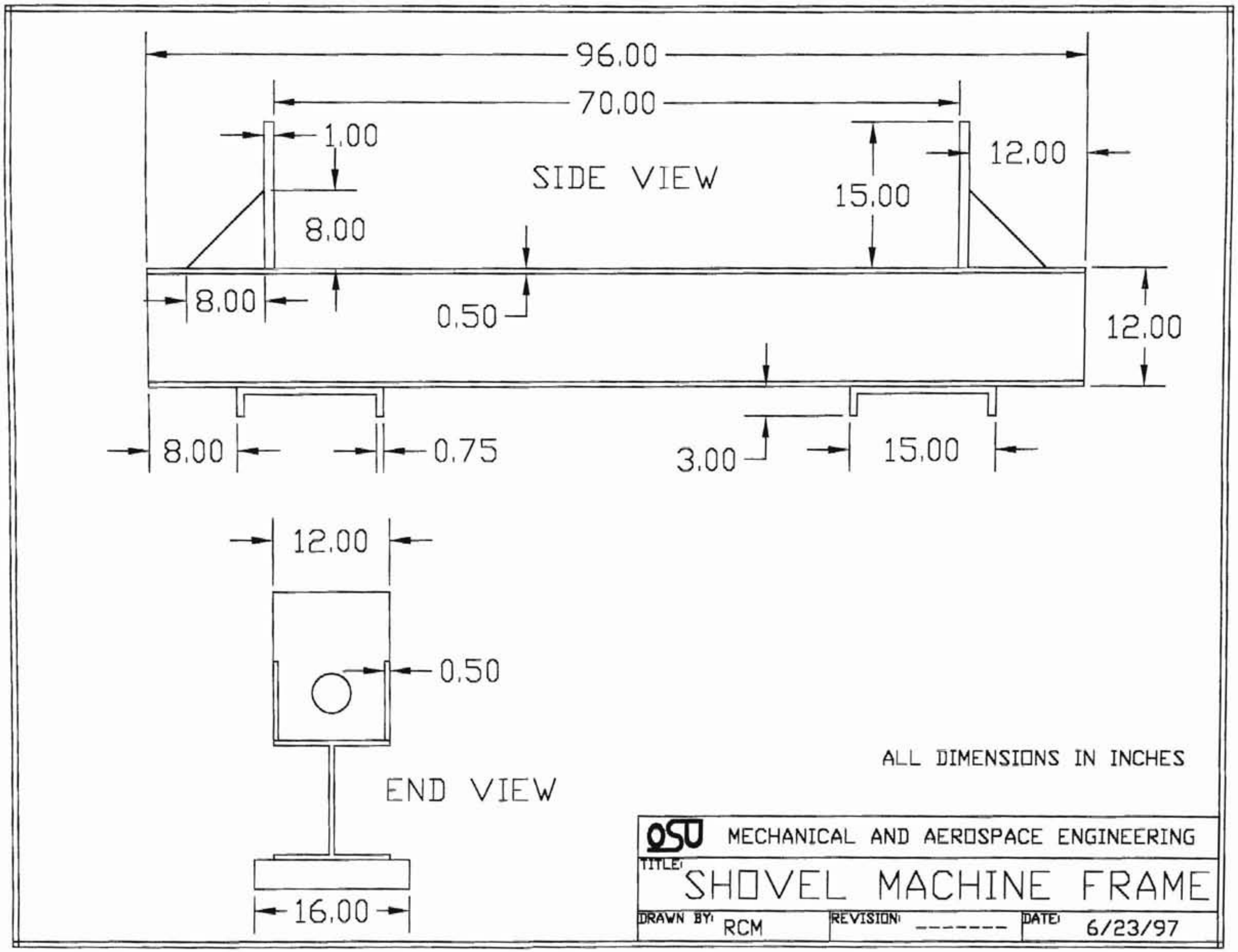
APPENDICES

APPENDIX A

EXPERIMENTAL "SHOVEL" PRESS MACHINE DRAWINGS

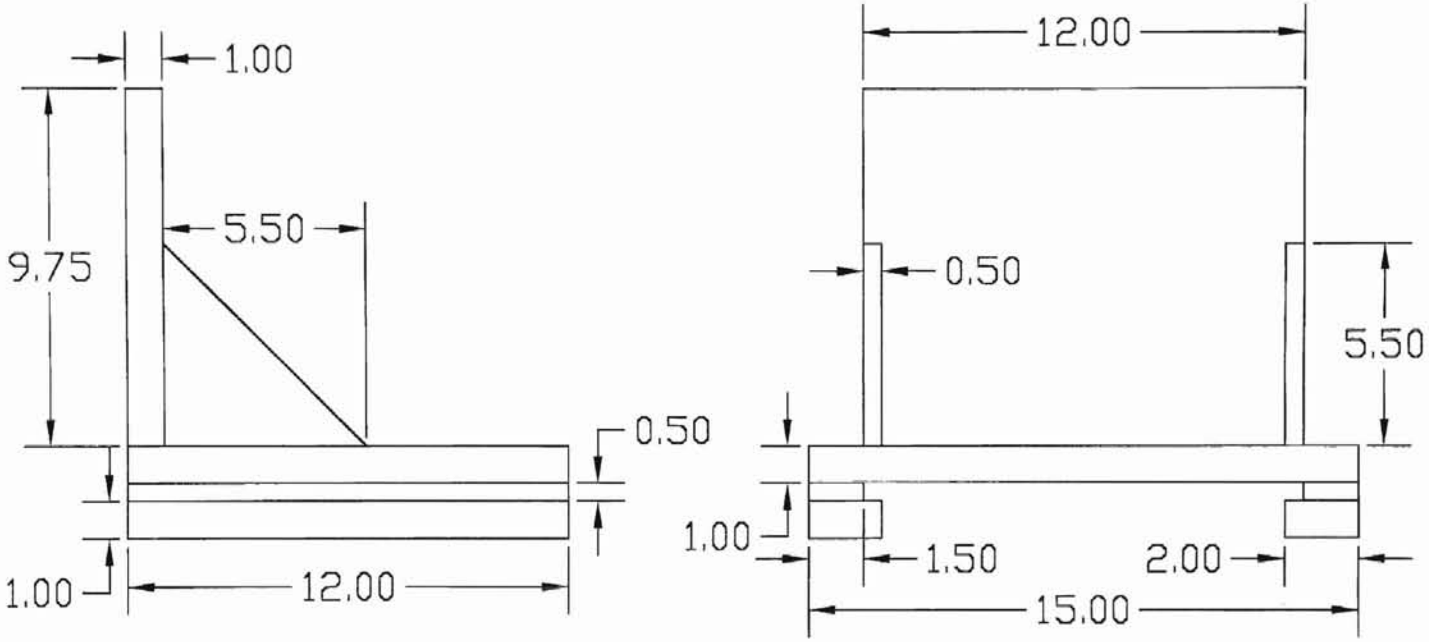


ALL DIMENSIONS IN INCHES

OSU MECHANICAL AND AEROSPACE ENGINEERING

TITLE: SHOVEL MACHINE FRAME

DRAWN BY: RCM REVISION: ------- DATE: 6/23/97



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TITLE: SHOVEL PRESS SLIDER

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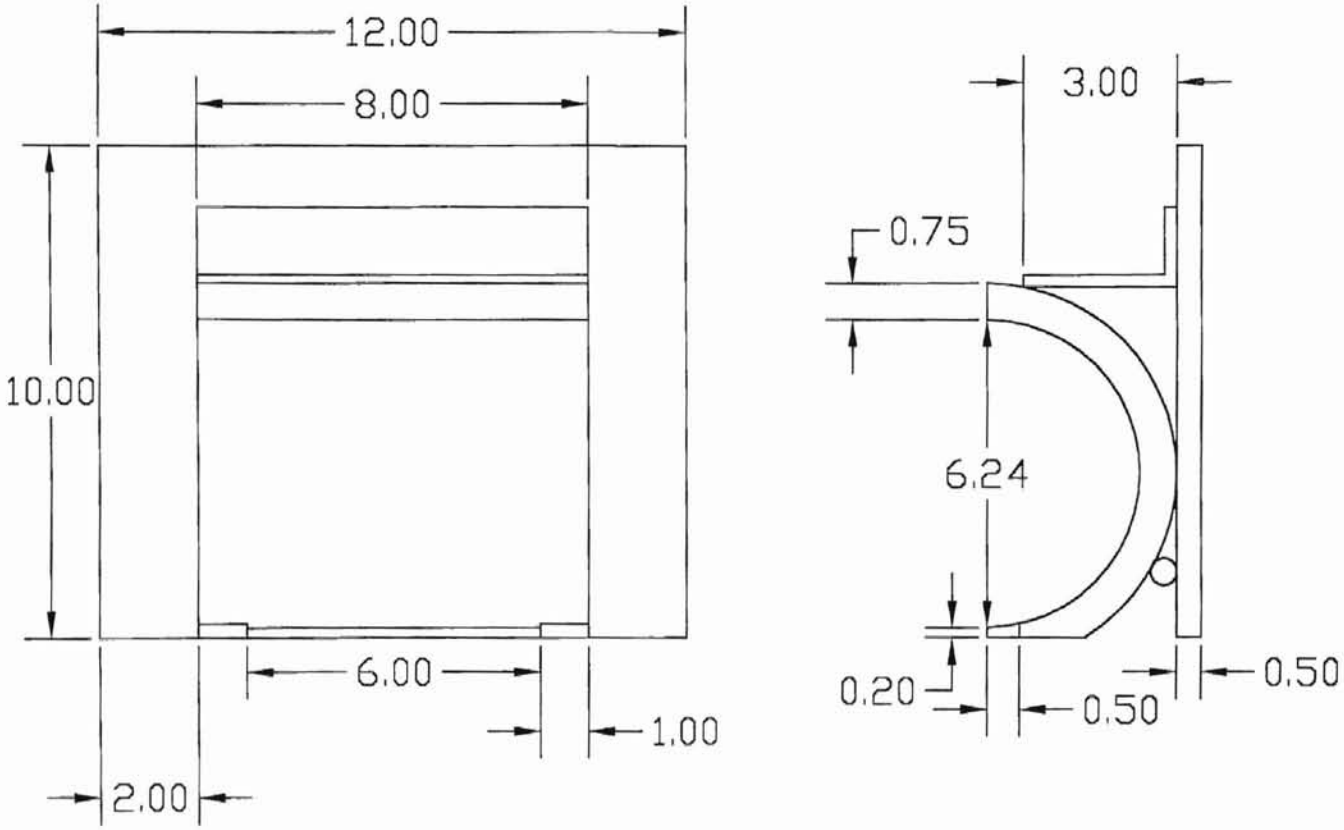

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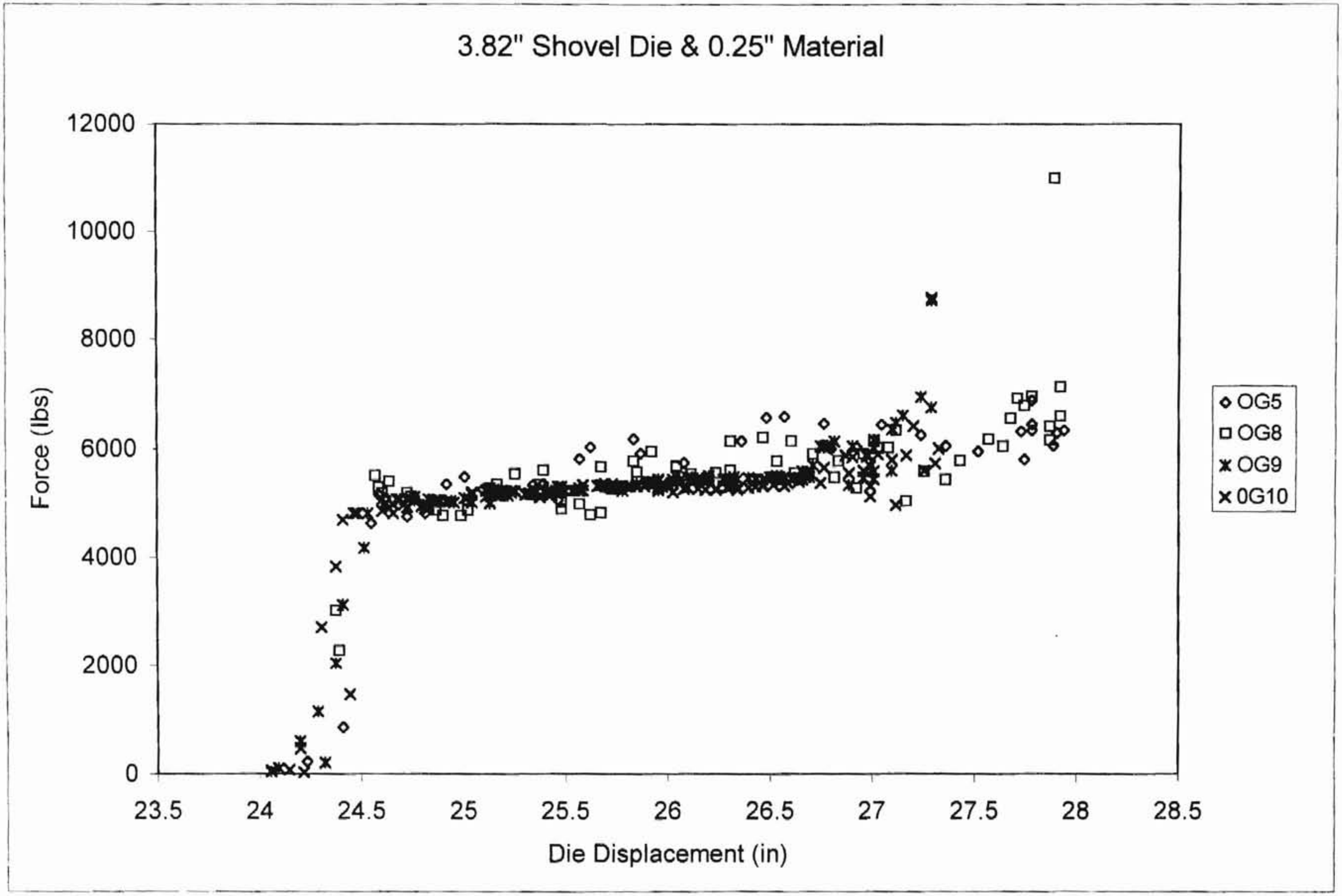
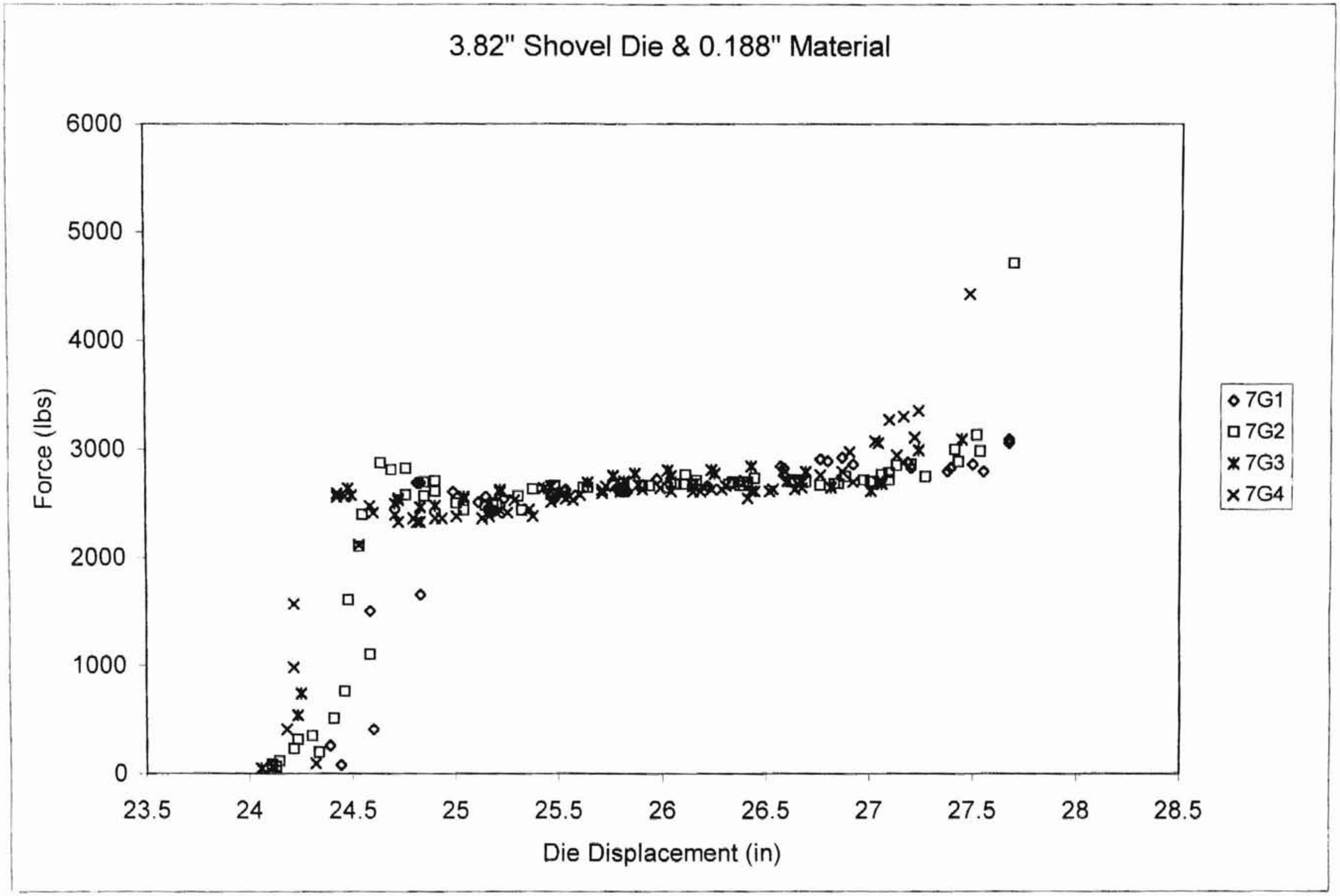
APPENDIX B

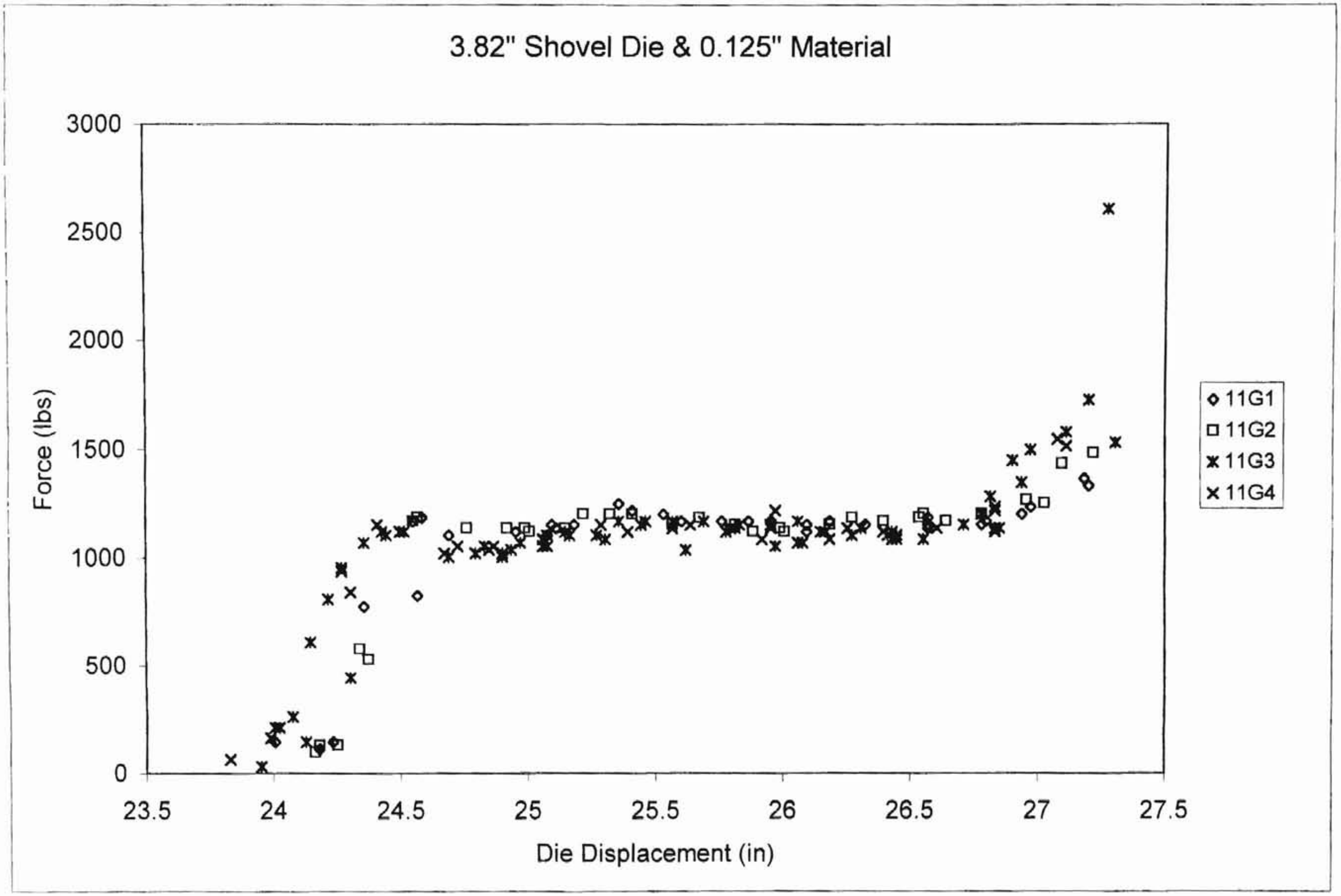
FORCE VS. DIE DISPLACEMENT PLOTS

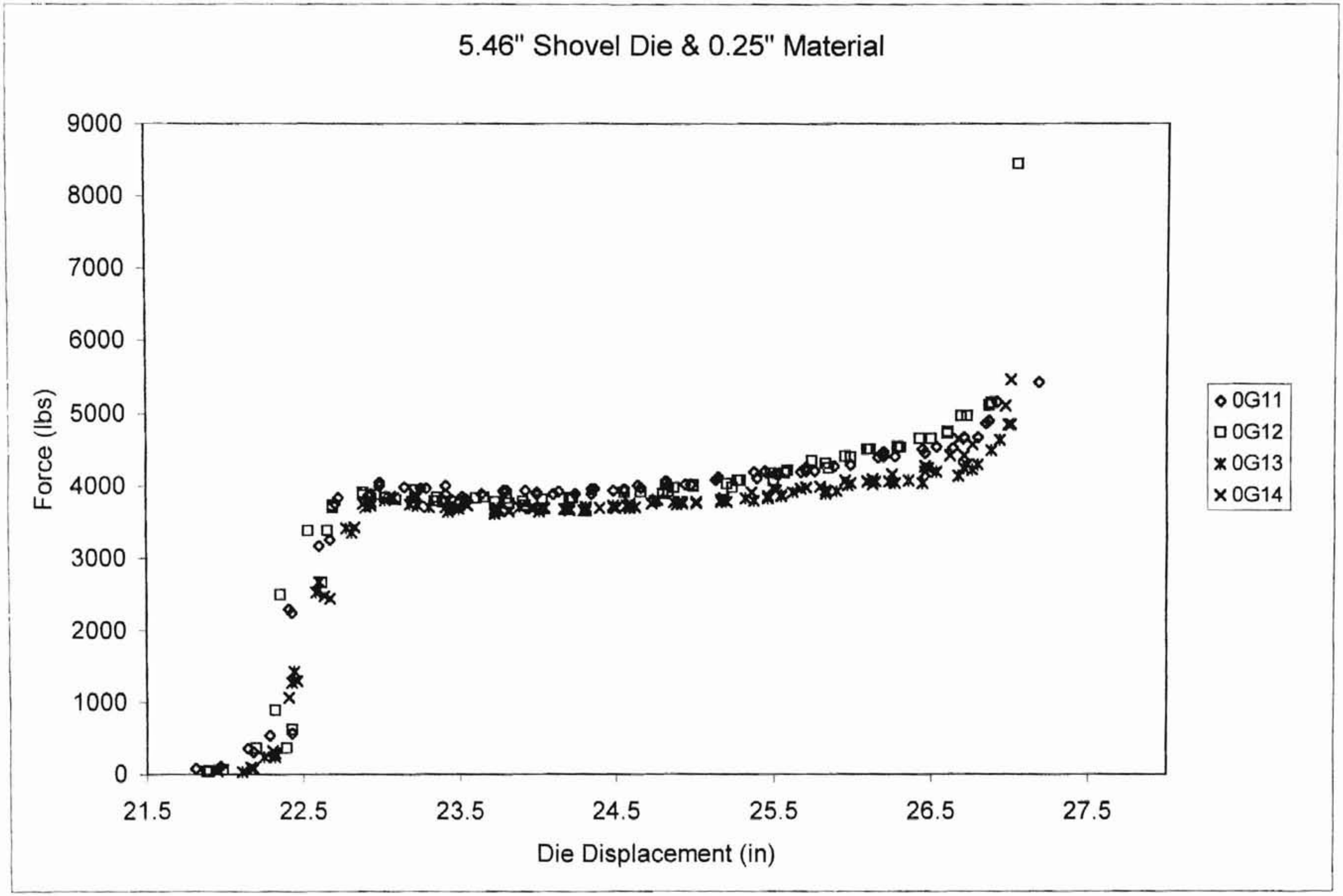


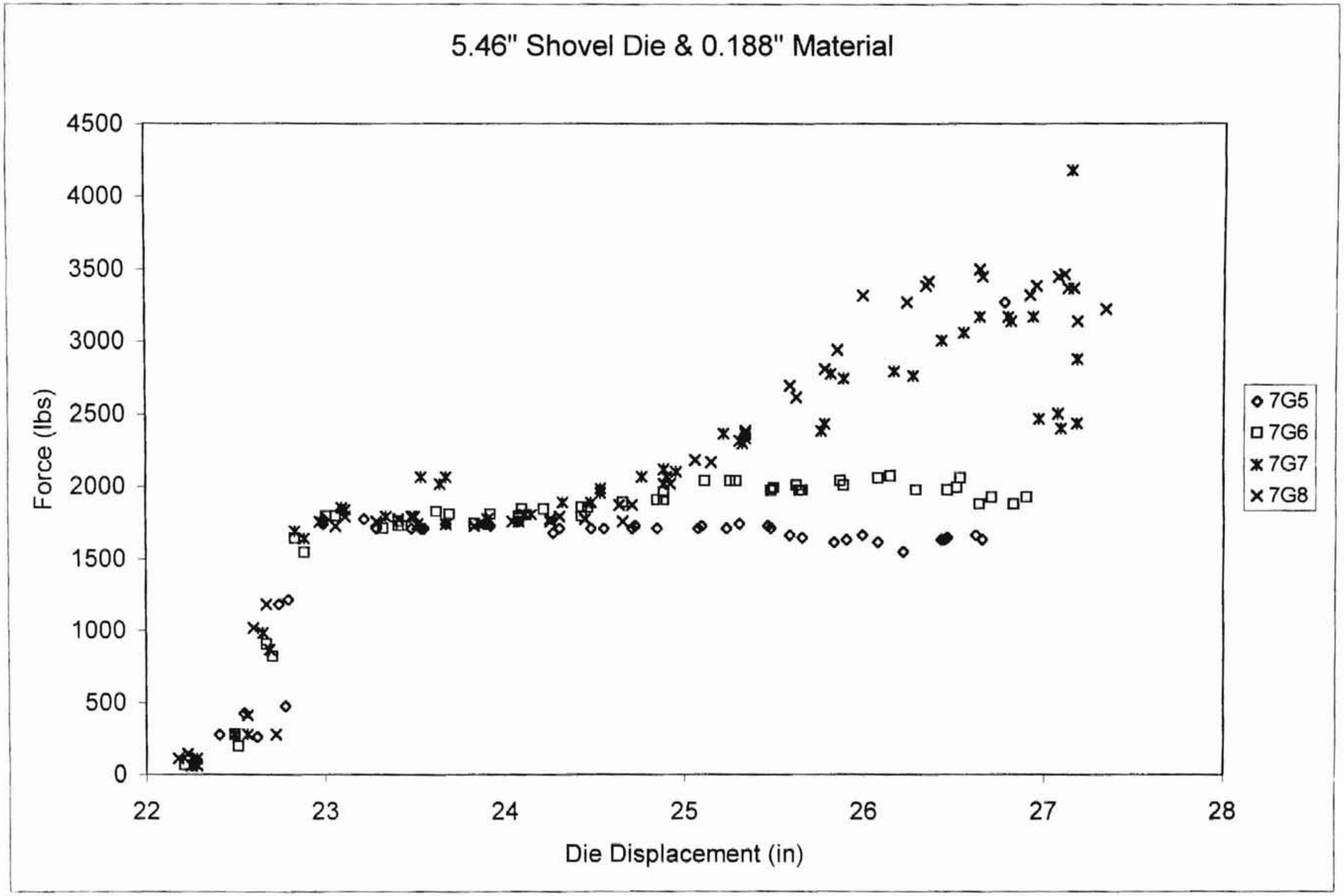
3.82" Shovel Die & 0.25" Material

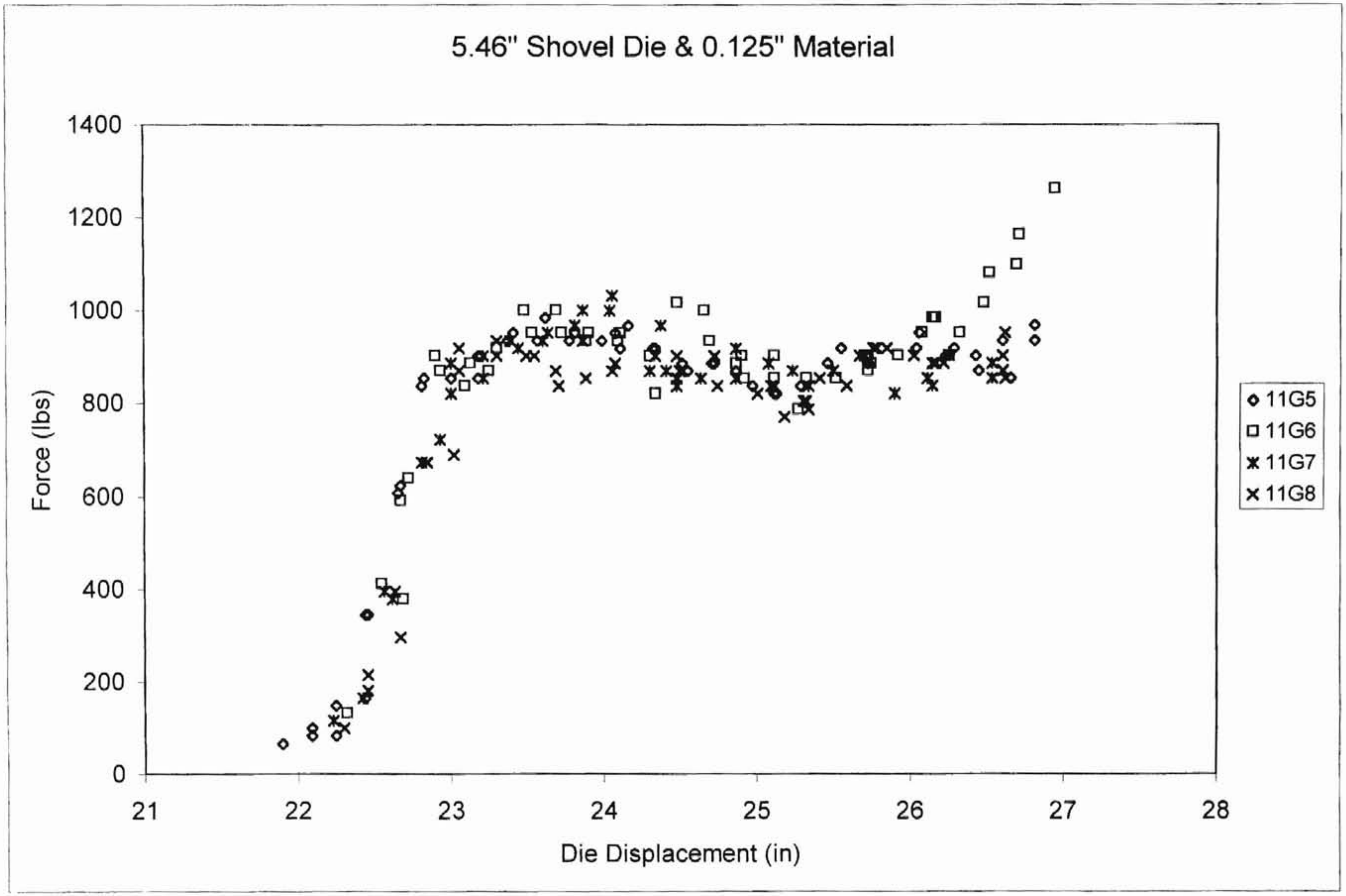


3.82" Shovel Die & 0.188" Material


3.82" Shovel Die & 0.125" Material
Force (lbs)
3000
2500
2000
1500
1000
500
0
23.5
24
24.5
25
25.5
26
26.5
27
27.5
Die Displacement (in)
◇ 11G1
□ 11G2
✱ 11G3
× 11G4


5.46" Shovel Die & 0.25" Material
Force (lbs)
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
21.5
22.5
23.5
24.5
25.5
26.5
27.5
Die Displacement (in)
◇ 0G11
□ 0G12
✱ 0G13
× 0G14


5.46" Shovel Die & 0.188" Material
Force (lbs)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
22
23
24
25
26
27
28
Die Displacement (in)
◇ 7G5
□ 7G6
✱ 7G7
× 7G8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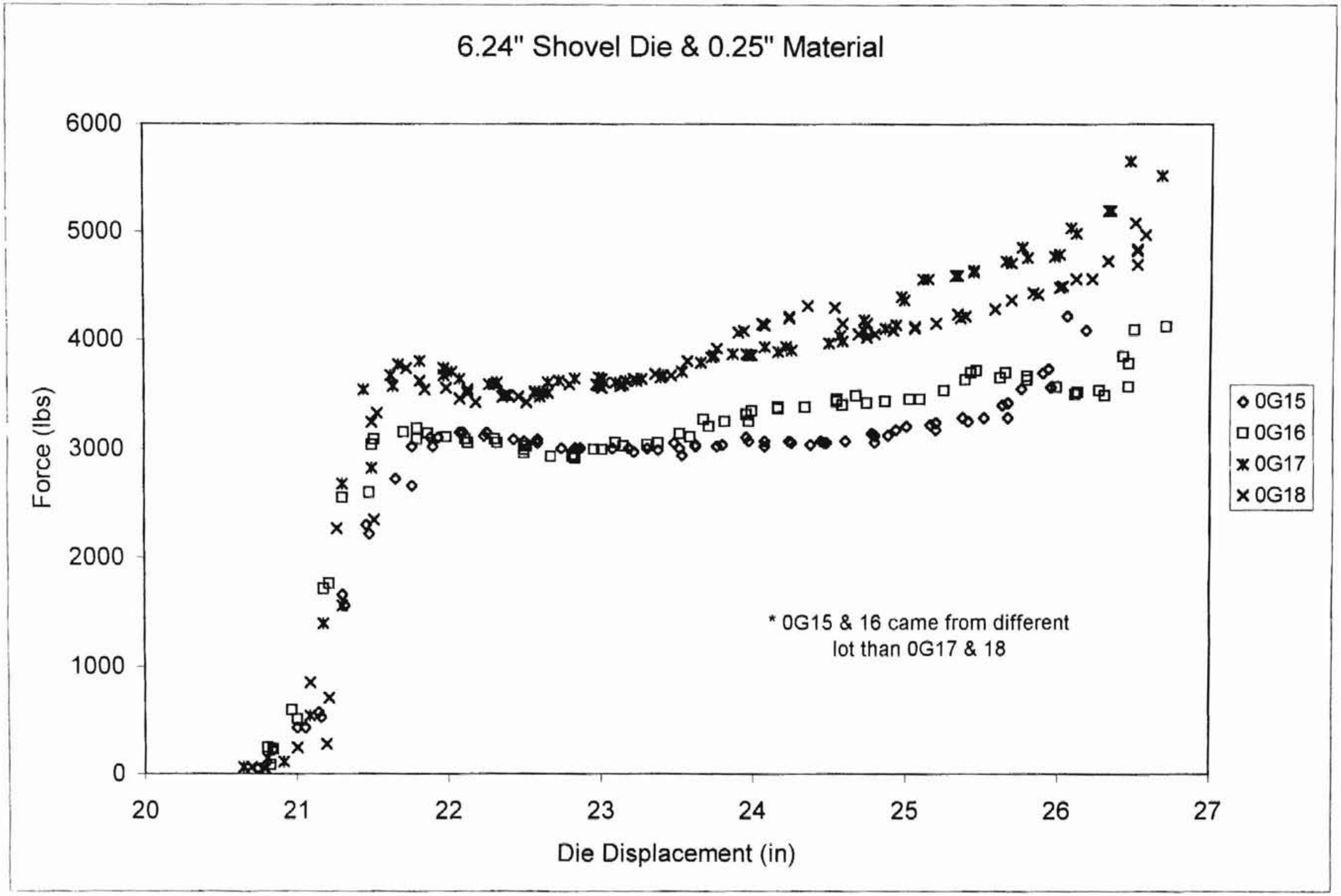
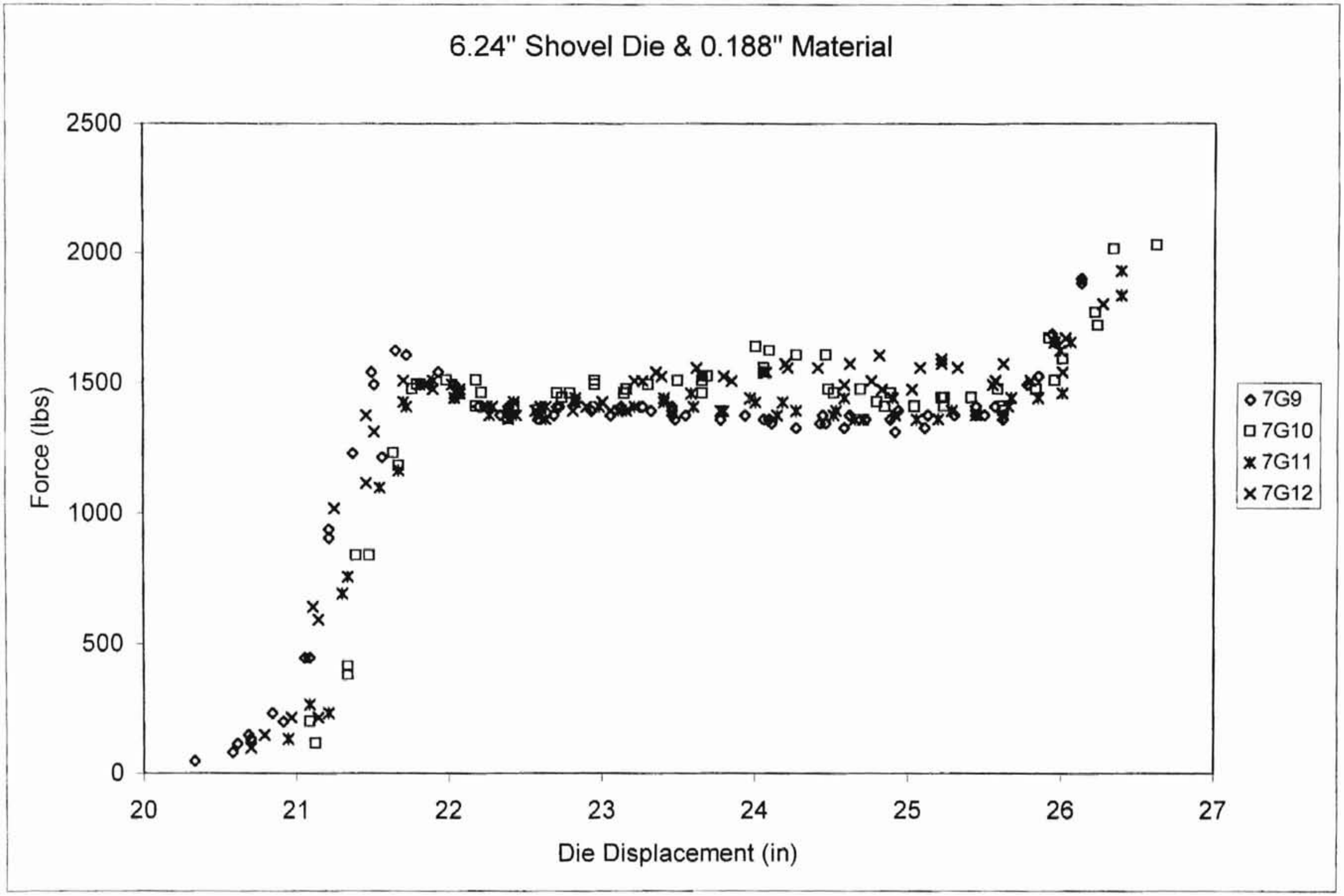
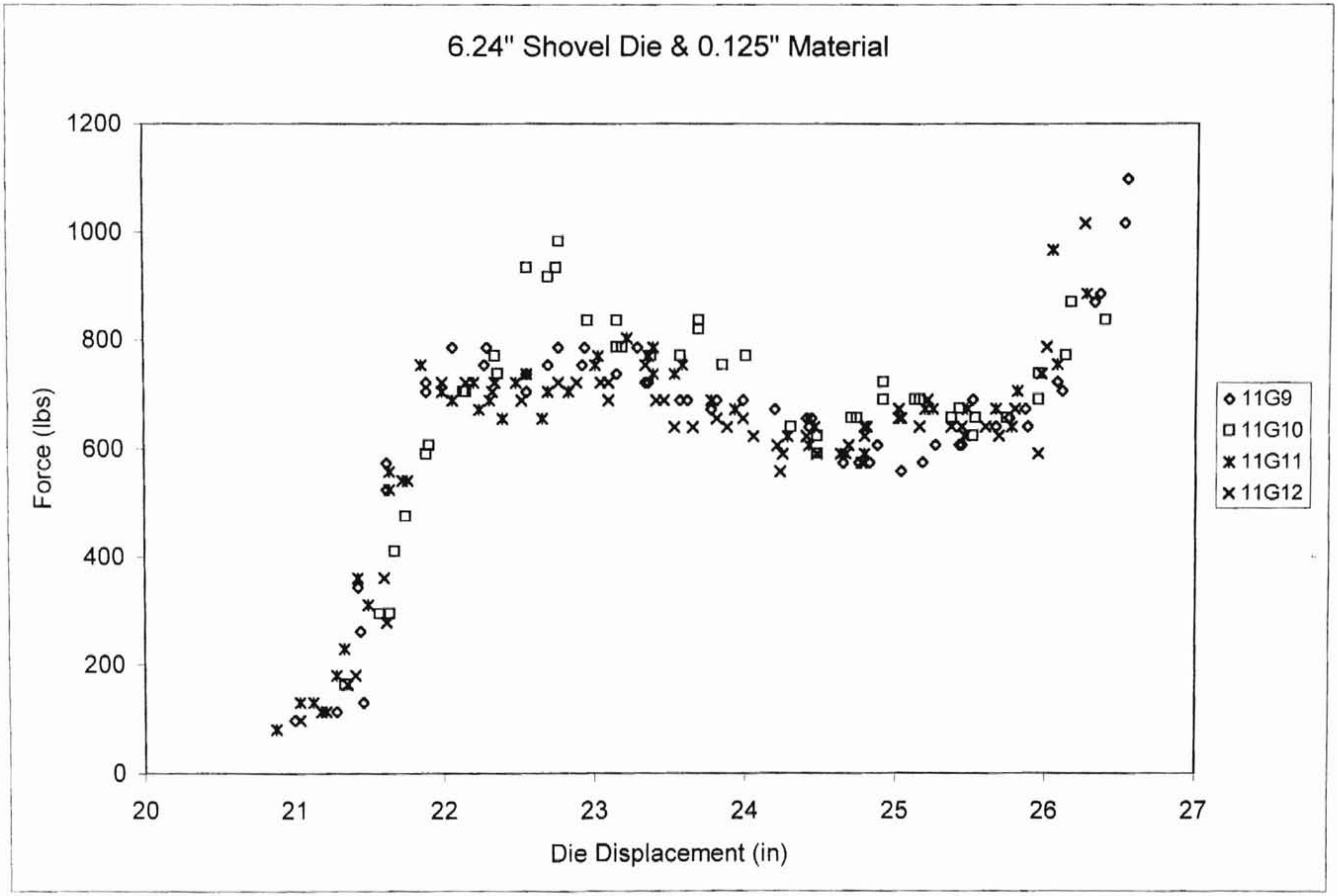
Force (lbs)
1400
1200
1000
800
600
400
200
0
21
22
23
24
25
26
27
28
Die Displacement (in)
◇ 11G5
□ 11G6
✱ 11G7
× 11G8



6.24" Shovel Die & 0.25" Material


6.24" Shovel Die & 0.188" Material
Force (lbs)
2500
2000
1500
1000
500
0
20
21
22
23
24
25
26
27
Die Displacement (in)
◇ 7G9
□ 7G10
✱ 7G11
× 7G12


6.24" Shovel Die & 0.125" Material

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