PROCESS IMPROVEMENT THROUGH DESIGNED EXPERIMENTS

by

Steven Hofstetter

B.S., Mechanical Engineering
Purdue University, 1985

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

Master of Science in Mechanical Engineering

and

Master of Science in Management

at the
Massachusetts Institute of Technology
June 1993
© 1993 Massachusetts Institute of Technology
All rights reserved

Signature of Author _____

Certified by _____
Anantaram Balakrishnan, Associate Professor
Sloan School of Management
Thesis Advisor

Certified by _____
Stuart Brown, Associate Professor
Department of Materials Science and Engineering
Thesis Advisor

Accepted by _____
Jeffery A. Barks, Associate Dean, Sloan Master's and Bachelor's Programs

Accepted by _____
Ain Sonin, Chairman, M.E. Committee on Graduate Studies

PROCESS IMPROVEMENT THROUGH DESIGNED EXPERIMENTS

by

Steven Hofstetter

Submitted to the Department of Mechanical Engineering and the Sloan School of Management on May 7, 1993 in partial fulfillment of the Requirements for the Degrees of Master of Science in Mechanical Engineering and Master of Science in Management

Abstract

The market for hard alloy thin wall aluminum tubing is becoming more competitive with small producers specializing in the products with the highest margins. This competitive situation places pressure on a producer who seeks to maintain a full set of products. One step in the production of this tubing is pilgering (also known as cold tube reducing). Pilgering is a cold forming process that performs a large reduction in cross sectional area of a hollow tube.

The first step in improving the productivity of the pilgering process is to establish a framework to guide the improvement activities. The framework consists of assessing and gathering process knowledge from both the industry and from inside the plant, followed by planning and completing designed experiments to quantify process understanding. This thesis presents one cycle of the process improvement framework as a model. This thesis demonstrates the framework by applying it to the pilgering process. We use designed experiments to show that extrusion speed and pilger feed rate influence pilger product quality.

Thesis Supervisors: Dr. Anantaram Balakrishnan, Associate Professor, Sloan School of Management
Dr. Stuart Brown, Associate Professor of Materials Science and Engineering

Acknowledgments

This thesis is a result of the efforts of many people, especially the people at the plant who worked with me sometimes for very long periods of time at unusual hours of the day. My thanks to the people who are closest to the process, Harold, Dick, John, Bob, Mike, and everyone else who helped at the reducers and the presses. Thanks to Harold for being incredibly resilient and for smoothing over at least 100 of my mistakes and thanks to John and Bob who I'm sure thought at least some of the "experiments" were academic exercises in futility. Thanks for putting up in the interest of learning and research! Thanks to Dick for always having wise answers to reducer problems. Thanks to Charlie for having yet another LFM project in his mill. Scott, I appreciate the time you spent, especially the "start, stop, continue" feedback sessions. However, dinner and guitar music were definitely the most fun. Your LFM background definitely made my experience less bumpy. Tom P., thanks for sharing your database of paper and brains with me to get up to speed and later for providing the all important tooling to run experiments with. Larry D, I could have done nothing without your contribution of reducer time and metal. Thanks to the shift supervisors, Larry, Bob, Mike, Tom, and Andy for helping me do things in a reasonable way and for providing people in the mill to help when I couldn't possibly get done by myself. Thanks also for putting up with my strange hours, strange questions, and weird phone calls and messages. I'm sure you guys can survive anything. I wish I had more of your qualities. The laser thermometer was a big help in collecting data. Thanks Dave D. Thanks to the guys in the die shop for, believe it or not, helping me use a lathe and several other tools to draw grid lines on tubes. I'm sure you thought I had lost it at least once or twice. Thanks Jenine for sales data. Finally everyone in the tube mill made my internship memorable with the Christmas dinner and jacket as a gift. I will long remember the experience.

Thanks to my friends Mitch, Eric, and Mike and our friends Jessica, Jill and Sherry who made life in Cambridge more memorable than classes, assignments, and projects.

Thanks to my advisors who put up with my learning antics and traveled to Lafayette to support me. Thanks Stu for coming out and living "in the trenches" with me for Experiment 3. Your insight was valuable and the operators really felt your attention was important. Thanks to both of you for having a sense of how to build research projects out of the messy real world.

I also appreciate David Coleman of Alcoa for providing keen insight into the evaluation of experimental data from a statistical point of view.

The author wishes to acknowledge the Leaders for Manufacturing Program for its support of this work.

Table of Contents

Page

Abstract 3

Acknowledgments 4

Table of Contents 5

List of Figures 9

List of Tables 10

Chapter 1. Introduction 12

1.1. Context 12

1.2. Objectives of Thesis 13

1.3. Summary of Methodology and Results 14

1.4. Organization of Thesis 15

Chapter 2. Framework for Process Improvement 16

2.1. Introduction 16

2.2. Project Framework 16

2.3. Discussion of Framework 18

2.3.1. Step 1; Assess Industry Knowledge 18

2.3.2. Step 2; Identify and Define Problem 21

2.3.3. Step 3; Develop Strategy for Learning 23

2.3.4. Step 4; Search Literature and Survey Experts 24

2.3.5. Step 5; Choose Parameters and Response 25

2.3.6. Step 6; Design Experiments 27

2.3.7. Step 7; Conduct Experiments 28

2.3.8. Step 8; Integrate Data from Various Sources 29

2.3.9. Step 9; Iterate Through Steps to Continuously Improve 30

2.4. The Problem Stated In Terms of the Framework 31

2.5. Chapter 2 Conclusions and recommendations 31
Chapter 3. Pilgering Process in the Context of Total Process 32
3.1. Introduction 32
3.2. Total Process Context 32
3.3. Ingot 34
3.4. Extrusion 35
3.5. Pilgering and Annealing 36
3.6. Drawing 37
3.7. Cost and Quality Trade-offs 37
3.8. Chapter 3 Conclusions and Implications 40
Chapter 4. Technical Process 41
4.1. Introduction 41
4.2. Process Description - Pilgering 41
4.2.1. Machine/equipment 42
4.2.2. Rate 44
4.2.3. Quality 45
4.2.4. Flexibility 47
4.2.5. Cost 47
4.3. Chapter 4 Conclusions and Implications 48
Chapter 5. Process Analysis 49
5.1. Introduction 49
5.2. Overview 49
5.3. Tooling Design 50
5.3.1. Tooling Design Details 50
5.3.2. Estimators of Quality 61
5.4. Quality 66
5.5. Chapter 5 Conclusions and Implications 69

Chapter 6. Design of Experiments 71
6.1. Introduction 71
6.2. Selection of Experimental Technique 71
6.3. Selection of Experimental Variables 75
6.4. Definition of Variables 76
6.5. Experimental Preparation 77
6.6. Integration of Experiments with Production 78
6.7. Chapter 6 Conclusions and Implications 78
Chapter 7. Experimental Results 80
7.1. Introduction 80
7.2. Presentation and Discussion of Results 80
7.2.1. Observation 1; Process Robust for Low Elongations 81
7.2.2. Observation 2; Cracking Occurs at Very Low Feed Rates . 82
7.2.3. Observation 3; Cracking Increases With Feed Rate 84
7.2.4. Observation 4; Cracking Is Related to Extrusion Speed 85
7.2.5. Summary by Experiment 86
7.2.6. Experimental Summary 90
7.3. Chapter 7 Conclusions and Implications 91
Chapter 8. Summary and Conclusion 93
8.1. Introduction 93
8.2. Concluding Remarks 93
8.2.1. Process improvement framework 93
8.2.2. Business purpose 93
8.2.3. Survey of experts 94
8.2.4. Literature review 94
8.2.5. Experiments 94
8.3. Recommendations 95

8.4. Future Work 96
8.5. Conclusion 96
Appendices 97
Appendix I. Survey 98
Survey results 98
Actual Survey 101
Appendix II. Experimental Data 104
Experiment 1 104
Experiment 2 106
Experiment 3 109
Experiment 4 111
Appendix III. Experimental Statistical Analyses 115
Appendix IV. Cost/Trade-off Computations 116
Bibliography 118

List of Figures

Figure Page

Figure 1.1. High Level Overview of Tube Making Process 13

Figure 2.1. Flow Chart of Steps in Framework 18

Figure 2.2. Information in Process as Function of Operation Number 26

Figure 3.1. Pilger Process in the Context of the Plant 33

Figure 4.1. Schematic of Basic Pilger Process 42

Figure 4.2. Detail of Pilger Tooling Features 43

Figure 5.1. Pilger Tooling Detail 50

Figure 5.2. Pilger Linear Tooling Detail 53

Figure 5.3. Various Side Relief Designs 59

Figure 7.1. "Zipper" Shaped Cracks 82

Figure 7.2. Combined Experimental Response 83

Figure 7.3. Response Hypothesized Over Full Range 83

Figure 7.4. Typical Reducer (Pilger) Cracks 85

Figure II.1. Experiment 2 Crack Rate Versus Feed Rate 107

Figure II.2. Experiment 3 Crack Rate Versus Feed Rate 110

Figure II.3. Experiment 4 Crack Rate Versus Extrusion Speed 112

List of Tables

Table Page

Table 2.1. Matrix of Industry-Firm Process Knowledge 19

Table 3.1. Process Data in Context of Plant 34

Table 5.1. Pilger Symptom, Cause and Correction Reference 69

Table 7.1. Summary of Experiments 81

Table I.1. Survey Results 100

Table I.2. Actual Survey for Learning About Pilger Variables 103

Table II.1. Experiment 1 Constant Parameters 104

Table II.2. Experiment 1 Results 105

Table II.3. Experiment 2 Constant Parameters 106

Table II.4. Experiment 2 Design Levels 106

Table II.5. Experiment 2 Parameter Values 107

Table II.6. Experiment 2 Results 108

Table II.7. Experiment 2 Environmental Variables 108

Table II.8. Experiment 3 Constant Parameters 109

Table II.9. Experiment 3 Design Levels 109

Table II.10. Experiment 3 Parameter Values 109

Table II.11. Experiment 3 Results 110

Table II.12. Experiment 4 Constant Parameters 111

Table II.13. Experiment 4 Design Levels 111

Table II.14. Experiment 4 Parameter Values 112

Table II.15. Experiment 4 Repetition 1 Results 113

Table II.16. Experiment 4 Repetition 2 Results 114

Table III.1. Statistical Summary of Experimental Models 115

Table III.2. Experiment 3 Environmental Variable Correlations 115
Table IV.1. Trade-off Spreadsheet for Press and Pilger 116
Table IV.2. Trade-off Spreadsheet for Press and Pilger (Cont'd)..... 117

Chapter 1. Introduction

1.1. Context

At a high level of abstraction, this thesis is about the challenge of conducting process improvement in a manufacturing production environment. We use the problem of how to eliminate cracks in an aluminum cold forming operation called pilgering (or cold tube reducing) to specifically illustrate the improvement process.

Implementing process improvement from ground zero requires an assessment of the organization's process understanding followed by experiments to quantify the inter-relationship between process variables. First, we identify the process and clearly define it. Then, we assess the state of knowledge about the process within the organization. Once this is complete, we formulate a strategy for learning more about the process. This strategy directs future activities such as literature searches, interviews, surveys of experts, process modeling and experimentation. These activities further focus the process goal, serving to stimulate iteration and continuous process improvement.

We use aluminum tube production as an example to illustrate process improvement. We can categorize aluminum alloys into hard and soft alloys. Soft alloys, as their name implies, are easier to form and are of lower strength than hard alloys. The hard aluminum alloy tube manufacturing process consists of four primary steps. These steps are ingot casting, extrusion, pilgering, and drawing. Figure 1.1. depicts the progression of the production process. The ingot plant first melts the aluminum alloy and then casts it into a large block or ingot. The press extrudes it into a long, hollow piece with a relatively thick wall. Pilgering and drawing reduce the wall to produce a thin wall tubing product. Pilgering is a cold operation consisting of two dies that rock back and forth over the outside of the tube. A mandrel inside the tube maintains the desired size. Pilgering can reduce the wall and diameter much more rapidly than drawing. The draw bench pulls the hollow tube through a die with a bulb in the center. The die on the outside forms the outer diameter, while the bulb forms the inside diameter.

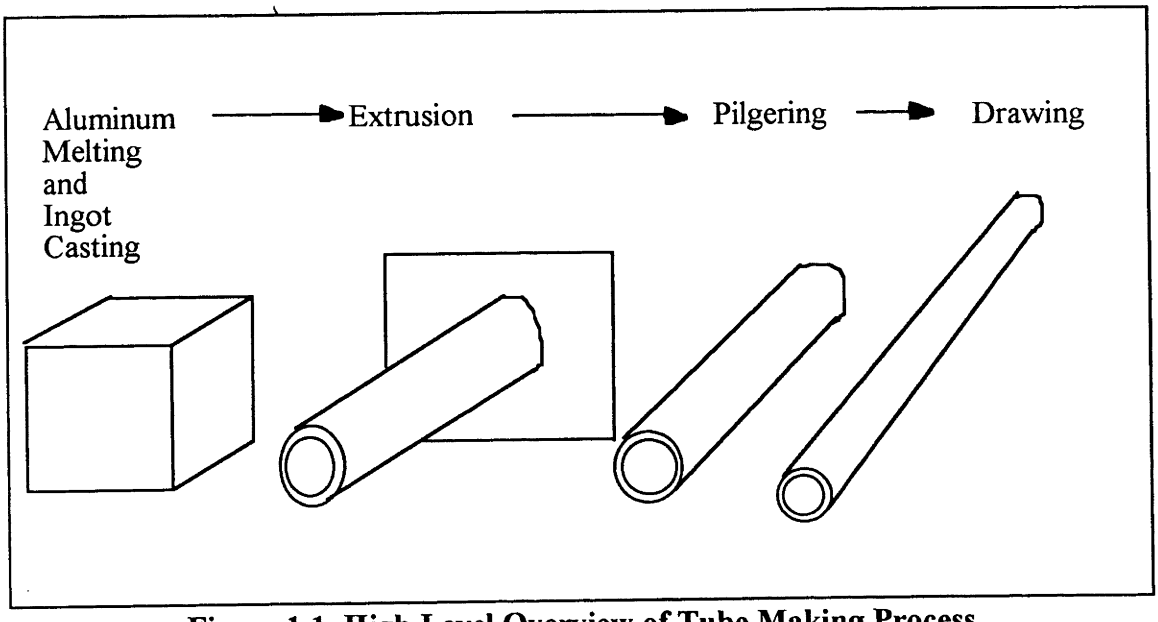

Figure 1.1. High Level Overview of Tube Making Process

1.2. Objectives of Thesis

The objective of this thesis is to illustrate a process improvement procedure from the beginning through one complete iteration. We can make this illustration through an examination of the pilgering process and its unique process characteristics.

One must understand both the technical and business aspects of a manufacturing process in order to plan and implement process improvement. This thesis investigates a process improvement technique that begins at a fundamental level by assessing the state of the process in an organizational context. At any point in time, an organization has a level of cumulative process knowledge and process understanding that characterizes the maturity of the process within the organization. One must make a judgment based upon the level of technical knowledge available about a process in order to begin process improvement. This thesis proposes and motivates a procedure for beginning improvement of a process that has been in existence for a long time, when the organization has a limited amount of process understanding.

Improving the pilgering process is the direct focus of this thesis. Cracks, the

primary indicator of low quality, often develop in hard aluminum alloys at or downstream from the pilger process. The pilger output size of 4.0" outside diameter by 0.174" wall thickness is a good product to focus on because of its low quality[1]. The processes that make aluminum alloys A and B into this size attain recoveries (percentage of input material passed on to the next operation) ranging from 49 to 65 percent[2]. We present a unified description of the process through literature reviews, personal interviews and experimentation. On the basis of experimental results, we quantify the sensitivity of process quality to factors of feed rate, amount of reduction, extrusion speed and extrusion billet temperature.

1.3. Summary of Methodology and Results

The improvement process begins with a business assessment of how the company's process understanding compares with the knowledge that is available in the industry. We formulate a strategy for learning after assessing our process understanding. In this case, we make a decision to analyze the process by surveying experts, searching the literature, and conducting production experiments.

The result of following this methodology is the essence of this thesis. The results of the business assessment show that the company needs to rapidly develop its internal process understanding by utilizing available industry knowledge. According to experimental results, the process of pilgering is robust to failure when there is little change in the material dimensions. Cracks do not occur when we change the dimensions of the stock by only a small amount. A quantifiable relationship exists between process parameters and product quality. A relationship also exists between the process parameters of the upstream process (the extrusion press) and the product quality at the pilger machine. Because we could only analyze four out of a large number of process variables,

---

[1]Data in this thesis have been disguised to protect proprietary information
[2]Data gathered from plant production reports, 1991 and 1992

we cannot make a strong statement about how to eliminate cracks in all pilgered products. We identify an operating point for each experiment where there is minimum likelihood of cracking.

This thesis contributes to the company database of process understanding in several ways. This thesis presents an improvement methodology that may serve as a model for future activities. It also presents a unified view of the process based upon a comprehensive literature search. Finally we present a model for judging the economic impact of improvement. The model can substantiate process improvement at various points in the overall production process.

1.4. Organization of Thesis

We present a logical sequence of events in this thesis that occur during a process improvement exercise. Chapter 2 presents the overall framework, or way of thinking about process improvement. Chapter 2 includes a brief discussion of each step in the framework, a discussion of the distinction between business and technical processes, and an assessment of industry process knowledge. It concludes with a statement of the strategy for accomplishing pilger process improvement. Chapter 3 presents a description of the overall process of tube manufacturing from the plant's point of view. Understanding the process is a very important part of accomplishing process improvement. Chapter 4 presents the pilgering process description. In Chapter 5 we present the process analysis based primarily upon tooling geometry. The chapters up to this point motivate the importance of the problem and develop a process understanding. Chapters 6 and 7 present the experimental designs and the results of our experimental activities. Chapter 8 contains concluding remarks. Throughout this presentation, we capture the essence of the results in text and concise graphics, and have placed detailed data. This should make the reading job easier, and allow us to focus on the improvement methodology without placing undue emphasis on the data unique to the pilger process.

Chapter 2. Framework for Process Improvement

2.1. Introduction

This chapter will present the framework used to address generally the process improvement problem, but specifically the pilger cracking problem. The steps in this framework represent over-riding milestones that guided all activities during the course of the project. We did not necessarily execute the steps in exactly the order presented. We present this material in a sensible order that we established after some reflection. We displaced two activities. The economic analysis did not receive as much emphasis early in the process as the framework suggests. Also the process understanding took place in parallel with and to some extent after the experimental activities. It is important to have a framework to guide thinking and events according to some long term plan. This list of planned steps served that purpose in this project. We can easily transfer the planned steps in whole or in part to other process improvement projects. After presenting the framework of planned events, we make statements about the planning and implementation of each step. The chapter concludes that the value of the framework lies in clearly communicating how the process improvement activities fit into a long term process.

2.2. Project Framework

When beginning a process improvement project, one must reflect about how the activity fits into a larger process of improvement. Specifically consider an ongoing process of improvement. Readers can repeat the set of activities that this thesis proposes over time with continual refinement. This is not new. Many total quality initiatives such as the Alcoa Eight Step Process[3], the Plan Do Check Act (PDCA) cycle and the "WV" model presented by Shoji Shiba[4] all contain an element of iteration and continuous improvement over time. The opportunity to conduct this research and improvement

---

[3] The Alcoa Eight Step Process, 1989

[4] Shoji Shiba, Professor, Total Quality Management class, MIT, 1991

project in a production environment starting from ground zero makes this thesis unique. "Ground zero" in this case meaning that no quantitative information was available about the inter-relationship of process parameters at the beginning of the process.

The improvement steps proposed are as follows:

1. Assess the knowledge available in the industry about the process and compare this knowledge with the knowledge available in the plant.
2. Identify and define the problem, especially noting whether the business problem has a technical component. Determine economic impact.
3. Develop a strategy for learning about the process.
4. Search available literature and survey internal and external experts to learn about the process. Conduct personal interviews where possible. Include process production operators as sources of knowledge.
5. On the basis of the knowledge gathered about the process, choose the most important parameters that are feasible to vary for investigation. Choose the response variable.
6. Design experiments that will quantify the relationship between process parameters. Plan explicitly based upon realistic estimates of effort, time, machine capabilities, etc.
7. Conduct experiments. Begin first with trial experiments to establish operator understanding, measurability of response, and general awareness on the part of the experimenter and the participants. Progress to scanning experiments that investigate the range of performance. Then focus on the desirable region of performance.
8. Integrate experimental results with production data, process analysis models and available information from the literature. To predict performance a priori, search for parameters that estimate the response variable.

9. In the short term, iterate through steps 4 through 9. In the long term iterate through steps 1 through 9.

Figure 2.1. presents the steps graphically:

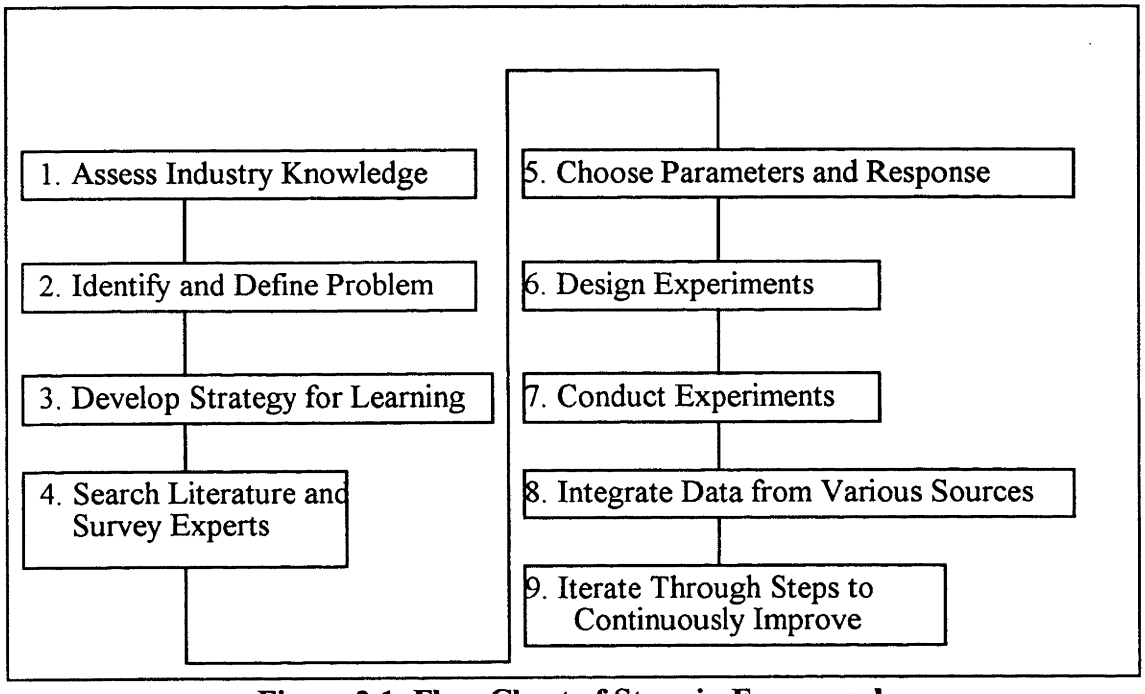

Figure 2.1. Flow Chart of Steps in Framework

2.3. Discussion of Framework

We discuss each step of this framework with specific reference to the case of the pilger process improvement process. We provide specific details that are examples of decisions made at each step. The details presented as examples are what actually occurred in the course of the pilger process improvement project. We note any exceptions explicitly.

2.3.1. Step 1; Assess Industry Knowledge

Assess the knowledge available in the industry about the process and compare this knowledge with the knowledge available in the plant.

Step 1 helps to place an order of magnitude estimate on the amount of effort

required in the process improvement activity. This step is different from gathering available information and augmenting internal knowledge. At this point, we must make a decision about how to proceed. Deciding *how* to augment the company knowledge is the essence of the assessment. It also helps to establish a global scope around the problem. The position of a firm is relative to the industry in terms of process understanding determines technological competitive position. Users of the process define the pertinent industry. This assumes that the process of interest is economically appropriate and the only question is how to apply the process to a set of products. The worst case is to be technologically backward in an industry rich with information. However, if this information is readily available among all the players, this situation may be easy to remedy. If rich information is available in the industry and the firm in question is lacking that information, the next question is how did they get into this situation in the first place.

Consider a matrix of possible situations that a firm can find itself in with regard to process knowledge and understanding. If we divide the world into knowledge rich and poor industries and into knowledge rich and poor firms, then a two by two matrix displays the possible combinations of process knowledge, as can be seen in Table 2.1.

Industry	Info-rich	Info-poor
In-house Info-rich	Parity with competitors. Continuously improve.	Competitive advantage. Determine value of collaborating.
Info-poor	Competitive disadvantage. Need to learn. As follower, determine how to learn best and how to establish parity.	Parity with competitors. Determine value of being first mover to advance process technology.

Table 2.1. Matrix of Industry-Firm Process Knowledge

There are three interesting positions in the matrix. As was already mentioned, if the firm is information poor in an information rich industry, one must understand how they got there and how they are going to establish parity. This firm possesses many available

alternatives for learning including, attending seminars, searching literature, experimenting and visiting other plants in the industry. The firm's ability to learn is subject to the willingness of others to share information. This firm resides in a strategically dangerous position. If the firm is information rich in an information poor industry, then the firm will likely be able to sustain a competitive advantage and there may be value in using the information as a bargaining tool. The value of collaborating to share information is probably low from this firm's point of view. If the firm is information poor in an information poor industry, then the firm must decide whether there is value in being a first mover to invest in technological understanding. It is wise to advance the technology of processes because increases in quality and productivity usually accompany increased process understanding. The challenge to this firm is to begin basic process understanding from a fundamental level.

Seldom will any firm fit exactly into one of the boxes. An industry and firm will fall somewhere in between. Consider first the pilgering industry presented in this thesis. The industry knowledge resides somewhere between information rich and moderately rich. Most of this information remains subjective and qualitative, shared in the form of heuristics. Some published quantitative and technical information exists, but without full integration. Publications contain very little empirical information that quantifies relationships between parameters. We can better understand the current state of industry knowledge by looking briefly at some of the players in the industry and their actions.

One firm in the industry is responsible for manufacturing over half of the approximately three hundred pilger machines in the world today. This firm is Mannesmann, who also manufactures die grinding machines for making tooling. Mannesmann has been the technology leader in the industry. They have been a leading equipment manufacturer and a leader in terms of process research for the past forty years. Another key player is a tooling manufacturer who uses Mannesmann equipment to manufacture tooling. A third player is an advanced producer of titanium nuclear fuel rod.

This firm employs people who know a lot about pilger processing and about die design. The Mannesmann company, the tool manufacturer, and the fuel rod producer created an alliance to develop the latest tooling designs. The industry recognizes the new tooling design as the best. The design is not public. (Refer to Chapter 5 for more information.) We can see from this alliance how the industry protects proprietary information.

General Electric is developing information for the industry. They have a machine that they have instrumented very completely to gather data about the process. They have volunteered the machine and the information to others for experimentation. Industry members also set an example of how they hold information by disguising data in papers about pilgering.

The pilgering process is very sophisticated. Being a quality producer of pilgered products depends heavily upon having access to the process technology and technological developments. The access can be in the form of purchasing a Mannesmann machine, since Mannesmann provides technical support to all owners of their equipment. Access can also be in the form of retaining a consultant in the field, or building one's own information and experience base. An alliance with an experienced producer or provider of tooling can provide access to technology.

2.3.1.1. Step 1 Example

Succeeding in the pilgering industry requires a high degree of process understanding. For the firm in this case, much of the in-plant expertise has left because of personnel retirement and turnover. Also, the tooling purchases have lagged the state of the art designs. This leaves the firm in an information poor situation within a relatively information rich industry. As well as can be understood, there are no other firms using the pilgering process on aluminum.

2.3.2. Step 2; Identify and Define Problem

Identify and define the problem, especially noting whether the business problem has a technical component. Determine economic impact.

It is worthwhile when embarking on a problem solution process to categorize the problem as much as possible. Depending upon the past experience of the person solving the problem, there may be a tendency to approach a problem from only a business or a technical point of view. This can be myopic. The primary difference between a business problem and a technical problem is that a technical problem has a technical component. In other words, both are business problems, but the technical problem is a business problem with an added complexity of having a technical process as one or more of its roots. We can approach both the business and technical process in a similar manner in order to identify and select the problem. Typical techniques for business problem solving begin with a brain-storming session to identify opportunities for improvement. We can further sort out the problems by constructing a pareto diagram to determine the most important problems. An Ishikawa diagram is useful to analyze the root causes of process problems. Finally we can select and apply a solution technique. Business problems commonly involve multiple functions of the organization, do not lend themselves to designed experiments, and often have people issues at their roots.

Business problem solving techniques become inadequate when called upon, for example, to determine the optimum setting for process parameters. We must use an experimental technique to answer questions about process parameters. We can identify technical process problems as being generally more quantitative than business problems. We are also able to isolate specific responses of a technical process to system inputs.

Since every problem is a business problem, it is valuable in this step to conduct some type of business economic analysis to determine where the best place is to begin process improvement. This is especially important in processes that reach across several departments within a plant. Factors to consider include shared resources and product mix across the resources.

2.3.2.1. Step 2 Example

The pilgering process is technical and therefore lends itself to investigation using an

experimental process. The business problem is to increase the sales and profitability of hard alloy thin wall tube by increasing the productivity of the pilger machine. We can improve productivity in the short term either by increasing quality or by increasing feed rate (through put). The technical problem is to identify the important technical process parameters to experiment with and quantify their inter-relationship.

The economic analysis shows that the pilger product quality and especially the quality downstream of the pilger is an economically important process improvement. The recovery downstream of the pilger determines how much excess material we must start at the pilger and further upstream at the extrusion presses. By improving recovery at the final operations, there is a huge benefit in not needing to process excess (or safety stock) material through the early operations. Appendix IV illustrates this.

2.3.3. Step 3; Develop Strategy for Learning

Develop a strategy for learning about the process.

There are many alternatives for learning about the process. Some of these include conducting literature searches, surveying experts both inside and outside of the company, interviewing experts, conducting experiments, modeling the process, and hiring consultants. Another strategy is to purchase equipment from vendors who provide ongoing technical support and training. In the pilgering industry, owning a Mannesmann machine has this side benefit. Some subset of these strategies will be appropriate depending upon what resources are available and the state of information availability in the industry. The pilgering industry offers all of the alternative methods of learning and technology transfer.

2.3.3.1. Step 3 Example

In the example of pilger process improvement, the plant decided to adopt the following knowledge acquisition strategy. The plant decided to take advantage of as much industry knowledge as possible. To the extent possible, the firm will learn from and acquire information from industry members. In order to reach parity with the industry, the

firm decided to attend industry conferences and seminars, gather available literature on pilgering, and distill lessons from in-house files. The firm will also begin a process of experimental process investigation and purchase tooling of the latest designs to upgrade old model machines.

2.3.4. Step 4; Search Literature and Survey Experts

Search available literature and survey internal and external experts to learn about the process. Conduct personal interviews where possible. Include process production operators as sources of knowledge.

Search available literature to the extent that it is consistent with the learning strategy. This is usually an inexpensive way to gain knowledge about the process. We can keep abreast of information in the industry by gleaning information from the literature if the industry is somewhat information rich but industry members do not widely share information. If there is a lack of quantitative information available both in-plant and in the industry, then the only alternative is to build upon the qualitative information possessed by experts in the field. Conduct interviews to canvass for all possible information about the process and especially to discover all possible experimental variables that influence the process. This provides an opportunity to gather information that production operators store in black books and catalogue that information formally.

2.3.4.1. Step 4 Example

We decided to conduct a literature search on "pilgering" and "cold tube reducing" that covered the world. This search yielded the results of several conferences (we found four) as well as some papers in Polish and German. One paper in particular contained the complete kinematic equations for pilgering. This paper, originally written in Russian, made use of unclear language and complex hand-drawn graphics that made it difficult to read. Some of the papers produced equations and relationships that can form the basis for numeric process modeling. About twenty technical papers are available dating back to the 1960's. A British technical publication also covers the topic within the scope of the tube

manufacturing industry.

We distributed a survey based upon current knowledge of all pilger process variables. The survey form with the survey results is in Appendix I. The purpose of the survey was to establish a prioritization of the variables in order to select those most important to begin experimenting with. We left the survey open ended in order to gather any other variables that we might have missed.

2.3.5. Step 5; Choose Parameters and Response

On the basis of the knowledge gathered about the process, choose the most important parameters that are feasible to vary for investigation. Choose the response variable.

We can best choose the important parameters through the use of the multi-functional team of people who will be conducting the investigation in the long term. Include people from production, management, tooling, maintenance, and research or quality if appropriate. Also include people from upstream processes if the process of interest makes use of material coming in from other parts of the plant. Including people who have various views of the process will develop a valuable understanding of the inter-relationships between different parts of the process. This understanding will be valuable in the future.

Consider the impact on the response variable of variables upstream from the immediate process. In this example, the extrusion press is the next operation upstream from the pilger process. (Refer to Chapter 3 for a thorough explanation of the process context from start to finish.) The nature of process industries is such that the material itself contains the product attributes. Tube making is not purely a continuous process industry because it has some discrete characteristics. Tube making is however similar in some respects to the process industry. For example, the tubing produced has not only a finished dimension and surface finish, but also internal material attributes such as strength, etc. Processing history establishes these attributes. This differs from many discretely

manufactured goods whose attributes are explicit geometric features or explicit product functions. The explicit product functions may depend upon material properties. The "process" element makes tracing defects more difficult the farther downstream we do the inspection. This impacts experiments, especially if the response variable is a material characteristic such as cracks. Figure 2.2. illustrates the accumulation of product "information" over a processing lifetime. The more operations that we have completed, the more operations we must consider when sorting out causes of defects at any downstream operation.

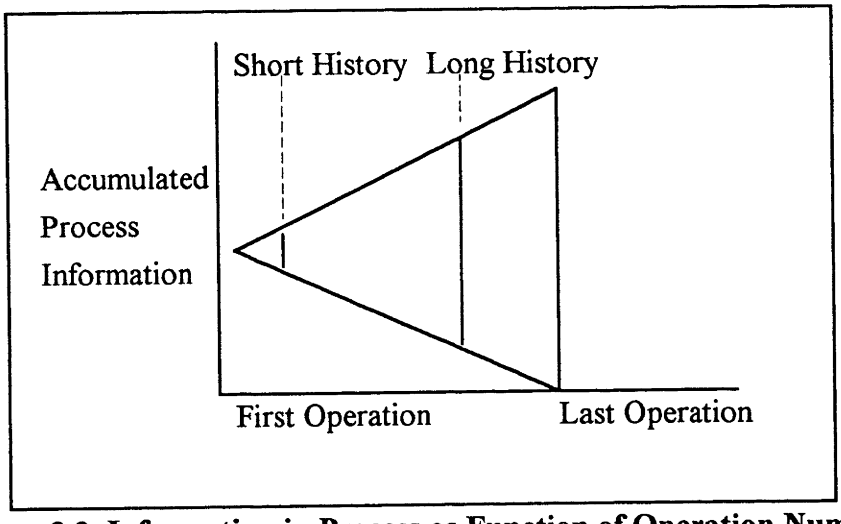

Figure 2.2. Information in Process as Function of Operation Number

The point of Figure 2.2. may be counter-intuitive. We may find that the response variable relates to variables located outside the immediate production area. This relationship is most likely to occur in process industries because of the interconnected nature of processing. The only way to discover these interactions is to plan experiments that include those variables. This usually increases the cost and complexity of the experiments. Simply put, if we conduct experiments at the last operation, then the likelihood of an upstream variable affecting the response is much greater than if we conduct experiments at the first operation.

2.3.5.1. Step 5 Example

The survey about pilgering uncovered sixty variables in total. Forty-six of these were in the local mill versus the upstream processes. Over eighty percent of the people surveyed felt that twenty-one of the variables were either moderately or very important. Thirteen of these are in the local mill. (The survey results are in Appendix I.) We selected elongation and feed rate as the most important and most easily manipulated variables. We selected these two by consensus out of the thirteen in the local mill. These variables also have a direct impact on productivity. We selected extrusion billet temperature and extrusion speed as the variables to experiment with outside of the tube mill. We chose tube cracking as the experiment response variable. Chapter 6 defines these variables along with the experimental discussion.

We need to emphasize a counter-intuitive point from the example. From the discussion of Step 5, we may conclude that we should identify pilgering defects at the extrusion press. This is true in a way. It is also true that pilger cracks do not occur at the extrusion press. There is an extrusion press parameter that, when out of range, results in predictable cracking at the pilger. Experiments showed this. This means that we can predict pilger cracks by conducting SPC on key parameters at the extrusion press. We can form a similar line of thought for the ingot re-melt process but we have not investigated it.

2.3.6. Step 6; Design Experiments

Design experiments that will quantify the relationship between process parameters. Plan explicitly based upon realistic estimates of effort, time, machine capabilities, etc.

We make the assumption that the experiments will take place in a production environment and not off-line in a lab. Many of the issues discussed here and further on will not apply to laboratory settings. We begin experimental design with the variable selections made in Step 5. Other decisions will depend upon the expected influence and controllability of noise on the process and on the amount of time and resources available. If the noise is controllable, for example, then we can select certain noise for use with

Taguchi style "outer noise" array. Also, if this is the first set of experiments being conducted on the process, then we can choose the range of variables and levels as wide as possible to increase the likelihood of obtaining a discernible response. Consider choosing variable levels that include at least one instance of "good results" in order to validate that we conducted the experiment over a range that included the threshold of failure. If all of the results are "failure", establishing where one is in the response spectrum will be difficult. This problem is more acute if the response variable is discrete and highly variable.

Coleman and Montgomery[5] co-authored one of the best papers about planning experiments in industrial environments. In this paper the authors point out many pitfalls of experimental design.

2.3.6.1. Step 6 Example

We decided to conduct experiments in the production environment using production equipment, tooling, operators and material. We designed experiments to investigate the variables chosen in Step 6. These variables also directly influence process productivity. We chose the experiments to be scanning in nature because these are the first experiments on this process and we anticipate other investigators will use the results to indicate the direction of future more detailed experiments. We documented experimental designs for each experiment by indicating the design matrix, the values of the parameters and the experimental levels, and the input and output material. We thought through everything as much as possible and prepared data sheets for documenting everything. We also included documentation for variables that we expected to remain constant.

2.3.7. Step 7; Conduct Experiments

Conduct experiments. Begin first with trial experiments to establish operator

---

[5]Coleman, D.E., and Montgomery, D.C., A Systematic Approach to Planning for a Designed Industrial Experiment, Technometrics, February, 1993, Vol. 35., No. 1.

understanding, measurability of response, and general awareness on the part of the experimenter and the participants. Progress to scanning experiments that investigate the range of performance. Then focus on the desirable region of performance.

Trial experiments are valuable because they permit learning in a safe environment. Process operators can get a feel for what it is like to run an experiment without being under the pressure of a real experiment. Because they may be learning something new, this freedom is important. Also the experimenter may learn that the response is not discernible or may learn that the logistics or machine setup is unreasonable. The early experiments should be scanning in nature. The important objective is to gather data to learn about the range of response. Once we identified the appropriate response range, we anticipated doing more experimentation in greater detail within that range. Doing scanning experiments may at first seem like a waste of effort, however, it is a trade off that we must make if no previous quantitative information is available about the process.

2.3.7.1. Step 7 Example

We initially planned for five experiments. However we did not complete the fifth experiment because of tooling lead time. We designed and implemented four experiments in detail. The first was a trial experiment. The next two experiments were to investigate the range of cracking response for various settings of elongation and feed rate. The second experiment investigated a very slow range of feed rate. The third experiment investigated a classical case of cracking. The fourth experiment investigated the relationship between pilger cracking and upstream press extrusion speed and billet temperature. These experiments were scanning in nature and future experiments will focus on a more narrow operating range.

2.3.8. Step 8; Integrate Data from Various Sources

Integrate experimental results with production data, process analysis models and available information from the literature. To predict performance a priori, search for parameters that estimate the response variable.

A first step toward achieving a process model is to correlate experimental results with product factors and characteristics obtained from literature. If we can achieve this, then we can make a first cut attempt at predicting response without going through the expense of experimentation. Of course, early in the learning cycle, we must always use experiments to substantiate estimates.

2.3.8.1. Step 8 Example

In the pilgering case, there is a question about tooling quality. By correlating tooling statistics with experimental and production results, we can identify suspicious tools and remove them from production early. We were able to do this to some extent. We explain this further in Chapters 5, 6 and 7.

2.3.9. Step 9; Iterate Through Steps to Continuously Improve

In the short term, iterate through steps 4 through 9. In the long term iterate through steps 1 through 9.

Iterating through steps 4 through 9 repeats the analysis portions of the improvement process. As the experiments provide more insight into the process, we can either validate or discard the information we gather from all sources. The primary change that occurs over time is a better understanding of the problem and more focused investigation. Over the long term, external variables may change causing the decisions in steps 1 through 3 to no longer be valid. For example economics may change or technology may change which change the process of economic importance or call for updated experimental platforms.

2.3.10.1. Step 9 Example

For the purpose of this thesis project, we will complete and document one cycle through this framework. The results of these activities will be useful in two ways. First they will serve as a guideline for future process improvement activities. Second they will provide a baseline of process data from which to launch future process analysis including experimentation.

2.4. The Problem Stated In Terms of the Framework

The objective of this thesis is to provide an explicit process improvement framework for establishing a base of quantitative process understanding and complete one cycle of the framework. We will illustrate the framework by applying it to the pilgering process in an effort to eliminate cracking. The problem is to develop a strategy for learning about the pilgering process and pursue that strategy. The strategy will include a literature search, interviews of experts, and designing and conducting experiments.

2.5. Chapter 2 Conclusions and recommendations

From a high level view, we can see the steps of Assessing Knowledge, Identifying and Defining the Problem, and Developing a Strategy for Learning (Steps 1 through 3) as problem definition and scope activities. We can see the steps of Searching Literature and Surveying Experts, Choosing Parameters, Designing Experiments, Conducting Experiments, Integrating Information and Iterating (Steps 4 through 9) as process analysis activities in a general sense. This framework serves as an explicit model of the goals of this project. By considering this set of goals and the ensuing results, the reader can see how the individual parts fit together into a larger activity and can see how the individual parts are a part of a long term process improvement exercise.

Even in this case, it was difficult to follow the process improvement framework exactly. Often success depends upon learning by experience. This project is the first time that we or anyone else applied this formal process improvement framework to the pilgering process. Validating the economic importance of the problem will be an important point to address when going through the steps the second time since we did not do this thoroughly the first time.

This framework is a road map for what is to come. This framework was a guideline for the example pilgering case and is a guideline for the presentation of this thesis.

Chapter 3. Pilgering Process in the Context of Total Process

3.1. Introduction

In Chapter 2, we presented a framework for process improvement. This chapter fits into Step 3, the strategy for learning, and Step 4, gathering information about the entire tube production process from people within the plant. A chapter that looks specifically at the pilgering process in order to understand what parameters influence product quality and therefore productivity follows this chapter.

Besides demonstrating Step 4 of the framework, this overview gives insight into the total processing path of tube production. Since there are over sixty variables that affect the tube production process throughout the plant (reference Appendix I for a list), understanding the entire process is necessary to appreciate the inter-relationship of parameters.

This chapter provides detail on the ingot melting, extrusion, and drawing areas. Each section has a comment related to the business impact of the area.

3.2. Total Process Context

The pilgering process at the plant of interest exists as one process within a much larger production process that extends across three mills. Figure 3.1. diagrams the process flow. The ingot mill produces billets. The extrusion mill produces blooms and the tubing mill produces finished tubes.

The data that follows in Table 3.1 summarizes the details of each part of the process according to rate, recovery and cost. This chart contains estimates for representative sizes. However, we have not generalized it to include an entry for every size and alloy produced. This chart gives an overview of the abilities of the various technologies in place at the plant. We can make some general observations from Table 3.1. We will point them out in the following discussion.

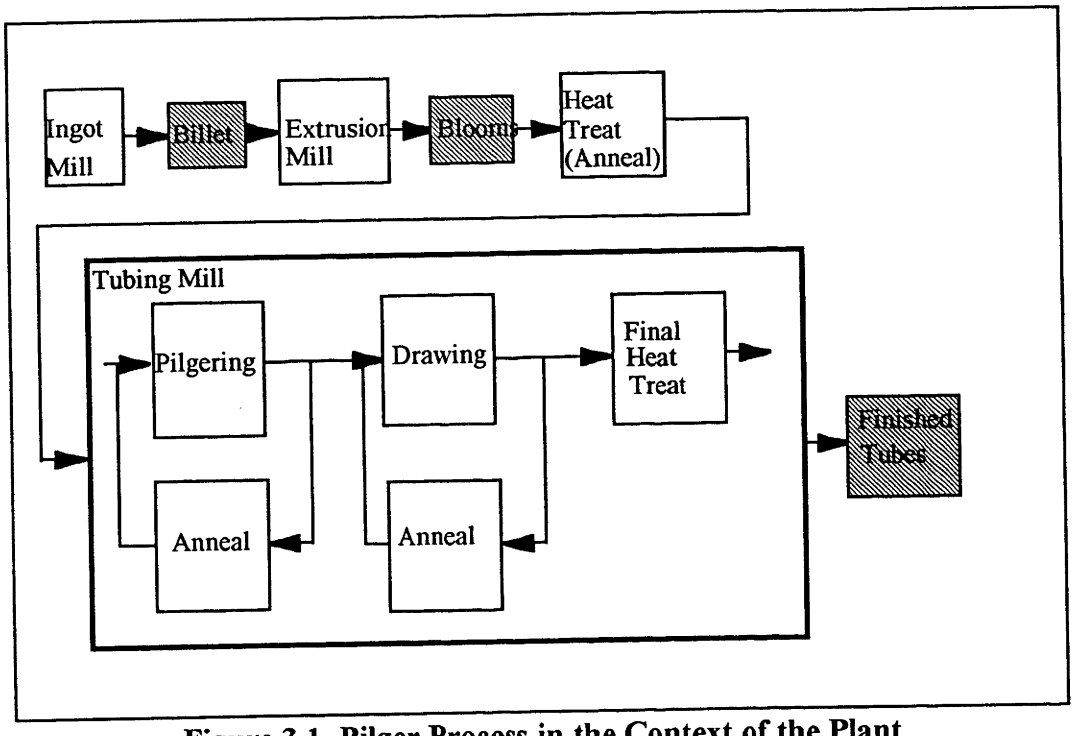

Figure 3.1. Pilger Process in the Context of the Plant

We will consider each row of the table. We document the type of equipment used to accomplish the process in the first row. The second row is a rough estimate of the capacity of one piece of the equipment. This estimate is for hard alloy which is the family of alloys considered in this thesis. Quality in the third row is an estimate based on the percentage of good pounds of product passed on to the next step in the process. Flexibility is the ability to run different sizes and types of products. Re-melting and extrusion are highly flexible since they can decide in short notice to run different products. The furnace only needs a change in recipe and the extrusion press a change in tools. The pilgering machine is less flexible since it requires a tool change that takes many hours. The draw bench tooling is changeable in minutes. Cost estimated is processing cost only and does not include raw material. It does include an estimate for overhead. The last row of data is the number of pieces of processing equipment available to the tube mill. The extrusion department has more than one press, but the tube mill has allocated to it the capacity of approximately one.

From the Rate and Number of Pieces of Equipment data, in conjunction with the

Quality data, it appears that the extrusion area is candidate for being the bottleneck from a plant wide perspective.

Tubing Process Data in Context				
Process Characteristic	Process Step			
	Re-melt	Extrusion	Pilgering	Drawing
Equipment	Furnace	Press	Pilger	Draw Bench
Rate (Theory) (lbs/hour)	7000	500	700	1000
Quality (Recovery %)	0.8	0.7	0.95	0.65
Flexibility (Multi-product)	High	High	Low	High
Cost (Est.) ($/lbs)	0.15	0.8	0.2	0.07
Hot/Cold	Hot	Hot	Cold	Cold
Number of pcs wrt tube mill	1	3	3	6

Table 3.1. Process Data in Context of Plant

3.3. Ingot

The ingot production process is the first process of interest at the plant. In the ingot facility aluminum pig and scrap are combined with alloying elements that are then re-melted and cast into "logs". The aluminum metallurgical structure formed in the casting process influences all of the downstream processing activities. At the time of melting, the metal is in its most "pure" and "original" state. We can summarize all process history in terms of the composition of the melt and its temperature. The recording of metallurgical history starts when the melt begins to transition from the liquid phase to the solid phase.

To understand the production of an ingot we must view it in terms of its macroscopic properties and its microscopic properties. The average pour temperature and cooling rate determine the ingot's composition from a macroscopic point of view. The ingot plant next heats the ingot in a furnace. Then it soaks at constant temperature for a period of time. Time in soak is the amount of time that the ingot stays within close temperature limits so that the internal metallurgical constituents will travel and change form to give the aluminum a particular set of properties. All of the macroscopic

characteristics represent average values that may not be representative of any particular microscopic point inside the ingot. From a microscopic point of view, the ingot has heterogeneity in its structure as a result of the cooling process after pouring the cast. Even though we take great care to build a process that cools uniformly, the outside of the ingot cools more rapidly than the inside. There may be variation in cooling rate from top to bottom of the ingot and along its length. On a microscopic view, the composition of the aluminum at any point in the ingot may vary according to the dispersion and diffusion of alloying elements within the ingot. Because of differences in cooling rates from the outside to the inside of the ingot, there are differences in micro structure and composition between the outer surface of the ingot and the inside of the ingot. The subsequent thermal process seeks to alleviate these differences, resulting in a more homogenous product prior to sending the material to extrusion. Any non homogenous characteristic is a candidate for becoming an initiator of a crack or product defect.

The ingot plant generally has more capacity than is necessary for the plant and sells ingot on the open market as a source of revenue.

3.4. Extrusion

The extrusion process is a hot technique for dramatically reducing the wall thickness and increasing the length of hollow material. The output from the extrusion press is a long constant cross-section shape. The extrusion mill heats the ingot to approximately 800 degrees Fahrenheit, places it in the press cylinder and then extrudes it. The extrusion process is either *direct* or *indirect* indicating whether the press pushes the ingot through the die or whether the press pushes the die back over the ingot. Another distinguishing factor among presses is whether the mandrel passes through a pre-drilled hole in the ingot or whether the mandrel pierces through the solid billet. The piercer press has advantages in that its product is of higher quality with a more uniform wall thickness and better straightness than extrusions from the die-mandrel press. Also, the piercer press is more efficient since the ingot does not require drilling prior to extrusion.

The key parameters in the extrusion process include extrusion speed, press cylinder temperature, ingot temperature going into the cylinder, and alloy. The primary objective in extrusion is to extrude as thick a wall as possible in order to process maximum material through the operation. Thick wall extrusions are easier to do and pass through the die more rapidly, thus improving productivity on a pounds per hour basis.

From a business and operations point of view, at the plant level the extrusion presses are typically the bottleneck. Production data in Table 3.1 indicate this. The tube mill has portions of about three press resources. Note that roughly the overall capacity of the presses is less than either the pilgers or the benches. Sharing the presses gives rise to resource contention issues. For example, the extrusion department has their own important customer product that sometimes precludes running product required for the tube mill.

3.5. Pilgering and Annealing

The pilgering process exists between extrusion and drawing. We discuss pilgering in detail in Chapters 4 and 5. Since this process is the subject of this paper, we will only explain annealing here. Annealing is a thermal operation conducted to restore the material to a metallurgically soft state. Annealing alleviates the structural dislocations that occur as a result of cold working the material. For aluminum it requires about 6 to 8 hours at about 800 degrees Fahrenheit. The annealing operation occurs between each pilgering step and between approximately every three draws.

In terms of productivity, the pilgering operation seeks to maximize the pounds of crack-free material produced. To maximize this measurement, the pilger operation operates the best when making small cross sectional area reductions on thick wall tubing. This permits maximum pounds per hour through the pilger machine, however it does not serve to minimize the number of draws at the draw bench. We must consider this trade-off.

3.6. Drawing

Drawing is a process which cold forms a cylindrical metallurgical shape by pulling it through a die that is slightly smaller than the material outside diameter. The nature of cold working the material provides enough strength in the material that it can pull itself through the die. A minimum amount of cold work is necessary to permit drawing to happen. Occasionally the material is defective and breaks during the drawing process. The drawing process is relatively slow in terms of amount of reduction per pass compared to the pilgering process. There is roughly a three to one ratio in terms of the number of draws to accomplish the same effect as one pass on the pilger machine. Drawing with a bulb in the center will effect changes in both inside and outside diameters simultaneously. While slower than pilgering, drawing is more accurate and results in better surface quality. The goal is to balance between drawing and pilgering in order to minimize the number of draws and avoid intermediate anneals.

3.7. Cost and Quality Trade-offs

The overall objective of the plant with respect to producing aluminum tubing is to effect a reduction in wall thickness and outside diameter in the most cost effective manner from cast billet through to customer-ready thin wall tubing. Extrusion, pilgering and drawing can all be used to accomplish wall thickness and outside diameter reduction. The most effective process at any moment in time depends upon economics, operations competencies, and available technology.

The primary factors to consider in trading off the different components of processing tubing are the *cost* of each process, the *quality*, and the *throughput rate*. We measure quality (recovery) as a percentage of good material produced in pounds relative to the total amount of material processed. Total pounds per hour processed is the measure of throughput rate. The cost of each individual operation is difficult to obtain. The various accounting systems used to collect data distort the dollar values associated with the value of one hour of a resource. Instead of using cost, we can form a ratio of value to evaluate

the trade-off between resource capacity. The ratio of extrusion press value to pilgering value is an important economic measure that we use to denominate the value of saved press hours. Taking less reduction on the pilger machine and thereby eliminating one or more pilger passes yields a benefit in terms of material savings. The material saving translates into saving the processing cost of additional material.

An example of the trade-off between extrusion and pilgering is the production of 4.0" outside diameter by 0.178" and 0.255" wall thickness products from either 7.39" by 0.773" input stock or from 6.08" by 0.787 inch input stock. If the 7.39" by 0.773" input stock is used, the process requires a pass first on the 5.87" dies and then the 4.0" dies and the recovery is historically very low. If the 6.08" input stock is used, only one pass on the 4.0" dies is required. This saves one pass and improves the recovery. There is also a benefit in terms of improved throughput rate because pilger operations with a small cross sectional area reduction run at a faster rate. The influence of quality is partially subjective, but is reflected also in the recovery at any step in the process. The next paragraphs discuss the economic analysis in detail. We present the detailed data of this analysis in two spreadsheets located in Appendix IV.

Let's look closer at the example of the 4.0" x 0.178" and 0.255" product analysis. We make several assumptions in this analysis since we only explicitly account for production speeds, recoveries and product sizes. We estimate the product speeds and recoveries from historical data. We estimate the downstream recoveries for the one pass pilger process (case 2 in Appendix IV) to be 5 percent better than current numbers based upon expected improvements in quality due to new tooling. We give no consideration to differences in lead-times and inventory levels between the two processing alternatives. The analysis only considers two products. A complete analysis needs to consider the entire system from ingot re-melt through drawing and consider the complete product mix. This analysis only trades off the pilger process against extrusion. The necessity of the pilger process is a fundamental premise in this analysis and future analyses should further

challenge the importance of the pilger. We can set up the spreadsheet in the limit so that no processing occurs at the pilger. However, setting the pilger equal to zero production will provide a rough estimate of the relative importance of the pilger. The processing cost assigned to the scrapped aluminum ($0.50) at the bottom of the second spreadsheet is the biggest cost assumption. The outcome of the analysis depends strongly on this cost estimate.

The decision at hand is whether to make the products using one or two passes of the pilger (reducer) machine. This is similar to deciding whether to make the products from a thick or thinner wall bloom. We consider in case 1 (refer to Appendix IV, Table IV.1.) the large bloom with two pilger passes. The analysis begins with the amount of final product in pounds required by the customer. We compute the number of pounds of metal required out of the pilger based on the estimated recovery downstream of the reducer. We can apply similar logic to each reducer pass by estimating the required pounds input to each pass based upon the recovery of each pass. We can compute the number of processing hours required at the pilger machine based upon the feed rate at which it operates. The recoveries of the two pilger passes determine the amount of material required from extrusion because the recoveries inflate the amount of material required. We apply a similar analysis to the press to determine the number of pounds required at the start of extrusion and the number of hours processing time required.

In the example presented in the appendix, for the large bloom size we need to extrude 412,217 pounds of metal to complete 141,421 pounds of finish product. This assumes a 0.57 recovery at the press and 0.95 recovery for each of the two reducer passes. The downstream recovery for the thick wall product is 0.71 and the thin wall product is 0.65. Producing the finished product requires 272 hours of press time and 206 hours of pilger time.

We present the analysis for the small bloom size in Appendix IV, Table IV.2. It follows the same procedure as Case 1 presented above. We need to extrude 305,322

pounds of metal to produce the same amount of finished product. This assumes a 0.68 recovery at the press and 0.95 recovery for the one reducer pass. The downstream recovery for the thick wall product is 0.76 and the thin wall product is 0.70. Producing the finished product requires 273 hours of press time and 72 hours of pilger time.

The most significant differences in these two processes are the number of pilger hours and the amount of metal required. The one pass pilger process saves 135 pilger hours and 106,884 pounds of metal. The change in press hours is insignificant at an additional 0.84. Because the press is the bottleneck, we will discard any process that requires significantly more press hours regardless of the pilger hours saved. The value in saving aluminum is not in the cost of aluminum but in the saved processing cost. We did not consider lead times and inventory explicitly in this analysis. However, qualitatively the large reduction in pounds of metal to be processed in the one pass case will likely result in improved lead-times and lower inventory levels.

After reviewing the spreadsheet results, it becomes apparent that the recovery (quality) is one of the most significant factors in the trade-off between processes. The analysis points toward keeping the processes with the highest recovery and less toward encouraging higher productivity.

3.8. Chapter 3 Conclusions and Implications

This overview positions the understanding of the pilger process within the overall plant. Experimental results indicate strongly that variation in upstream extrusion parameters influence the product quality at the pilger machine. A similar example exists in the tube drawing area of the plant where the reducer receives blame for failed material at the end of the drawing operations. Quality at all points in the process of tube making has a high impact on cost. Low quality, especially at downstream operations, results in a large amount of excess material being started at the first operation.

Chapter 4. Technical Process

4.1. Introduction

Chapter 3 presented an overview of the process from the plant point of view. This chapter will go into detail on the specific process of interest, cold pilgering. The following chapter begins a description of the issues of concern in designing experiments in an industrial production environment. This chapter fits into Step 4 of the framework, Conduct Literature Search and Survey Experts, presented in Chapter 2.

The goal of this chapter is to provide an overview of the process from five points of view, equipment, production rate, product quality, production flexibility, and cost. Although this discussion does not go into much technical detail with descriptive process equations, this discussion will be valuable to the reader who is not completely familiar with the pilgering process. We present process equations in Chapter 5.

4.2. Process Description - Pilgering

After being developed in Germany in the late 1800's, the Mannesmann company accomplished most of the improvement in the pilger process. Tube Reducer Corporation manufactured in the early 1900's the particular machine we used in this project. Tube Reducer Corporation was one of the first American manufacturers of pilger machines. The process consists of two reciprocating dies which operate over a mandrel to elongate a cold hollow tube. The work piece rotates to perform even deformation of the material around the perimeter of the hollow tube. The nuclear industry commonly uses this process for the purpose of manufacturing titanium nuclear fuel rod cladding. Aluminum, copper, and steel are other materials formed with the pilger process. The process is exceptional because of the extreme amount of cold work imparted to the material. The nature of the process is very complex when viewed on a microscopic scale. The die and mandrel geometry vary along their length which results in complex deformations and rates of deformation during the process. The parameters that influence the final product are

numerous.

4.2.1. Machine/equipment

We present a simple diagram of the essential parts of the process in Figure 4.1. We describe the machine that effects the pilger process in terms of several components. These are the die head and dies, the feeding mechanism, the mandrel, the cooling system and the controls.

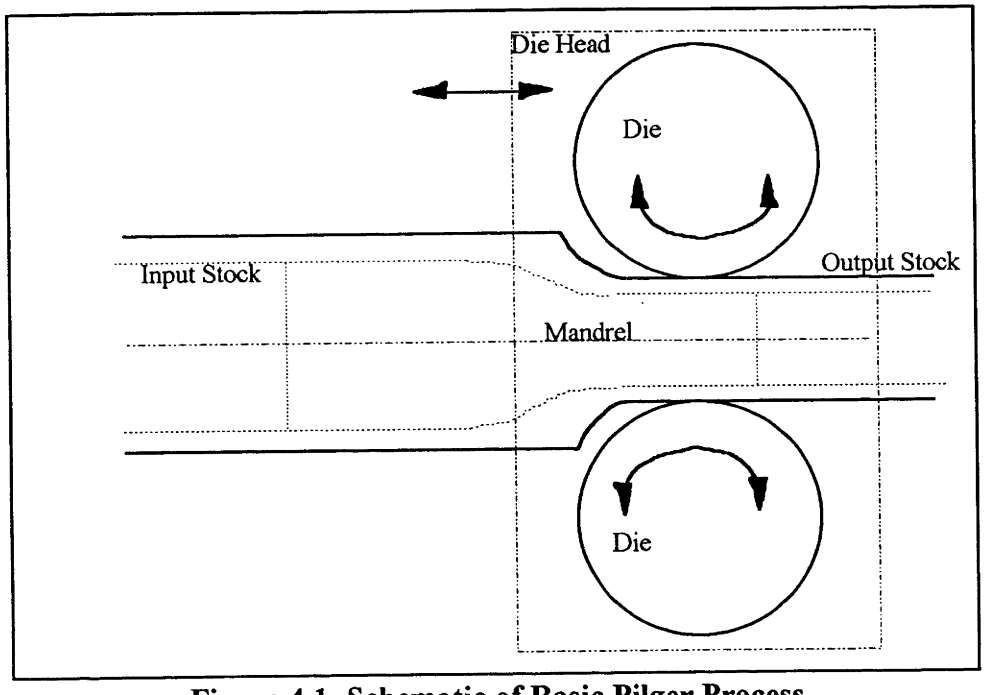

Figure 4.1. Schematic of Basic Pilger Process

The die head and dies are a distinguishing characteristic among pilger machines. The dies are the hard movable objects that pass over the outside diameter of the process material and form the size and shape of the outside of the finish product. The die head is the structure that supports the dies and which contains the drive mechanism for rotating the dies. A slider crank mechanism typically drives the die head via the primary pilger machine power plant. The major distinction is whether the dies are half die which rotate approximately 180 degrees or whether they are full dies that rotate 360 degrees. The type of die has a direct impact on the throughput of the machine, since the full die has a much

longer contact surface with the process material. Because of the longer contact surface, a more gentle reduction can occur over a longer distance of the tool which translates into either higher throughput or higher quality. Higher quality results if the machine operates more slowly in order to produce better quality product. The dies themselves have many unique characteristics that have an impact on the quality and rate of the process. There are many die surface features including relief angles, amount of relief along the die profile, rates of taper, and so forth. We illustrate these features in Figure 4.2.

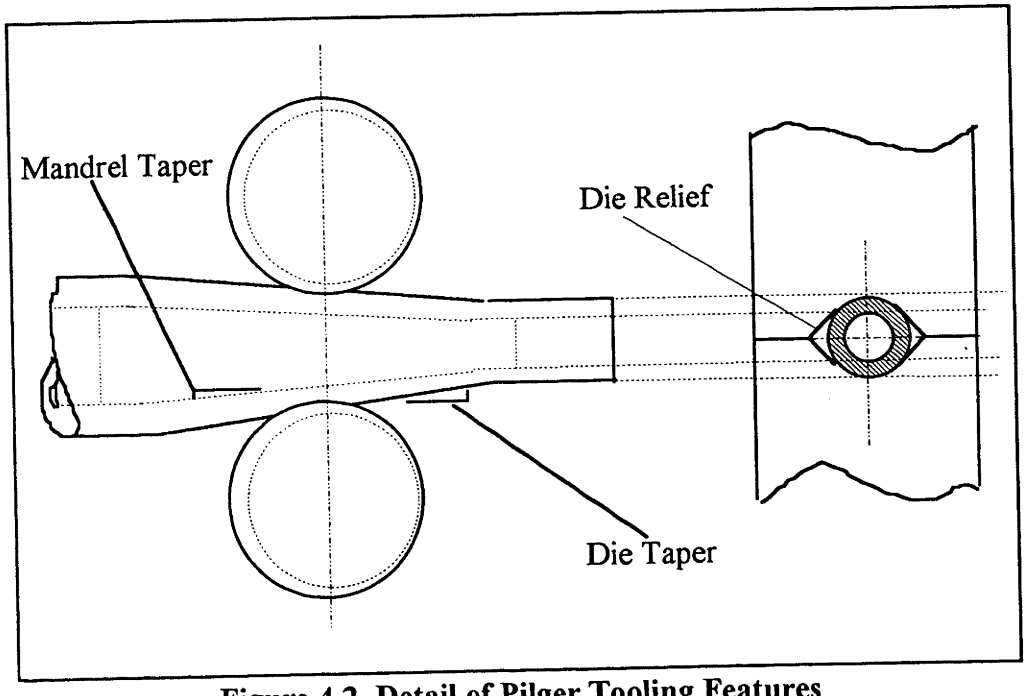

Figure 4.2. Detail of Pilger Tooling Features

The feeding mechanisms on various pilger machines distinguish the machines on the basis of whether the feeding mechanism is mechanical or hydraulic and whether or not the feed occurs once per cycle or twice per cycle of the die head. A hydraulic feeding mechanism is better because of its ability to more smoothly and accurately feed the material into the die head. The mechanical feeding mechanisms are also unreliable because of the large number of moving parts and the high accelerations of such a mechanism.

Typical feed rates for a pilger machine which feeds once per stroke range from

0.005" to 0.75" per stroke of the die head. For machines that feed twice per stroke, these numbers double. Whether or not the machine feeds once or twice is primarily a function of how new the machine is. Newer equipment with high capacity and more advanced tooling usually advance both on the forward and reverse strokes of the die head.

The mandrel is the tool that forms the inside characteristics of the process material. The dies press the material from the outside down onto the mandrel. The mandrel is typically a solid piece. However some more sophisticated designs include cooling and lubrication passages inside the mandrel.

The cooling system is usually a flood of liquid coolant pumped over the hot parts of the machine. The choice of coolant and the flow rate are critical decisions in determining the cooling ability of the system. More efficient cooling results by applying coolant directly to the problem locations.

The controls on the machine function at two levels. First they provide basic coordination among the elements of the machine, making operation much simpler. Second the controls affect directly the final product characteristics. The controls on primitive machines permit control by push button of the primary components as well as manual control of the feed rate, die gap, and material loading. The controls on sophisticated machines will operate the machine components in concert, not only making the machine easier to operate, but operating it in a manner that produces higher quality pilgered tubing. Some of the components coordinated by the controls include material load/unload devices, prevention of head movement until the clamps that hold the work piece in the machine are secure, and startup of the lubrication pumps before machine operation.

4.2.2. Rate

Two primary characteristics determine the rate of production of the pilger machine, the stroke rate and the feed rate. Do not confuse the rate of production with the productivity of the machine. Productivity takes into account the amount of good product

produced. The machine may operate at a very high rate of production, but have a very low productivity if the output quality is sub-standard. Older machines typically have a fixed stroke rate of 58 strokes per minute. The stroke rate on more modern machines is variable and may be as high as 400 strokes per minute depending upon the physical size capability of the machine. The rate of a machine depends on the size of the machine, the tooling being run in the machine and the cooling ability of the machine. The smaller the machine, the higher the stroke rate because smaller tooling with nominal product cross sectional area reduction will generate less heat than large tools. A machine running technologically advanced tooling will run faster. However, the faster the machine runs, the more heat it generates which the cooling system must dissipate.

The quality of the finished product usually limits the rate in production. If the process runs at too high of a feed rate or stroke rate, the material surface will begin to flaw and possibly crack. It is not easy to explain the exact reason for this. One probable cause is the capability limits of the material to endure high rates of material flow in the dies.

The following equation characterizes the productivity of the Pilger machine (feet/hour):

$$P = \frac{SPM(FR)(E)(N)(T)(60)}{12}$$

where

SPM is the stroke rate per minute

FR is the feed rate in inches per stroke

E is the elongation

N is the number tubes per roll

T is the utilization

4.2.3. Quality

We focus on surface quality, particularly cracks, in the tubing product as the primary measure of quality. Other quality attributes include dimensions and material properties. We define quality as the presence of visually obvious cracks or other surface abnormalities. We used visual techniques for measurement of quality. We need to develop more sophisticated measurement techniques in order to provide more accurate data for measuring process improvement. Two alternative methods are eddy current and ultrasonic inspection. Many factors determine the quality of the process. The purpose of this investigation is to discover the factors that affect surface quality (cracks), to quantify the relationships between variables and to quantify the impact of individual variables. Generally, the quality depends on the incoming material characteristics, the amount of reduction the material undergoes in the pilgering process and the feed rate at which the material feeds into the process.

The quality of the process is dependent upon the rate at which the material deforms. As hypothesized earlier, the rate of material deformation is dependent primarily upon the rate of change of tool geometry from the inlet to the outlet of the dies. Higher feed rates bring more material into the dies with every stroke which results in more material deformation per die pass. The stroke rate of the machine and the feed rate of the material affects the deformation rate. On a microscopic scale, we can relate the quality of the process to the strain rate that the material is subject to. The strain rate is a function of the die geometry, feed rate, and stroke rate.

4.2.4. Flexibility

Flexibility is the ability to run different products and processes on the same machine. Flexibility only has meaning with respect to something such as product size. The pilger machine is flexible with respect to product size and feed rate. The dies are typically much more difficult to replace than the mandrel. The plant can typically replace a mandrel in

about 20 minutes, where die replacement takes on the order of 5 or 6 hours depending upon the particular machine technology. Hence the pilger machines we studied are much more flexible to changes in wall thickness and inside diameter than to outside diameter. Pilger machines typically have fixed speeds, i.e., the head and dies cycle back and forth at the same constant rate. The rate at which the product feeds into the moving dies is the feed rate.

A pilger machine usually processes a particular type of material. However with better process understanding, the same machine can run multiple materials, and possibly on the same tooling. Tooling geometry (both die and mandrel), feed rate, stroke rate, and temperature all determine product quality. Certain tooling geometries result in higher quality than others. Die and mandrel geometry determine the geometry of the outgoing product. Therefore, the amount of reduction in wall and outside diameter are a direct result of the tooling geometry. Dedication to a particular type of metal and dedication to a particular range of material input and output sizes sometimes occurs because of the large number of inter-related process parameters (there are 60 parameters identified in appendix I), and because of the large investment required to establish superior operating procedures.

4.2.5. Cost

The cost of the equipment and the cost of operation determines the cost of the process. The equipment cost depends primarily upon the sophistication and technology and age of the machine. The cost of operation depends upon the costs of tooling, human operators, and maintenance of the machine. A machine of new technology costs approximately 2 million dollars for 30 millimeter inlet diameter capability and requires one person to operate it.

4.3. Chapter 4 Conclusions and Implications

We present for discussion the particular machine that we used for this project. We

describe it in particular using the terms and definitions just presented. In the current example, the machine is of the half die type operating at 58 cycles per minute and processes a single tube at a time. The machine has a mechanical feed and the pinion gear is larger than it should be for large stock. The machine has a simple cooling system and controls. Some of these features, the dies, and pinion gears primarily and the cooling system secondarily have a direct impact on product quality. Future chapters will discuss quality issues.

A primary goal of this project is to improve the productivity of the pilger process. From the productivity equation we see that we can not easily change the number of tubes processed at once nor the stroke rate of the machine. Also the utilization is a function of machine usage so we cannot use it as an experimental variable This leaves only the feed rate and the elongation as variables. These are the same variables we identified as the primary variables that contribute to machine flexibility. These are also the primary variables chosen in the process improvement exercise.

Chapter 5. Process Analysis

5.1. Introduction

This chapter presents a more detailed view of the pilgering process than Chapter 4. The contents of this chapter fit into Step 4 of the framework, Search Literature and Survey Experts, for process improvement that we presented in Chapter 2. Understanding the process of pilgering is a very important part of being able to improve it. This discussion about the technicalities of the process serves to increase awareness about the myriad of parameters that are intrinsic within tooling. This discussion will also help to develop a sense for which parameters have the most influence on product quality and throughput. Tooling influences most of the product characteristics of pilgered material. The tooling that causes the material shape to change most significantly influences the cold working process. Consequently this chapter includes an extensive discussion of tooling. This chapter begins with an overview and then describes several different types of tooling which have evolved over time. With each tooling style we make an evaluation about how it impacts product quality. There are some tooling statistics that we can compute for any set of tooling. Some of these statistics are estimators of quality. The chapters that follow this one describe the experimental design and results.

We base the technical information in this chapter upon literature about pilgering. We integrate experimental experience with information from the literature to draw conclusions and recommendations about tooling and its impact on product quality.

5.2. Overview

Tooling design and tooling quality will comprise the two sections of the discussion about process. The tool design section covers the basic relationships for the various types of tooling. The section on quality outlines the ways to measure quality. We present a table of product symptoms and suggested causes and corrections based upon heuristic and theoretical information.

5.3. Tooling Design

Tooling is a critical component in the process of pilgering. Most experts of the pilgering process feel that tooling is the single most important variable that affects the quality of the finished product. The tooling is a very complex portion of the process. Tooling consists of two components, the dies and the mandrel. Each of these components have a myriad of detailed geometric characteristics that we must take into account when selecting tooling that is optimal for a given application. Figure 5.1 illustrates the basic tooling features. This presentation of tooling analysis will begin with the fundamental tooling details and then proceed to a presentation of the impact of the tooling features on product quality.

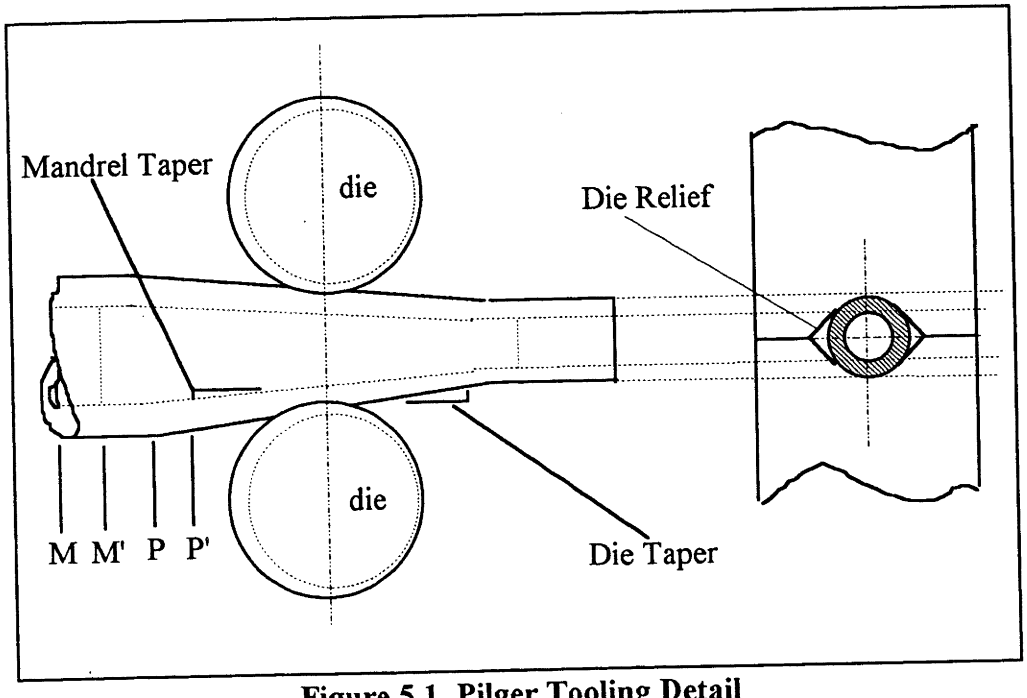

Figure 5.1. Pilger Tooling Detail

5.3.1. Tooling Design Details

There are three types of tooling designs in the industry. The first is linear and uses straight lines (tapers) to make all transitions in diameter. Curved tooling is the second type. It uses smooth curves to make the transitions in diameter. The third is a new

proprietary design. It uses not only curves for all transitions but uses higher order mathematical functions to provide a continuous model over all parts of the die from the full depth of the die groove to the side relief. With this continuous function, a computer mathematical model can simply place the features in the die wherever the designer desires. Because of the proprietary nature of the new design no equations are available. We provide more detail on the commonly available linear and curved tooling techniques.

The sophistication in tooling design lies primarily in being able to design a geometry that accomplishes a certain geometric change within the material capability constraints. The material is work hardened at each point along the tooling according to the amount of cross sectional area reduction that has occurred up to that point. The challenge is to distribute that work hardening along the transition in a manner that never exceeds the material capability. Because the material gets harder farther along the tooling, it is good not to attempt large reductions near the outlet of the tooling because the harder material at that point is more likely to fail.

We introduced the two main parts of tooling, the die and the mandrel, earlier. Tooling has two main features, the die groove and the side relief. These are two of the most important design decisions. Modeling of the geometric design for the die groove begins with a straight line, progresses to several straight lines, and finally a continuous curve. The second major design decision, apart from the die groove design, is the design of the die relief. In simple designs craftsmen grind the relief in by hand based on experience. In the most sophisticated designs higher order mathematical functions describe geometry that transitions continuously from the outside diameter into the relief pocket on either side of the process material. Figure 5.1. illustrates this. The optimal side relief is primarily a function of the feed rate and the elongation as well as the material.

The relationship between feed rate and elongation is basic to all tool design. The distance that the material moves forward along the tooling is equal to a stretch factor times a feed factor:

$$PP' = \frac{CSA_M}{CSA_P} MM'$$

We measure the cross-sectional areas at points M and P. The ratio of cross-sectional areas is the same as the elongation. Figure 5.1. identify M and M' and P and P'. The distance the unprocessed input stock feeds into the pilger with each stroke is MM'.

5.3.1.1. Die Groove Design

We will discuss the tooling with respect to the die groove and the side relief. First consider the different die groove design techniques. They are linear, curved and the new design.

5.3.1.1.1. Linear Tooling Die Groove Design

Figure 5.2. shows a schematic of linear tooling. Mannesmann has formally documented the relationships for this design.[6]

[6]Gerretz, J. and Stinnertz, H., Mannesmann-Meer Aktiengesellschaft, The New Mannesmann-Meer Tooling Design, Cold Pilger Symposium, Mannesmann-Meer, Moenchengladbach, Western Germany, March 1969.

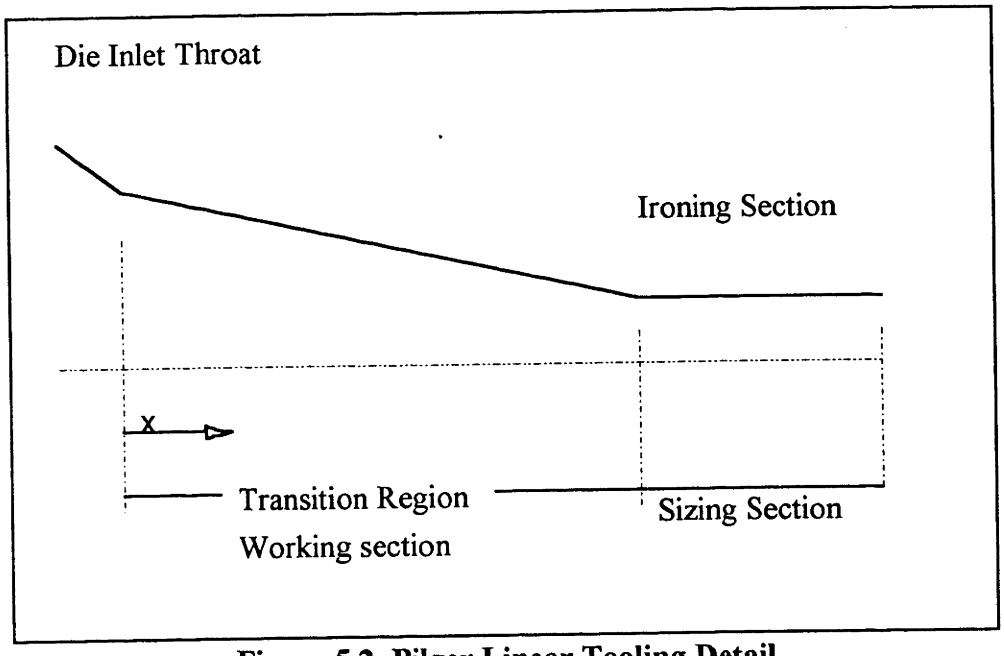

Figure 5.2. Pilger Linear Tooling Detail

The equation for the die groove of a linear die is:

$$D_x = d_x + 2S_{Fx} + 2W_x$$

where

D_x is the die groove diameter at point x along the transition

d_x is the mandrel diameter at point x

S_F is the final wall thickness of the finished tube (shell final wall)

W_x is the wall reduction

This relationship is a simple linear offset from the mandrel. It just adds the final wall thickness and the amount of wall reduction onto the mandrel diameter to get the die groove diameter.

The linear design of tooling can begin from several points. In the simplest case, a designer uses a single straight taper and based upon the starting and final material dimensions, they design the die and mandrel. The designer can design the die groove given a mandrel to start with. If the designer selects a straight multi-tapered mandrel, and the input and the designer has chosen the finished material dimensions, then the designer

can design the die groove.

Another variation of linear tooling takes into account a particular taper, tolerances, and matching of the die and mandrel. The equation for the geometric features of the die is:

$$D_x = D_F + cx(D_L - D_F - Z - li) + \frac{x}{l}(Z) + nx$$

where

D_x is the die groove diameter

D_F is the outside diameter of the finished tube

c_x is a factor which is a function of the rolling conditions

D_L is the outside diameter of the hollow bloom (input material)

Z is the minimum mandrel taper desired

l_i is the clearance between the inside diameter of the hollow and the mandrel

$\frac{x}{l}$ is the ratio of the working groove length related to the length of the working groove

n_x is the clearance which is to be taken into account between the hollow and the maximum mandrel diameter

The equation for the geometric features of the mandrel is:

$$d_x = d_F + c_X (d_L - d_F - Z - l_i) + \frac{x}{l} (Z) + n_x$$

where

d_x is the die groove diameter

d_F is the inside diameter of the finished tube

c_x is a factor which is a function of the rolling conditions

d_L is the inside diameter of the hollow bloom (input material)

Z is the minimum mandrel taper desired

l_i is the clearance between the inside diameter of the hollow and the mandrel

x/l is the ratio of the working groove length related to the length of the working groove

n_x is the clearance which is to be taken into account between the hollow and the maximum mandrel diameter

The relationships for the die and the mandrel are linear. The designer obtains the die groove by taking the finish diameter and adding to it a correction for the desired inlet conditions of the die plus an amount equal to the desired taper at the point along the transition. The values of c_x, Z, and l_i must be the same in order to match the die and the mandrel at all points x. The designer extracts the factor n_x from tabulated values available in the Mannesmann literature.

5.3.1.1.2. Discussion of Linear Tooling Die Groove Design

There are two important aspects of die groove design in linear tooling. These points apply to all tooling. First the designer must match the die and the mandrel. This means that in order to obtain a certain pattern of material deformation, the designer must locate the die and mandrel in a specific position relative to one another. This is important because the mandrel is typically moveable and setting it properly is a function of the machine setup. If the die and mandrel are not setup according to the way they the designer intended, then they will not perform as designed and the product will not have the proper characteristics of size or quality.

The second important aspect of die groove design is the number and intensity of tapers. The single taper design is simple, however it results in more work being done near the outlet of the tool than at the inlet[7]. This is undesirable because at the outlet, the

[7]Eddens, F.C., General Electric Co., Wilmington, NC, USA, Tube Reducer Tool Design and Manufacturing, 10th ASM Conference on Advances in the Production of Tubes, Bars and Shapes, Orlando, Florida, 1986, Published by ASM International

tooling has already manipulated the material considerably and it is not capable of withstanding high deformations.

In the project considered in this case, the third experiment utilized straight tooling. As the feed rate increased, the quality of the product decreased dramatically. Also because the tooling was old and not well documented, it was very difficult to get the die and mandrel set at the proper matching point. An uneven match results in material deformation taking place at unexpected locations along the tooling. We mention unmatched tooling in the results of experiment 3.

Linear tooling is obsolete. There are better design techniques available including curved designs and ideally the new design. Multiple taper tooling addresses the problems of single straight tapered tools to some extent, however it introduces the problem of discontinuous variations in the area reduction with respect to distance along the tool at the intersections of the tapers. Everywhere the tapers meet and change, there is a geometric discontinuity that affects the material deformation. We used straight taper tools in one of the experiments in this project because a particular size tooling was only available in that style. The experiment did result in the lowest quality output.

5.3.1.1.3. Curved Tooling Die Groove Design

The curved tooling design rests upon the fact that it is desirable to have the intensity of strain be distributed evenly across the length of the working section. This is equivalent to requesting that the rate of change of the cross sectional area be proportional to the cross sectional area reduction remaining beyond the point in question.[8] There is one other complicating fact. The material in the pilger machine moves through the tooling for two reasons. First is because the machine feeding mechanism forced it to advance. The second is because of the nature of the process, the material elongates and therefore

[8]Ibid., Eddens, F.C., Tube Reducer Tool Design and Manufacturing

advances. The feed as a result of elongation is stretch feed. At a point along the transition, the stretch feed is equal to the cumulative elongation at that point multiplied by the feed rate. Because this extra feed grows as a function of the distance along the transition, the governing relationship is

$$\frac{\partial a}{\partial x} = kAx$$

which has a solution of

$$A = ke^{ax^2}$$

where

a is the cross sectional area at a point x along the transition

k is a proportionality constant

A is the function of x for cross sectional area of the tooling

x is the distance along the transition starting with zero at outlet end

(Note: x is the distance remaining from the point being reduced to the end.)

Note that we define the value of x such that the process "grows large tubes". In other words it increases from the small end of the transition to the large end. This relationship implies two equations for wall thickness and diameter at any point x along the transition

$$W = ke^{ax^2}$$

$$D = Ce^{bx^2}$$

where k, C, a and b are constants fit to the particular curves or material dimensions.

The designer can compute the constants k and C by fitting known points based upon the starting and ending material dimensions. For more sophisticated application of this design technique, the designer can constrain multiple points along the transition design curve by choosing multiple values and fitting the equations through them. Typically desirable values for the exponents a and b are on the order of 2.

5.3.1.1.4. Discussion of Curved Tooling Die Groove Design

Curved tooling is desirable because by choosing the exponents in the above equations, the designer can select the amount of deformation along the tooling and design for it. By varying the exponent, we can place the larger amount of deformation near the inlet of the tool or near the outlet. It is desirable to use exponents that place most of the deformation near the inlet. This corresponds to exponents equal to about two. The curved design permits designing matched die and mandrel.

We think that the new design that we present next makes use of a curved die groove design similar to what we just presented. However, we cannot confirm he exact design because the design is proprietary.

From available literature and an understanding of the development of die groove technology, it appears that the exponential design equations are adequate for quality die groove design. The most important feature is being able to smoothly control the rate of deformation along the transition, which the curved die groove design accommodates.

5.3.1.1.5. New Tooling Die Groove Design

There is not enough information available publicly, since this is a proprietary design, to document the design equations used for this design. We leave the derivation of these relationships for public information to future work.

5.3.1.1.6. Discussion of New Tooling Die Groove Design

Once again, not much is known about the new designs. On the basis of an understanding of the development of tool designs, we suspect the basis of the new design die groove is the exponential design. The uniqueness of the new design is primarily in the treatment of side relief design. We will discuss side relief designs next. No new design tooling was available for the example project presented in this thesis. However, shortly

after we completed this process improvement project, the plant received a set of new design dies and they performed well.

5.3.1.2. Side Relief Design

Tooling must have side relief because as the tubing is being rolled over the mandrel, it elongates and moves forward. When the material moves forward, it moves straight off the mandrel. Because the material does not elongate along the path of the mandrel, there must be some space in the tooling for the material to move into. The side relief provides this space.

There are five basic styles of side relief design. They vary mostly in their sophistication. The more sophisticated the design technique, the better control the design has on the geometry. The five types are hand ground, tangential, circular, parabolic, and the new design. Figure 5.3 shows examples of these side relief designs.

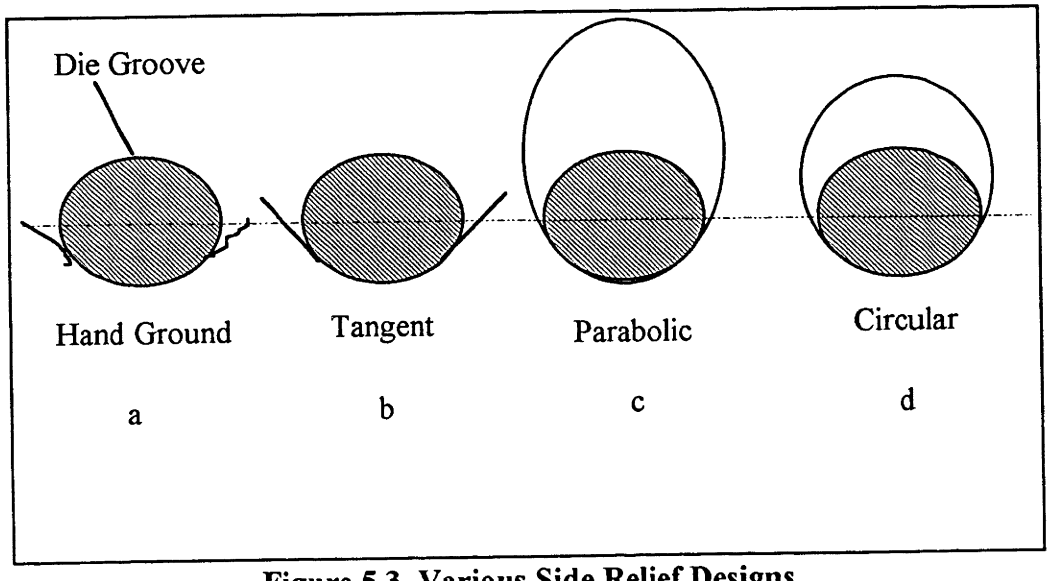

Figure 5.3. Various Side Relief Designs

5.3.1.2.1. Discussion of Hand Ground Side Relief

Hand ground side relief is the earliest form of side relief. This was the way tool and

die makers in the early days fixed tooling that did not work well. Die makers ground it out until it worked. Figure 5.3 picture "a" shows this style. The picture shows the full tube round and then one half of the side relief. Refer to die relief labeled in Figure 5.1 for a more complete view. Hand ground side relief is obsolete.

The tooling used in experiment 3 had hand ground side relief. This tooling performed poorly. Putting in side relief by hand is not realistic. Because of the complex three-dimensional functions required to get good designs, die making requires sophisticated tool manufacturing equipment.

5.3.1.2.2. Discussion of Tangent Side Relief

Tangential side relief is better than hand ground, but it is also obsolete. Tool designers construct tangent side relief by simply forming a straight line tangent to the die groove. Figure 5.3. picture "b" shows this type of side relief. It does not provide enough side relief. Tangential side relief does not evenly distributed relief about the die groove. It concentrates side relief in a small region at either side of the die groove.

5.3.1.2.3. Discussion of Parabolic and Circular Side Relief

Parabolic and circular side relief designs are similar. Figure 5.3. pictures "c" and "d" illustrate these types of side relief. Both of them place a geometric shape, either a parabola or a circle, over the die groove. The space between the die groove and the superimposed figure forms the side relief. The key dimension is the distance measured at the die groove diameter between the outside of the work piece and the inside of the die. Both of these designs are reasonable if properly designed. The designer must take the feed rate, elongation and taper into account to insure that the proper amount of side relief exists at each point along the transition.

Typically liberal side relief accompanies the parabolic and circular side relief designs. Too much side relief results in low quality product because the tube becomes too oval.

When the metal gets oval, it squeezes repeatedly into the side relief and weakens as it gets reworked.

The dies used in experiments 2 and 4 were of this style side relief design.

5.3.1.2.4. Discussion of New Design Side Relief

The new design is proprietary and therefore we do not know the design for certain. We feel that the side relief design is the proprietary advantage of the new die design. Given an understanding of the development of side relief designs in the past, we can speculate about what the new design consists of. The new design probably provides a design that has more variables than the old designs so that a designer can work with a closed form solution to calculate all points around the die groove including the side relief. The multiple geometries probably include one or more arcs that the designers solve so the arcs are all tangent one to another insuring smooth geometry throughout the die groove. The new design, probably because of having better control over the geometry, typically has tighter side relief at the edges. This is possible because the new design more evenly distributes the side relief around the die groove instead of concentrating it at the edges of the die groove (on the diameter).

New design dies were not available for this project, but were available recently thereafter. Early results indicate they are superior, especially when running the process similar to experiment 3.

5.3.2. Estimators of Quality

The primary measure of quality in the design process is the degree to which the process exhausts the maximum material capability. The most common problem is too large of a reduction or too much work in the final portion of the transition after the material has already been substantially work hardened. The work distribution and strain intensity computations done over the transition region will indicate how the work

hardening progresses. The Q Factor gives an indication of how much we reduce the wall in relation to the diameter. Problems sometimes arise if little reduction occurs in the wall because diameter-reducing rolling means rolling with tangential compressive stresses and consequently an inclination to the formation of laps as long as there is not an adequately large wall reduction to cater for relief.[9]

5.3.2.1. Q Factor

The Q Factor is a ratio of the percentage change in wall thickness to the percentage change in cross sectional area. Designers commonly think that a Q Factor equal to one is desirable. A Q Factor greater than one implies a large wall reduction relative to diameter and a Q Factor less than one implies a small wall reduction.[10] The equation for Q Factor is

$$Q = \frac{\ln(w1/w2)}{\ln((D1-W1)/(D2-W2))}$$

where

w1 and w2 are the starting and ending wall thicknesses

D1 and D2 are the starting and ending outside diameters

An alternative definition of Q Factor is

$$Q = \frac{(\frac{(WT1-WT2)}{WT1})}{(\frac{OD1-OD2}{OD1})}$$

5.3.2.1.1. Discussion of the Q Factor

We can think of the Q Factor as a ratio of material deformation in the wall to

---

[9] Stinnertz, H., Mannesmann Demag Huttentechnik, Cold Pilger Tool Design Prevention of Product Defects, ASM Conference, Scottsdale, AZ, May 1988

[10] Ibid., Stinnertz, H., Cold Pilger Tool Design Prevention of Product Defects

material deformation in the diameter. If the Q factor is high, typically a sign of low quality, then intuitively one can reason that the material in the wall is being deformed a large amount. This deformation will likely be forward along the tool. A more moderate value of Q implies that there is a balance between the wall and diameter reduction and consequently the material deformation will be less along the longitudinal axis of the tooling. Q Factors have been a problem for larger products that are being reduced to a thin wall.

5.3.2.2. Work Distribution

We can use work distribution as an indicator of tool quality. The Work Distribution is a computation done either at a point along the tooling transition or over the full length of the tooling transition as a macro indicator of total work. The computation estimates and sums up the amount of work hardening that occurs over the length of the tool. By looking at a plot of work versus displacement, we can identify peaks and sharp transitions that might alert a designer to an inferior tooling design. The first step in obtaining a work distribution plot is to compute the strain at all points along the transition based on cross sectional area changes.[11]

$$\Delta\varepsilon_A = \ln \frac{Area_{mandrel,\,die,\,P}}{Area_{mandrel,\,die,\,P'}}$$

where the logarithm is of the ratio of the areas between the die and the mandrel at two distinct points along the transition of the tooling. The P and P′ points in Figure 5.1. are indicative of the amount that the material within the dies moves as a result of the movement from M to M′ of the input stroke. This occurs when the material feeds. We can apply this equation globally over the length of the transition to get a net strain or apply it at individual points along the transition to get a plot of strain as a function of distance.

[11]Eddens, Fletcher, C., The Cold Pilger Mill: Why Does It Work?, Fabricators and Manufacturers World Tube Congress, Chicago, IL, October, 1992

The integral of the strain multiplied by the flow stress at that strain over the distance of the tooling gives a relative value for the work distribution. A more comprehensive technique for calculating the work distribution includes an estimate of the stress strain plot and a numerical approximation for the work integral.[12]

5.3.2.3. Discussion of Work Distribution

The work distribution can give an exact indication of what material deformation takes place at points along the tooling transition. The biggest difficulty associated with work distribution is how to compute it. To be accurate we need a true stress strain relationship for the material at each point along the transition since with each stroke of the pilger machine, the material in the tooling is further work hardened. Also there is a need to compute the cross-sectional area of the tooling at many points. Because the cross-section is a variable complex three-dimensional shape, this is not easy without computer estimation tools. Because much of the tooling was old that we used in this project, there was not a good database of dimensional data to draw upon for this computation.

We completed the work distribution computation and a related computation, strain distribution, for a few tools. On the basis of the simplifying assumptions made, there was no clear difference in the tooling. This is suspicious since experiment three had such poor results. Because experiment 3 tooling had questionably accurate prints, we took geometric data by hand. The die groove profile and side relief are difficult three dimensional surfaces to profile by hand. A coordinate measuring machine is a better tool for this measurement.

---

[12]Kawamura, Kaz, Anco-Tech Inc., Dearborn Heights, MI, Work Distribution Analyses on Cold Pilger Mandrel and Die Groove Profile Evaluation, presented at the Emerging Methods for the Production of Tubes, Bars and Shapes Conference, Scottsdale, AZ, October 1992

5.3.2.3. Slip Factor

The slip factor is a measure of how the roll diameter, pinion pitch circle, in-going shell outside diameter, and outgoing tube outside diameter relate to one another. It is an important indicator of outside surface quality and also die life.

$$SF = \frac{DW - DR}{(DL + DF)(.45)}$$

where

DW is the roll diameter

DR is the pinion circle diameter

DL is the shell outside diameter

DF is the reduced output outside diameter

Ideally this value will be close to 0.7 or 0.8 for good quality performance[13].

5.3.2.3.1. Discussion of Slip Factor

Figure 5.1., shows the dies coming in contact with the incoming tube. The dotted lines on the dies indicate the outline of the die groove. The pinion gears attach directly to the dies and cause them to rotate. The pinion gears determine the speed with which the dies rotate. The linear velocity of the die surface is a function of the die groove radius and the angular velocity of the dies.

If the pinion diameter is larger than the die groove diameter, then the input material tends to get sucked into the machine. This is because the velocity at the die groove is slower than the forward velocity of the pinion gear. This affected experiment 3. Dies with a large inlet size cause material to be pulled into the dies that results in several quality problems. The product developed a very wavy surface and developed severe cracks at high feed rates. The pulling of yet more material into the dies when the machine is already

[13]Ibid., Stinnertz, H., Cold Pilger Tool Design Prevention of Product Defects

operating at a high feed rate, results in a large amount of material being processed through the tooling that easily exceeds the material capability. Improper slip factors are noticeable when the pinion is too large. We saw the symptom of too large of a pinion frequently in production as "sucking" or material being pulled into the die. Another name for this is self-feeding. This phenomenon indicates clearly that the tooling is setup improperly. The information about quality factors in Table 5.1 supports this conclusion.

5.4. Quality

The large number of interacting variables and the nature of metal deformation processes make the reducer process very complicated. The actual metallurgical changes in the process are the least understood aspect of the process. In particular, we need to more thoroughly investigate the affect of various process parameters, especially geometric attributes, on final product grain structure. There are several ways to further develop understanding in this area. One is to conduct theoretical and experimental research activities to obtain models that predict behavior. The production environment encourages us to document rules or heuristics that we learn through experience. Table 5.1. (which extends over several pages) is such a documentation. Some of the items come from published technical journal articles. Some of the entries come from experience.

Symptoms	Causes	Suggested Actions
Outside diameter defects[14]	CSA reduction too intense	Change tool design so there is a tapering off of strain intensity near the output end[15]
	Wall reduction too intense	Change tool design
	OD reduction too intense	Change tool design
	Elongation too high	Redesign process
	Free-sinking tube	Change tool design
	Side relief too large	Change tool design
	Feed rates too high	Change tool design or slow down feed rate
	Q factor too high	Change tool design, need smaller relief[16]
Outside diameter defects[17]	Bad in going shell	Inspect and improve
	Too tight or sharp edge on side relief	Change tool design
	Irregular shell feed caused by excess mandrel friction	Change tool design or change lube
	Pickup of metal on mandrel	Use high pressure stable lube or hard plate the mandrel
Self-feeding[18]	Wrongly adjusted inlet or outlet chuck	Re-adjust chuck to grip shell more solidly
	Excessive forward and rearward forces	Change roll-diameter and pinion pitch circle and reduced tube O.D.
		Select long pass length
		Select thickest possible mandrel rod
		Select a feed mechanism with recoil possibility at max load

[14]Stapleton, Glen, D., Examination of Selected Process Variables Associated with Pilgering..

[15]Ibid., Eddens, Fletcher, C., The Cold Pilger Mill: Why Does It Work?

[16]Stinnertz, H., Cold Pilger Tool Design Prevention of Product Defects, ASM Conference, Scottsdale, AZ, May 1988

[17]Ibid., Stinnertz, H., Cold Pilger Tool Design Prevention of Product Defects

[18]Ibid., Stinnertz, Cold Pilger Tool Design Prevention of Product Defects

		Reduce stroke rate
		Optimize tool pass design
Mandrel failure[19]	Deformation too intense at end of pass	Change tool design or slow feed rate
Lube breakdown and marred tools[20]	Deformation too intense at end of pass	Change tool design or slow feed rate
Product fractures[21]	Deformation too intense at end of pass	Change tool design or slow feed rate
Loss of dimensions; oval, bamboo, bowing[22]	Deformation too intense at end of pass	Change tool design or slow feed rate
Splitting with small feed rate[23]	Large wall reduction at end of taper or end of mandrel	Change tool design
Flat spots on tube[24]	Insufficient side relief	Change tool design
Ovalizing[25]	Too much side relief	Change tool design
Die pick up[26]	Too little side relief	Change tool design
End splitting[27]	Too little side relief	Change tool design
Tube shear marks[28]	Too little side relief	Change tool design
Micro cracks on I.D.[29]	Bad starting material; extrusion score marks, wrinkles or dirty	Improve quality of input material
	Sharp edge or damage on mandrel rod. (pipe wrench damage for example)	Polish mandrel, avoid abrasions such as wrench marks
	Mandrel too hot	Poor lube filter or lube
	Pickup material on mandrel	Polish mandrel, increase lube
	$Q << 1$	Change tooling or process

[19]Ibid., Eddens, Fletcher, C., The Cold Pilger Mill: Why Does It Work?
[20]Ibid., Eddens, Fletcher, C., The Cold Pilger Mill: Why Does It Work?
[21]Ibid., Eddens, Fletcher, C., The Cold Pilger Mill: Why Does It Work?
[22]Ibid., Eddens, Fletcher, C., The Cold Pilger Mill: Why Does It Work?
[23]Gerretz, J., and Stinnertz, H., The New Mannesmann-Meer Tooling Design, Cold Pilger Symposium, Mannesmann-Meer, Moenchengladbach, Western Germany, March 1969
[24]Randall, S.N., Tubular Production In the Cold Pilger Machine
[25]Ibid., Randall
[26]Ibid., Randall
[27]Ibid., Randall
[28]Ibid., Randall
[29]Ibid., Stinnertz, H., Cold Pilger Tool Design Prevention of Product Defects

	Tangential compressive stress in partial sink deformation zones which cause wrinkles and have notch effects	Reduce stress by changing tool design or lube
Generally poor quality[30]		Increase wall reduction in relation to diameter reduction
Generally too many surface[31] defects passing through	Increase area reduction	
Rectangular shaped surface defects not being mitigated[32]	Inadequate area reduction	
Oval shaped surface defects not being mitigated[33]	Too much area reduction	Change process to obtain less area reduction

Table 5.1. Pilger Symptom, Cause and Correction Reference

5.5. Chapter 5 Conclusions and Implications

Tooling has a direct impact on pilger product quality and throughput. In this way it is a key variable that affects productivity. Tooling is not just one variable. When looked at in detail, there are many tooling detail dimensions that affect pilger performance. Although it is changing, there is still an attitude that tooling is an art and only a few people know how to do it. Even though we use computer programs today to come up with tool designs, there is still a lot of personal judgment associated with the complete development of tooling.

This chapter has presented two sides of the tooling story. First we presented the equations and history in an attempt to describe the thought process behind tool design. Second we presented the table of heuristic rules that describe the non-quantitative techniques for tool development.

---

[30]Ibid., Stapleton
[31]Ibid., Stapleton
[32]Ibid., Stapleton
[33]Ibid., Stapleton

Generally the best designed tooling is of the new design type. This has been proven in several production cases. Even though we can purchase the new design tooling, there is still some value in us understanding the new tooling design process. If a firm understands the new tool design process, then the firm will also have a better understanding of how to best use the new design tooling. The new design tooling is a product of many inputs such as stroke rate, feed rate, input material size, elongation, material type, etc. Since all of these inputs have some variation in production, we can achieve optimal process operation only if we understand how the designers take these various parameters into account during the design process.

We can make several conclusions about the state of the experimental equipment used in this exercise. We expect that the use of any tooling of the straight taper type will result in performance that is inferior to the later designs such as curved and the new design. Whenever "sucking" or self-feeding is observed in the work piece, there is something not set up properly. We have probably not matched the pinion gear with the tooling. Large Q Factors are also indicative of upcoming problems. Table 5.1. can be helpful in choosing how to resolve these problems. Even though we knew about these fixes, the lead time was such that improved tooling was not available for use.

Chapter 6. Design of Experiments

6.1. Introduction

This section describes the experimental process used to supplement the process analysis. We present the experimental technique and the selection of variables.

"ALL experiments are designed experiments; the only question is whether well or poorly."[34] The point of this chapter is to describe the planning that went into the experiments used in this process analysis. The experimental design is Step 6 in the process improvement framework being followed. The purpose of conducting these experiments is to complement the process analysis activities as a part of the total process improvement project. We designed the experiments to seek a process optimum that maximizes the feed rate of the pilger machine while minimizing cracks in the product.

This chapter describes how and why we chose the experimental techniques used in the example and then defines the variables we used in the experiments. We describe the experimental preparation and integration with production. The chapter ends with concluding remarks. We follow this chapter with a chapter describing the experimental results.

6.2. Selection of Experimental Technique

We can segregate the experimental technique into two components, one related to the preparation and theoretical approach to the experiment, and the other related to the implementation of the experiment. First consider the preparation and theoretical approach, namely a decision about how to design the experimental setup.

We considered two experimental techniques, Box Hunter style full-factorial design and Taguchi design.[35] The treatment of noise in the variables and the assumptions made

---

[34]Gunter, Burton, H., Statistical Consultant, Hopewell, NJ, Discussion of A Systematic Approach To Planning for a Designed Industrial Experiment, Technometrics, February 23, 1993, Vol. 35, No. 1.

[35]For a description of these two techniques refer to Schmidt and Launsby, Understanding Industrial Designed Experiments, Second Edition, CQG Ltd. Printing, Longmont,

about what interactions are important are the primary differences in the two techniques. Taguchi categorizes noises into two categories, inner and outer. Inner noises are product related such as tolerance stack up and deterioration in the product. The outer noises are environmental and we cannot control them. They are what we commonly refer to as noise.[36] Taguchi also makes the distinction between on-line quality control and off-line quality control. On-line quality control occurs during production and therefore manipulation of the outer or inner noises is usually not possible. Off-line quality control occurs outside of the production environment and we can therefore manipulate at least the inner noises. Manipulations of inner noise may take the form of particularly assembling the test specimen to assure certain tolerance stack-up. Another manipulation of inner noise is to use a machine with all new parts to eliminate the noise of product deterioration. Taguchi searches for a robust design with respect to all noises, but in particular with respect to inner noises. His techniques utilize an "inner noise array" to explicitly measure the relationship between these noises and experimental parameters. Taguchi deals with the outer noises in a way similar to Box Hunter or any randomizing technique. Taguchi chooses an orthogonal noise array to randomly distribute the noise over all trials and parameters. In the production environment then, with only "outer" noises, the Taguchi technique for dealing with noise is very similar to Box Hunter.

The estimated inter-relationship that we expect to exist between the variables is another factor in selecting the experimental design technique. Taguchi techniques assume that higher order effects are negligible. Box Hunter techniques make no such assumptions and set up the experiments to investigate all inter-relationships. If we do not understand a process very well and if the process does not have a heritage of experimental data, it is

---

Colorado, 1989

[36]Clausing, Don, Concurrent Engineering - Improved Total Development Process, MIT 2.870 text and class notes, 1991

difficult to estimate a priori which inter-relationships will be significant. Therefore Box Hunter full factorial designs are desirable.

Another factor to consider in setting up experiments is the cost of experimentation. This is the biggest reason to make the assumptions that facilitate use of Taguchi techniques. Taguchi techniques can reduce by orders of magnitude the number of experiments required compared to full-factorial techniques. In the example of pilger process improvement, we made a decision to do several experiments that investigate two to four variables. With this small number of variables, there is not a significant difference in cost between the two techniques.

For this process investigation, we chose Box Hunter full-factorial designs because the noise in the production and experimental environment are the same, the inter-relationship between variables is difficult to know a priori, and because the experimental designs were relatively simple making full factorial techniques reasonable.

We considered implementation of the experiments at two levels. First we envisioned a family of experiments that would provide a base of information and that built each other. Second, we planned the implementation of individual experiments in detail so they were similar. The objectives of the experiments were to understand the response of tube cracking to changes in elongation and feed rate. We accomplished the changes in elongation by changing the inside diameter only via mandrel changes. We established the final experiment to investigate the extrusion process that is upstream of the pilger machine. Finally, the experiments provided information to establish the "best practice". This was an optimistic goal for a scanning type experiment at this early stage of process development.

We planned a family of four experiments such that the early experiments were simple and the later ones were more complex. The experiments also progressed from strictly manipulating variables within the tubing mill to manipulating variables outside of the tubing mill, namely the extrusion mill. The planning of these experiments took into

account the particular product sizes that were the focus of the project.

The first experiment was a simple investigation to determine whether a response function existed and if so what magnitude of response was available. Because we were conducting the first designed experiments on the pilgering process, we did not know whether cracks would result from the planned variation in the experimental variables. The trial experiment permitted us to change the experimental variables so we could elicit a cracking response. The purpose of the trial experiment was to be able to conduct this preliminary investigation promptly and conduct it informally. We used the information we obtained to establish reasonable values for the second experiment.

The second experiment looked more closely at a particular size and alloy of product. It was a two factor three level experiment with nine data points. The factors were elongation and feed rate.

The third experiment was analogous to the second except it focused on a size and alloy of product that was historically problematic. The intent was to quantify the variables we knew would produce a particular phenomenon of failure. The third experiment was a two factor, three level experiment with nine data points. The factors were elongation and feed rate.

The fourth experiment was analogous to the first three with the exception that it included variables in the extrusion mill, the process preceding pilgering. The intent was to quantify the relationship between extrusion parameters and pilgering process results. The fourth experiment had four factors. Three of the factors had two levels and one of the factors, feed rate, had three levels for twenty-four data points. The factors were pilger elongation, pilger feed rate, extrusion billet temperature and extrusion speed. We repeated this experiment once to get a total of forty-eight data points.

We envisioned a fifth experiment that was to be analogous to the first three experiments with the exception of manipulating tooling parameters. In particular, we were going to compare three sets of tooling (including dies and mandrel) against one another in

an effort to determine the impact of tooling on product quality. This experiment did not materialize due to long lead time associated with obtaining the new technology tooling.

6.3. Selection of Experimental Variables

We used a survey to gather knowledge about the experimental variables. We distributed the surveys to people who were expert and knowledgeable about the pilgering process. A full list of the variables investigated in the survey is in Appendix I. Appendix I also includes a copy of the survey itself. We surveyed people inside and outside of the company. Most information came from the ingot, extrusion, and tubing mills inside the company. The questions on the survey were all qualitative. Our intent was to determine which variables people felt were the most significant. The most important variables from the survey provided a starting point for choosing the variables for the process investigation.

Tooling features, feed rate, and amount of reduction were the primary pilgering variables as indicated from the survey. The primary extrusion variables included extrusion speed, cylinder temperature, and billet temperature. The primary ingot variables included temperature of the pour, cooling rate, composition of melt, and thermal soak process parameters (times and temperatures). (The survey results are in Appendix I.)

We could only manipulate a few variables feasibly. For example, at the extrusion press it would have been desirable to manipulate the press cylinder temperature. This would have required up to several hours of heating or cooling of a very massive press cylinder to arrive at a steady state value for the run. To expect a large heavily burdened piece of equipment and crew to sit around waiting for temperatures to change, especially when priority customers are waiting for production orders to ship, was simply not reasonable.

The number of variables investigated was small, being limited to extrusion speed, extrusion billet temperature, pilger feed rate, and pilger cross-sectional area reduction.

6.4. Definition of Variables

Throughout this process improvement example, we conducted experiments that investigated the impact of four key variables on one response variable. The experimental variables were pilger feed rate, pilger crack rate, extrusion billet temperature, and extrusion speed. The elongation factor is similar to a size factor. Changing the elongation of a particular output diameter changes the inside dimension. We kept the alloy the same within each individual experiment. The response variable is the number of cracks in pilger output material. We define each of these variables in this section.

Pilger feed rate: This is the amount of material fed into the pilger machine with each stroke of the machine. People at the plant refer to the feed rate as the "number of strokes". This is an informal measure which refers to the number of cycles the machine makes at that feed rate to advance the material 6.5" into the machine. The unit of measure used in the thesis is feed rate in inches per stroke. We measure the feed rate in terms of the movement of the input stock and not the output stock. Because of the elongation that occurs in the machine, it is important to maintain the distinction between movement of the input material and movement of the output material. The input material is a different size and moves at a different rate than the output material. We measure the feed rate by taking a ratio of the distance traveled by the input material and dividing it by the number of machine strokes.

Pilger Elongation: Elongation is the ratio of the starting cross sectional area to the finish cross sectional area. It represents the amount of work that a particular product undergoes during processing. Elongation is a dimensionless value. We measure it by measuring the diameters and wall thicknesses of the input and output material and then computing the ratio of cross sectional areas.

Extrusion Billet Temperature: This is the temperature at which the extrusion press operator removes the billet from the preheat furnace on the press and places it into the press cylinder. Three thermocouples on the press loading rack measure it in degrees Fahrenheit. The press sensors take an average of the three temperature values from the front, middle and rear of the billet. The billet temperature is difficult to control because of the time lag associated with the temperature rise in the billet and because of the cooling that occurs between the time the billet leaves the oven and enters the press cylinder.

Extrusion Speed: This is the rate at which the hollow tube exits the extrusion press die. We measure it using a stop watch and a ruler to compute the rate. We took the measurement periodically along each extrusion. We averaged the individual values to arrive at an extrusion rate for each extrusion.

The response variable is the cracking rate.

Cracking Rate: This is the number of cracks per foot that we counted visually on the tube. We counted the cracks visually for a certain distance (from 9 to 50 feet) and then formed a ratio. This measurement is somewhat subjective. It does present challenges when comparing results across experiments because it does not capture the exact type of crack. Within a particular experiment, the cracks are typically the same.

6.5. Experimental Preparation

The experimental preparation consisted of planning the experiment and gathering the required materials and tooling. We documented the experimental plans in order to facilitate following the procedures. We documented each plan according to the experimental design and then organized the plans into a series of steps. The steps covered both the preparation and the implementation of the experiment. We then discussed these

steps with the people knowledgeable of the process to determine validity and with the people who were going to participate in the process to confirm their support. We took the current production flow through the factory into account since we had to obtain the material required for experimentation and we had to allocate the processing time on equipment leading up to the pilger machine. Setting up the experiments in the shop usually ended up being an informal process.

6.6. Integration of Experiments with Production

We simply had to integrate the experiments with production because this was our only mode of conducting the experiments. Running experiments in the shop helped the operators learn about the process. They could transfer this learning directly to their daily activities. The most important aspect of integrating with the production activities was communication with the production people about the experiments and about the improvement project. The communication included gathering information from them, recording and responding to their ideas, and sharing the results of the experiments with them.

6.7. Chapter 6 Conclusions and Implications

Designing and planning experiments is crucial to their success. We increased the probability of experimental success by carefully selecting experimental variables, laying out clearly the experimental procedure to be followed, and by preparing data sheets in advance. Working closely with all people involved with the process is important in order to gain complete knowledge and to build a team who can work together to accomplish process improvement.

Every experiment must have a clear objective and must fit within a framework of process improvement so we can make a decision as a result of the experiment. There is a trade-off between putting a large amount of effort to put into a single experiment versus putting a relatively small amount of effort into several small experiments. This decision depends upon the amount of time available, and the amount of risk that the organization

can absorb. If the investigator plans one large experiment, the risk of not getting any results will be higher than the same risk associated with running several smaller experiments. With several experiments, we can at least be certain of at least some intermediate results.

Chapter 7. Experimental Results

7.1. Introduction

The goal of the experiments is to optimize the process by simultaneously increasing the feed rate while minimizing or eliminating cracking. This chapter presents the results of the experiments. This corresponds to Step 8 of the process improvement framework, Integrate Experimental Results, that we presented in Chapter 2. The results of the experiments are first summarized in an overview and then described in detail according first to major result and then individual experiment. The individual results correspond closely to the different experiments. This chapter concludes with comments and recommendations.

7.2. Presentation and Discussion of Results

We summarize the experimental results in the following illustrations and descriptions. We present a complete overview of the experiments and their results in Table 7.1. We include a complete data set and statistical analysis in Appendices II and III for reference. We present initially the results of the experiments as conclusions of the project as a whole and subsequently according to individual experiments.

We can categorize the primary observations of the experiments into four areas: First very little cracking occurs at low values of elongation. Cracking only occurs significantly at medium and high feed rates (with one exception being very low feed rates). Second, for very low feed rates, there is tendency for cracking rate to increase as feed rate decreases which is possibly counter-intuitive. Third, for medium and high elongations and medium and high feed rates, cracking tends to increase with increasing feed rate. Finally cracking at the pilger increases substantially for high press extrusion speeds.

Ex-periment #	Material	Input Size	Output Size	Elong-ation	Range of Feed rates ("/str)	Purpose	Factors	Response
1	Alloy A	4.0"x0.40"	2.82"x0.07" 2.82"x0.14" 2.82"x0.16"	7.35 3.77 3.39	0.81 0.72 0.46	Trial experiment Learn about the procedures	Elongation Feed rate	No cracks resulted
2	Alloy A	5.9"x0.38"	4.0"x0.12 4.0"x0.17 4.0"x0.25	2.96 2.07 1.46	4.5 3.2 2.2	Quantify relation-ship between factors and response	Elongation Feed rate	At very low feed rate, cracking occurs
3	Alloy B	7.4"x0.65"	5.9"x0.16" 5.9"x0.22" 5.9"x0.32"	4.9 3.5 2.3	1.2 0.50 0.14	Reconstruct known case of cracking	Elongation Feed rate	Cracking increases with feed rate
4	Alloy A	6.1"x0.79"	4.0"x0.14" 4.0"x0.35"	7.95 3.28	0.80 0.26 0.43	Quantify relation-ship between extrusion speed and cracking	Elongation Feed rate Ext. Speed Ext. Temp.	Cracking increases with extrusion speed

Table 7.1. Summary of Experiments

7.2.1. Observation 1; Process Robust for Low Elongations

The first experimental observation is that in all experiments the process is relatively robust to cracking at low elongations (approximately 2 to 3). This makes sense considering that at low elongations, the process is minimally affecting the input material

that naturally leads to reduced likelihood of cracking. Low elongations correspond to very little material deformation. This result alone implies that for pilgering with no cracking we should choose processes with low elongations. (This is the trivial solution.) The problem with the trivial solution is that it penalizes production by operating at a non-optimal production point where we add very little value. In the limit this strategy negates the reason for introducing the pilger machine into the context of the tube production process in the first place. The lack of cracking at low elongations indicates that elongation is a threshold variable with respect to cracking. Below certain values of elongation, there is little or no cracking response.

7.2.2. Observation 2; Cracking Occurs at Very Low Feed Rates

The second experimental observation is that for very low feed rates (0.02" per stroke or 0.11 feet per minute) a high quantity of cracks were observed. Experiment 2 illustrated this. These cracks were not typical (refer to the third experiment for "typical" cracks) in that they were small "zipper" shaped cracks that measured on the order of 0.125" in length. Figure 7.1. characterizes these cracks.

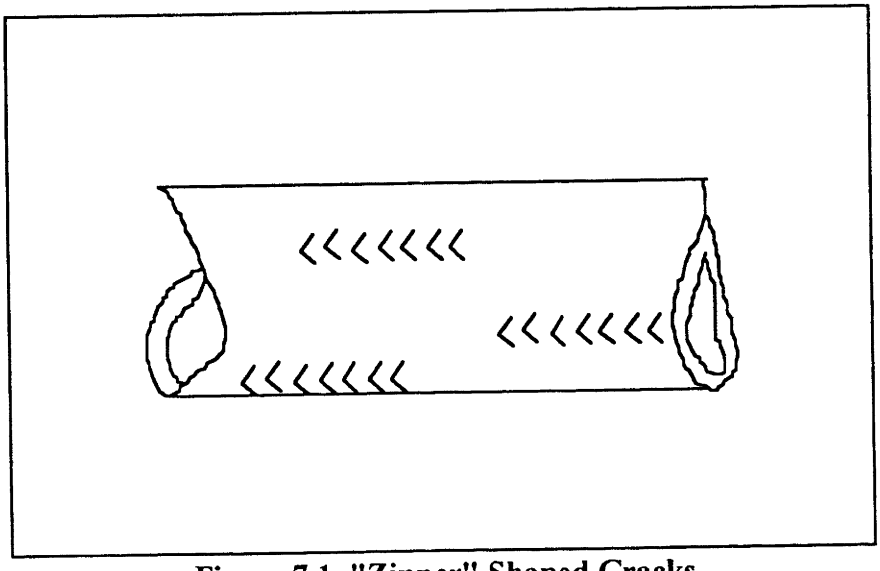

Figure 7.1. "Zipper" Shaped Cracks

To better understand the phenomenon of cracking at low feed rates, it is useful to

visualize the cracking response over the full range of feed rates. We did not observe this total range of response in any one experiment. Experiments show that for one pilgering setup cracking occurs at very low feed rates and for another setup cracking occurs at high feed rates. If we put the results of experiments 2 and 3 together the plot in Figure 7.2. is the result. This plot combines data from two products. If we make a hypothesis about cracking, the plot in Figure 7.3. of cracking versus feed rate results. The hypothesis indicated by this plot is that if we had experimented with a single product over the entire range of feed rates, cracking would have been high at both ends of the range.

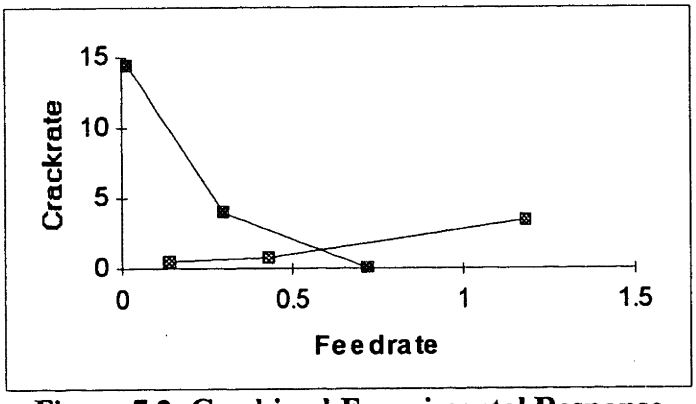

Figure 7.2. Combined Experimental Response

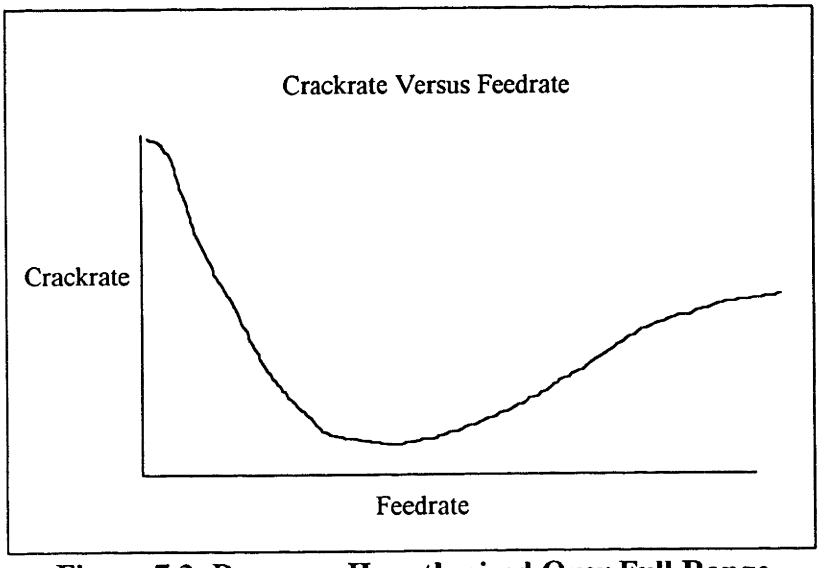

Figure 7.3. Response Hypothesized Over Full Range

Thinking of the crack response over the full range is useful in two respects. First it helps to break a paradigm of a narrow operating range. There is a possibility that there are other acceptable operating regions than have been explored in the past during normal production. Second, by getting a larger view of the response function, it is possible to observe the nature of the process. As it turns out, the heuristics of the operators corroborate the results of initial experimentation in that we produced the product without cracks at parameter settings similar to those used every day in production.

One reason that we did not observe the full range of behavior in any one experiment is that the equipment available for experimentation did not have the capability of operating over the entire range. For experiments where we observed no cracking, we might conjecture that we could have caused cracking if the machine had a higher feed rate capability. In the short term, only the behavior within the operating range of the equipment is relevant. Even though the machines currently have this rate limitation, we can envision a situation in the future where the machines have higher capability that permits a more thorough investigation. For the third and fourth experiments we judged that it was not worthwhile to investigate the increase in crack rate at the very low feed rates considering that we would not operate the process in production at such slow feed rates.

7.2.3. Observation 3; Cracking Increases With Feed Rate

The third experimental observation is that for medium and high elongations (3 to 8) and medium and high feed rates (0.5 to 1.5" per stroke) the cracking rate increases approximately linearly with increasing feed rate. Experiment 3 displayed this most prominently. Experiment 4 also displayed it to some extent. With increasing feed rate, as is discussed in Chapter 5 in the Process Analysis section, there is a complex process that takes place that results in an increasing amount of material being fed into the dies per stroke.

The third experiment was unique because it used an input stock which notoriously

produced cracks. The cracks produced were very large and typical of reducer cracks in shape although some of the cracks were larger than typical. Figure 7.4. shows these cracks.

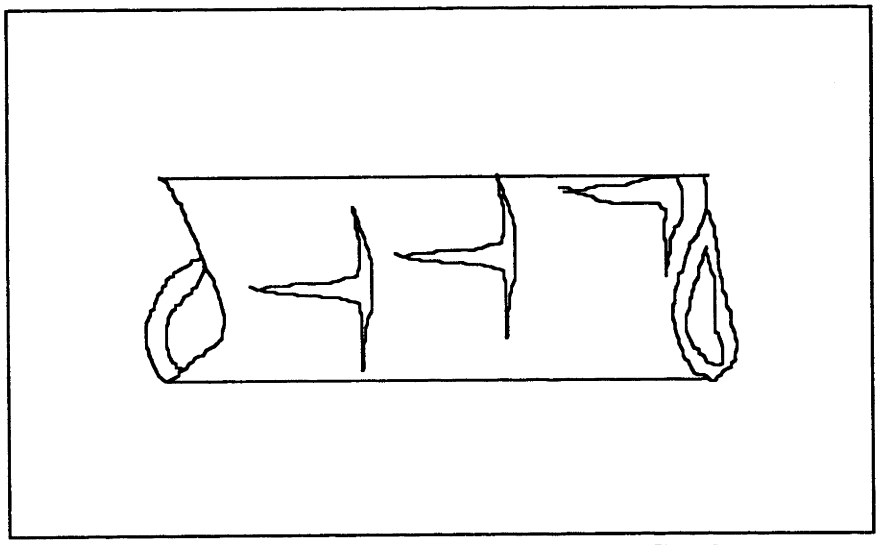

Figure 7.4. Typical Reducer (Pilger) Cracks

7.2.4. Observation 4; Cracking Is Related to Extrusion Speed

Fourth, for bloom extruded at high press extrusion speeds, cracking at the pilger tends to increase with increasing extrusion speed. We showed that material processed at the same elongations and feed rates at the pilger machine had different crack rates when the material had different extrusion speeds. This occurs because of differences in micro structure of the extruded material. The material extruded at high speeds is more likely to have an un-crystallized structure where the material extruded at low speeds will likely have a fine re-crystallized structure.[37] We can sometimes observe this structure by inspecting the grainsize on a polished cross-sectional surface of an extrusion. Although we do not entirely understand the effect of the input material's grainsize on pilger product

[37]Interview with Bob Emory, Extrusion Expert, November 1992.

quality, we showed in Experiment 4 that extruded bloom that appears to be exactly the same by visual inspection can have dramatically different behavior in terms of cracking during the pilgering process. For example a piece of bloom that we extruded hot and fast was unable to run through the pilgering process without severe cracking and breaking up. We followed it immediately with a piece of bloom that we had extruded cold and slow and this bloom ran through with little or no cracking. Both pieces of bloom appeared the same visually prior to pilgering.

7.2.5. Summary by Experiment

7.2.5.1. Experiment 1; Trial Experiment

The purpose of this experiment was to learn what the range of response was for the experimental variables and to learn what variables we could reasonably modify. The first experiment was unique because we saw no cracking response. The material size, tooling and machine did not produce the cracking phenomena. This made one point very clear. The process was not easy to understand. We planned this experiment to see how easy it was to set up the equipment and run an experiment. It did serve the purpose of helping the experimenter and operator learn about running experiments on the machine.

7.2.5.2. Experiment 2; Test of Typical Product Tested Over Wide Parameter Range

The purpose of this experiment was to exercise the pilgering process over the range of operating parameters to get a sense for the cracking response with respect to feed rate and elongation. This experiment was unique because the feed rate was extremely slow compared to daily production. There are two major observations.

First, there was not any significant cracking at the low elongations. This is reasonable since at low elongations there is little reduction and therefore little material deformation taking place. No cracking at low elongations is a useful experimental result because it confirms normal behavior as one of the experimental outcomes. This result shows that the experimental setup is capable of producing acceptable material.

The second result was that at very low feed rates this experiment produced unusual small cracks. Figure 7.1. shows the unusual small cracks. At high feed rates, cracking was insignificant. This is unique considering that intuitively cracking rate increases with increasing feed rate. Because this experiment tested the range of operation including feed rates such as .02 inches per stroke (260 strokes per 6.5 inches), we observed some unusual behavior. The process usually does not operate at these low feed rates. This experiment shows that it is possible to generate a cracking phenomenon by running the process at too low a feed rate. This experiment also shows that there is some optimal speed to operate the process.

Statistical analysis of the data shows that after eliminating the three data points at low elongation, the crack response can be modeled as

$$Crackrate = -15.82(Feedrate) + 12.52$$

where the slope has a p value of 0.008 and the intercept 0.001. On the basis of six data points, this model has less than a 0.1 percent chance of being a result of random variation of parameters. We investigated models that included a linear elongation term and quadratic feed rate terms but their fit was not significantly better than the above cited model.

7.2.5.3. Experiment 3; Test of Traditionally Poor Quality Product and Process

This experiment was unique because the material used was notorious for causing cracks such as those shown in Figure 7.4. The dies used were of a very old design and there was a mismatch of the pinion gear size with the dies. The purpose of this experiment was to test the hypothesis that we could cause cracking to occur on demand based upon the selection of alloy, elongation, feed rate, and tooling. The particular input material had a reputation for cracking during the pilgering process. Another reason for this experiment was to understand in more detail the failure phenomenon associated with cracking. Since this particular input material had a reputation for failing in a dramatic way, this experiment

could also serve as a way to get an amplified perspective of the metallic and mechanical details of failure.

We can cite three primary observations as a result of this experiment. First the notoriously problematic material, 7.38 x 0.65" B alloy stock being reduced to 5.86 inch outside diameter stock responded characteristically. This indicates that at least we can reproduce this behavior on demand and it is repeatable for this size and alloy. Second, we showed that cracking once again is not significant at low elongations. Third, at medium and high elongations, cracking increases linearly with increasing feed rate.

This experiment did not include trials at the very low feed rates that we used in Experiment 2 because the very low feed rates were not reasonable for production. We can hypothesize that at very slow feed rates the cracking rate may increase like in experiment 2.

The primary result of this experiment from a production point of view is to run the thickest wall at the highest feed rate and the medium and thin walls at the lowest feed rate to minimize cracking.

Statistical analysis of the data shows that after removing the three data points at low elongation, the remaining six data points can be modeled as

$$Crackrate = -.1189(Feedrate) + 2.021$$

where the slope has a p value of 0.049 and the intercept 0.84. In these models, because cracking may be zero for zero feed rate, the intercept is not of great concern. In this case the intercept is not significant, however the slope has less than a 5 percent chance of being a result of purely random variation of the parameters. We tried models including the linear product of elongation and feed rate however the fit was no better. We also tried models including quadratic feed rate with no better success. This experiment primarily confirms the bad performance of old style tooling being run on a machine that has an improper tooling and pinion gear setup.

7.2.5.4. Experiment 4; Test of Extrusion and Pilger Parameters

Experiment four was unique because it included parameters in the extrusion area (outside of the tube mill). The purpose of this experiment was to validate the hypothesis that changes in extrusion speed and extrusion billet temperature (although not obvious by visual inspection of the extruded product) affect the quality of product produced at the pilger machine. By varying the pilger feed rate and elongation, we caused changes in quality of product at the pilger machine. This was the most complicated experiment conducted in this project.

The cracks created in experiment four were similar to those pictured in Figure 7.4., but were not quite as large. There were some pieces that we extruded hot and fast which broke up continuously and we could barely process. These pieces were the exception. The two repetitions of data were not exact replicates because we could not repeat the experiments exactly.

When we analyzed the data, the first observation was once again that the low elongation cases had no crack response. We removed these data points as threshold data with no particular statistical value. Next the data from the high extrusion speed samples was identified as outlier data and also removed. This data being exceptional is the most significant result of this experiment because it confirms the initial hypothesis that the extrusion press speed impacts pilger product quality. Finally after we removed these twelve data points from each repetition, we identified the remaining twelve data points (at high elongations and low extrusion speeds) to have no significant information left in them. Regressions on this data revealed no significant relationships. This means that in light of the extrusion speed effect, all other changes in variables resulted only in noise or insignificant changes in the cracking response.

The result of experiment four is significant when considered in the context of the other two experiments. The results suggest that if the extrusion parameter had been a part of experiments 2 and 3, the responses of cracking as a function of feed rate would also

have been insignificant. We must of course test this hypothesis in order to validate it.

7.2.6. Experimental Summary

The experimental results are another set of information that is useful in the quest to understand the pilgering process. Experimental results are of considerable short term value because unlike data taken from literature that documents theoretical understanding or which documents the results of another process, experimental results reflect the actual response of the process in the factory of interest. We must however interpret the results in the proper context. For all except the last experiment, we sampled only a single repetition of data. This resulted in a small number of data points, typically nine total for each experiment with these being blocked in groups of three. It is difficult or impossible with this limited amount of data to adequately identify outliers and to establish estimates of error in measurement. We repeated the final experiment twice, although it was not a perfect replication. Because of limitations in equipment set up, we seldom if ever reproduced exactly the targeted experimental values at both the extrusion press and the pilger machine.

One of the most significant factors in the experiments that we fixed over the short term was the tooling. We ran the experiments with old design tools and with questionably sized pinion drive gears on the dies. The plant changed these two factors after we completed this project and the quality and productivity of the process improved. The experimental results presented here will probably be the same in a qualitative way if they are re-run on new tooling, however the plant must also validate this.

Aside from collecting data for the experimental designs, we also collected data on background and environmental variables such as input and output material hardness, oil, die and mandrel temperatures, input eccentricity values, and input straightness values. We checked these data for correlation with the cracking response variable. The results of these investigations show that there is a relationship, not necessarily causal, between increasing cracking and increasing die temperature, mandrel temperature, and amount of

curvature in the bloom. We show the table of correlations in Appendix III, Experimental Statistical Analyses. From these experiments alone, it is difficult to tell whether, for example, the increase in tooling temperature caused cracking or whether the increase in tooling temperature was a result of the experimental parameters chosen. On the basis of a limited understanding of the process, and upon the survey of experts, we made a conclusion that the temperature itself did not cause the cracking and that the temperature increases as a result of the larger material deformations. An increase in elongation, and an increase in feed rate implies larger material deformations.

7.3. Chapter 7 Conclusions and Implications

Conducting experiments in the production environment is one of the best ways to contribute to process analysis and build process understanding. Since our goal is to improve production, conducting the experiments with the production line people, production material, and production equipment provides realistic results. The results are not achievable only in a laboratory. Step 7, Conducting Experiments, in the framework presented in Chapter 2 provides an opportunity to integrate all of the process understanding into an activity that validates or invalidates the accumulated knowledge and hypotheses.

The experimental results lend insight into the process. There is a quantifiable relationship between cracking and the feed rate. At slow feed rates, cracking decreases with increasing feed rate. At medium and high feed rates, cracking increases with increasing feed rate. There is also an observable relationship between cracking and extrusion speed. Cracking increases at high extrusion speeds. Because we based the experiments upon variables that were easy to manipulate and because the experiments had only one or two repetitions, there is a need for further investigation. The experimental results are useful mostly for planning further investigation.

This set of experiments was enlightening because it confirmed in a quantitative way what we knew heuristically:

- Material at low elongations does not crack.
- Material at medium and high elongations will crack worse when the feed rate increases from medium to high.

There were also two counter-intuitive results:

- Material when run at very slow feed rates will actually crack less when sped up.
- Material at the pilger machine that we extruded hot and fast at the extrusion press is more likely to crack than other extrusions even though on the surface it may not appear to be different. Further, the changes in extrusion speed completely overshadow any changes in the elongation and feed rate variables made at the pilger machine.

The experiments reported on here were preliminary since they were the first in the process improvement process. We conducted the experiments over a wide range of experimental variables. In order to identify optimal values for the process, the plant must conduct experiments over a smaller range of inputs.

One question that arises after reviewing the experimental results is whether or not we should have done one large experiment instead of these small experiments. One large experiment would have been an advantage because we could have evaluated more variables and we could have established a distinct set of results versus three somewhat independent results. The execution of this experiment would be much more complex. The logistics of coordinating a large amount of material, each with unique features through the mill could have been very difficult. The biggest reason not to do the large experiment at this stage of process development is risk. The risk is that we might receive no good results after going through such a large set of activities. The series of smaller experiments provides incremental results.

Chapter 8. Summary and Conclusion

8.1. Introduction

We have made many points about the process improvement framework, the identification of the process and experimenting to learn more about how to improve the technical aspects of the process. Chapter 2 proposed a process understanding and improvement methodology that we have followed throughout the remaining chapters. This chapter contains concluding remarks on each major project result. It also contains recommendations, and some suggestions for future work.

8.2. Concluding Remarks

8.2.1. Process improvement framework

The improvement framework is in itself an undeniably good thing to have. The framework presented in this thesis started with an evaluation of how the internal process knowledge compares with that available in the industry. It progressed through various forms of process analysis and ended with iterating back through the steps that require formulating improvement goals. Without the framework, process investigation and learning proceeds without long term direction. (Granted, in the short term, learning often appears to occur like a random walk.) The important thing is to have a framework within which to plan process improvement activities. This framework will also provide impetus for continuing the activities by providing definite activities "to do next".

8.2.2. Business purpose

Ideally we should prioritize all problems based upon economic need. This would ensure proper distribution of limited resources among competing process improvement activities. In this case we did not perform a rigorous economic analysis before choosing a process for improvement activities. Operating personnel had a "sense" that the pilger process was economically important and that productivity at the pilger was important. We interpreted productivity at the pilger as either recovery or processing speed improvements. This thesis provides a better sense for the economics of this problem. It turns out that

improving recovery at and downstream of an operation, especially for operations near the beginning of the operation stream, is the most important goal. A simple spreadsheet that assists with balancing economic value to various portions of the extrusion, pilgering, and drawing operations, will allow plant personnel to make better decisions about processing and tooling changes.

8.2.3. Survey of experts

A survey of experts provided strong evidence that out of sixty parameters, twenty-one of them are worth including in experimental plans. This information is valuable because it comes from people who work daily with the processes. In many cases, however, the operators did not base their opinions upon collected quantitative data, making it less valuable. There is a possibility that one or more of the variables in the "very important" category made it there because of something counter-intuitive happening. We can understand counter-intuitive happenings in the process only by improving technical process understanding and analyzing process data. The survey data provided a place to start even though it was subjective. As the organization improves its understanding, survey information such as this will reflect higher levels of quantitative understanding

8.2.4. Literature review

The literature presents a broad range of information ranging from how to pilger various materials to how a particular process parameter affects the product output. Most of the literature emphasizes tooling design methods and heuristics for improving quality and throughput. The literature uses little empirical data to integrate the design relationships with the production results and heuristics. The literature review points out that there is a lack of empirical process information and a lack of models that take into account the mechanics of materials at a microscopic level, i.e., at a level that models the deformation within the tooling.

8.2.5. Experiments

Extrusion speed affects cracking at the pilger. We caused this response by pushing

the limits of the extrusion speed to produce material at or near the threshold of failure. The material however was in all cases visually conforming. There were no visual defects in the selected pilger test pieces as a result of the extrusion process.

Feed rate affects cracking. We caused this response primarily by pushing the limits of the tooling capability. In experiment 3, we found after the fact that the tool design and machine setup influenced the cracking response. This does not invalidate the results, but diminishes their credibility somewhat.

There are unusual results at very slow feed rates where small cracks form at the pilger. This is not a situation seen in production, but may be useful information in the future if tool design models come about which are capable of designing tools to operate over the full range of parameters such as feed rate.

Pilgering is robust to cracking at low elongations. Cracks do not occur in this process when run at low elongations. This is what one would intuitively expect.

8.3. Recommendations

Determine where process improvement can make the most economic impact. This is framework Step 2. Determining where process improvement can make the most impact can be difficult and may require doing extensive business analysis and number crunching. To arrive at the value of improvement, we must know the value of resources. This may require identifying the bottleneck and taking into account the opportunity cost of not running certain products. We must know the product mix or we must make some assumptions. Going through this analysis may not seem like conducting process improvement, but because every problem is a business problem, this analysis is useful for understanding where the technical process fits into the business. We defined a technical process in Chapter 2 as a business problem with a technical process at its roots. After looking at the economics, it appears that the pilger process was not the highest leverage improvement opportunity in the plant.

Continue to follow through the framework for process improvement. Re-run the

experiments presented in this thesis on new design tooling. We expect that the results will be similar but less dramatic. Design future experiments that further investigate variables outside the tube mill and which focus on the desired operating regions of the parameters. Invest to the extent possible in latest technology tooling and pilgering equipment. Specifically, continue to upgrade the inventory of currently used tool sizes to the new design.

8.4. Future Work

Continue the process improvement cycle. The experiments should be re-run with the new tooling to determine the impact of the new design dies and the new pinion gear size. After the plant validates the results of the experiments with the new tooling, the plant should expend more effort in measuring the material quality at the press. The plant can design a set of more detailed experiments and implement them to determine more accurately the impact of extrusion speed on pilger output quality.

Develop a material deformation model that can describe behavior of the metal while in the tooling. The plant can integrate this result with die design equations to come up with die geometry that is optimum. A side challenge is to derive equations for a new style die design. This is currently proprietary information.

8.5. Conclusion

By establishing a framework for process improvement, including designed experiments for investigating technical processes, a firm can re-establish excellence in a "mature" process. The firm can facilitate this path of progress by taking advantage of technology available in the industry.

Appendices

Appendix I. Survey

Survey results

We distributed this survey to determine which pilgering variables were the most important. The percentages indicate what percentage of the respondents answered in the various categories. The "very + mod" category is the summation of those answering "very" and "moderate" for a given item. We distributed thirty surveys and we received fifteen back.

Survey Results[38]

Alloy	Very Impt 100%	Moderate 0%	Not Impt 0%	Total 1	Very + Mod 100%
Ingot Processes	0%	0%	100%	1	0%
Composition targets and variation	100%	0%	0%	1	100%
Impurity levels	100%	0%	0%	1	100%
Casting cooling rate	100%	0%	0%	1	100%
Internal metallurgical structure of ingot	50%	25%	25%	4	75%
Ingot preheat process	40%	60%	0%	5	100%
Purity of alloy	40%	20%	40%	5	60%
Size of ingot	0%	75%	25%	4	75%
Temperature of pour	0%	50%	50%	4	50%
Extrusion Processes					
Ingot preheat time	100%	0%	0%	2	100%
Ingot extrude temperature	100%	0%	0%	1	100%
Mandrel/submandrel size (ext. ratio)	100%	0%	0%	1	100%
Extrusion pressure	100%	0%	0%	1	100%
Ingot pre-heat temperature	50%	33%	17%	6	83%
Surface crystallization after extrusion	33%	50%	17%	6	83%
Press cylinder temperature	33%	17%	50%	6	50%
Extrusion speed	29%	43%	29%	7	71%
Press type (mandrel or piercer)	20%	20%	60%	5	40%
Hardness of ingot going into press	0%	50%	50%	4	50%
Particular press	0%	17%	83%	6	17%

[38]Survey results are sorted by importance. The factors in italics were added by survey recipients. The factors in bold are considered most important.

Time between ingot pour and extrude	0%	0%	100%	5	0%
Pressure (extrusion) profile					
Ingot length					
Product temperature					
Position in extrusion length					
Extrusion die					
temperature					
relief angle					
relief design					
Tube Processes					
Degree of 'solutionization' in anneal	78%	22%	0%	9	100%
Presence of temperature gradients in furnace	70%	20%	10%	10	90%
Bloom anneal practice	69%	31%	0%	13	100%
Crane speed from anneal to reducer	20%	30%	50%	10	50%
Amount of roll straightening	18%	36%	45%	11	55%
Ambient temperature	13%	25%	63%	8	38%
Grain size after anneal	0%	57%	43%	7	57%
Reducer Process					
Mandrel position with respect to 'gage' pos	88%	0%	13%	8	88%
Hardness of bloom going into reducer	80%	20%	0%	10	100%
Time since anneal	80%	10%	10%	10	90%
Stroke rate of reducer	56%	44%	0%	9	100%
Eccentricity of bloom going into reducer	55%	45%	0%	11	100%
Straightness of bloom going into reducer	50%	30%	20%	10	80%
Reducer pass (1st, 2nd, 3rd...)	33%	33%	33%	6	67%
Metal repaired prior to reduction	30%	30%	40%	10	60%
Full radius chamfer on front of bloom	0%	43%	57%	7	43%
Temperature of bloom when reduced	0%	22%	78%	9	22%
Incoming material dimensions	20%	80%	0%	5	100%
Outside diameter	56%	33%	11%	9	89%
Wall thickness	50%	38%	13%	8	88%
Inside diameter	38%	50%	13%	8	88%
Outgoing material dimensions	33%	67%	0%	3	100%
Wall thickness	60%	30%	10%	10	90%

Outside diameter	44%	44%	11%	9	89%
Inside diameter	25%	63%	13%	8	88%
Percent cross sectional area reduction	70%	30%	0%	10	100%
Percent wall thickness reduction	82%	18%	0%	11	100%
Lubricant	60%	20%	20%	5	80%
Viscosity	50%	40%	10%	10	90%
Temperature	33%	44%	22%	9	78%
Type (wax and water, oil, ...)	33%	56%	11%	9	89%
Die	100%	0%	0%	2	100%
Gap between dies	88%	13%	0%	8	100%
Maximum variation in die gap (front - back)	86%	14%	0%	7	100%
Cross sectional area reduction	78%	22%	0%	9	100%
Bearing length	75%	13%	13%	8	88%
Die grind surface (hand or machined)	71%	14%	14%	7	86%
Relief design (straight or curved)	67%	33%	0%	9	100%
Relief angle	67%	33%	0%	9	100%
Size of rear die opening	67%	17%	17%	6	83%
Amount of 'sinking' prior to mandrel touch	63%	38%	0%	8	100%
Temperature	44%	44%	11%	9	89%
Mandrel	100%	0%	0%	2	100%
Type of taper (straight or curved)	75%	25%	0%	8	100%
Length of taper	63%	38%	0%	8	100%
Particular reducer machine	33%	33%	33%	3	67%
Pinion pitch gearing size	100%	0%	0%	3	100%
Feed rate of machine	100%	0%	0%	9	100%
Timing of machine	100%	0%	0%	9	100%
Amount of rotation per stroke	78%	22%	0%	9	100%
Name plate size	33%	67%	0%	3	100%

[39]Table I.1. Survey Results

[39]Survey of 15 people both inside and outside of tubing plant. Survey conducted 8/92.

Actual Survey

Actual Survey

	Very Impt	Moderate	Not Impt	Top 5
Alloy				
Ingot Processes				
Temperature of pour				
Purity of alloy				
Ingot preheat process				
Size of ingot				
Internal metallurgical structure of ingot				
Extrusion Processes				
Ingot pre-heat temperature				
Press cylinder temperature				
Extrusion speed				
Surface crystallization after extrusion				
Press type (mandrel or piercer)				
Particular press				
Hardness of ingot going into press				
Time between ingot pour and extrude				
Tube Processes				
Bloom anneal practice				
Degree of 'solutionization' in anneal				
Presence of temperature gradients in furnace				
Crane speed from anneal to reducer				
Ambient temperature				
Amount of roll straightening				
Grain size after anneal				

	Very Impt	Moderate	Not Impt	Top 5
Reducer Process				
Metal repaired prior to reduction				
Time since anneal				
Temperature of bloom when reduced				
Hardness of bloom going into reducer				
Straightness of bloom going into reducer				
Eccentricity of bloom going into reducer				
Full radius chamfer on front of bloom				
Mandrel position with respect to 'gage' pos				
Reducer pass (1st, 2nd, 3rd...)				
Stroke rate of reducer				
Incoming material dimensions				
Outside diameter				
Inside diameter				
Wall thickness				
Outgoing material dimensions				
Outside diameter				
Inside diameter				
Wall thickness				
Percent cross sectional area reduction				
Percent wall thickness reduction				
Lubricant				
Viscosity				
Temperature				
Type (wax and water, oil, ...)				
Die				
Temperature				
Cross sectional area reduction				
Relief design (straight or curved)				
Relief angle				
Gap between dies				
Maximum variation in die gap (front - back)				
Die grind surface (hand or machined)				
Bearing length				
Amount of 'sinking' prior to mandrel touch				
Size of rear die opening				
Mandrel				
Length of taper				
Type of taper (straight or curved)				
Particular reducer machine				
Name plate size				
Pinion pitch gearing size				
Feed rate of machine				

Timing of machine				
Amount of rotation per stroke				

Table I.2. Actual Survey for Learning About Pilger Variables

Appendix II. Experimental Data

Experiment 1

Purpose

We conducted this experiment for the purpose of learning what the range of response was of the experimental variables and to learn what variables we could reasonably modify.

Design

Experiment 1				
Alloy	**Input Size**	**Output Size**	**Dies**	**Starting CSA**
A	4.0 x 0.40 Inches	2.82 O.D.	New K1 and Old	4.52 Sq Inches

Table II.1. Experiment 1 Constant Parameters

Results

The experiment showed that the for the alloy, tooling, elongation and feed rates tried, cracking is not a problem for this pilgering process. The explanation for this behavior is complex. As the first experiment in this study, experiment 1 indicates that the cracking phenomenon is not simply a function of elongation and feed rate.

Experiment 1 Results						
Ending Wall (Inch)	Starting CSA (Sq Inch)	Finish CSA (Sq Inch)	Elongation (CSA1/ CSA2)	Feed Rate (Stroke Per 6.5 Inch)	Feed Rate (Inch Per Stroke)	Crack Rate (Cracks Per Foot)
0.27	4.52	2.16	2.10	14	0.46	0.0
0.16	4.52	1.34	3.39	14	0.46	0.0
0.16	4.52	1.34	3.39	9	0.72	0.0
0.14	4.52	1.21	3.73	9	0.72	0.0
0.14	4.52	1.20	3.77	9	0.72	0.0
0.14	4.52	1.20	3.77	9	0.72	0.0
0.07	4.52	0.62	7.35	22	0.30	0.0
0.07	4.52	0.62	7.35	14	0.46	0.0
0.07	4.52	0.62	7.35	8	0.81	0.0

Table II.2. Experiment 1 Results

Experiment 2

Purpose

The purpose of this experiment was to exercise the pilgering process over the range of operating parameters to get a sense for the cracking response with respect to feed rate and elongation.

Design

Experiment 2				
Alloy	**Input Size**	**Output Size**	**Dies**	**Starting CSA**
A	5.87 x 0.383 Inches	4.0 Inches O.D.	Old dies	6.60 Sq Inches
Note: This metal had already had one reducer pass.				

Table II.3. Experiment 2 Constant Parameters

Experiment 2 Design Levels										
	Trial	1	2	3	4	5	6	7	8	9
Variable										
Mandrel Size		1	1	1	2	2	2	3	3	3
Bloom Feed Rate		1	2	3	1	2	3	1	2	3

Table II.4. Experiment 2 Design Levels

Experiment 2 Values			
Levels	Low	Middle	High
Variables			
Elongation	2	3	5
Bloom Feed Rate	0.02 Inches/Stroke	0.3 Inches/Stroke	0.7 Inches/Stroke

Table II.5. Experiment 2 Parameter Values

Results

We discovered the most interesting results at the very slow/low feed rates. There are two major observations made about this experiment. First there was not any significant cracking at the low elongations. The second major observation is that the cracking decreases linearly with increasing feed rate.

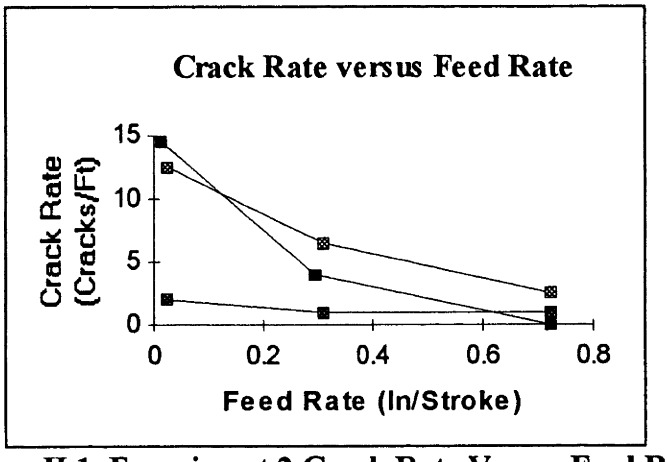

Figure II.1. Experiment 2 Crack Rate Versus Feed Rate

Experiment 2 Results						
Ending Wall	Starting CSA	Finish CSA	Elongation	Feed Rate	Feed Rate	Crack Rate
(Inch)	(Sq Inch)	(Sq Inch)	(CSA1/ CSA2)	(Stroke Per 6.5 Inch)	(Inch Per Stroke)	(Cracks Per Foot)
0.2517	6.6021	2.9635	2.2278	260	0.0250	2.0
0.2534	6.6021	2.9826	2.2135	21	0.3095	1.0
0.2543	6.6021	2.9921	2.2065	9	0.7222	1.0
0.1677	6.6021	2.0192	3.2696	256	0.0254	12.5
0.1721	6.6021	2.0692	3.1907	21	0.3095	6.5
0.1738	6.6021	2.0891	3.1602	9	0.7222	2.5
0.1112	6.6021	1.3589	4.8584	440	0.0148	14.5
0.1164	6.6021	1.4207	4.6471	22	0.2955	4.0
0.1199	6.6021	1.4618	4.5164	9	0.7222	0.0

Table II.6. Experiment 2 Results

Experiment 2 Environmental Variable Summary					
Starting Hardness	End Hardness	Input straight.	Oil Temp	Die Temp	Mandrel Temp
B-60	B-60	In/Foot	deg F	deg F	deg F
86	105	0.00946	96	106	
86	106	0.00401	89	96	
86	104	0.00697	89	96	173
86	103	0.00587	93	116	120
89	105	0.00557	93	122	170
85	108	0.01199	96	120	226
85	107	0.00355	100	104	
86	108	0.00735	115	150	250
86	106	0.00519	94	130	

Some data for Mandrel Temperature was not available.
ambient temp = 69F

Table II.7. Experiment 2 Environmental Variables

Experiment 3

Purpose

The purpose of experiment three, was to test the hypothesis that we could cause cracking to occur on demand based upon selection of alloy, elongation, feed rate and tooling.

Design

Experiment 3				
Alloy	**Input Size**	**Output Size**	**Dies**	**Starting CSA**
B	7.38 x 0.652 Inches	5.87 Inches O.D.	Old dies	13.3 Sq Inches

Table II.8. Experiment 3 Constant Parameters

Experiment 3 Design Levels										
	Trial	1	2	3	4	5	6	7	8	9
Variable										
Mandrel Size		1	1	1	2	2	2	3	3	3
Bloom Feed Rate		1	2	3	1	2	3	1	2	3

Table II.9. Experiment 3 Design Levels

Experiment 3 Levels			
Levels	Low	Middle	High
Variables			
Elongation	2.3	3.5	5.0
Bloom Feed Rate	0.1 Inches/Stroke	0.4 Inches/Stroke	1.4 Inches/Stroke

Table II.10. Experiment 3 Parameter Values

Results

There are three primary results or observations we can cite from this experiment. First the notoriously problematic material, 7.38 x 0.652" B alloy stock being reduced to 5.86 inch outside diameter stock responded characteristically. Second, cracking is once

again not a significant factor at low elongations. Third, at medium and high elongations, cracking rate increases approximately linearly with increasing feed rate.

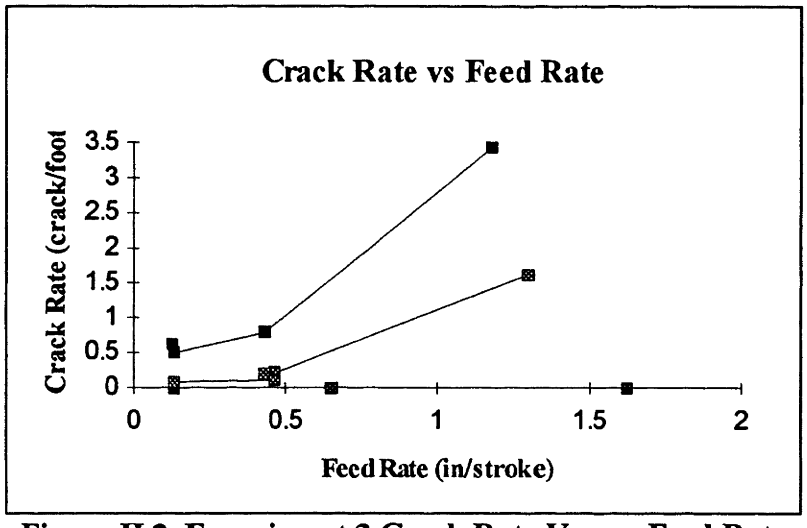

Figure II.2. Experiment 3 Crack Rate Versus Feed Rate

Experiment 3 Results						
Ending Wall (Inch)	Starting CSA (Sq Inch)	Finish CSA (Sq Inch)	Elongation (CSA1/ CSA2)	Feed Rate (Stroke Per 6.5 Inch)	Feed Rate (Inch Per Stroke)	Crack Rate (Cracks Per Foot)
0.342386	13.7811	5.9457	2.3178	4	1.6250	0.00
0.328482	13.7811	5.7186	2.4099	10	0.6500	0.00
0.328482	13.7811	5.7186	2.4099	47	0.1383	0.00
0.229416	13.7811	4.0653	3.3899	5	1.3000	1.62
0.224202	13.7811	3.9766	3.4655	14	0.4643	0.17
0.218988	13.7811	3.8877	3.5448	47	0.1383	0.08
0.19118	13.7811	3.4108	4.0405	5.5	1.1818	3.44
0.15642	13.7811	2.8077	4.9083	15	0.4333	0.78
0.15642	13.7811	2.8077	4.9083	47	0.1383	0.55

Table II.11. Experiment 3 Results

Experiment 4

Purpose

The purpose of Experiment 4 was to validate the hypothesis that changes in extrusion speed and extrusion billet temperature (although not obvious by visual inspection of the extruded product) affect the quality of product produced at the pilger machine, particularly when the pilger parameters of feed rate and elongation vary.

Design

Experiment 4				
Alloy	**Input Size**	**Output Size**	**Dies**	**Starting CSA**
A	6.08x 0.787 Inches	4.0 Inches O.D.	Old dies	13.09 Sq. Inches

Table II.12. Experiment 4 Constant Parameters

Experiment 4 Design Levels																								
Trial	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Variable																								
Extrusion Speed	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2
Extrusion Billet Temperature	1	1	1	1	1	1	2	2	2	2	2	2	1	1	1	1	1	1	2	2	2	2	2	2
Elongation	1	1	1	2	2	2	1	1	1	2	2	2	1	1	1	2	2	2	1	1	1	2	2	2
Bloom Feed Rate	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3

Table II.13. Experiment 4 Design Levels

Experiment 4 Levels			
Levels	Low	Middle	High
Variables			
Extrusion Speed	1 Foot Per Sec.		3 Feet Per Sec.
Extrusion Billet Temperature	680 Degrees F.		800 Degrees F.
Elongation	3		8
Bloom Feed Rate	0.2 Inches/Stroke	0.4 Inches/Stroke	0.7 Inches/Stroke

Table II.14. Experiment 4 Parameter Values

Results

There are three primary observations. First, once again at low elongations there is insignificant cracking. Second at medium and high elongations extrusion speed most strongly affects cracking. Third, the remaining data is insignificant when we remove the low elongation trials and the high extrusion speed trials from the data set. This indicates elongation and feed rate are meaningless when we take extrusion speed into consideration.

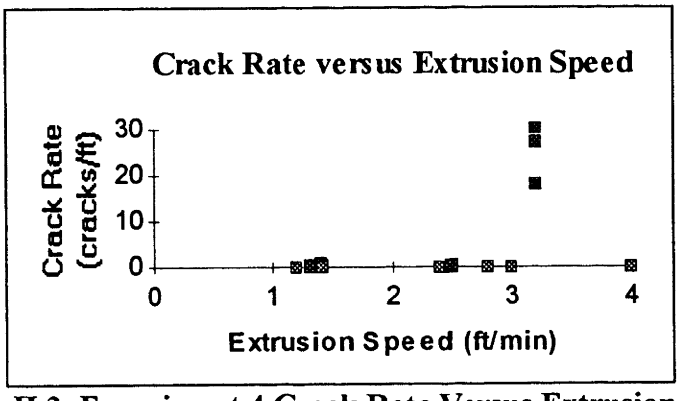

Figure II.3. Experiment 4 Crack Rate Versus Extrusion Speed

Experiment 4 Results - Repetition #1									
Extrusion Type	Ending Wall	Starting CSA	Finish CSA	Elong-ation	Feed Rate	Feed Rate	Extrude Speed	Extrude Billet Temp.	Crack Rate
	(Inch)	(Sq. Inch)	(Sq. Inch)	(CSA1/ CSA2)	(Strokes Per 6.5 Inches)	(Inch Per Stroke)	(Feet/ Minute)	(Degree F.)	(Cracks Per Foot)
fast/cold	0.14	13.09	1.65	7.95	11	0.5909	2.5	680	0.0784
fast/cold	0.14	13.09	1.65	7.95	15	0.4333	2.5	680	0.5185
fast/cold	0.14	13.09	1.65	7.95	28	0.2321	2.5	680	0.3111
slow/hot	0.14	13.09	1.65	7.95	10	0.6500	1.2	792	0.0556
slow/hot	0.14	13.09	1.65	7.95	14	0.4643	1.32	770	0.2353
slow/hot	0.14	13.09	1.69	7.76	28	0.2321	1.32	770	0.0926
slow/cold	0.14	13.09	1.69	7.76	8	0.8125	1.42	665	0.5179
slow/cold	0.14	13.09	1.65	7.95	15	0.4333	1.4	671	0.6987
slow/cold	0.14	13.09	1.65	7.95	28	0.2321	1.4	671	0.1042
fast/hot	0.14	13.09	1.65	7.95	8	0.8125	3.2	783	30.0000
fast/hot	0.14	13.09	1.65	7.95	15	0.4333	3.2	783	27.1698
fast/hot	0.14	13.09	1.65	7.95	30	0.2167	3.2	783	17.7778
fast/hot	0.35	13.09	3.99	3.28	8	0.8125	4	790	0.0000
fast/hot	0.35	13.09	3.99	3.28	14.5	0.4483	3	775	0.0000
fast/hot	0.35	13.09	3.99	3.28	28	0.2321	3	775	0.0000
fast/cold	0.35	13.09	3.99	3.28	28	0.2321	2.4	660	0.0000
fast/cold	0.35	13.09	3.99	3.28	15	0.4333	2.4	660	0.0000
fast/cold	0.35	13.09	3.99	3.28	8	0.8125	2.8	694	0.0000
slow/cold	0.35	13.09	3.99	3.28	8	0.8125	1.42	665	0.0000
slow/cold	0.35	13.09	3.99	3.28	14	0.4643	1.42	664	0.0000
slow/cold	0.35	13.09	3.99	3.28	25	0.2600	1.42	664	0.0000
slow/hot	0.35	13.09	3.99	3.28	15	0.4333	1.2	792	0.0000
slow/hot	0.35	13.09	3.99	3.28	25	0.2600	1.2	792	0.0000
slow/hot	0.35	13.09	3.99	3.28	8	0.8125	1.2	792	0.0000

Table II.15. Experiment 4 Repetition 1 Results

Experiment 4 Results - Repetition #2									
Extrusion Type	Ending Wall	Starting CSA	Finish CSA	Elong-ation	Feed Rate	Feed Rate	Extrude Speed	Extrude Billet Temp.	Crack Rate
	(Inch)	(Sq. Inch)	(Sq. Inch)	(CSA1/ CSA2)	(Strokes Per 6.5 Inches)	(Inch Per Stroke)	(Feet/ Minute)	(Degree F.)	(Cracks Per Foot)
fast/cold	0.13	13.09	1.58	8.26	10.50	0.62	2.5	680	1.822
fast/cold	0.12	13.09	1.47	8.89	15.00	0.43	2.5	680	0.021
fast/cold	0.12	13.09	1.46	8.95	29.00	0.22	2.5	680	0.493
slow/hot	0.13	13.09	1.64	8.00	10.50	0.62	1.3	770	0.578
slow/hot	0.12	13.09	1.48	8.83	13.00	0.50	1.3	770	0.500
slow/hot	0.12	13.09	1.46	8.95	30.00	0.22	1.3	770	1.905
slow/cold	0.13	13.09	1.57	8.34	10.50	0.62	1.4	671	0.624
slow/cold	0.13	13.09	1.54	8.48	13.00	0.50	1.4	671	0.269
slow/cold	0.13	13.09	1.56	8.37	30.00	0.22	1.4	671	0.870
fast/hot	0.14	13.09	1.67	7.85	10.00	0.65	3.0	775	3.364
fast/hot	0.13	13.09	1.55	8.45	15.00	0.43	3.0	775	2.606
fast/hot	0.13	13.09	1.56	8.40	31.00	0.21	3.0	775	5.476
fast/hot	0.36	13.09	4.07	3.22	8.00	0.81	3.4	767	0.738
fast/hot	0.34	13.09	3.90	3.36	15.00	0.43	3.4	767	0.000
fast/hot	0.34	13.09	3.90	3.36	29.00	0.22	3.4	767	0.000
fast/cold	0.36	13.09	4.09	3.20	8.00	0.81	2.5	680	0.000
fast/cold	0.35	13.09	4.02	3.25	15.00	0.43	2.5	680	0.000
fast/cold	0.35	13.09	4.02	3.25	29.00	0.22	2.5	680	0.000
slow/cold	0.35	13.09	4.05	3.23	8.00	0.81	1.4	671	0.000
slow/cold	0.35	13.09	4.02	3.25	15.00	0.43	1.4	671	0.000
slow/cold	0.35	13.09	4.02	3.25	33.00	0.20	1.4	671	0.000
slow/hot	0.35	13.09	4.04	3.24	8.00	0.81	1.3	770	0.000
slow/hot	0.35	13.09	4.04	3.24	14.00	0.46	1.3	770	0.000
slow/hot	0.35	13.09	3.97	3.30	30.00	0.22	1.3	770	0.000

Table II.16. Experiment 4 Repetition 2 Results

Appendix III. Experimental Statistical Analyses

Table III.1. summarizes the statistical models for experiments 2 and 3.

Statistic	Model	Coefficient	P value
Experiment Number			
2	Crack Rate = A + B (Feed Rate)	A = 12.52 B = -15.82	0.001 0.008
3	Crack Rate = A + B (Feed Rate)	A = -0.1189 B = 2.021	0.84 0.049

Table III.1. Statistical Summary of Experimental Models

Table III.2. shows correlations with the cracking response of some variables beside the experiment 3 factors (elongation and feed rate).

Correlation of Crack Rate with Environment	
Variable	*Correlation Coefficient*
Die Temperature	0.69
Mandrel Temperature	0.59
Oil Temperature	0.27
Bloom Straightness (Total Indicate Run-out per Foot)	0.63
Eccentricity	0.25

Table III.2. Experiment 3 Environmental Variable Correlations

Appendix IV. Cost/Trade-off Computations

Trade-off of 7.4 x 0.787 with 6.08 x 0.787 (Alloy A)[40]

Case 1 - from 7.4 x 0.787 inch bloom						
Reducer die size (Semi Finished Stock size)					4.0 x 0.178	4.0 x 0.255
Total product out (lbs)				141,421.00		
Production volume split					0.70	0.30
Volume per reducer die size (lbs)					98,994.70	42,426.30
Current recovery downstream of reducer					0.65	0.71
Volume output from reducer (lbs)					152,299.54	59,755.35
Total volume output required from reducers (lbs)				212,054.89		
Reducer pass 2						
	Weight per foot (input to pass 2)(5.86 x 0.382)				7.89	7.89
	Recovery, reducer pass 2				0.95	0.95
	Production feedrate (stroke/6.5 inches)				11.00	11.00
	Production rate, reducer pass 2 (#/hr)				1,584.99	1,584.99
	Volume started at reducer pass 2 (lbs)				160,315.30	62,900.37
	Reducer production time at pass 2 (hrs)				101.15	39.69
Reducer pass 1 (5.86 x 0.382 output)						
	Weight per foot (input to pass 1)(7.4 x 0.773)				19.31	19.31
	Recovery, reducer pass 1				0.95	0.95
	Production feedrate (strokes/6.5 inches)				12.00	12.00
	Production rate, reducer pass 1 (#/hr)				3,556.71	3,556.71
	Volume started at reducer pass 1 (lbs)				168,752.95	66,210.92
	Reducer production time at pass 1 (hrs)				47.45	18.62
Volume started at reducer (lbs)					168,752.95	66,210.92
Total volume started at reducers (lbs)				234,963.87		
Total reducer production time (hrs)				206.89		
Bloom size 7.4 x 0.773						
	lbs/foot = (OD-WT)(WT)(3.77)			19.31		
	Total volume of bloom (lbs)			234,963.87		
	Press recovery			0.57		
	Volume of material started at press			412,217.31		
	Bloom extrusion rate from rept /rec(output #/hr)			861.40		
	Hours press time required			272.77		
	Feet extruded			21,344.62		
	Extrusion speed calculated (ft/min)			1.30		

Table IV.1. Trade-off Spreadsheet for Press and Pilger

[40]Production data from reports LF619 and LF998 for year to date 7/31/92.

Case 2 - from 6.083 x 0.787 inch bloom					
Reducer die size (Semi Finished Stock size)		4.0 x 0.178	4.0 x 0.255		
Total product out (lbs)	141,421.00				
Production volume split		0.70	0.30		
Volume per reducer die size (lbs)		98,994.70	42,426.30		
Estimated recovery downstream of reducer (+5% improve)		0.70	0.76		
Volume output from reducer (lbs)		141,421.00	55,824.08		
Total volume output required from reducers (lbs)	197,245.08				
Reducer pass 1		4.0 x 0.178	4.0 x 0.255		
Weight per foot (input to pass 1)(6.08 x 0.787)		15.70	15.70		
Recovery, reducer pass 1		0.95	0.95		
Production feedrate (strokes/6.5 inches)		12.00	12.00		
Production rate, reducer pass 1 (#/hr)		2,892.20	2,892.20		
Volume started at reducer pass 1 (lbs)		148,864.21	58,762.19		
Reducer production time at pass 1 (hrs)		51.47	20.32		
Volume started at reducer (lbs)		148,864.21	58,762.19		
Total volume started at reducers (lbs)	207,626.40				
Total reducer production time (hrs)	71.79				
Bloom size 6.08 x 0.787					
lbs/foot = (OD-WT)(WT)(3.77)	15.70				
Total volume of bloom (lbs)	207,626.40				
Press recovery	0.68				
Volume of material started at press	305,332.94				
Bloom extrusion rate from rept /rec(output #/hr)	758.82				
Hours press time required	273.62				
Feet extruded	19,442.66				
Extrusion speed calculated (ft/min)	1.18				
Summary					
7.4 x 0.773 bloom					
Press hours	272.77				
Reducer hours	206.89				
Total hours	479.66				
Cost ratio (Reducer burden/Press burden)	0.22				
(*1 reducer hour worth 5 press hours)					
Rel Cost Press	272.77				
Rel Cost Reducer (=Reducer*Cost Ratio)	45.75				
Total Rel Cost	318.52				
6.08 x 0.787 bloom					
Press hours	273.62				
Reducer hours	71.79				
Total hours	345.40				
Cost ratio (Reducer burden/Press burden)	0.22				
Rel Cost Press	273.62				
Rel Cost Reducer (=Reducer/Cost Ratio)	15.88				
Total Rel Cost	289.49				
Comparison Savings with 6.08 x 0.787					
Press hours	-0.85				
Reducer Hours	135.10				
Material Saved (lbs)	106,884.37				
Net relative savings (in Press hours)	29.03				
Summary at estimated dollar values					
Comparison Savings with 6.08 x 0.787					
Press hours saved	-177.14		Press =	$209.00	
Reducer hours saved	6,214.82		Reducer =	$46.00	
Material saved	53,442.19		Aluminum	$0.50	
Total savings	59,479.87				

Table IV.2. Trade-off Spreadsheet for Press and Pilger (Cont'd)

Bibliography

Mannesmann Sales Brochure, Reference List for Cold Tube Reducing Mills, 1991

Mannesmann Sales Brochure, Machinery and Equipment for the Manufacture of Tubes Using the Cold Pilger Process, 1991

Stapleton, Glen D., AL Tech Specialty Steel Corporation, Watervliet, NY, An Examination of Selected Process Variables Associated with Pilgering Seamless Stainless Steel Hollows, Presented at the Emerging Methods for the Production of Tubes, Bars and Shapes Conference, Scottsdale, AZ, October 1992

Kawamura, Kaz, Anco-Tech Inc., Dearborn Heights, MI, Work Distribution Analyses on Cold Pilger Mandrel and Die Groove Profile Evaluation, Presented at the Emerging Methods for the Production of Tubes, Bars and Shapes Conference, Scottsdale, AZ, October 1992

Cook, C.S., Westinghouse Electric Corporation Science and Technology Center, Pittsburgh, PA, The Evaluation of Pilger Mill Lubricants, Presented at the Emerging Methods for the Production of Tubes, Bars and Shapes Conference, Scottsdale, AZ, October 1992

Keramati, B. and Tuck, P.B., GE Research and Development Center, Schenectady, NY and GE Nuclear Energy, Wilmington, NC, Monitoring the Pilger Tube Reduction Process, Presented at the Emerging Methods for the Production of Tubes, Bars and Shapes Conference, Scottsdale, AZ, October 1992

Kahl, W., Professor and Dr., Rhein-Westf. Technishe Hochschule Aachen, The Theory of The Cold Reduction of Tubes, Cold Pilger Symposium, Mannesmann-Meer, Menchengladbach, West Germany, March 1969

Zeunert, F. Dr, Mannesman-Meer Aktiengesellschaft, Development to Date and Future Development of the Cold Pilger Mill, Cold Pilger Symposium, Mannesmann-Meer, Menchengladbach, West Germany, March 1969

Gerretz, J. and Stinnertz, H., Mannesmann-Meer Aktiengesellschaft, The New Mannesmann-Meer Tooling Design, Cold Pilger Symposium, Mannesmann-Meer, Menchengladbach, West Germany, March 1969

Prieur, H., The McKay Machine Company, USA, Cold Pilger Mill Dies and Mounting of Same, Cold Pilger Symposium, Mannesmann-Meer, Menchengladbach, West Germany, March 1969

Spittler, H.J., and Wall, L.N., Combustion Engineering, Inc., USA, Mandrel Monitors and Continuous, Automatic Wall Thickness Measuring Instruments for Cold Pilger Mills, Cold Pilger Symposium, Mannesmann-Meer, Menchengladbach, West Germany, March 1969

Dobson, W.E. and B.R. Cope, The Phoenix Steel Tube Company, England, The Cold Pilgering of Carbon Steel Tubes, Cold Pilger Symposium, Mannesmann-Meer, Menchengladbach, West Germany, March 1969

Eddens, Fletcher, C., The Cold Pilger Mill: Why Does It Work?, Fabricators and Manufacturers World Tube Congress, Chicago, IL, October, 1992

Randall, S.N. and Prieur, H., McKay-Mannesmann-Meer Div, The McKay Machine Co., Youngstown, OH, Tubular Production in the Cold Pilger Machine, Iron and Steel Engineer, August 1967

Prieur, H., The McKay Machine Co., Wean Industries, Inc., Youngstown, OH, The Cold Pilgering of Carbon Steels, Iron and Steel Engineer, 1969

Stinnertz, H., Mannesmann Demag Huttentechnik, Cold Pilger Tool Design Prevention of Product Defects, ASM Conference, Scottsdale, AZ, May 1988

Prieur, H., Wean United, Inc., Eccentricity in Tube Reducing, American Society for Metals Conference, Chatham Center, May 1973

Friedman, L., Dr. and Sokolovskiy, V., Prof., The Theory of Cold Rolling Tube (Pilgering) Part I, Tube International, July 1992

Friedman, L., Dr. and Sokolovskiy, V., Prof., The Theory of Cold Rolling Tube (Pilgering) Part II, Tube International, September 1992

Eddens, F.C., General Electric Co., Wilmington, NC, USA, Tube Reducer Tool Design and Manufacturing, 10th Annual Conference on Advances in Production Tube, Bars, and Shapes, ASM International, Materials Park, OH, 1987

Robson, George, D., Continuous Process Improvement, Free Press, New York, NY, 1991

Schmidt, Stephen, R. and Launsby, Robert, G., Understanding Industrial Designed Experiments, Air Academy Press, Colorado Springs, CO, 1989

Hogg, R.V., and Ledolter, J., Engineering Statistics, MacMillan Publishing Co., 1987

Scherkenbach, William, W., The Deming Route to Quality and Productivity, Creep Press, Washington, D.C., 1988

Brooks, memo, 1958

Rearick, W.S., letter, 1958

Bartelt, memo, 1980

Tubeplant, memo, 1952

Tech. Div., memo, 1980

Coleman, D.E., and Montgomery, D.C., A Systematic Approach to Planning for a Designed Industrial Experiment, Technometrics, February, 1993, Vol. 35., No. 1.

The Alcoa Eight Step Process, 1989

Shoji Shiba, Professor, Total Quality Management class, MIT, 1991