Process Improvement Methodologies Applied to Tube Drawing

by

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Submitted to the Department of Materials Science & Engineering
and the Sloan School of Management
in Partial Fulfillment of the Requirements for the Degrees of

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ABSTRACT

This thesis presents a case study that focuses on two methodologies of process improvement. The first method addresses the reliability of the processing centers (machines) in the flow-path. The second deals with reducing the number of processing centers as well as the number of iterations performed at each of these processing centers.

The research was performed at an aluminum tube drawing mill. The objective of the study was to gain some insights in the problems being encountered in this mill, to analyze some of these problems using basic process improvement tools and to make simple recommendations in an effort to improve the reliability of the tube drawing process.

Data collected over a two month period forms the basis of the analysis in this thesis. Lots that did not fulfill the customer's requested amounts (lbs) were compared to lots that fulfilled the requirements using several attributes. The results of the analysis indicates that lots that did not fulfill the customer requested amounts had more iterations at the draw benches, spent longer times in the mill and tend to have lower yields.

Two experiments were done to see if the number of iterations at the draw bench could be reduced without reducing the process yield. The first experiment dealt with variables that were controlled by the planning department, while the second dealt with variables controlled by operators and shop floor supervisors. The second experiment provided no conclusive results because of the amount of variation in the data collected. Some recommendations on performing future experiments are presented as a result of doing the second experiment.

A finite element model of the drawing process was undertaken to get a better understanding of the variables that were important to this tube drawing process. This model provides a basis for doing what-if type analysis on the drawing process prior to performing future experiments.

In order to improve the process reliability and reduce the number of processing steps in a manufacturing process, manufacturers must go beyond "the charts on the wall", they must understand what variables drive the process and just as important what variables don't.

Thesis Supervisors: Anantaram Balakrishnan
                        Stuart Brown
Associate Professor of Management
Associate Professor of Materials Science & Engineering.
This thesis is dedicated to my mother, Ulrica Dorah. You always know when to push, when to back-off and when to push harder. "Dem a go tired ji si wi face, dem caan get wi outa de race".
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This thesis would not exist without the help of the people at “the plant” whose insights into the process led to many fruitful discussions. Thank you Rob, Scott, Vern, Rick and Charlie for giving me the opportunity to work and play and think. Dave, John, Howard, Tom, Randy, Ram, Gary, Gloria, Jim, Jack and Jay for taking me into the “trenches” and coming to my rescue when I needed help. I can never repay the “boss”, Pam; hope the cheesecake was good! I’m am particularly in debt to the people “on the floor”; John, Tim, Rose, Dennis, Chewy, Paul, Mike, etc, etc. Thank you to all the people outside the tube mill who made my life so much easier; Gerry, Iron-man Bill (thanks for being human), Jazz-man Perry, Susie (volleyball champs!), Bob (see you in Hoboken), Karen, Mike, Teresa and anyone else who I annoyed while doing this thesis.

Dave and Sue, I really enjoyed “hanging” with you guys.

Special thank you to Carl and Marge; my parents away from home, my teachers and my friends. You are always welcome and wanted wherever I am. Thanks for all those meals. Fishing will never be the same. Tunaaaa!

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Thank you Lord for watching over me. “Jah wil neva give de powa to a bald-head....”

Several people assisted with this thesis and share credit for whatever successful results are contained in it, but I alone take the responsibility for errors and omissions that may still be present.

Thanks to the Leaders for Manufacturing Program for providing support (financial and otherwise) for this research.
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Process Improvement Methodologies Applied to Tube Drawing

A host of world class manufacturing sub-goals can be contained within two overriding goals. One is the reduction of deviation, and the other is the reduction of variability.

-Richard J. Schonberger

CHAPTER 1

1.0 Introduction

Manufacturing process improvement has become a part of the jargon in almost every manufacturing organization [Schonberger, 1986]. This thesis presents a manufacturing case study that focuses on two methodologies of process improvement. The first addresses improvements in the yield of the individual processing centers (machines) in a process flow path. The second deals with reducing the number of processing steps as well as the number of iterations performed at each of these steps. Like most manufacturing organizations, this thesis will use a reactive approach to process improvement by looking at current problems in a myopic fashion. This reactive process improvement is often done (or attempted) in the pursuit of better product quality. These quality requirements are becoming more and more stringent as manufacturers are now being called upon to become quality partners with their customers.

The push on quality requirements has forced process improvement into the strategic decision making process in many manufacturing organizations. "The relative importance of process innovations usually increases with maturity.....to facilitate lower-cost manufacturing and control." [Porter; 1980]. We can say process improvement is crucial to the survival of a manufacturer, however there is no single formula for success. How do process improvement changes in one part of a flow path affect other parts? What
are the potential benefits if a process is improved? What is the first thing that should be done? Should anything be done?

1.1 Variation and Probability

Consider a manufacturing process line with N machines (or processing centers) in series; each machine has a probability, P, of producing acceptable input for the next process downstream. If we assume that once a product (tube) is seen with defects, those defects cannot be removed, then the maximum number of acceptable products leaving any machine cannot be greater than the number of acceptable products entering the next machine. The probability, S, of getting acceptable (yield) products through N machines each with probability, P (assuming independence), is therefore given by:

$$S = P^N$$

Figure 1a plots S versus P for various values of N. From this figure we see that are basically two ways to increase overall process yield, S;

1) lower N, i.e. reduce the number of processing steps and/or reduce the number of iterations performed at each process step.

2) increase P, i.e. improve the reliability of each machine (processing step).
1.2 The Focus of the Thesis

The primary focus of this thesis is to apply a basic process improvement methodology outlined in section 1.3 to the drawing of seamless aluminum tubes in an effort to reduce the total number of processing steps without reducing throughput or yield. A secondary aim is to improve the fundamental understanding of the levels of stress and strain state experienced during the drawing of seamless aluminum tubes in an effort to improve the reliability of the drawing process. The material presented is based loosely on information collected during a six month internship at a tube drawing facility. The data has been modified for proprietary reasons, however the methodology is generic.

By using historical data, designed experiments and finite element modeling to analyze one section of the tube drawing process, this thesis provides a simple and cost effective way to implement a framework to begin process improvements. Process
improvement is a dynamic activity and as such the way the tools are used will be different for each process. However the tools must not be used separately; they must be used to complement each other. This is what was done in this study.

The rest of the thesis is organized in the following manner:

- **Section 1.3** will discuss some generic process improvement methodologies. This is done to illustrate what types of tools are available to be used in process improvement efforts.

- **Section 1.4** describes the tube drawing process and a discussions of some the issues facing the industry is discussed.

- An analysis of data (production and process) collected over a two month period is analyzed and presented in **chapter 2**.

- **Chapter 3** describes and summarizes two designed experiments performed as part of the process improvement effort.

- **Chapter 4** discusses the application of a finite element model of the drawing process. Further research areas and a summary is also presented.

1.3 The Process Improvement Methodology

This thesis will apply established process improvement tools (see **Table 1a**) to the tube drawing process in an effort to answer some of the questions posed in the previous sections, but will combine the techniques to provide a step by step approach to process improvement. **Table 1a** is generic "check sheet" used in process improvement efforts and is meant to serve as a guideline. According to Hamburg [1991] most quality
improvement efforts never get past the planning stage. Once the data is collected and the pareto diagram are drawn, only 25% to 30% of manufacturers ever get to the “DO” stage. This study tries to incorporate aspects of all four stages, even though they are not all thoroughly dealt with. The process improvement push in this thesis will concentrate on reducing the number of processing steps (operations) in a flow path. The process improvement methodology presented is not new [Shiba, 1989], but rather an existing methodology that is often underutilized. In this study we will use existing process improvement methodologies to provide a framework to go beyond “the paper charts.”

<table>
<thead>
<tr>
<th>PDCA</th>
<th>7 Steps</th>
<th>7 Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plan</td>
<td>1. Identification of the problem</td>
<td>• Check sheets</td>
</tr>
<tr>
<td></td>
<td>2. Collecting and analyzing facts</td>
<td>• Graphs</td>
</tr>
<tr>
<td></td>
<td>3. Finding out the main causes</td>
<td>• Pareto diagram</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Histogram</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Scatter diagram</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Cause and effect diagram</td>
</tr>
<tr>
<td>Do</td>
<td>4. Planning and implementing improvements</td>
<td></td>
</tr>
<tr>
<td>Check</td>
<td>5. Confirmation of the effects</td>
<td>The same process as above plus Control chart</td>
</tr>
<tr>
<td>Action</td>
<td>6. Standardize the process</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7. Review of the activities and planning for the future</td>
<td></td>
</tr>
</tbody>
</table>
1.3.1 Modes of Problem Solving

It is important to realize that the application of this generic process improvement methodology does not guarantee that a manufacturer will be 'world-class'. Sirkin and Stalk [1990] emphasize that there are four problem solving modes in which an organization can function (see Table 1b). The ability to approach 'world-class' through the use of the process improvement tools mentioned above depends on the problems solving mode that the organization is in. A 'world-class' organization will most likely be in the Anticipation mode or between the Root-cause mode and the Anticipation mode.

Table 1b: Sirkin and Stalk’s problem solving modes

<table>
<thead>
<tr>
<th>Problem Solving Mode</th>
<th>What is done in this mode</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fix-as-Fail</td>
<td>Problem arises and is fixed</td>
<td>Bad product are scrapped instead of being shipped</td>
</tr>
<tr>
<td>Prevention</td>
<td>Production process monitored for quality</td>
<td>Solution leads to preventive action</td>
</tr>
<tr>
<td>Root Cause</td>
<td>Production process changed to improve quality</td>
<td>Fewer problems create time to find underlying causes</td>
</tr>
<tr>
<td>Anticipation</td>
<td>System changes create time to find improvements</td>
<td>New product and processes are developed</td>
</tr>
</tbody>
</table>

This generalized problem solving mode that organizations find themselves in will often determine how successful process improvement efforts are. Organizations that fail to realize what mode they are in will often implement improvement efforts that have very low probabilities of success. Keeping this in mind and realizing that the tube drawing industry is probably in the prevention mode, a discussion of the tube drawing industry is presented in the next section.
1.4 The Tube Drawing Process

When a hollow tube is drawn through a die with a fixed mandrel supporting the inside diameter, the process is called tube drawing\(^1\). Drawing operations involve forcing metal through a die (or sets of dies) by applying a tensile force to the metal at the exit side of the die. Most of the plastic flow is caused by compressive forces due to the contact between the die and the metal. A schematic representation of the drawing process is shown in Figure 1c.

The starting stock or blooms in the drawing process were manufactured by an extrusion process\(^2\). Cold drawing (hereafter referred to as 'drawing') involves the pulling (drawing) of extruded tubes at room temperature through a die that controls the dimensions of the outside diameter, while the inside diameter (ID) is controlled by a mandrel. For the purpose of this thesis “tube” refers to hollow cylinders with outside diameter (OD) ranging from 3/4 inch to 14 inches and with lengths up to 40 feet.

---

\(^1\) There are other tube drawing methods, such as drawing with a floating mandrel, that are not discussed in this thesis. For a full discussion of all the drawing methods see chapter 9 of *Metal Forming Processes* by Betzalel Avitzur.

\(^2\) The process of extrusion is similar to drawing. Both processes make use of a tool in the form of a nozzle. In extrusion a billet is pushed through a die, usually at elevated temperature.
The die and the mandrel, often referred to as the “tooling”, are fixed during the drawing process (see Figure 1c) and are positioned such that the mandrel is located in the “draw zone” of the die. The “draw zone” or the “bearing” is the inner space of the die and helps to determine the contact area between the OD of the tube and the die. Inside the tube a mandrel is attached to a stationary rod. For a fixed change in cross-sectional area, this mandrel along with the draw zone of the die partially determines the amount of stress the tube experiences during drawing [Avitzur, 1977]. The change in cross section of the tube which is being drawn results from a combination of diameter and wall thickness (hereafter referred to as "wall") changes. It is important to note that the actual drawing of the tubes is only one operation (step) in the manufacture of cold-drawn tubes, but multiple
passes (iterations) are usually done at this processing step. A typical flow path is shown Figure 1d. The process starts with cast aluminum logs being sawed into billets. These billets are then transferred to an extrusion press, where they are reheated and extruded. The extruded tubes exit the press at elevated temperatures. The “hot” tubes are then air cooled or water quenched depending on the end-use. Tubes that are to be drawn are usually air cooled. The cooling of the tubes usually cause them to “warp”. A stretching operation is included to straighten the tubes. The tubes are then sawed and inspected. Following inspection, they are sent to an anneal oven, to relieve residual stresses. All the processing steps mentioned thus far are prior to entering the tube mill. Once the tubes are annealed they are sent to the tube mill. These tubes are called “bloom” or “starting stock”. The blooms are then “pointed” so they can gripped at the drawing operation (see Figure 1c). They may also be “repaired” to remove blemishes before the drawing operations. The process of repairing will be dealt with again in chapter 3. The tubes are then sent to the “draw bench”. This is where the cross sectional area reduction takes place. The tooling seen in Figure 1c are used at the draw bench. Depending on how much plastic work is done to the tube, intermediate anneal(s) are necessary. The shaded boxes in Figure 1d shows two drawing operations. It is important to realize that both of the drawing steps are done at the same draw bench. There are typically two or three draws before an anneal. For the data set studied, there were on average three draws (see Figure A.12). Part of the discussion is chapter 3 focuses on reducing the total number of draws and on reducing the number of draws done prior to anneal. Once the final dimensions are obtained at the draw bench, the tubes are sent to the finish area. This consists of heat treat (for some alloys, depending on the temper ordered), stretch/straighten, saw, deburr, clean, inspect and then pack for shipping.
Figure 1d: Generic Process Flow Diagram for the Production of Drawn Tubes

1. Import logs to Ingot Plant
   - Logs sawed into billets
   - Billets transferred to extrusion
   - Reheat
   - Extrude
   - Stretch
   - Saw
   - Inspect
   - Bloom annealed

2. Assign bloom to lots
   - Point
     - Repair
   - Draw
     - Anneal
       - Heat Treat
       - Stretch/Straighten
       - Saw/Deburr
       - Clean
         - Inspect/Pack ship
1.4.1 Uses for Drawn Tubes

Cold-drawn tubes are used in applications such as copier drums, bicycle frames, drive shafts and rotor shafts. The cold drawing of extruded tubes generally provides "closer dimensional tolerances, better surface finish, smaller diameters, thinner walls and improved mechanical properties" than could be obtained by hot forming processes [Khare, 1991]. The advantages and disadvantages of cold-drawing over other techniques are summarized in Table 1c.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closer dimensional tolerance control, very thin walls, repeatable in high volume production. Set-up costs are low for high or low volume production.</td>
<td>Sharp transition in diameter are difficult to produce using cold-drawn tubes.</td>
</tr>
<tr>
<td>No expensive machining, such as cutting a part from bar stock. Parts that would otherwise require several machining operations can be cold drawn as a single piece of tubing which can be easily shaped to create more complex parts.</td>
<td>Tube drawing is not the fastest way to produce prototypes in very small (3 or 4) quantities.</td>
</tr>
<tr>
<td>A cold drawn part can be bent, flared, dimpled, end-formed, flattened, beaded, groove-rolled, expanded, reduced or otherwise modified.</td>
<td>Cold drawing is limited to metals that flow plastically at room temperature. Metals such as Tungsten and Titanium are difficult, if not impossible to draw at room temperature.</td>
</tr>
<tr>
<td>Cold-drawn tubes offer significant improvements in strength-to-weight ratio and finish than could be achieved by most processes taken separately.</td>
<td>The finish on drawn tubes is usually limited by the finish of the die. Drawn tubes that are used in precision applications are usually machined to obtain better surface finish.</td>
</tr>
</tbody>
</table>

Table 1c: Advantages and Disadvantages of Cold-Drawn Tubes

---

1.4.2 *What does lowering N and increasing P mean to tube drawing?*

Lowering N, the number of processing steps in the drawing operation is one way of directly affecting S, the yield of the drawing process. This requires reducing the number of iterations through a process (i.e. number of draws) and eliminating non-value added operations. Increasing P, means increasing the process yield of the draw bench. Increasing P involves minimizing variability at a particular operation. This involves using the same operator, the same tools and trying to find the optimum setting at each machine.

1.5 *What direction is the Tube Drawing Industry taking?*

The two product variables that have traditionally defined the operating region for tube drawing are the outside diameter (OD) and the wall thickness (wall). This operating region defines the range of OD and wall combinations that can be made. The trend in tube drawing today is toward thinner tubes, with minimum reduction in the strength-to-weight ratio [Pederson, 1991]. *Figure 1c* compares the minimum wall thicknesses for 1990 and 1991.

Thinner tubes require starting with extruded tubes (blooms) that have smaller wall-to-OD ratios and/or additional steps in the drawing process. The extrusion process has a lower limit on the wall-to-OD ratios that can be produced. This limit is usually larger than the lower limits seen in *Figure 1c*. The greater this difference between the extrusion process and the tube drawing process, the larger is the required cross sectional area reduction in the drawing process. As the cross sectional area reduction increases, more draws are necessary to maintain surface quality. Doing a single draw would be the ideal situation, but if the overall percent cross sectional area reduction is say 80%, then one draw is almost impossible. Multiple draws are therefore used because the forces
associated with making extremely large reductions would damage the tubes. The production of thinner tubes is therefore forcing many manufacturers to either invest in extrusion presses that can produce tubes with thinner walls or add drawing processing steps to their flow path.

**Figure 1c: Comparison of the minimum wall sizes made in 1990 and 1991**

![Graph showing the comparison of wall thickness and outside diameter for 1990 and 1991 data.]

The trend towards thinner tubes also has important quality implications. One of the most important quality characteristics of drawn tubes is surface finish. Most manufacturers will only ship products with surface defects limited to a depth of ten percent of the wall thickness.

---

4 The data for Figure 1c was derived from product sheets obtained by the author from the sales department of four manufacturers of cold drawn aluminum tubes and is by no means exhaustive.
As the walls become thinner, the allowable depth of defects is becoming increasingly difficult to maintain. Coupled with the additional handling required for thinner tubes (because N increases), quality requirements are becoming more and more difficult to achieve and consistently maintain [Pederson, 1991]. The consistent use of process improvement tools is one way to address this challenge and will be discussed further in this thesis.
2.0 Problem Identification

Given the fact that the tube drawing industry is faced with increasingly difficult quality requirements, we expect some manufacturers to have problems producing tubes with these higher quality requirements. Thinner tubes tend to have lower yields (see Table 2b). More starting stock must be used in order to compensate for the lower yields. More tubes on the floor of the mill, causes congestion and scheduling problems. This congestion of the mill, increases the lead time and ultimately makes the mill less competitive.

Drawn tubes are current manufactured in batches. It is clear that yields, as well as the planning of the batches, dictates how well the tube mill performs. These batches (called lots) are sometimes grouped (by dimensions, alloy and thermal practice) to take advantage of the economies of scale. Lots are planned to compensate for “point” and “tail” scrap. This so-called inherent process scrap is predictable. This study will focus mostly on the unplanned or unanticipated scrap. For a full discussion of planning and scrap, see section A.D of the Appendix. To get an understanding of the problems currently facing some manufacturers, production data for a two month period was collected at a tube drawing facility (a tube mill). Data from all of the lots (179 lots) that fell short of the customer’s requested amounts (usually expressed in pounds) were collected. This data set is called “short” and lots in this data set are called “short” lots. Data set "short” represents approximately 20% of all lots that went through the plant within the two month period. A similar size sample (179 lots) was taken (for comparison) from lots that fulfilled the customer’s requested amount. This data set is called “non-
short” and lots in this data set are called “non-short” lots. Both data sets have been modified for proprietary reasons.

The short and non-short data sets were compared using several attributes. The attributes chosen gives some insight into the process yield, the lead times and the product mix. These attributes along with a discussion on their significance are listed in Table 1a. With slight modifications these attributes can be applied to almost any manufacturing industry.
Table 2a: Attributes and their Significance

<table>
<thead>
<tr>
<th>Attributes of each production lot</th>
<th>Significance of the attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of days spent in the tube mill</td>
<td>Gives an indication of the lead time.</td>
</tr>
<tr>
<td>Number of days past the promised date</td>
<td>Gives an indication of how well we are satisfying the customers.</td>
</tr>
<tr>
<td>Number of draws.</td>
<td>Large number of draws signifies more processing steps (draws, handling, anneals) and hence more cost.</td>
</tr>
<tr>
<td>Number of feet ordered</td>
<td>Gives some perspective on the lot sizes.</td>
</tr>
<tr>
<td>Number of pieces per lot</td>
<td>Gives some perspective on the lot sizes.</td>
</tr>
<tr>
<td>Yield 5</td>
<td>Self evident.</td>
</tr>
<tr>
<td>Percent cross sectional area reduction</td>
<td>Large cross sectional area reduction requires multiple draws. More draws...more cost.</td>
</tr>
<tr>
<td>Pounds ordered</td>
<td>Gives some perspective on the lot sizes.</td>
</tr>
<tr>
<td>Percent short of total number of pounds ordered</td>
<td>How much are we throwing away.</td>
</tr>
<tr>
<td>Percent over the total number of pounds ordered</td>
<td>How much unnecessary tubes are we producing.</td>
</tr>
<tr>
<td>Wall (inch)</td>
<td>Tells us what products we are having trouble with.</td>
</tr>
<tr>
<td>Outside Diameter (inch)</td>
<td>Tells us what products we are having trouble with.</td>
</tr>
<tr>
<td>(wall/OD)*100</td>
<td>Tells us what products we are having trouble with.</td>
</tr>
</tbody>
</table>

Table 2b lists these attributes, their averages, as well as their standard deviations. The data sets are also compared graphically in the Section A.A of the Appendix. The comparison of the data sets, yields the following observations:

- On average short lots spend 40% more time (11.39 days) in the Tube Mill than non-short lots.

5 Most of the pieces scrapped are done so at inspection.
Table 2b: Comparison of Short and Non-Short data sets

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Lots short of customer requested amount (lbs): 179 lots from a total of 180</th>
<th>Lots fulfilling the customer requested amount (lbs): 179 lots from total of 1000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average (per lot)</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>Number of days spent in the tube mill</td>
<td>40.1</td>
<td>23.5</td>
</tr>
<tr>
<td>Number of days past the promised date</td>
<td>34.2</td>
<td>40.4</td>
</tr>
<tr>
<td>Number of draws</td>
<td>3.6</td>
<td>1.7</td>
</tr>
<tr>
<td>Number of feet ordered</td>
<td>2764</td>
<td>2419</td>
</tr>
<tr>
<td>Number of pieces per lot</td>
<td>257.1</td>
<td>856.6</td>
</tr>
<tr>
<td>Yield</td>
<td>40.5</td>
<td>28.8</td>
</tr>
<tr>
<td>Percent cross sectional area reduction</td>
<td>74.6</td>
<td>17.6</td>
</tr>
<tr>
<td>Lbs ordered</td>
<td>1026</td>
<td>815</td>
</tr>
<tr>
<td>Percent short (lbs)</td>
<td>40.1</td>
<td>35.5</td>
</tr>
<tr>
<td>Percent overage (lbs)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Wall (inch)</td>
<td>0.089</td>
<td>0.083</td>
</tr>
<tr>
<td>Outside Diameter (inch)</td>
<td>2.76</td>
<td>1.89</td>
</tr>
<tr>
<td>(wall/OD)*100</td>
<td>3.2</td>
<td>1.89</td>
</tr>
</tbody>
</table>

- Short lots have 21% more draws (iterations) than non-short lots.

- Non-short lots have 41.79% better yields than short lots.

- The average wall-to-outside diameter (OD) ratio [(wall/OD)*100] for short lots is 3.18, much less than the 5.581 for non-short lots.

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6 The values in this table are disguised for proprietary reasons. The values were obtained by eliminating outliers from the data sets. Figures A.9 through A.16 plot the full data sets. The outliers eliminated are those values that are outside the box plots.

7 These attributes are for the original short lots; the data list here does not take into account the replenishment lot.

8 Most of the pieces scrapped are done so at inspection.
2.1 The Impact of Short lots on the planning and processing of Non-Short lots.

In chapter 1 the changing requirements on drawn tube quality were discussed. The data collected indicates that short lots have lower yields and tend to have thinner walls. Short lots by definition are as a result of variability in process yield and/or poor planning. Figure 2a shows the planning process and the direct impact short lots have on the planning of non-short lots.

Defects within the tubes could have developed anywhere along the flow path since the information used in this study was collected after the lots went through inspection. Table 2b (as well Figures A.9 through A.16 in section A.A of the Appendix) highlights the major differences between short and non-short lots.

Shorts lots tend to spend longer times in the tube mill, have more processing done to them (more draws, anneals, cleaning and handling), are larger (feet, lbs & pieces), have lower yields, greater cross sectional area reduction and smaller wall-to-OD ratio than do non-short lots. Differences in processing path and product requirements might be responsible for the differences in attributes between short and non-short lots. However, variations also shows up within the non-short lots. There is a 20% overage for non-short lots. This is significant because we are making 20% more tubes per non-short lot than is necessary. This indicates that the process is not in statistical control, even when non-short lots are being produced, and/or the planning is being done inefficiently.
Figure 2a: Planning Flow Diagram for Drawn Tubes

1. Customer inquiry
2. Sales rep. quotes price & lead time
   - Are prices & lead time ok?
     - Yes → Input order into computer
     - No → Possible renegotiation
3. Print all orders from previous day
4. Is the order for drawn tube?
   - Yes → Orders sent to the planner
   - No → Planning of extruded tube lot tickets
5. Shortage and scrapped orders
6. Lots tickets are planned based on due date and customer priority
7. Is the bloom available?
   - Yes → Is this a shortage lot?
     - Yes → Review of tickets by tube mill staff w/ the planner
     - No → Wait
   - No → Planning of "bloom" lot
8. Stock clerk matches bloom w/ ticket → Metal is released onto the floor
9. Wait
The results of Table 2b are important to the discussion on process yields and reducing the number of processing steps (section 1.1). Short lots have more process steps than do non-short lots and as a result we would expect them to have lower yields. The difference in the number of processing step is directly related to the total cross sectional area reduction (which is usually large for “thin wall” tubes). The larger the cross sectional area reduction becomes, the more draws are needed. This increase in the number of draws, increases the number of times the tubes are cleaned, annealed and handled. It is important to note that increasing the cross sectional area reduction affects more than just the number of draws, since handling and possibly more anneals are necessary. As a results the increase in the total number of processing steps is magnified much more than just the increase in the number of draws.

On average the standard deviation for the attributes associated with the short lots are larger than those associated non-short lots. Part of reason the large variations in the standard deviations of the short lots might be due to complete lots being scrapped for bad starting stock or failure to meet ASTM requirements. When this happens the data set is heavily skewed.

2.1.1 Who cares if there is variation in the process!?

If we assume that within the two month period for which the data was collected there are 10 weeks and within each week there are 1,000 equipment hours per week (multiple draw benches), then we have a total of 10,000 equipment hours over the two month period. Equipment hours per week is defined (on the slowest process in the flow path; in this case the heat treat ovens) as the maximum number of hours that the equipment

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9 Count over-time hours as an extra two weeks.
can be up and running. Considering that 20% of all lots end-up short (assume 200 lots, the number in data set "short" is 179) over this two month, we can make the gross assumption that these lots accounts for 20% of the total equipment time (10,000*0.2 = 2000 equipment hrs). Since short lots have average yields of 40%, the total time wasted on short lots is 1200 (0.6*2000) equipment hrs. The actual percentage is larger than 20% because short lots have more processing steps. If an equipment hour cost the company $15 ($14/hr for labor and $1/hr for "wear and tear" on the equipment ), then the company is losing $18,000 ($15*1200) over this two month period. This works out to $108,000 per annum. This estimate does not account for the cost of lost customers, the materials cost of making blooms and scrapping tubes, or the opportunity cost of re-making the lots.

If we start with the assumption that the plant is operating at 90% of its maximum capacity, and there are no lots in back-log, then we will see that the short lots affect the overall lead time of the products in the next time period (see the planning flow chart, Figure 2a). Assume that the lead times are purely a function of the time the lots spends in the tube mill. Short lots are usually given first priority in the production queue. Since 20% of all lots (200 lots during a 2 month period) end up short and since there is only 10% excess capacity (1000 equipment hrs) in the tube mill, then lots in the next two month period would see an average delay of 1000 equipment hours; thus producing a backlog. This is a gross approximation, but one can see that if demand stays constant and the maximum available capacity is fixed, then the average time waiting in the production queue prior to entering the flow path increases with each time period. The lead time that customers are quoted must now be increased. No longer is this lead time solely a function of the time the lot spends on the floor, but it is also a function of the number of lots in the back log.

The focus on quality and quality partners in industry today demands that tube manufacturer produces tubes of consistent quality at minimum cost. The discussion above
illustrates some of the implications of scrapping tubes. The next chapter will begin an investigation in the cause of some the reasons for scrapping tubes.
The two methods for increasing process capability levels are reducing variables which tend to widen process width and increasing the specification width through product design.

-Robert E. Stein

CHAPTER 3

3.0 Using Experiments to understand the problems

Understanding the variables that affect a manufacturing process is the first step in addressing quality problems. Stabilizing these process variables directly affects the process yield. If relationships can be drawn between process variables and yield, then the possibility of decreasing the number of processing steps becomes easier.

An analysis of the data collected for a two month period in 1990, indicates that most of the defects seen in drawn tubes were due to handling (scratches, torn OD and dents) and cracks (combined)\textsuperscript{10}. Since lots with more processing steps are handled more often they are therefore prone to having lower yields. Reducing the number of processing steps that the tubes go through increases the probability of having higher yields. Therefore we chose to pose the question: Can a reduction in the number of processing steps be accomplished without significantly affecting some other measure of productivity and quality?

As mentioned in chapter 2 most of the differences between short and non-short lots is tied directly to the percent cross sectional area reduction and hence the number of draws. To answer the questions posed above let us look at the variables that are associated with the draw bench. If we assume that the size of the starting stock (bloom)

\textsuperscript{10} "Pits" were shown on a Pareto analysis to be the largest single cause for rejecting tubes. I chose not to address this cause because several types of defects were being grouped and labeled "pits".
for a particular finished size is fixed, then the total reduction in cross-sectional area is also fixed. Variations can enter the process through the following variables:

- Cross sectional area (csa) reduction per draw: Ideally we would like this to be as low as possible. Increasing csa reduction increases the force needed to pull the tubes. As mentioned in chapter 1, increasing the pull force affects the stress state at the surface of the tube, which in turn affects the surface quality (yield).

- Cross sectional area reduction prior to anneal: As the cross sectional area reduction before anneal increases, the hardness of the tubes increases. This makes the tubes less ductile and hence harder (more force) to draw. This decrease in ductility affects the yield in a manner similar to that mentioned above for csa reduction per draw.

- Die geometry (angle, blend radius & bearing length): These variables partially determines the contact area between the tube and the die. Small angles and blend radii are usually associated with larger contact area, hence increased pulled force. The same is true for large bearing length.

- Outside diameter (OD) reduction versus wall reduction: Pure OD reduction requires more cold work on the outside surface than on the inside surface of the tube. Since the outside surface quality is the most important aspect of drawn tubes, pure OD reduction reduces the chance of getting acceptable quality. Doing wall reduction distributes the cold work and hence the stresses more evenly across the tube.

- Repair: This is a processing step that was introduced to remove blemishes from the blooms. Most of the blemishes seen in the
blooms were due to handling and storage. Removing this step from the flow path would not only reduce the number of processing steps, but also force the operations prior to repair to handle and store the blooms more carefully.

- Lubrication (type and practice): The additives in the lubricants helps to determine the coefficient of friction between the tube and the tools. The additives also dictate how long the lubricant will maintain its initial viscosity. Operators generally run the oil pump on all draws in a lot except the last.

- Environmental conditions (room temperature & humidity): These effects are not clearly understood, but four operators have indicated that on humid days, the drawing process becomes more difficult (i.e. tubes break, tolerances are harder to keep). At low temperatures (40° F or less) the lubricant becomes extremely viscous and flows slowly. This slow down in flow, creates “dry spots” (areas void of lubricant) on the tubes. This causes the surface of the tubes to tear.

- Draw bench setting (alignment, draw speed): The alignment of the draw-bench determine how straight the tubes are when they exit the dies. Tubes that are drawn on mis-aligned benches tend be eccentric.

- Bloom quality: Here we are talking about blemishes, and eccentricity. There is no real metric for this variable. It is usually a judgment call on the operators part.

- Time out of anneal (air quench): Tubes that are left in inventory after leaving the anneal oven, will age harden and become harder to draw.
- Annealing conditions (time, temperature & quench rates): These factors determine the extent to which the residual stresses in the tubes are reduced.

- Die/Mandrel set-up: The position of the mandrel affects the contact surface on the inside of the tube. This a variable that the operator has control over.

The variables listed above can be categorized into three basic groups:

1) Variables that are determined (in planning) prior to the release of the lot onto the floor. These are cross sectional area reduction per iteration, cross sectional area reduction prior to anneal, outside diameter reduction versus wall reduction, and repair.

2) Variables that are controlled by the production supervisor and/or the draw bench operator. These are die geometry and die/mandrel settings.

3) Variables that are (at present) not controlled by either planning, the production supervisor or the operator. These include room temperature, humidity, lubricant and temperature of the metal.

Two experiments were performed to address the issue of reducing the number of draws by altering some of these variables. The factors used in the first experiment were the variables controlled by planning, while the second experiment used those controlled by the production supervisor and/or the operator. These experiments were meant to be used as a foundation for future experiments. Doing process improvement is an iterative process and as such these experiments are the first step in that iteration. Because of this not all the variables mentioned above were used.
Each experiment had three factors and each factor had two levels. Although this type of experiment may not be the most efficient (number of treatments per experiment), it does provide more reliability when interactions are thought to be important.\textsuperscript{11}

3.1 Experiment #1: Planning controlled variables

Eight lots (each with approximately 30 pieces) of 4.0" x 0.028" (finished size) were used in the experiment. Each lot was split into two racks; each rack being considered as a separate run (treatment).\textsuperscript{12}

The designed experiment was a $2^3$ (2 levels, 3 factors) factorial design. The three factors were:
- percent cross sectional area reduction per iteration (referred to as $x_1$)
- percent cross sectional area reduction prior to anneal ($x_2$)
- repair\textsuperscript{13} ($x_3$)

The first two factors were chosen because they varied considerably from lot-to-lot. Repair was chosen because it was considered a non-value added process. The levels used for each factor are listed in Table 3a.

\textsuperscript{11}For a complete discussion on design experiments see Handbook of Quality by Juran.

\textsuperscript{12}I could have treated each lot as a run, but the level of significance calculations would be trivial, because of lack of repeatability.

\textsuperscript{13}Repair refers to the grinding of the entire surface of the tubes with a ‘flap-wheel’. The grinding wheel rotates and the tube moves axially under the wheel. The force of contact between the tube and the wheel is controlled by the operator.
Table 3a: Factors and factor levels used in experiment #1

<table>
<thead>
<tr>
<th>FACTORS</th>
<th>HIGH LEVEL (+)</th>
<th>LOW LEVEL (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>% reduction per draw (x1)</td>
<td>x1(high)</td>
<td>x1(low)</td>
</tr>
<tr>
<td>% reduction prior to anneal (x2)</td>
<td>x2(high)</td>
<td>x2(low)</td>
</tr>
<tr>
<td>Repair (x3)</td>
<td>Repaired</td>
<td>Not Repaired</td>
</tr>
</tbody>
</table>

The tubes were all given the same processing and handling up to and including the pointing operation. Four of the eight lots were then repaired. The lots that were not repaired were covered with plastic and kept in inventory until the repairing was done. All eight lots were then sent to the draw bench. Once the required reduction in cross sectional area before annealing for each rack was achieved, the racks were sent to the dip tanks. Racks that were dipped first were placed in inventory before being annealed so that all eight lots could be annealed together. After annealing the tubes were returned to the draw bench. This 'draw-anneal-draw' iteration continued until the final dimensions were obtained. A total of six draws (5 draws for lots with high csa reduction per draw) was given to each lot. Once the final dimensions (4.0" x 0.028") were obtained, the processing (thereafter) for all the lots was the same.

The primary output variable measured was "piecewise" yield\textsuperscript{14}. The experiment was performed on one draw-bench and on the same shift with the same operator. The bloom for these lots came from two extrusion lots\textsuperscript{15}. Die set-ups used the same angles, bearing length and blend radius. All lots had a fiber-glass strap inter-weaved between the tubes, so that the tubes were completely separated from each other. The lots went through the

\textsuperscript{14} For a complete discussion on the definition of yield see Section A.D of the Appendix.

\textsuperscript{15} It would have been better to use a single extrusion lot but extrusion fills a tube mill order first from inventory and the remainder is then extruded on a separate extrusion lot.
mill together in random order (i.e. if lot #1 went to anneal first, it was not the first to start the next operation). Table 3b summarizes the experimental set-up and observations for each run (treatment).

Table 3b: Experimental set-up and observation

<table>
<thead>
<tr>
<th>Lot # &amp; size (# of pieces)</th>
<th>% Red. per Draw (x1)</th>
<th>% Red. before Anneal (x2)</th>
<th>Repair (x3)</th>
<th>% Piece-wise yield per rack(^{16})</th>
<th>Reasons for scrapping</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (45)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>44.6 78.7 Avg=61.6</td>
<td>Pits, Chip marks, Die-lines</td>
</tr>
<tr>
<td>2 (45)</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>70.8 68.8 Avg=69.8</td>
<td>Pits, Handling marks</td>
</tr>
<tr>
<td>3 (30)</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>80.8 76.9 Avg=78.8</td>
<td>Chip marks, Handling marks</td>
</tr>
<tr>
<td>4 (30)</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>81.5 88.8 Avg=85.15</td>
<td>Handling marks</td>
</tr>
<tr>
<td>5 (30)</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>67.9 82.1 Avg=75.0</td>
<td>Pits, Handling marks</td>
</tr>
<tr>
<td>6 (30)</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>69.2 84.6 Avg=76.9</td>
<td>Handling marks, Roller marks</td>
</tr>
<tr>
<td>7 (30)</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>70.3 48.2 Avg=59.25</td>
<td>Pits, Handling marks</td>
</tr>
<tr>
<td>8 (30)</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>71.4 92.8 Avg=82.1</td>
<td>Pits, handling marks</td>
</tr>
</tbody>
</table>

3.1.1 Known Sources of Variability for Experiment #1

- Two Extrusion Lots were used to make up the eight tube mill lots.
- Two of the tube mill lots did not have fiber-glass inter-weave when they came from extrusion.

\(^{16}\) This is my response variable, Y
• One tube mill rack came from extrusion in a rack with rivets sticking-up through the bottom of the rack. All the bloom on the bottom of the rack had markings from these rivets.
• Two heat treat ovens were used.
• Two tube mill lots (lots 1&2) had more pieces per lot than the rest of the lots.
• Lots with "large" csa reduction per draw had 5 draws. Lots with "small" csa reduction had 6 draws.

3.1.2 Calculations for Experiment #1

The main effect of a factor \((x_1, x_2 \& x_3)\) is the change in response produced by a change in the level of the factor. The response variable, \(Y\), which we are interested in is yield per rack. In some instances we find that the effect of one factor depends on the level of another factor. In this case we say there exist an interaction effect \((x_1x_2, x_1x_3, x_2x_3 \& x_1x_2x_3)\). An analysis of variance and a subsequent regression analysis are aimed at finding which effects are significant and what is the relationship between the effects and the response variable.

From the data listed in Table 3b an analysis of variance (ANOVA) was performed using the software Data Desk. The ANOVA table (Table A.B.1) is listed in section A.B of the Appendix. This type of table is found in most statistical packages and is a standard entry in most text books on statistics. The first column identifies the sources of variation. The second and third columns the corresponding sums of squares (SS)\(^{17}\) and degrees of freedom (df). See Data Desk manual, Vol. 2 for a complete discussion on the values listed in the tables.

\(^{17}\text{SS}_{\text{total}} = \text{SS}_{x_1} + \text{SS}_{x_2} + \text{SS}_{x_3} + \text{SS}_{x_1x_2} + \text{SS}_{x_1x_3} + \text{SS}_{x_2x_3} + \text{SS}_{x_1x_2x_3} + \text{SS}_{\text{Error}}\)
The most important numbers in Table A.B.1 are the F-ratios. The F-ratio are the appropriate statistics for testing the significance of main and interaction effects. The assumed null hypothesis is that no main or interaction effects are significant are far as yields are concern. To do this significance testing, the F-ratios calculated in the ANOVA table are compared to some critical value, $F(a; r1,r2)$, where $a$ is the significance level, $r1$ is the degrees of freedom for the effect being tested and $r2$ the degree of freedom for the Error treatment. For a 95% confidence level ($a=0.05$), the F statistics, $F(0.05; 1,14)$, taken from Table C.7 of *Engineering Statistics* by Hogg and Lodelter is 4.60. Any group (treatment) i.e. Table A.B.1 with F-ratio greater than 4.60 is significant with a 95% confidence level. From Table A.B.1 we see that only one factor is significant at this confidence level; the interaction ($x1x2$) between percent reduction per draw and percent reduction prior to anneal. This means there is strong evidence that this interaction cannot be explained as being the result of chance.

The linear regression analysis (also done in Data Desk) for the main and interaction effects is shown in Table A.B.2. The signs of the coefficients are important figures in this table. A positive (negative) coefficient means that increasing the effect increases (decreases) the yield. The “s.e. of Coeff” are the standard error of each coefficient and the “t-ratios” are used to test that the true coefficients have any specified value.

The $R^2$ (adjusted) of 31.7% means that this regression explains 31.7% of the variation in yield. Ideally, we would like $R^2$ to be 100%. This regression is significant because $F = 2.89 > F(0.05; 7,14) = 2.79$. Looking at the partial (individual) t-tests, and comparing the t-ratios with $t(0.05; 14) = 1.761$, we find that the important variables that affect yield are $x3$ (repair), $x1x2$ (interaction between percent CSA reduction per draw and percent CSA reduction prior to anneal). Repeating the regression with only the significant variables yields an $R^2$ value of 29.3%.

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To check the adequacy of the regression model, a plot of residuals versus the predicted values of yield is shown in Figure A.B.1. The differences between the predicted values of yield from the regression model and the observed values are known as residuals. In successful regression analyses, residuals are small relative to the predicted values. From Figure A.B.1 we see no clear patterns and relatively small residual values.

3.1.3 Discussion of Experiment #1

The interaction between percent reduction in cross sectional area per iteration (x1) and percent reduction in cross-sectional area prior to anneal (x2) appears to be the most significant effect in this experiment as far as the yields are concerned. This seems logical because high csa reduction per draw allows us to do fewer draws. Low values of csa reduction before anneal dictates an increase in the number of anneals. The increase in the number of anneals increases the potential for increased handling losses (the tubes have to be cleaned before being annealed). According to Table A.B.1, the coefficient of this interaction is negative. Further experimenting is necessary in order to predict the exact relationship between x1 and x2 and how this interaction affects the yield. If we can maximize the x1x2 interaction, without reducing the draw bench yield, the opportunity to reduce the number of processing steps could be significant.

Handling marks account for the most defects in this experiment. Most of these handling marks occurred during the transition from the draw bench to the anneal oven and then back the draw bench. Eliminating the need for this anneal would address the root cause. A short term solution is to maximize cross sectional area reduction prior to annealing. The long term solution involves better bloom selection, so that only one or two
draws are made in the entire process. This would eliminate completely the need for an intermediate anneal and would be in line with the initial objective of reducing the number of processing steps.

With high values of percent reduction per draw, the 'back-ends' of the tubes broke\textsuperscript{18}. The broken piece was often stuck in the die. This increases the chance of the die being damaged since the broken piece must be hammered out of the die.

Repair\textsuperscript{19} was a significant factor. It appears to help slightly. However, visual inspection of the finished tubes that were repaired suggests that this could be a misleading conclusion. The lots that were repaired have significantly more cracks on them than lots without repair. The cracks on the repaired lots were not deep enough to scrap the metal, but these cracks could potentially "open-up" if the tubes are stressed. The lots that were not repaired had surfaces that were aesthetically more appealing than the repaired lots. Eliminating repair not only reduces the number of operations in the process, but it forces the processes prior to the draw bench to be more efficient in terms of minimizing defects.

More than half of the total number of pieces scrapped were unusable because of handling marks: scratches, dents, etc. The variability introduced into the experiment, through the use of different racks, crane operators, heat treat oven & crews, positioning of the racks and rack lining, makes it difficult to judge the impact of handling on yield. This difference in handling was magnified in lot #1. This lot was placed below a rack that had tubes with stretcher oil on them. This stretcher oil creates a film on the surface of the tubes and does not allow the draw-bench oil to directly contact the surface of the tubes. This caused the surface of sixteen pieces of tube to be torn up. Stretcher oil was found on

\textsuperscript{18} According to the operators this was directly related to the eccentricity of the blooms.

\textsuperscript{19} Repair refers to the grinding of the entire surface of the tubes with a 'flap-wheel'. The grinding wheel rotates and the tube moves axially under the wheel. The force of contact between the tube and the wheel is controlled by the operator.
other lots, however the lot in run #1 was the most severe. If the pieces affected by the stretcher oil are remove from the calculation (this leaves 29 pieces in lot #1) there are no significant changes in the analysis. The changes observed were an increased (from 4.28 to 4.34) in the F-ratio associated with repair and an increase (from 0.52 to 1.1) in the F-ratio for the interaction of all three variables (x1x2x3). All the effects that were (were not) significant remained that way.

3.1.4 Conclusions from Experiment #1: What should be done next

- The interaction between percent reduction per draw and percent reduction prior to annealing is important to the process yield and as such provides the best opportunity for reducing the number of draws. Future experiments should use larger (smaller) values for the upper (lower) limits of these variables. The ideal experiment should test just these two variables and should not include any movement from the draw bench.

- Repair appears to improve process yields, but at the cost of surface appear and possibly tensile strength. It does not add any value to the process and such all attempts should be made to eliminate this processing step.

- Future experiments must involve more planning in the earlier stages, so that more people are made aware of what the experiments' purpose. The extrusion department should also be made aware of similar experiments that will be attempted in the future.
3.2 Experiment #2: Production supervisor and/or operator controlled variables

From a production point of view, the idea of reducing the number of operations by making larger cross sectional area reductions per draw and larger cross sectional area reductions before anneal seems very appealing. Doing this means we can reduce the number of processing steps involved in drawing tubes. The implication of making larger reductions is that larger forces are required to pull the tubes and higher residual stress levels are experienced prior to annealing. One aspect of the drawing process that directly affects the forces and stresses the tubes experiences is the choice of tooling. Tooling variables are generally controlled by supervisors and operators.

As part of the process improvement study on tube drawing, another $2^3$ factorial experiment was performed using factors that the supervisors and operators controlled. The purpose of the experiment was to determine how these factors affect the force required to pull the tubes. Minimizing this force allows for larger cross sectional area reduction per draw and possibly larger cross sectional area reduction prior to annealing. The factors chosen were not all inclusive, but were used to illustrate how much variability could be introduced into the drawing process once the lots left the planning area. The following is a partial list of variables (obtained via a brainstorming session with several tube mill personnel) that are thought to affect the drawing process once the lot reaches the floor. The implications of these variables on the drawing process was already discussed for the first experiment.

- Die angle
- Blend Radius
- Bearing Length
- Draw Speed (usually fixed)
- Die Material (Steel versus Carbide)
- Back Die (Angle, Radius, Length, Material)
- Lubricant (usually the same from lot to lot)
- Mandrel Position

I chose to experiment with die angle, back die and mandrel position because these factors varied most frequently from lot to lot.

Table 3c: Factors and factor levels used in experiment 

<table>
<thead>
<tr>
<th>FACTOR</th>
<th>HIGH LEVEL (+)</th>
<th>LOW LEVEL (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Die angle (w1)</td>
<td>w1(high)</td>
<td>w1(low)</td>
</tr>
<tr>
<td>Back die (w2)</td>
<td>with</td>
<td>without</td>
</tr>
<tr>
<td>Mandrel position (w3)</td>
<td>extending 1&quot; beyond the die exit</td>
<td>even with the die exit</td>
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</tbody>
</table>

The experiment used a single lot (with four iterations at the draw bench) containing 32 pieces of non-repaired bloom. The finished size for this lot was 3.00" x 0.022". Four tubes were used for each of the treatments. The percent cross sectional area reduction per draw was the same for all four draws. All the tubes had the same cross sectional area reduction before being annealed. The tubes were randomly selected from draw to draw. This was done so that each draw could be used as an independent experiment. This minimizes the total number of runs that must be done in order for the experiment to have any statistical significance. One problem with this approach is that starting stock for each draw is a slightly different size, which might account for some of the variation that was seen in the dependent (response) variable.

The tubes were given the same processing and handling prior to arriving at the draw bench. At the bench the tooling was selected according Table 3c. Four tubes were
drawn and the maximum (peak) value of the current measured\textsuperscript{20}. The tooling was then changed for the next run and four more tubes drawn. This continued until the eight runs were completed. The lot was then sent to the dip tank and then to the anneal oven. Upon leaving the anneal oven the tubes were then returned to the draw bench where the draw sequence was repeated. This 'draw-anneal-draw' sequence continued until the final dimensions were obtained. The lot was then sent to the finishing area.

This experiment was not meant to measure absolute forces, but to illustrate how tooling variables and their interactions affected the pull force. The current passing through the motor of the draw bench is proportional to the pull force and was used as the dependent variable. The maximum value of the current (in Amperes) required for each draw was measured. These are the values listed in Table 3d. To run the carriage without any load (no tubes) required 80Amperes. This value is already subtracted from the values listed in Table 3d. The table also lists the three factors and the level at which each was used.

\textsuperscript{20}The pulling of a tube consumes a certain amount of power, P; where P=Force x Distance x Time. This power must be equal to the power of the motor plus efficiency losses. If we assume the efficiency losses are constant from draw to draw, the power of the motor is given by Voltage x Current. Since the draw bench operates at constant speed and constant voltage, the current must be proportional to the pull force.
<table>
<thead>
<tr>
<th>Run no.</th>
<th>Die Angle (w1)</th>
<th>Back Die (w2)</th>
<th>Mandrel Position (w3)</th>
<th>1st Draw current (A)</th>
<th>2nd Draw current (A)</th>
<th>3rd Draw current (^{21}) (A)</th>
<th>4th Draw current (A)</th>
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<td>1</td>
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<td>+ (With)</td>
<td>+ (1 inch beyond die exit)</td>
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<td>450</td>
<td>399</td>
<td>441</td>
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<td>8</td>
<td>- (low)</td>
<td>- (w/out)</td>
<td>- (Even with the die exit)</td>
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<td>478</td>
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<td>Avg=403.5</td>
<td>Avg=441.5</td>
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</table>

\(^{21}\) Cell with less than four values are those runs where the tubes broke.
3.2.1 Known Sources of Variability for Experiment #2

- Two different operators had to be used because of scheduling issues.

- Variations in die sizes were present because of the way the die made and repaired. If dies are ordered for a finished size of 3.550", the die shop is allowed to give the operators dies of sizes between 3.540" and 3.560". This is because dies are not kept in specific sizes; the sizes present are merely a function of how much polishing was done to the dies the last time they were used.

- Eccentric bloom.

- There is a chain on the draw bench that pull a hook on the "head" of the bench. The initial force and hence the current is dependent on the speed that the chain is moving at when the hook is engaged.

3.2.2 Calculations for Experiment #2

Using the same analytic techniques mentioned in experiment #1, the F-ratios for the main and interaction effects were calculated using the actual draw currents in Table 3d. The results are listed in Table A.C.1.

Comparing these F-ratios with \( F(0.05;1,23) = 4.28 \), (taken from Table C.7 of Engineering Statistics by Hogg and Lodelter) we see that none of the effects are significant at this confidence level. It is important to note however, that Table A.C.1 was calculated with two outliers in the raw data. These two data point were measured on the second draw (Table 3d; column 6). The first outliers was 450A and is the first
measurement taken during the second draw. The second outlier, 501A, was recorded on the first tube in run number four during the second draw. A box plot of the data shows that these two values were (considerably) above the upper limits. Repeating the calculation without outliers brings the F-ratio for w2 (back-die) very close to 4.28. There is also a 5% chance that w2 could be greater than or equal to the value (4.05) given in Table A.C.1.

A linear regression analysis of this data provided an R² (adjusted) value of 19.2%. This means only 19.2% of the variability in the draw current can be accounted for by the factors (and their interactions) used in this experiment. This is a low R² value and indicates that the regression model does not accurately predict the draw currents as a function of the variables used in the experiment.

The plot of residuals versus the predicted draw currents is shown in Figure A.C.1. This figure shows that the residuals are large and appears to form a linear cluster. This means that the proposed model has a very large error term and some other factor(s) introduced variability into the measured draw currents. It could also mean that a simple linear model, such as the one use by Data Desk, does not adequately represent reality. More importantly it shows that there is an increase (almost linearly from -60 to 60) in the residuals as the draw current is increased. If a relationship exists between the residuals and the predicted values of the draw current, the treatments were not taken randomly.

3.2.3 Discussion for Experiment #2

The experiment gives no clear indication as to the importance of the factors chosen. It does however indicate that the order in which the data was collected is important. The
idea of mixing the tubes from draw to draw and then randomly selecting them was probably not a good idea.

From the calculations above, it would appear that the interactions might not be important factors since the F-ratio associated with the are so low. The main effect of the variables might be the important factors. We would expect the force to be reduced when the back die was not being used, because there is less surface contact with the tube. We would also expect to have lower forces with the large die angle, since the wider opening allows the tube to proceed farther into the die-opening before touching the wall of the die. According to the numbers from the calculation (Table A.C.1), the large angle [w1(high)] die actually works to increase the pull force. When the 10° dies are used the tube tend to ‘wobble’. This ‘wobbling’ is more pronounced when back dies are absent and might be the reason the pull force appear to be higher for the large angle dies.

From the calculation it is obvious that the amount of variability in the data does not allow us to draw conclusions with regard to the variables used in the experiment. The remainder of the discussion will deal with experienced-based conclusion and inferences. From discussions with operators and supervisors, it seems like back dies tend to stabilize the drawing process. This stabilizing effect is more pronounced with eccentric and bent tubes. Tubes tend to bend when they are very long and as such might require back-dies.

If the back dies can be removed completely from the drawing process, there seems to be some indication that the pull force could be lowered. Assuming the starting stocks (blooms) are pointed and are of a high quality, then the draw-benches becomes the first (and probably the most) crucial step in processing drawn tubes. An integral part of any draw-bench is the die set-up. The bulbs and dies are the parts of the manufacturing process that impart the most deformation to the tubes and, as such, determine how much stress the tubes experience. These issues will be discussed further in chapter 4. The
level of stress at or near the surface of a tube directly affects the surface profile of the tube (Dieter: *Mechanical Metallurgy*). Minimizing the stress levels in the tubes allows for larger cross sectional area reduction per iteration and possibly larger cross sectional area reduction before anneal. This is just one step toward reducing the number of steps that are observed in drawn tubes.

### 3.2.4 Conclusions from Experiment #2: What to do next

- Based on observations and discussions with operators, eccentric bloom creates a need for the use of back dies. However, this adds to the amount of die that have to be polished each day. Steps should therefore be taken to reduce the use of back die by processing shorter lengths of tubes and using less eccentric bloom. This will require working with the extrusion department.

- Future experiments involving tooling should avoid mixing the tubes from draw to draw. The tubes from one particular set-up should be marked and used for a similar set-up on the following draws. This allows the experimenter to trace the deformation history of each tube.

- The position of the mandrel in the die appears to be insignificant. This collaborates what most operators have been saying to us from the start of the experiment. The finite element model in chapter 4 will look at this issue in greater detail.

- Better measurement techniques must be used next time. Measuring the draw current does not adequate reflect the draw force. This is because there are losses associated with the motor and the other moving parts. The transitions that are introduced into the measured currents, such as those introduced when the chain engages the hook, makes
it difficult to use the peak values. Strain gauges attached to the die would probably result in "cleaner" data.

3.3 Other issues

There are still some questions left unanswered about the use of these factors in the drawing process. Currently back dies are used on all products for almost all draws. If the tubes can be kept straight with uniform dimensions are back dies necessary? The interaction of the back die and the die angle needs further investigation also. Is there an optimum die angle/back die combination for a certain size tube?
Quality control refers to the actions taken throughout the engineering and manufacturing of a product to prevent and detect product deficiencies and product safety hazards.

-George Dieter

CHAPTER 4

4.0 Using Finite Element Analysis (FEA) to model the Drawing Process

Process Improvement is an iterative effort, requiring constant monitoring and updating. If experiments are being used to make strategic decisions, the experiments must be repeatable. Repeatability becomes increasingly difficult when cost, time, and resources (man-power, equipment) are limiting factors. The experiments discussed in chapter 3, were performed on current production lines. This is both costly and time consuming; the experiments were scheduled when there was a gap in the production schedule. This created planning problems, since operators were not always available when the equipment became available. One way to alleviate some of the problems associated with process improvement efforts, particularly experiments, is to develop process models [Dieter, 1983].

Process modeling provides an easy way to perform what-if type analyses without interrupting production. It allows the investigator to be creative without having mistakes become a detriment to the production line. Having gone through the difficulties associated with planning and performing two designed experiments, it is obvious that a model of the drawing process would have provided some direction in the early stages of the experiments. Like process improvement, modeling is an iterative process. We start with a problem that is roughly defined, then we refine it and arrive at some optimal solution. Modeling, like most processes, does not provide the user with the "best" solution, but
rather, the user has to make trade-offs, based on what inputs to the model are most important to that user.

The 'predictive' model developed for the drawing process allows the user to change the following production and planning controlled parameters:

- The blend radius.
- The dimensions of the tooling.
- The stress-strain curve for the tube being drawn\textsuperscript{22}.
- The coefficient of friction between the tools (die and mandrel) and the tube.
- The die angle.
- The bearing length
- Percent cross sectional area reduction per draw.

Simulating the drawing process allows engineers and production supervisors to determine what product-process combinations they might have problems with. This can be done prior to the production of these potentially troublesome combinations and is therefore less costly and less disruptive.

The model can also be used in die design. Currently there is a lot of debate in the tube drawing industry concerning the optimum geometry of dies based on the dimensions and materials properties of the tube being drawn.

4.1 The FEA Model for Tube Drawing on ABAQUS

A two dimensional axisymmetric finite element model of the tube drawing process was created using ABAQUS. ABAQUS is an FEA code written in FORTRAN. The

\textsuperscript{22} Changes in these variables corresponds to changes in alloy of the tube being drawn.
input deck (input file) is shown in section A.E of the Appendix. Figure 4a shows the model before any deformation is done. The model’s axis of symmetry is about the z-axis (2-direction). The tube is being pulled in the positive 2-direction. The inside diameter of the tube is represented by the distance from the z-axis to the edge of the tube touching the mandrel.

Being a determinstic model, the choice of certain model parameters will affect the speed of convergence of the model as well as the reliability of the models output. The following parameters can be varied in the input deck:

- PTOL; The value of this parameter is the basic tolerance measure for the solution of the equilibrium equations at each increment. If PTOL is too large the solution will be of poor quality; if it is too small, excessive iterations will be needed.

- Stiffness-in-Stick; small values allow the model to converge quickly, but as mentioned above, at the expense of the model’s ability to mimic reality. This parameter is used with the FRICTION keycard. This stiffness is a “penalty” to simulate the fact that there should be no relative motion between the surfaces until slip occurs.

- Coefficient of friction.

- The element types (ISR21A versus IRS22A and CAX4 versus CAX4R).

4.2 The Details of the Model

There are 1000 (5 x 200) four node, bilinear interpolation, reduced integration, solid (continuum) stress/displacement (CAX4R) elements used to define the tube and 200

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23 The choice of parameters determines how well the model represents reality.
24 A 5 inch section of the tube was modeled.
axisymmetric, 3-node, rigid surface interface elements (IRS21A) for the interfaces associated with the die and mandrel respectively. The coefficient of friction between these interfaces was assumed to be 0.1. Isotropic hardening of the elements in the tube (CAX4R) was also assumed. The model assumes that the tube is homogenous and isotropic.

Static stress analysis was used to determine the stresses in the tube. The program used Newton's method to solve the equilibrium equations. Unsymmetric matrix storage was used in the calculations. This was done because of the non-linearities that are associated with the contact between the rigid surfaces (tools) and the tube\textsuperscript{25}. The tube was 'pulled' by tying the nodes at the (point) exit end of the tools together and then displacing them in the 2-direction in a specified time.

4.3 Testing the Model

The model was tested by pulling the point of the tube (shown in Figure 4b) one inch in the positive 2-direction. This was done in 10 time units and required 111 increments. The input deck for this simulation is shown in the section A.E of the Appendix. Contour plots were drawn for the last increment\textsuperscript{26}. These plots are shown in section A.F of the Appendix. The values are listed in English unit (psi for stresses and inch-per-inch for strains). The section shown in the plots represent approximately 0.3 inch of the tube in the die.

The plot of Mises stress indicates that the contours with the highest stress levels are in the draw zone of the die. This should come as no surprise to us since, most of the

\textsuperscript{25} For more details on the stress analysis procedures that ABAQUS uses, see ABAQUS User's Manual, pp. 2.2.1 - 2.2.2.

\textsuperscript{26} The contour plots are of normal stresses (S11, S22, S33), shear stress (S12), Mises yield stress, normal strains (E11, E22), shear strain (E12) and equivalent plastic strain (PEEQ).
deformation takes place there. What is interesting is the concentration (proximity) of the contours at the entrance and at the exit of the draw zone. This means the rate of change of stress at these two points is very fast, indicating that the portion of the tube on either side of the die is not being deformed significantly.

Large (in absolute values) values of compressive stress for the component, S11, confirms that this area is reduced. Our initial reaction prior to this analysis was that the component, S22, might be the most significant component since we are displacing the tube in the 2-direction.

The plot of equivalent plastic strain has contours that are decreasing as the tube leaves the die. This indicates that we are not at steady state. If we were at steady state we would expect to see contours that are increasing in magnitude.

We must keep in mind that this form of the model is a first cut at emulating the tube drawing process. It is meant to provide an easy way to see the effects of varying the parameters listed above. Ideally we would like to minimize the stresses at the OD surface of the tube, since this is the area that most defects are seen. Testing the various possibilities is now much easier than running experiments during production. The cost of using the model is very low, once ABAQUS is paid for. Now the model needs to be tested and refined and re-tested.

4.3.1 The effect of variation in Die Angle on the speed of the simulation.

As discussed in chapter 3, the size of the die angle chosen does have an impact on the surface quality of the tube. Small die angles contact the tube in more areas than large die angles. Hence we expect the draw forces for small die angles to be greater than those
for large die angles. **Figure 4a** and **4b** shows the undisplaced models of the drawing process as simulated in ABAQUS using small and large die angle respectively. Notice that the die angle are exaggerated here. **Figure 4a** shows the die with almost all of its inner area touching the tube. **Figure 4b** shows the die with just the bearing or the 'draw zone' in contact with the tube.

The input deck (file) for each model in **Figure 4a** and **4b** was the same, except for the change in draw angle. The input deck specified that ABAQUS displaced the point of the tube three inches, in 10 arbitrary units of time\(^{27}\). ABAQUS attempted to complete this task with the minimum number of increments. The speed at which an increment was completed was indicative of the number of iterations ABAQUS performed to complete that increment. The more iterations, the slower the convergence rate for that increment was. The speed of convergence was dependent on the amount of contact (and hence pull force) the tube underwent. **Figure 4c** compares the time it takes to simulate pulling the point of tube when small and large die angles were used. The figure shows that small die angle tend to use more increments for the same amount of cross sectional area reduction.

\(^{27}\) This means we simulate drawing at constant speed.
Figure 4a: Small Die Angle Simulation

DRAWING OF ALUMINUM TUBES WITH A MANDREL (MICHAEL DORAH 1992)
Figure 4b: Large Die Angle Simulation
It is important to note that even though small die angle required more effort to simulate in this example, in reality they do offer certain advantages. When extremely lengthy tubes are being drawn, small die angles tend to stabilize the tube as it passes through the die. Operators have indicated that this stabilizing force is essential especially for tube with thin walls.

There are trade-offs that must be made in terms of die angles. As the percent cross sectional area reduction increases, large die angles become more efficient. As indicated before, the length of the tube also determines what die angle should be used.

28 This simulation time indicates how much effort ABAQUS must put forth in order to complete a certain increment. This “effort” gives an indication of how much force is required to draw the tube.
4.4 Draw-backs to the Model

In chapter 3 the problems associated with drawing were discussed. In order to see these effects, a 3 dimensional model must be developed. The model in its current form assumes that the tube is uniform in all direction.

The coefficient of friction that is used for the interfaces between the tools and the tube has traditionally been a problem in most FEA problems involving contact. There are two common ways to model this friction: constant coefficient of friction (Coulomb friction) and constant shear. Obviously the choice of this parameter affects the resulting stress distribution in the tube.

In most metal working processes, the materials are neither homogenous or isotropic. This assumption becomes worse when the material is severely deformed.

4.5 Further Work

The model’s output in its current form is only as good as the quality of the input. Hence iterative verification is needed to improve the models accuracy. This can be done through the use of experiments and tests. It is important to keep in mind that operators’ knowledge of the process must not be ignored.

Developing a three dimensional model will come close to the realities of the drawing process. The eccentricity of the tubes were mentioned in the previous sections, but there are other issues that are not clearly understood. For example, what happens when the lubricant is applied to one half of the tube and not the other?
In its current form the model is not very user-friendly. A better interface with the user should therefore be developed. Once this is done, it would allow production supervisors to use to model. Since most of the manufacturing decision are made on the floor, this is where the model should ultimately be.
The framework presented here is by no means the only one that can be used for process improvement projects in tube drawing [Pitt, 1985]. The data collection and subsequent analyses did show however that planning of the improvement effort is crucial to its success. Ishikawa in his "Guide to Quality Control" indicates that the planning aspect of any process improvement effort might be the most crucial.

Throughout this thesis the iterative process was stressed. Increasing the size of the data sets and repeating the experiments is part of this iterative process. The information collected must now be refined; rather than saying what types of defects are present in the finished tube, we must determine where these defects are being formed. Once we know where they are being formed, the cause and hence potential solution should be studied. This is not a new process, but too organizations approach process improvement as an static process. Manufacturing organizations must realize that even when processes are ‘in control and capable’ there are still improvements to be made. Just like the model present in this thesis, refining and tweaking of any improvement effort must become a dynamic process.

The model presented in this thesis represents one of many ways that simulations can be used in process improvement. We must keep in mind though that the output of any model is only as good as the input. Iteration and constant tinkering with models and processes will provide manufacturers with significant benefits.

Although some of the methods used in this study require some degree of technical expertise, the operators of the process must ultimately be in charge of quality control. No amounts of data collection, statistical analyses or modeling will be successful if operators
are not involved in the process. The planning and ultimately the execution of the improvement effort must incorporate the various functions in the organization.
Section A.A

A graphical comparison of the short data set and the non-short data set is presented in this section. Figures A.1.1 through A.8.2 are histograms plots (and comparisons) of the attributes mentioned in Chapter 2. The reader must keep in mind that the x-axis of these plots are not always the same for each attribute.

Figures A.9 through A.16 are box-and-whisker plots of the same data sets. "In box and whisker plots we depict the three quartiles, together with the two extremes of the data. The box...encloses the interquartile range with the lower identifying the 25th percentile and the upper line the 75th percentile. The line sectioning the box displays the 50th percentile and its relative position to within the interquartile range. The whiskers at either end extend to the extreme values. In large data sets, where the sample size is 100 (as in the case of the short and non-short data sets), "the whiskers may extend only to 10th and 90th percentile instead of the extreme values" [Hogg & Ledolter, Engineering Statistics, p.36].
Figure A.1.1: Number of draws per lot for "Non-Short" lots

Figure A.1.2: Number of draws per lot for "Short" lots
Figure A.2.1: Percent cross sectional area reduction for "Non-Short" lots

Figure A.2.2: Percent cross sectional area reduction for "Short" lots
Figure A.3.1: Number of days spent in the plant\textsuperscript{29} for "Non-Short" lots

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1}
\end{figure}

Figure A.3.2: Number of days spent in the plant for "Short" lots

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2}
\end{figure}

\textsuperscript{29} Plant refers only to the Tube Mill.
Figure A.4.1: Number of days past customer requested date for “Non-Short lots”

Figure A.4.2: Number of days past customer requested date for “Short” lots
Figure A.5.1: Number of feet ordered for “Non-Short” lots

Figure A.5.2: Number of feet ordered for “Short” lots
Figure A.6.1: Number of pounds ordered for "Non-Short" lots

Figure A.6.2: Number of pounds ordered for "Short" lots
Figure A.7.1: Wall-to-Outside Diameter ratio for “Non-Short” lots

Figure A.7.2: Wall-to-Outside Diameter ratio for “Short” lots
Figure A.8.1: Percent over customer requested amount (lbs) for “Non-Short” lots

Figure A.8.2: Percent under customer requested amount (lbs) for “Short” lots
Figure A.9: Short and non-short comparison of the number of days elapsed beyond the planned date

Figure A.10: Short and Non-Short comparison of the number of feet per lot a customer orders
Figure A.11: Short and Non-short comparison of the number of days lots spent in the Tube Mill\textsuperscript{30}

Figure A.12: Short and Non-short comparison of the number of draws per lot

\textsuperscript{30} This includes the "idle" time the lots spends between processes.
Figure A.13: Short and Non-short comparison of the number of pounds customers order

Figure A.14: Short and Non-short comparison of the total percent cross sectional reduction per lot
Figure A.15: Short and Non-short comparison of the wall-to-OD ratio

Figure A.16: Short and Non-short comparison of yield
Section A.B.: Summary statistics and Regression analysis for Experiment #1

Table A.B.1: Summary statistics for the “yield per rack” data listed in Table 3b

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<tr>
<th>Analysis of Variance For</th>
<th>YIELD</th>
</tr>
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<tbody>
<tr>
<td>Source</td>
<td>df</td>
</tr>
<tr>
<td>x1</td>
<td>1</td>
</tr>
<tr>
<td>x2</td>
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<td>x1x2</td>
<td>1</td>
</tr>
<tr>
<td>x3</td>
<td>1</td>
</tr>
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<td>1</td>
</tr>
<tr>
<td>x2x3</td>
<td>1</td>
</tr>
<tr>
<td>x1x2x3</td>
<td>1</td>
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<tr>
<td>Error</td>
<td>14</td>
</tr>
<tr>
<td>Total</td>
<td>21</td>
</tr>
</tbody>
</table>

Table A.B.2: Regression analysis for the “yield per rack” data listed in Table 3b

Dependent variable is: YIELD
R² = 54.5%    R²(adjusted) = 31.7%
s = 7.030 with 22 - 8 = 14 degrees of freedom

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F-ratio</th>
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</thead>
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<td>Regression</td>
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<td>118</td>
<td>2.89</td>
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<tr>
<td>Residual</td>
<td>691.888</td>
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<td>49.4206</td>
<td></td>
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</tbody>
</table>

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<th>Coefficient</th>
<th>s.e. of Coeff</th>
<th>t-ratio</th>
</tr>
</thead>
<tbody>
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<td>49.5</td>
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<td>x1</td>
<td>-0.644792</td>
<td>1.522</td>
<td>-0.424</td>
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<tr>
<td>x2</td>
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<td>1.56</td>
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<tr>
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<td>3.14896</td>
<td>1.522</td>
<td>2.07</td>
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<td>1.522</td>
<td>-2.39</td>
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<tr>
<td>x1x3</td>
<td>1.65729</td>
<td>1.522</td>
<td>1.09</td>
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<tr>
<td>x2x3</td>
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<tr>
<td>x1x2x3</td>
<td>1.09479</td>
<td>1.522</td>
<td>0.719</td>
</tr>
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</table>

81
Figure A.B.1: Residuals versus Predicted Yields
**Section A.C.: Summary statistics and Regression analysis for Experiment #2**

**Table A.C.1: Summary statistics for the ‘draw currents’ listed in Table 3d**

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F-ratio</th>
<th>Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>w1</td>
<td>1</td>
<td>3984.81</td>
<td>3984.81</td>
<td>2.8810</td>
<td>0.1031</td>
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<tr>
<td>w2</td>
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<td>5596.92</td>
<td>5596.92</td>
<td>4.0466</td>
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<tr>
<td>w1w2</td>
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<td>3031.07</td>
<td>3031.07</td>
<td>2.1915</td>
<td>0.1523</td>
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<tr>
<td>w3</td>
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<td>4279.46</td>
<td>4279.46</td>
<td>3.0941</td>
<td>0.0919</td>
</tr>
<tr>
<td>w1w3</td>
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<td>69.2723</td>
<td>0.05008</td>
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<tr>
<td>w2w3</td>
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<td>2747.05</td>
<td>2747.05</td>
<td>1.9861</td>
<td>0.1721</td>
</tr>
<tr>
<td>w1w2w3</td>
<td>1</td>
<td>643.815</td>
<td>643.815</td>
<td>0.46548</td>
<td>0.5019</td>
</tr>
<tr>
<td>Error</td>
<td>23</td>
<td>31811.8</td>
<td>1383.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>30</td>
<td>51359.2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table A.C.2: Regression Analysis for ‘draw currents’ in Table 3d**

**Dependent variable is:** Draw current

$R^2 = 38.1\%$  \hspace{1cm} $R^2(\text{adjusted}) = 19.2\%$

$s = 37.19$ with 31 - 8 = 23 degrees of freedom

<table>
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<th>Mean Square</th>
<th>F-ratio</th>
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</thead>
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<tr>
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<td>31811.8</td>
<td>23</td>
<td>1383.12</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>s.e. of Coeff</th>
<th>t-ratio</th>
</tr>
</thead>
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<td>w1w2</td>
<td>10.2075</td>
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<td>1.48</td>
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<tr>
<td>w1w3</td>
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<td>0.224</td>
</tr>
<tr>
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<tr>
<td>w1w2w3</td>
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<td>6.895</td>
<td>-0.682</td>
</tr>
</tbody>
</table>
Figure A.C.1: Residuals versus Predicted Draw Currents
Section A.D: Yield

Currently yield is measured on a per pound basis in many tube drawing facilities. It is defined as the number of pounds packed as a percentage of the number of pounds started (total bloom weight). Consider the following example:

Finished size = 3.999" x 0.028"
Finished length = 10.5ft
Weight/Foot = 0.411lb
Bloom size = 5.000" x 0.125"
Bloom weight = 17.5lbs
Maximum number of cuts = 3
Therefore yield (lbs) = [(0.411*10.5*3)/17.5]*100 = 73.98%

This is the maximum yield possible for the above finished size/bloom size combination. The scrap weight (point and tail) would be = 17.5 - (0.411*10.5*3) = 4.55 lbs.

Consider now the same finished size and length being made from the same bloom size, but now the bloom weight is increased to 21.8lbs. From this we can now get 4 cuts and the scrap weight remains the same. The maximum yield would now be [(0.411*10.5*4)/21.8]*100 = 79.2%.

From this it is obvious that if one quotes a yield number for 3.999" x 0.028" then the bloom size and bloom weight must also be specified. Comparing the yield on different sizes is rather like comparing "apples and oranges." "Games" can be played with these yield numbers by simply changing the bloom size, the bloom weight and the cut length.
This yield number is not an adequate indicator of the tube mill's performance. There are basically two things being measured in this one yield number:

(1) "Quality" losses due to defective tubes

(2) The so-called "inherent" process scrap

Both of these things are important, but if we can "improve" yield from 73.98% to 79.2% without any improvements in quality, this single yield number is not sufficient.

What can we do?

A better measure of "quality" losses due to defective tubes would be number of good pieces finished as a percentage of the maximum number of pieces that could have been finished. I choose to call this number "piece-wise" yield. Using the 21.8lb bloom and finishing all four pieces would yield "piece-wise" yield of 100%. The same would be true of finishing three pieces from the 17.5lb bloom. If we scrapped one piece from each bloom size, the 21.8lb bloom would have yield of (3/4)*100 = 75% and the 17.5lb bloom would have (2/3)*100 = 66.67%. This measure provides a better indication of how "in-control" the process is.

A second measure would be the scrap weight as a percentage of total bloom weight. This mean that the 17.5lb bloom would have (4.55/17.5)*100 = 26% scrap because of the point and the tail. This number for the 21.8lb bloom would be (4.55/17.5)*100 = 20.87%. This would provide some measure of the so-called "inherent" scrap losses.
By using both measures one can separate the effects of a process being out-of-control from the planning and process capability effects (17.5lb bloom versus 21.8lb bloom).
Section A.E:  ABAQUS code for the simulation of the drawing process

*HEADING,UNSYMM
DRAWING OF ALUMINUM TUBES WITH MANDREL (MICHAEL DORAH 1992)
*PREPRINT,ECHO=NO,HISTORY=YES,MODEL=NO
*RESTART1,WRITE,FREQ=1000
**DATA CHECK
*NODE
4000,1.75,0.0
6160,1.75,2.7
7200,1.745,4.0
7440,1.745,4.3
8000,1.745,5.0
4005,1.795,0.0
6165,1.795,2.7
7205,1.773,4.0
7445,1.7734.3
8005,1.773,5.0
*NGEN,NSET=BOT1
4000,6160,20
*NGEN,NSET=BOT2
6160,7200,20
*NGEN,NSET=BOT3
7200,7440,20
*NGEN,NSET=BOT4
7440,8000,20
NGEN,NSET=TOP1
4005,6165,20
*NGEN,NSET=TOP2
6165,7205,20
*NGEN,NSET=TOP3
7205,7445,20
*NGEN,NSET=TOP4
7445,8005,20
*NSET,NSET=BOT
BOT1,BOT2,BOT3,BOT4
*NSET,NSET=POINT
8001,100,400
*NSET,NSET=TOP
TOP1,TOP2,TOP3,TOP4
*NFILL,NSET=PIPE
BOT,TOP,5,1
*ELEMENT,TYPE=CAX4
4000,4000,4001,4021,4020
*ELGEN,ELSET=PIPE
4000,200,20,20,5,1,1000
*ELGEN,ELSET=BACKEND
6000,5,1,20,80,20,100
*NODE,NSET=MANDREL
100,1.865,2.7
*NODE,NSET=DIE
400,1.5,2.7
*ELEMENT,TYPE=IRI21A
100,4000,4020,100
*ELGEN,ELSET=MANDREL
100,200,2,1
*ELEMENT,TYPE=IRS21A
400,4005,4025,400
*ELGEN,ELSET=DIE
400,200,2,1
*ELSET,ELSET=SSTATE
14000,14080,200,500
*SOLID SECTION,MATERIAL=ALUMINUM,ELSET=TUBE
*MATERIAL,NAME=ALUMINUM
*ELASTIC
10E+6,0.33
*PLASTIC,HARD=ISO
45E+03,0.00E+00
55E+03,8.00E-02
203E+03,1.00E-02
*RIGID SURFACE,TYPE=SEGMENTS,ELSET=MANDREL,SMOOTH=0.125
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LINE,1.746,5.0
LINE,1.745,0.5
LINE,1.5,0.5
*RIGID SURFACE,TYPE=SEGMENTS,ELSET=DIE,SMOOTH=0.125
START,2.0,2.5
LINE,1.841,2.5
LINE,1.774,4.25
LINE,1.774,4.5
LINE,2.0,4.5
*INTERFACE,ELSET=MANDREL
*FRICITION
0.1,100
*PLOT,COLORS=32, PLOT SIZE=5,TRUE SCALE=1.5
*DRAW
*DETAIL ELSET=TUBE
*ZOOM,FACTOR=5
*BOUNDARY
DIE,1,1
DIE,2,2
DIE,6,6
MANDREL,1,1
MANDREL,2,2
MANDREL,6,6
*EQUATION
2
8000,1,-1,8001,1,1
2
8002,1,-1,8001,1,1
2
8003,1,-1,8001,1,1
2
8004,1,-1,8001,1,1
2
8005,1,-1,8001,1,1
*STEP,INC=3000,CYCLE=30,NLGEOM,SUBMAX
PULLING THE TUBE
*STATIC,PTOL=100.0
0.0000125,10.0,0.000001,3.0
*BOUNDARY
8001,2,2,2.0
*PLOT,FREQ=200,COLORS=64
*DETAIL,ELSET=BACKEND
*DISPLACED
U
*CONTOUR
S22
*CONTOUR
S11
*CONTOUR
S33
*CONTOUR
MISES
*CONTOUR
S12
*CONTOUR
E11
*CONTOUR
E22
*CONTOUR
E12
*CONTOUR
PEEQ
*EL FILE,ELSET=SSTATE,FREQ=100
S
E
PE
*NODE FILE,NSET=POINT
RF
*EL PRINT,FREQ=0
IE,PEMAQ,CEMAQ
*NODE PRINT,FREQ=0
U
V
A
NT
*END STEP
Section A.F: Contour Plots of the Drawing Process obtained from ABAQUS
Mises Stress Plot

Time completed in this step: +1.00E+01
Total accumulated time: +1.00E+01

ABAQUS 4.9-1  Date: 19-Mar-10  Time: 21:53:16  Step 1  Increment 111
S11 Stress Plot

S11 VALUE

1  -5.92E+04
2  -5.25E+04
3  -4.57E+04
4  -3.89E+04
5  -3.22E+04
6  -2.56E+04
7  -1.86E+04
8  -1.19E+04
9  -5.16E+03

ABAQUS VERSION 4-9-1  DATE: 19-12-2000  TIME: 21:53:16  STEP 1  INCREMENT 111
S22 Stress Plot

S22 VALUE
1 -4.28E+03
2 -1.36E+03
3 +1.54E+03
4 +4.46E+03
5 +7.37E+03
6 +1.02E+04
7 +1.32E+04
8 +1.61E+04
9 +1.90E+04

TIME COMPLETED IN THIS STEP +1.000E+01
TOTAL ACCUMULATED TIME +1.000E+01

ABAQUS VERSION 4-9-1 DATE: 19-11-2021 TIME: 21:53:16 STEP 1 INCREMENT 111
S12 Stress Plot

S12  VALUE
1  -2.84E+03
2  -1.55E+03
3  -2.60E+02
4  +1.03E+03
5  +2.32E+03

TIME COMPLETED IN THIS STEP  +1.000E+00  TOTAL ACCUMULATED TIME  +1.000E+01

ABAQUS VERSION 4-9-1  DATE: 19-MAY-94  TIME: 21:53:16  STEP 3  INCREMENT 113
E22 Strain Plot

TIME COMPLETED IN THIS STEP +1.000E+01  TOTAL ACCUMULATED TIME +1.000E+01

ABAQUS VERSION 4-9-1  DATE: 19-JUN-94  TIME: 21:53:16  STEP 1  INCREMENT 111

<table>
<thead>
<tr>
<th>E22 Value</th>
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<tbody>
<tr>
<td>1: +1.18E-02</td>
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<tr>
<td>2: +2.42E-02</td>
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<tr>
<td>3: +3.66E-02</td>
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<tr>
<td>4: +4.91E-02</td>
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<td>5: +6.15E-02</td>
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<td>6: +7.39E-02</td>
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<td>7: +8.63E-02</td>
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<tr>
<td>8: +9.88E-02</td>
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<td>9: +1.11E-01</td>
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### E12 Strain Plot

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<th>E12</th>
<th>Value</th>
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<tbody>
<tr>
<td>1</td>
<td>-1.15E-02</td>
</tr>
<tr>
<td>2</td>
<td>-8.31E-03</td>
</tr>
<tr>
<td>3</td>
<td>-5.08E-03</td>
</tr>
<tr>
<td>4</td>
<td>-1.85E-03</td>
</tr>
<tr>
<td>5</td>
<td>+1.38E-03</td>
</tr>
</tbody>
</table>

ABAQUS VERSION 4-9-1  DATE: 19-Mar-92  TIME: 21:53:16  STEP 1  INCREMENT 111

Time completed in this step: +1.000E+01  Total accumulated time: +1.000E+01
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