PRODUCT/PROCESS IMPROVEMENT THROUGH PERFORMANCE MEASUREMENTS AND MODELLING: A CASE STUDY OF AEROSPACE WELDING

by

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ABSTRACT

The climate of competition in the commercial airline industry has placed a heavy burden on airframe and aircraft engine manufacturers to reduce costs. These costs include not only direct manufacturing costs, but also the costs associated with the product development cycle.

One technology which contributes significantly to product costs and long lead times is metal joining; specifically welding. By its nature, the welding process does not lend itself readily to automation. There are many variables which can effect its outcome and the interactions are so complex that control is extremely difficult. For this reason, welding has been labeled by many as an art rather than a science. As one of the older and most basic of technologies, welding is steeped in tradition and folklore (and hidden costs) which has made change all the more difficult. The foundation and guiding principle for this thesis is that regardless of whether welding is an art or a science, the process can be improved through the application of scientific approaches and manufacturing discipline.
This thesis is divided into two parts. The first part covers the development of a cost model which examines the Gas Tungsten Arc welding process and all the associated overhead costs and attempts to: a) Separate value adding activities from non-value adding activities and b) Better allocate overhead costs to the individual part level using principles of activity based accounting. This model will provide management with the information to identify the opportunities for improvement of both the process and the product design (which often defines the process).

The second part of the thesis examines, from a technical perspective, the hidden cost of correction for distortion and residual stress in GTA welding of thin materials. Using a finite element model which simulates the GTA welding process in the presence of a welding fixture, it is shown that proper differential heating and cooling of the fixture in the vicinity of the weld joint can have a positive effect. This model, or a future derivative of it, can be used as a tool for fixture design to achieve minimum distortion and residual stress.

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CHAPTER 1
Introduction

1.1 The Aircraft Industry; A Move to Cost-Based Competition
In the years since airline deregulation, the U.S. commercial aircraft industry has seen a number of significant changes, the most significant of which has been the displacement of technology by cost as the major factor in choosing new aircraft [MIT Commission..., 1989]. Under Civil Aeronautics Board (CAB) regulation, entry, pricing and route structure were controlled so that the only available avenues for competition among airlines were performance and service. This encouraged an environment in which aircraft and engine manufacturers competed through the rapid adoption of the most advanced new product innovations. Because the costs of the new technologies could be passed on to the consumers (by way of the CAB controlled fares), manufacturers were not particularly concerned with achieving high efficiencies. The aircraft and engine manufacturers were further supported by the large orders of military derivatives of the commercial airliners (e.g. the KC-135/Boeing 707). By shifting the emphasis of competition from performance to cost (purchase price and operating costs), deregulation has done away with the adoption of technology for technology’s sake and has placed a new importance on economic justification for new investments.

Deregulation has had the positive effect of forcing manufacturers to rethink their design and development processes (encouraging Design for Manufacturability and parts commonality), reorganize their operations to be more efficient (adopting manufacturing cell concepts and synchronous manufacturing) and to work with their subcontractors to provide better quality and reduced costs. On the negative side, the push of deregulation toward
lower aircraft purchase price and operating costs has forced a new approach toward development risk sharing which discourages the pull of new technologies and could eventually undermine the U.S. dominant position in the industry.

In an effort to gain flexibility, many airlines now lease rather than buy; weakening their commitment to particular equipment or suppliers. Often aircraft purchase decisions are delayed for several years, so that launch customers no longer provide working capital to the manufacturers. The manufacturers, in order to cover the enormous costs ($2 to $4 billion and 10-14 years to break even [MIT Commission, 1989]) associated with new development programs, are forced to find other partners with which to share the risks. In many cases, this risk sharing takes the form of an international consortium (e.g. GE's SNECMA and Pratt & Whitney's V2500 consortia) or offset agreements which guarantee a country the right to manufacture a portion of the product in exchange for doing business. This process accelerates the international flows of technology and program management skills which can, if the pattern continues, lead to the eventual loss of dominance of the U.S. aircraft industry. Figure 1 is a "causal loop diagram"¹ which graphically depicts the positive feedback loop just described. In words, the diagram says that: as Aircraft Manufacturer Competition increases, Cost Reduction gains in importance, which leads to more International Risk Sharing, which leads

¹ The causal loop diagram is a useful systems dynamics tool for understanding the behavior of complex systems. More use will be made of this in the chapters to come.
and Skills, which draws New Entrants into the industry, which feeds back to increase the Aircraft Manufacturer Competition.

Figure 1.1 - Causal loop diagram depicting positive feedback loop tending to promote higher levels of competition among aircraft and engine manufacturers.

1.2 Context and Motivation for this Thesis
The recognition that the policies currently in place tend to promote higher levels of competition and, therefore lower margins; have placed a heavy burden on airframe and aircraft engine manufacturing management to reduce costs. At one aircraft engine manufacturer, the site of the 7 month field study which is the basis of this thesis, a major initiative has been undertaken to reduce costs throughout the entire product development cycle. Specifically, the Company's manufacturing vision for 1995 states the following goals:

- Technology will be available at the start of full scale design
- Lead-time from design to utilization will be reduced by 50%
- Product cost will be reduced
- Engineering changes will be reduced by 50%
One technology which contributes significantly to product costs, long lead-
times and engineering changes is metal joining, specifically welding. By
some estimates, the cost of welding wastes, not only in terms of scrap, but also
in inspection, rework and program delays due to engineering changes and
process development delays, can run in the tens of million dollars annually.

The motivation for an academic study of this industrial process is obvious. But
the staggering estimate for the excessive wastes in welding combined with the
results of a study which shows only a 95% learning curve\(^2\) for welding
improvement, begs the question; Why is it apparently so difficult to bring
metal joining technology out of the dark ages?

The process of joining metals by welding and brazing has been perceived as the
very epitome of traditional manufacturing. It congers images of dark,
subterranean, smoke filled factories and of hooded, heavily clad iron workers
working in unbearable heat and surrounded by noxious fumes and blinding
arc light. The reality of metal joining processes in the aerospace industry
today is, for the most part, far removed from this image. But, although there
has been and continues to be a widespread effort to automate many of the
joining processes, the majority of them remain demanding manual tasks.

\(^2\) A 95% learning curve means that for every doubling of cumulative volume, costs decrease by
5% to 95% of the initial costs. This will be discussed in more detail in Chapter 4.
By its nature, the welding process does not lend itself readily to automation. There are many variables which can effect its outcome and the interactions are so complex that control is extremely difficult. Many manual welding processes require a great deal of dexterity and several senses - vision, touch and even hearing, to correct for the slight disturbances that always seem to occur during the welding process. For this reason, welding has been labeled by many as an art rather rather than a science. The foundation and guiding principle for this thesis is that regardless of whether welding is an art or a science, the process can be improved through the application of scientific approaches and manufacturing discipline.

1.3 Scope of Work

The research presented in this thesis is the culmination of a seven month field study at an aircraft engine manufacturing facility. During this study period, the author collected data from observations, interviews, surveys, literature searches and experimentation related to two primary topics: 1) Cost and quality data to determine the true costs (and wastes) associated with welding and 2) The minimization of distortion (a significant source of extra costs) in Gas Tungsten Arc Welding (GTAW) of thin sheet material.

The majority of information for topic 1 was obtained from interviews and surveys with personnel in four Business Units which do large volumes of welding fabrication. There were also extensive conversations with managers in the accounting and finance departments.
Chapter 1

The material for topic 2 was obtained primarily from literature searches conducted through both the Company and the MIT libraries and through conversations with MIT faculty and Company welding experts. The finite element analysis was carried out in the Company's manufacturing analysis group.

The thesis is divided into two parts: Part I of the thesis begins in Chapter 2 with a broad overview of welding processes and design procedures currently being practiced at the Company. Chapter 3 introduces the notion that "you get what you measure" in a general discussion of the characteristics of good and bad manufacturing performance measurement systems. The current, traditional system of performance measurement at the Company is then discussed as it relates to welding. The concept of Activity Based Cost accounting is presented as an improvement over traditional cost accounting practices in which overhead costs are allocated on the basis of direct labor dollars. Chapter 4 discusses the differences between the actual welding process flow and how the cost accounting system perceives the flow to be. Out of this discussion, a generic welding performance/cost model is developed using a System Dynamics approach which attempts to emulate the structure of the actual process flow. The model is used to illustrate the importance of performance measures which clearly delineate value added and non-value added activities and enable management to clearly see the possibilities for improvement. With the refinement of the cost modeling sector to include more accurate sensitivities to cost drivers, it can be used to more accurately determine the welding cost of a product because it allocates welding related overhead more sensibly. It is also used to show the effect of organizational
learning and alternative management incentive policies on the costs of welding.

Part I points out that current welding practices have much room for improvement. The percentage touch-time in welding related operations (for one part) is shown to be only one-quarter of that in machining related operations. One specific area for process improvement in welding is the control of distortion and minimization residual stresses, which account for a good portion of the uncovered wastes. Part II begins in Chapter 5 with a search of the literature for previous work in the area of distortion and residual stress control. Special attention will be given to work on the application of fixturing strategies to minimize distortion. Next, an analysis of the input parameters which effect distortion will be presented to establish a prioritization of cause and effect. This will be based on the available literature as well as on the opinions of experienced welding engineers within the Company. Chapter 6 presents the results of a finite element analysis to study the on the effect of fixturing thermal conditions on residual stress levels and the associated buckling distortion. The fixturing technique being modelled has been dubbed by The Welding Institute (in Cambridge, U.K.) as Low Stress Non-Distortion (LSND) welding. This finite element model (or a future derivative of it) could be used to aid in the fixture design process as well as for any future work on adaptive control of fixtures.
PART I - Incentives for Improving Welding

CHAPTER 2
An Overview of Welding Processes in Jet Engine Manufacturing

2.1 Metal Joining - Creating Form and Function from Simplicity
As a process, joining lies at the interface between materials science and manufacturing engineering. New materials, no matter how superior they may be in terms of material properties, cannot be used practically unless they can be produced with defined geometries. Without geometry or shape, which defines function, the properties of the material are useless. But, with practicality as the goal, even form and function are insufficient determinants of the success of a new material in a jet engine. Production costs and product operating costs (tied to weight) are interwoven into the formula for success. Joining processes offer the benefit of achieving complex form and function and low weight from a collection of simple, inexpensively produced shapes.

This simple statement of fact is sometimes obscured because joining processes often appear to consume greater fractions of the product cost and create more production difficulties than might be expected. The process of joining materials is much simpler in principle than in practice. This is true for several reasons. There are many disciplines that must be brought to bear to solve a joining problem (mechanics, materials science, physics, chemistry, electronics, etc.), requiring engineers with unusually broad training. Furthermore, the fact that welding or joining difficulties usually occur well downstream in the manufacturing process means that the value of scrap (and inventory in rework cycles) tends to be very high. A final reason for the critical
attention given to joining processes is that joints are often the weakest link or highest stressed points in a product and are notorious for being the sites of failures.

Companies have taken two approaches to the challenge of providing product form and function in a cost effective manner. The favored approach seems to be to design joints out of the product. A one-piece casting, for example, leads to a greatly simplified manufacturing assembly process and greatly reduced overhead requirements. The tradeoff, however, is a significantly increased product development lead-time and very high direct material costs (if the part is purchased from outside). The second approach, one which involves significant changes from the inside, is an overhaul of manufacturing joining processes to increase quality and throughput, while at the same time rethinking joint design practices to minimize the criticality of joints. The correct approach, it seems reasonable to surmise, is a combination of the two, where the mix can only be determined through a thorough understanding of the processes involved and the costs associated with each process.

The first section of this chapter provides a broad overview of the welding joining processes used in aircraft jet engine manufacturing and then focuses specifically on the most pervasive of processes, the Gas Tungsten Arc Welding (GTAW) process. Section 2.2 then goes on to outline the typical new engine development process with an eye toward joint design and joining process development. All of the organizations that effect the design process are represented and their functions are detailed. The chapter ends in section 2.3 with a description of a typical welding manufacturing process flow. As with
the design process, all of the outside organizations which influence the welding process are included and their functions are described.

2.2 Overview of Welding Processes in Jet Engine Manufacturing

The five basic forms of metal joining used in aircraft jet engine manufacturing are fasteners (rivets), adhesives, brazing, welding and diffusion bonding. Of the five, welding is by far the most pervasive of the joining processes currently in use. Table 2.1 lists the advantages and disadvantages of welded structures as represented by Masubuchi [Masubuchi, 1980].

<table>
<thead>
<tr>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>• High Joint Efficiency</td>
<td>• Complex process with sensitivities to many disturbances</td>
</tr>
<tr>
<td>Fracture Strength of Joint X 100 Fracture Strength of Base Metal</td>
<td>• Difficult to reliably inspect - leads to very stringent inspection criteria and slows throughput significantly</td>
</tr>
<tr>
<td>• Air Tight</td>
<td>• Residual Stresses</td>
</tr>
<tr>
<td>• Weight Savings = High Performance</td>
<td>• Distortion</td>
</tr>
<tr>
<td>• Simple Structural Design</td>
<td></td>
</tr>
<tr>
<td>• Reduction in Lead Time and Material Costs</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1 - Advantages and disadvantages of welding over other joining methods.
<table>
<thead>
<tr>
<th>Welding Type</th>
<th>% Usage* at Company</th>
<th>No. of Machines</th>
<th>Cost of Equipment ($)</th>
<th>Operator Skills</th>
<th>Comments, Common Defects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Arc</td>
<td>65%</td>
<td>630(all)</td>
<td>3.5K to 7.0K</td>
<td>Highest</td>
<td>• Sensitive to human error</td>
</tr>
<tr>
<td>Manual GTAW</td>
<td></td>
<td></td>
<td>7.5 to 125K</td>
<td>Medium</td>
<td>• Keyhole process, less heat input</td>
</tr>
<tr>
<td>Semi-Auto GTAW</td>
<td></td>
<td></td>
<td>5K to 9K</td>
<td>High</td>
<td>• For thicker mat'l - poor control</td>
</tr>
<tr>
<td>Manual PAW</td>
<td></td>
<td></td>
<td>75K to 150K</td>
<td>Medium</td>
<td>• For tube welding - low defects</td>
</tr>
<tr>
<td>Semi-Auto PAW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Used for weld buildups</td>
</tr>
<tr>
<td>Machine Gas Metal Orbital</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulse Wire</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistance Spot/Seam Flash 20%</td>
<td></td>
<td>153(all)</td>
<td>150K to 300K</td>
<td>Low</td>
<td>• Quality = f(heat, press, time)</td>
</tr>
<tr>
<td>Butt Welder</td>
<td></td>
<td></td>
<td>180K to 200K</td>
<td>Low</td>
<td>• High Quality, lots of flashing</td>
</tr>
<tr>
<td>Electron Beam</td>
<td>7%</td>
<td>18</td>
<td>1.2M to 1.7M</td>
<td>High</td>
<td>• High Quality, Tracking is critical</td>
</tr>
<tr>
<td>Laser Beam</td>
<td>4%</td>
<td>?</td>
<td>400K to 800K</td>
<td>High</td>
<td>• Same as EB, lower thickness, no vacuum required</td>
</tr>
<tr>
<td>Friction and all Others</td>
<td>4%</td>
<td>?</td>
<td>500K to 800K</td>
<td>High</td>
<td>• Similar to Flash Butt weld</td>
</tr>
<tr>
<td>Inertia Friction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: (*) By number of operations performed
Table 2.2 presents a listing of the welding processes currently in use at the Company. About 65% of the welds produced in engine components at the Company fall into the arc welding category. There are 7 arc processes used, each evolving from a common heat source, the electric arc. The most prevalent process by far is manual gas tungsten arc welding (GTAW) with approximately 50% of all welds belonging to this category. Figure 2.1 is a schematic diagram of a GTAW system where the torch end can be either hand held or machine controlled. Looking at the purchase costs per machine, and the flexibility of the process, it is easy to understand why this is so. Also, a well made GTA weld has a joint efficiency approaching 100%. The majority of defects associated with GTAW welding stem from starting and stopping of welds. Another problem associated with the GTAW process is distortion and residual stresses due to high heat inputs (this is especially true in aerospace applications where the materials tend to be very thin and lightweight).

![Figure 2.1 - Schematic diagram of gas tungsten arc welding (GTAW)]
Electrical Resistance welding is used for about 20% of the Company's welding. These processes are carried out, for the most part, on semi-automatic machines that require low operator skill/attention once the proper weld schedule is determined. A great deal of effort has gone into designed experiments which can determine the proper weld schedule for a given combination of material type and thicknesses.

Flash butt welding (used at the Company to join combustion liner segments) represents a small percentage of the usage for resistance processes, but it's integrity is generally unparalleled. Because of the amounts of flash produced in this process, high maintenance seems to be its largest drawback.

Electron beam and laser beam welding represent about 11% of the welds produced at the Company. The processes are very similar in their effect at the weld joint, but laser beam welding has the advantage of being executable at atmospheric pressure (as opposed to in a strict vacuum for EB welding). The advantage of EB welding is it's higher energy and corresponding ability to achieve deeper penetrations (up to 2 inches). Both processes are characterized by a narrow weld bead that minimizes the heat input into the part (reducing residual stresses and distortion), but, at the same time, places a critical importance on accurate seam tracking.

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1Based on conversations with the chairperson of the Company's core weld team, regarding the use of SPC techniques in welding. (Weld quality is a function of heat input, pressure and dwell time)
Inertia friction welding is an important process for joining the rotationally symmetric rotor disks that make up the core of the engine. These joints represent the majority of the "other" category.

2.3 The Life of a Weld in a Jet Engine - Concept to Service

2.3.1 The Product Development Process

The description of the GTAW process begins with a system approach to the entire product development cycle from the initiation of component and process technology to concept generation, leading to preliminary design, to detailed design, pilot production and finally to full-scale production. Within each broad process step are complex information flows and an underlying process flow converting inputs into outputs. Figure 2.2 shows the typical process flow for the complete product development cycle with a focus on the welded joint.

In the days before deregulation and intense price competition in the airline industry, new developments in jet engines were primarily technology driven. If a new material or technology breakthrough was achieved in the advanced component groups, it would find its way into a commercial application. In today's climate, another significant input to the conceptual phase of the development program emanates from marketing studies that identify important customer needs (such as weight, thrust, price range, noise level, etc.). Once the concept for the new engine product is developed, work must be done to focus on how the product specifications are to be achieved. This is accomplished in the preliminary design phase through an iterative trade study procedure that faces off cost (both manufacturing and operating) and performance of one option versus another. Cost data to make these tradeoffs
Figure 2.2 - Typical Jet Engine Product Development Cycle (with iterations)
generally come from Financial Manufacturing Accounting and are based on historical financial data for similar processes. A drawback of this approach is that the cost numbers used are generally accounting numbers and not necessarily representative of real costs associated with the particular process. For example, costs of extra intensive engineering support or high inventory carrying costs and "rework as required" steps, because of variability, may not be considered. Also, for newer processes, the historical data may not exist and cost estimates may have to come from advanced process technology people. The problems with accurately measuring costs and performance are more fully addressed in Chapter 3.

When the preliminary design process ends, the basic processes for joining are established and design work on welding fixtures can begin on a parallel path with final product design. This is the 2nd iterative loop, in which drawings and weld specifications are interpreted and translated to the actual welders in the form of detailed Manufacturing Operations Sheets (MOS's) and Process Operation Procedures (POP's) - detailing the Company's internal weld specifications. Direction is passed down to the quality inspectors in the form of Manufacturing Quality Instructions (MQI's). Welding processes and fixturing concepts are also refined within this loop.

The third and hopefully final iterative loop occurs in the early stages of production where the bugs are worked out of the system. The MOS's and POP's and MQI's are corrected as necessary and the process parameters are fine tuned. A fourth and very costly iterative loop can occur if their are problems that surface only after the product has been placed in service.
This entire process, from concept to final production currently takes on the order of X years for a typical engine. With programs under way to enhance concurrent (simultaneous) engineering and "rule-based" design, the Company has committed itself to a goal of a 1/2X year product development cycle. One major source of delays in the current system is the Engineering Changes due to causes ranging from simple drawing errors to design flaws and product/process enhancements at late dates. A second serious source of delays occurs in preliminary and final design due to non-commonality of products and parts. The lack of common or standard joint designs (for instance) has, in the past, led to non-standard approaches to solving joint design problems that often times led to poor design practices. In addition, the proliferation of different methods of accomplishing the same end goal eroded the possibilities of economies of scale in process technology.

The Company, since 1988, has made a laudable effort to resolve these issues with their introduction of the "Charter Part Council" that assures that big-ticket items (Charter Parts) such as diffuser cases are all designed in the same way and that all of the necessary information is incorporated onto "instructional drawings." Any variation from the standards incorporated into the instructional drawing must be approved by a multi-disciplined Council made up of members from, at the very least, Design Engineering, Manufacturing and Quality Assurance. Significant improvements in the
product or process must be made before a change is permitted to the instructional drawing.  

In addition to the enormous costs associated with delays (lost sales, opportunity costs, higher risks of competition), there are also high costs if poor decisions are made in the preliminary design stage. Figure 2.3 shows the well known Life Cycle Cost curve that relates the committed life cycle costs with the phases of the product development cycle. The message is that nearly the entire life cycle cost of a product is determined in preliminary design. This highlights the importance of comprehensive trade studies that can accurately predict manufacturing costs of various alternatives. One would like to be able to determine the impact of detail design decisions on the performance of the manufacturing system. The model presented in chapter 4 is one piece of what is required to accomplish this task.

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2 One drawback with this “design rule” approach to DFM is that it can be a vast oversimplification of a set of complex decision criteria. There is little mechanism for making tradeoffs when design rules such as “design out welding” are put into place.
2.3.1.1 Joint Design

Historically, the only requirement for standards in joint design was the common use of the Design Handbook and the use of common weld symbols. Experienced weld engineers know that the Design Handbook does not contain all of the answers and, in some cases, the recommended practices are actually counter to “good” design practices. Unfortunately, when the experienced weld engineers leave, so will much of the weld expertise.

Another historic barrier to good weld design is that designers generally consider welding to be a very forgiving process that does not require too much effort or attention. Hence tolerances are fairly loose (except for the concentrated energy beam methods) and variability is high. Additionally, because weld-joint design ownership rarely exists, if a problem does crop up on a joint design, the original designer is not likely to even find out about it, let alone fix it him/herself.
Because welded joints have always been considered the weak links in structural designs, they have been treated extremely conservatively by designers. "Knockdown" factors are used to degrade the material capabilities of weld joints so that the expected variability in quality can be accommodated. It is important to note that innovations which eliminate quality variations must be incorporated into the design rules (reducing the tendency to over-design) to achieve the full benefits of the improvement.

In keeping with the conservative approach to welded joints, the emphasis on inspection criteria appears to be quite high. Currently, there is no weld classification system in place, so that all welds, regardless of their criticality, are subject to the same stringent standards. This is something that is now being seriously examined at the Company.

\subsection{2.3.1.2 Fixture Design}

The process of fixture design is generally less sophisticated than product design, but this appears to be changing as more and more CAD is being used. Figure 2.4 shows the typical fixture design process. A trend in fixture design, apart from the use of CAD, is the Generic Tool Group which consists of Tool Designers and Manufacturing Engineers and performs a function similar to the Charter Part Council for product design. The Generic Tool Group is responsible for seeing that principles of good design and commonality of processes are adhered to.
An trend in fixture design, apart from the use of CAD, is the Generic Tool Group which consists of Tool Designers and Manufacturing Engineers and performs a function similar to the Charter Part Council for product design. The Generic Tool Group is responsible for seeing that principles of good design and commonality of processes are adhered to.

2.3.1.3 Weld Schedule Generation
The Business Unit concept has led to a decentralization of responsibilities for weld schedule generation. This may have led to the creation of some non-optimal or non-robust weld schedules that could eventually lead to yield problems. An effort is currently underway to centralize and computerize weld schedule generation to ensure consistency and optimality.

2.3.2 The Process Development Process
Other sources for delays occur outside of the product development loop in the area of process development. The process development cycle is typically much
Powder metallurgy disk development began in the mid-1960's and went into production in the mid-1970's. Cycle time: 10 years.

Friction welding (inertia bonding) of drum rotors development work began in 1980 and went into production in 1988. Cycle time: 8 years.

In general, the lead-time for major process development efforts seems to range from 6 to 18 years. The important issues to be considered in improving this performance are: 1) Providing the up front guidance and technology planning needed to guarantee technical readiness (in process technology) for new product development and 2) Smoothly transferring new process technologies from the development/research stage onto the production floor.

The Company has recognized these challenges as well and has initiated multi-disciplined Integrated Product Development Teams, Program Readiness Teams and Transition Teams as means to assure that processes and products are both compatible and timely. They are also considering formalizing their technology planning process to deal with the longer range issues.

2.3.3 The GTAW Manufacturing Process
The most visible phase in the life of the weld is the welding process itself. The total welding process is typically very complex, with many steps to the process and a large number of support organizations involved. Figure 2.5 is a sketch of a part that is somewhat representative of the fabricated parts for one Business Unit.
Figure 2.6 shows the process flow, through the welding stage, for a hypothetical part. For this product, there are approximately 60 steps running the gamut from tackwelding to welding to cleaning to straightening to inspecting and reworking-as-required. The figure attempts to visually separate out clearly non-value adding steps by highlighting them in bold boxes. The darker shaded boxes represent process steps associated with distortion and residual stress correction.
TYPICAL PROCESS FLOW SHOWING DISTORTION CORRECTION AND NON-VALUE ADDED ACTIVITIES

Figure 2.6a

-33-
Figure 2.6 b
A summary of the operations is as follows.

<table>
<thead>
<tr>
<th></th>
<th>Direct Labor Hours</th>
<th>Clock Time</th>
<th>Percent Touch Time (2 shift day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value Adding Activities</td>
<td>73%</td>
<td>53%</td>
<td>6.0%</td>
</tr>
<tr>
<td>Non-Value Adding Activities (Insp and Rework Time)</td>
<td>15%</td>
<td>25%</td>
<td>2.6%</td>
</tr>
<tr>
<td>Distortion and Residual Stress Correction</td>
<td>12%</td>
<td>22%</td>
<td>2.4%</td>
</tr>
<tr>
<td>Totals</td>
<td>100%</td>
<td>100%</td>
<td>4.4%</td>
</tr>
</tbody>
</table>

Table 2.3 - Relationship of direct labor hours and clock time for welding activities for a part.

The last column of Table 2.3 represents the ratio of direct labor hours to clock time (based on a two-shift, 16 hour day). As can clearly be seen, a very small amount of direct labor time, as a percentage of total throughput time, is spent in welding related operations. This compares with a touch time percentage of approximately 20% for machining operations on the same part. It appears that most of the time, the weldment is merely WIP. This is especially true for the work done in distortion correction (due perhaps to the transit delays between the welding line and the heat treat furnaces) and in inspection and welding rework related activities. The reasons for the low touchtime percentage in inspection and welding rework are 1) inspection time is not considered direct labor and 2) there are significant delays in transit from the weld line to the inspection facilities (namely X-ray).
There appears to be much room for improvement in the flow of welding processes. In the past, it has been taken for granted that large, central facilities were the most economical way to deal with X-ray inspection and heat treating. In light of the large margin available for improvement in cycle times, it seems that welding flow cells which cut down on transit time delays might warrant a another look.

When considered from beginning to end, welding is a multi-faceted, complexly intertwined process. It is no wonder, therefore, that control is so difficult to achieve. Perhaps control can only be approached by a careful structuring of the system so that continuous improvement becomes a natural behavior. The best place to start seems to be the establishment of a performance measurement system based on accurate, relevant data. The next chapter provides the background for the design of a new system.
CHAPTER 3
Measuring Performance in Welding Operations

3.1 General Approach to Measuring Manufacturing Performance
In virtually all manufacturing systems, performance can be expressed as a combination of the three dimensions of cost, quality, and timeliness. One of the greatest difficulties in performance measurement systems is how to best represent these measurements in the real world of manufacturing. One possible list of criteria used to evaluate measurements is as follows:

1) The measurements should be understandable, unambiguous and acceptable to all members of the organization who are effected (implies joint management / worker development).

2) The measurements should be results oriented and the path toward improvement should be clear.

3) The corresponding rewards should be compatible with the measurements both in significance and in timing.

4) The measurements should not be easily manipulated.

One of the greatest problems with selecting the proper measurements is the violation of criterion 1. Cost, for example, can take many forms - fixed costs, variable costs, value adding costs, non-value adding costs, etc. And, along with a meaningful consideration of costs, comes the concept of a planning horizon: A cost savings today may mean lost business in the future. The ambiguity of "cost" can lead to a whole range of decisions, each of which can be correct, taken in it's own context, but may lead to problems in the broad scope
or the long range. In the area of *quality*, one can expect a whole set of behaviors depending on whether the quality is expressed as % yield at final inspection or an overall measure of scrap, repair and rework along the entire process. Along the dimension of *timeliness*, its representation as "on-time deliveries" is very different from its representation as manufacturing leadtime (throughput time) or the percentage of value adding time in the total time in production.

In an effort to satisfy criterion 2, many organizations have seen a proliferation of measurements geared to specific elements of the business which are felt to be key to success (key indicators). It often becomes a case of "not being able to see the forest for the trees" (the forest being the cutting of costs and improvement of quality and throughput, and the trees being the individual metrics). The process of 'selective harvesting' of the metrics for the good of the forest requires a great deal of insight on the part of the forest managers. If, on the other hand, each tree could be looked at as a little part of the forest, the task of managing might be made easier. This points to the concept of a *total performance metric* which could combine traditional individual metrics (using methodologies such as Cost of Quality and the Economic Value of Lead Time\(^1\)) to state the various measurements in a common denomination - dollars. This is in keeping with the underlying goal of manufacturing; which is, of course, to make money.

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Implicit in the concept of measurement systems is the idea of rewards, either in the form of recognition or compensation. Another compelling argument to express measurements in monetary terms is criterion 3. It seems a natural thing to reward monetary gains in performance with money. It also seems straight-forward to link the size and timing of the reward to the significance of the improvement and the time horizon over which the gains are seen (yearly or quarterly for the general manager to perhaps daily for the factory floor worker).

Criterion 4, the robustness of the measurement, also lends credence to the monetarization of the measurements. Any manipulation of this measurement to show improvements will produce the side benefit that improvements will actually be made.

3.2 A Typical System for Performance Measurement

As part of the research for this thesis, the author spent nearly seven months on site at a jet engine manufacturer. Based on interviews, surveys, and observations within several operating Business Units at this site and others, a composite of key performance indicators was established at three levels: The Plant Management level, the Business Unit Management level and the Lead Welder level. This composite is presented in Table 3.1. The salient features of this composite are as follows:

1) The measurements at each of the three levels can be categorized into three different groups: Cost, Quality and Timeliness measurements.
## Performance Measurement Key Indicators at Different Management Levels

<table>
<thead>
<tr>
<th><strong>Plant Management</strong></th>
<th><strong>Business Unit Management</strong></th>
<th><strong>Welding Process Management</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>(examined infrequently)</td>
<td>(12 week running numbers)</td>
<td>(examined frequently)</td>
</tr>
<tr>
<td><strong>Total Plant Costs ($)</strong></td>
<td><strong>Total Salaries and Wages ($)</strong></td>
<td><strong>Direct Labor</strong></td>
</tr>
<tr>
<td>• Direct Costs</td>
<td>• Supervision (headcount)</td>
<td>• Overtime (hrs)</td>
</tr>
<tr>
<td>• Total Plant Overhead Costs</td>
<td><strong>Total Supplies and Expenses ($)</strong></td>
<td>• Absenteeism (%)</td>
</tr>
<tr>
<td><strong>Quality</strong></td>
<td></td>
<td><strong>Shop Consumables &amp; gas ($)</strong></td>
</tr>
<tr>
<td>• Total QA Scrap, Repair &amp; Rework ($)</td>
<td><strong>Total Fixed Expenses ($)</strong></td>
<td><strong>Fixture Expenditures ($)</strong></td>
</tr>
<tr>
<td>• Engineering Changes (backlog)</td>
<td></td>
<td><strong>Process Control</strong></td>
</tr>
<tr>
<td>• Feedback on Customer Satisfaction</td>
<td><strong>Rework Labor (hrs) per Area</strong></td>
<td>• Yield Rate at QA inspection (%)</td>
</tr>
<tr>
<td>• <em>Matchup to Malcolm Baldrige Award</em></td>
<td>• QA Production Rework Labor</td>
<td>• Rework &quot;as Required&quot; effort</td>
</tr>
<tr>
<td><strong>Timeliness (Throughput Time)</strong></td>
<td>• QA Reinspection Labor</td>
<td>• Defects/Distortion Elimination</td>
</tr>
<tr>
<td>• LASOC</td>
<td>• QA Rework WIP</td>
<td>• Cleanliness</td>
</tr>
<tr>
<td>• Total Labor + Burden</td>
<td>• Greensheet Insp &amp; Rework</td>
<td>• Welder qualification</td>
</tr>
<tr>
<td>• Return on Assets</td>
<td><strong>Scrap per Area ($)</strong></td>
<td></td>
</tr>
<tr>
<td>• Product Development Lead time</td>
<td>• Labor</td>
<td><strong>Timeliness (Delivery Performance)</strong></td>
</tr>
<tr>
<td>• Total Manufacturing Lead Time</td>
<td>• Material</td>
<td>• Meeting time Stds</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Weeks Overdue</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Machine downtime</td>
</tr>
</tbody>
</table>

*NB: Values in parentheses indicate units*

Table 4.1 - Performance Measurement Key Indicators at Different Management Levels
2) The number of key indicators at each level is approximately the same, yet the scope of the information at the upper levels is much, much broader. This necessarily leads to a large degree of subjective information filtering and potentially inaccurate translation. In other words, what is important in determining performance at the welder level is not necessarily supported by what top management measures (and vice versa).

Other performance measures exist for promoting various company initiatives, but these have not been included here for the sake of clarity.

3.2.1 Pitfalls of the Traditional Performance Measurement System

Point 2, above, is a natural consequence of the hierarchical structure of virtually all organizations. The challenge is in limiting the degradation of information to a level that does not inhibit good decision making. In the past, the decisions which aircraft and engine manufacturers were faced with were fairly coarse and could be expressed in terms like "project profitability", "capacity" and rough "make-or-buy decisions." For those kinds of decisions, the measures of performance currently in use have been quite satisfactory. Now, however, in the face of the current competitiveness crisis, the decisions have in some sense become more refined and are expressed in terms of 'product attributes' and their effect on manufacturing costs. This is more of a fine tuning task for which the tried and true methods of measuring performance are simply not adequate. According to the four criteria for effective performance measurements set out at the beginning of the chapter, the traditional measurement system falls short in several ways.
**Criterion 1 - The measurements should be understandable, unambiguous and acceptable to all members of the organization who are effected (implies joint management / worker development).**

Examining the measurements on the basis of the first criterion, it appears that there is a good deal of ambiguity from one level to the next. The classic ambiguity is the mixed message which comes from a cost reduction initiative at the upper levels. The obvious intent of a cost reduction initiative is to improve efficiency, but one simple way to cut costs is to cut expenses by cutting corners. Figure 3.1 shows a causal loop diagram which highlights this ambiguity. Reduced headcount and reduced capital expenditures on equipment and fixtures and reduced spending on process improvement and maintenance can all effectively reduce costs and may be an attractive alternative for a Business Unit manager - but, they are also tied strongly to performance in Quality and Timeliness. The tradeoffs under the traditional system are not clear.
Another ambiguity in the system lies in the interpretation of Quality. At the plant management level, quality costs are fairly clearly represented by \( SR^2 \) (scrap, rework and repair), No. of Engineering Change's and Feedback on Customer Satisfaction. But other quality costs, specifically as they affect manufacturing system performance at the Business Unit level and at the Welding Process level are filtered out or lost in the translation and are not readily visible to the upper levels.

This phenomenon became clear during the interview portion of this research. In an attempt to ascertain the seriousness of distortion problems in welding, the question was asked of welders, line Supervisors and Business Unit managers: "Do you perceive distortion and/or residual stresses to be a serious problem in your welding operations?" Of the three levels, only the welders
perceived there to be a problem with residual stresses and distortion. Business Unit Managers and even direct line Supervisors were of the opinion that "those types of problems have been solved." The "solution," as discovered in the Manufacturing Operations Sheets, was the addition of bonafide operations designated by such terms as "straighten as required" and "stress relief heat treatment." Since management was focussed on final yield, delivery and standard costs, they could not see distortion and residual stress problems as important. Figure 3.2 is a causal loop diagram which shows how this behavior might have been encouraged.

![Causal loop diagram](image)

**Figure 3.2 - Causal loop diagram illustrating how emphasis on Yield could encourage the undesired side effect of condoning distortion correction and stress relief rather than process improvements to eliminate the root causes.**
Along with ambiguity comes a violation of criterion 2 from the list:

*Criterion 2 - The measurements should be results oriented and the path toward improvement should be clear.*

The objectives of the measurements at the top management level can be met, at least superficially, by a number of different actions at the lower levels. Therefore, *the path to real improvement is not clear.* An element often is missing at all three levels is a clear idea of what the endpoint goal for each measurement should be. Costs, for example, are compared to historical standards which include a great deal of hidden wastes. Most of the measurements for all three main categories are tracked against historical performance and "standards" and are represented as "trends."

One visible opportunity for cost reductions is the elimination of SR$^2$. But this goal can be approached without even scratching the surface on many of the issues of quality which lead to long lead-times and high total costs. Some of the additional *hidden costs of poor quality* were alluded to before and include:

1) Pre-QA Inspection and Rework operations designed to catch and correct flaws in welding before they can be caught and corrected in Q.R.

2) Straightening operations and Stress Relief Heat Treating operations

3) Operations dubbed "Rework as Required" to rout out bad welds and reweld.

4) Inventory Holding Costs which grow with WIP and manufacturing cycle time
Other, more intangible costs include:

5) Slow learning because of delayed feedback.

6) Higher WIP leads to more congestion and therefore larger floor space requirements, longer transport distances, higher material handling costs and even more cycle time delays (a positive feedback loop).

One might argue that the intent of the measurements at the upper levels is clear and it is up to the lower level managers to interpret them and implement their own versions of them at their level. While this is ideologically true, it requires a change in traditional behavior patterns and measurement systems which, by the organizational analogy to Newton’s second law of motion, will not occur without a significant outside force. There is also the question of how the traditions evolved in the first place. It appears that over the years (and sometimes generations), the measurements of the higher levels have been altered at the lower levels to make the objectives easier to obtain. This appears to be a violation of the fourth criterion, that of non-manipulability, for performance measurement to be fully effective.

3.3 Manufacturing Cost Accounting

The purpose of manufacturing accounting systems is, in general, to assist managers in identifying the sources of their problems or the reasons for their success. When managers collect data from their operations, they do so for a variety of reasons, depending on their time horizon or, more visibly, their level in the organization. There are three basic levels at which cost accounting data is used:
1. At the **Corporate level** it provides the CEO and board of directors with a capability for external reporting. It allows them to answer questions relating to profit, value of inventories, and value of property, plant and equipment.

2. At the **Plant Manager level** it can provide useful information regarding: which products to develop or drop, which components to make or buy, how to distribute performance bonuses and raises, and how to allocate resources (equipment and manpower) to the various areas in the plant.

3. At the **Business Unit Manager level** it can provide insight into: the allocation of labor and machines to a given job, and the allocation of supervision and process improvement specialists to a given process and the distribution of performance incentives

It does not take much reflection to determine that each of the three different levels requires the collection of very different data and the preparation of entirely different reports. Traditionally the emphasis for accounting systems has been on the top two levels, with very little emphasis on the collection and reporting of relevant, accurate data at the Business Unit Manager level.

The basic cost accounting methodology for the upper levels is quite simple (see Figure 3.3). The costs of operating a manufacturing facility are collected and divided into two categories: those that can be directly assigned to the product - such as direct labor and materials (direct costs), and those that are necessary for the production to take place, but are not directly assignable on a part by part basis (indirect costs). These costs include such things as capital equipment, managers' salaries, and support for overhead functions such as quality
assurance and supply cribs. The use of a standard plant-wide system which allocates fixed costs on the basis of direct labor hours (for example) often smears the indirect costs in such a way as to be totally unrepresentative of any one particular manufacturing operation. In a sense, the use of a 'one-size-fits-all' cost accounting system robs B.U. managers of their ability to measure the nuances of their particular operations. Invariably, companies use direct measures (usually non-monetary, such as on-time deliveries and yield rate), based on operations, to track performance at the lower levels [Kaplan Chap 4].

![Diagram of Total Plant Costs]

**Figure 3.3** - Schematic diagram of basic two-stage cost accounting process.
3.3.1 The Problems with the Traditional Approach

In the 1800's and early 1900's, the allocation of indirect costs based on direct labor hours was fairly accurate, since direct labor costs represented the majority of the total cost of production. But today, the cost of direct labor in a typical high-technology company seldom exceeds 10% (for a jet engine it is close to 6%). The use of more capital intensive equipment and automation, along with increases in indirect factory expenses - particularly materials control, quality assurance, maintenance and software development - has increased the indirect costs to, in some cases 5 to 10 times the direct labor costs. As a result, traditional cost accounting systems which are being used to measure performance and influence behavior, devote the majority of their energies to measuring costs that are likely to account for less than 15% of the total. Hayes, Wheelwright and Clark [Hayes. 1988] describe the discrepancy between the costs as represented by the traditional cost system and the costs actually encountered in a particular manufacturing operation as the "reality variance."

The increasingly complicated cost inter-relations between WIP levels and throughput time, between design effort and manufacturing productivity, between purchasing efforts and supplier relations, make traditional, straightforward cost accounting methods more and more ineffectual as a guide for the Business Unit Manager.

Beyond being ineffectual, the use of incorrect measures can lead to bad decision-making which can jeopardize the company's long term survival. The pursuit of good "bottom line" financials often leads to cutbacks in new process development investments, a reduction in maintenance budgets and a
"hollowing out" of the core competencies by reliance on outside suppliers for critical skills and parts.

An example of how an incorrect measure can result in behavior which may actually be deleterious to the longer term success of the operation is shown in the causal loop diagram in Figure 3.4. A focus on reducing manufacturing costs in an organization where the overhead rate (per direct labor dollar) is high, will create a strong incentive to reduce the labor content in products by either extensive automation, or by sourcing subsystems to outside suppliers. While this high leverage maneuver may look good on the B.U. Manager's books in the short term, the additional overhead costs associated with increased maintenance or training or with purchasing the subsystem and maintaining supplier relations will tend to offset this apparent gain. In fact, the increasing overhead rate will reinforce the tendency to eliminate more direct labor and a positive feedback loop is created.

Figure 3.4 - Causal loop diagram showing that high overhead rates in conjunction with an incentive system based on lowering operating costs can lead to higher-still overhead rates.
Another instance where the use of an inaccurate cost accounting system can lead to poor decision-making occurs if a company uses indirect workers for equipment changeovers and setups, but it allocates indirect costs on the basis of direct labor hours. In this case, it will invariably underestimate the cost of lower volume products while overestimating the costs of high-volume products. This mis-information, if extreme enough, might cause a company's strategic planners to drop a profitable product line in favor of an unprofitable one.

In effect, yesterday's systems for measuring manufacturing performance have become an obstacle to the attainment of competitive advantage. Their focus on variances from internal standards and annual budgets can render the phrase "continuous improvement" into just another buzzword. To quote a quote from Kaplan's *Measurements for Manufacturing Excellence* [Kaplan, 1990]:

"The idea of the Standard Cost model and analysis of variances does not square with the concept of continuous improvement and learning. Standard costs and variances forces you to measure results against static budgets and historically determined standards - Where is the drive for improvement?"

3.4 New Approaches to Performance Measurements

As a result of today's increasingly competitive environment, many aerospace manufacturers (including the Company) are beginning to act on their intuition that change is warranted and have begun to search for new approaches to measuring and evaluating manufacturing performance. A
new paradigm is being developed which flows, in part, from the JIT philosophy that scrap and rework are wastes to be eliminated, not costs to be held below acceptable levels. The old paradigm say that profitability comes from optimization within constraints (e.g. lowering costs raises profits). The new paradigm says that profitability comes from continuous improvement at eliminating waste while increasing quality, dependability and flexibility.

Some companies, notably General Electric and Hewlett Packard, are experimenting with more relevant ways of allocating overhead costs, based on different "cost drivers" such as machine hours, throughput time or the number of times a certain "activity" is performed during an operation (Activity Based Costing will be discussed below). Other's are exploiting the capabilities of computers to capture the details of a specific job in real-time in order to better "assign" what had previously been allocated costs - specifically setup and material handling costs. Yet others are creating entirely new performance measures which strongly parallel the manufacturing strategy of the company (e.g. high customer service, fast time to market for new products, etc.).

3.4.1 Activity Based Accounting
To achieve continuous and rapid flow of value adding activity means eliminating anything that causes delay, unevenness, or excess inventory in the flow of value-adding work. As such, it is imperative that sources of delay and unevenness, including long machine setups, unscheduled maintenance, defective work or material be identified. It is also important that performance measures that encourage these wastes be rooted out. One common hiding place for inefficiencies is in overhead functions. A fairly recent accounting

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methodology, Activity Based Cost accounting, forces one to take a closer look at what generates overhead costs (utilizes resources) so that cause and effect relationships can be established and the culprits of cost can be dealt with accordingly.

An excellent source for basic understanding of the tenets of ABC accounting can be found in Robert Kaplan's *Measurements for Manufacturing Excellence* [Kaplan, 1990].
CHAPTER 4
A Manufacturing Cost Model for Performance Measurement

In this chapter a cost model is developed to allocate indirect costs associated with welding from one particular Business Unit to one part (product). It is believed that the model is applicable to many welding applications where quality and dimensional accuracy are critical. It is hypothesized that many of the indirect costs of welding are strongly tied to the total throughput time through the welding related operations (especially materials handling and QA inspection). It will be shown that this throughput time is strongly tied to the level of rejects at the various inspection points in the process as well operational parameters such as the number of times the product must be moved, the queuing delays between successive operations and, over time, the level of learning within the welding organization. Three major goals of this chapter are:

1) To make visible the major sources of waste in welding and present some order of magnitude estimates of the cost savings available through their elimination.

2) To provide a framework for intelligent trade studies based on how various design options or manufacturing options effect throughput time and thus welding overhead costs.

3) To illustrate how throughput time reductions not only effect overhead costs, but also contribute to intensifying the learning experiences of repetitive welding and can accelerate continuous improvement.

A corollary to goal 3 is that direct improvements in the learning intensity through investments in Statistical Process Control (SPC) or in welder (and associated personnel) training will lead to reductions in throughput time.
(through reduced rejection rates) that will in turn accelerate the continuous improvement process. This discussion is presented in section 4.4.

Before boring into the details of the cost model it is useful to spend some time understanding the current standards for cost accounting, specifically for welding, as observed in a jet engine manufacturing plant. This is done in section 4.1. Section 4.2 introduces a "process flow approach" to manufacturing costs and develops a list of cost drivers for the allocation of indirect costs. The cost model is then discussed in section 4.3 and the organizational learning model analyses and results are presented in section 4.4. Section 4.5 and 4.6 represent the recommendations and conclusions from part 1 of the thesis.

4.1 The Current Approach to Cost Accounting

While performance measures encompass a wide range of activities and can vary significantly from one organization to the next, cost is something that all performance systems measure to some extent. A general description of the two stage allocation process for cost accounting was given in Chapter 3. Stage 1 of the process, allocating plant costs to cost centers (Business Units), is often done by direct measures as is the case with the Maintenance organization, which charges time directly to the Business Unit for which it is doing work, and with Manufacturing Engineering which often dedicates M.E.'s to work for a particular Business Unit. Another method used for first stage allocation to the Business Unit is on the basis of floor space; for utilities and industrial gas use. And, if all else fails, overhead costs are dumped into the overhead pool and distributed on the basis of headcount or total Business Unit earned hours (or direct labor dollars). Examples of overhead costs that are truly fixed and
untraceable are rare (executive board members' salaries and Research and Development are good ones), but none-the-less, the direct labor dollars method is used to allocate the vast majority of overhead costs to the Business Unit level.

The second stage, the assignment of costs to the various products within the cost centers is where major complications start to develop. Traditionally the complications have been handled by lumping costs together and then spreading them out evenly over all the parts on the basis of direct labor. But, as discussed previously, direct labor is not necessarily the driving factor in determining the use of "overhead" resources. As a simple example, size and weight of a part must have a good deal to do with the material handling resources it utilizes - An anvil and a thumbtack may each require the same amount of direct labor to manufacture, but the effort to move them about the factory is substantially different.

In welding, which is a particularly sensitive process, direct labor dollars may have little to do with how the resources are expended in the various overhead areas. For instance, a poorly designed, hard-to-access joint may require a good deal more supervision resources and inspection effort than a well designed one. This would suggest that supervision and inspection dollars should be allocated to the product on the basis of some complexity attribute such as number of weld joints per part or number of weld related operations per part or alternatively (as will be done here), by throughput time through the welding process. Additionally, the highly cross-functional nature of the welding process involves many organizations outside of the Business Unit's immediate control. These all contribute to higher overhead costs than, for
example, typical machining operations. Figure 4.1 shows the various outside organizations that are involved in producing quality welds.

**Indirect Support of B.U. Welding Activities**

![Diagram showing indirect support of B.U. welding activities]

**Business Unit Welding Related Operation**

- Industrial Gases
- Inspection Depts (X-ray, FPI, etc)
- Hazardous Waste Disposal
- Quality Assurance (QR Crib)
- Materials Engineering
- Materials Control Lab
- Weld Test Lab
- Maintenance
- Supervision
- Tooling and Fixtures (Design and Fab)
- Mfg. Engineering (1st line troubleshooting)
- Process Development Ops
- Config. Control (Engin. Changes)

Figure 4.1- Overhead resources that relate to plant welding operations

In order to determine the extent to which each of the above overhead resources is utilized by the company’s welding operations, the author interviewed the managers of the the various functions and several Business unit Managers. In most cases, the percentage of welding overhead dollars allocated to each overhead function was based on the relative count of people dedicated to welding related activities (Salaried personnel were counted, on the average, as 7/5 more expensive than hourly personnel based on a previous internal cost analysis). If the usage of welding overhead dollars was allocated based strictly
welders as a portion of total welders plus machine operators the breakdown would be approximately 18-20% welding related. Table 4.1 shows the breakdown in more detail. The relative dollar amounts for each of the overhead items is depicted graphically in Figure 4.2.

<table>
<thead>
<tr>
<th>Overhead Function</th>
<th>Percentage of Plant O.H. Item Used by Welding</th>
<th>Percentage of Total Plant Welding O.H. Cost</th>
<th>Basis for Apportionment to Welding</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Weld Test Lab</td>
<td>100%</td>
<td></td>
<td>• Dedicated</td>
</tr>
<tr>
<td>• Industrial Gases</td>
<td>50%</td>
<td></td>
<td>• 50% weld related</td>
</tr>
<tr>
<td>• QA Inspection</td>
<td>45%</td>
<td></td>
<td>• Division of personnel</td>
</tr>
<tr>
<td>• Chem. and Waste Water Disposal</td>
<td>31%</td>
<td></td>
<td>• 50% of total Chem $ (Ti pickling)+ 30% waste H₂O $</td>
</tr>
<tr>
<td>• Matls Handling</td>
<td>30%</td>
<td></td>
<td>• Division of personnel</td>
</tr>
<tr>
<td>• Quality Rev Crib</td>
<td>30%</td>
<td></td>
<td>• Division of personnel</td>
</tr>
<tr>
<td>• Direct Supervision</td>
<td>20%</td>
<td></td>
<td>• Division of personnel</td>
</tr>
<tr>
<td>• Tooling(Des.,Fab.)</td>
<td>18%</td>
<td></td>
<td>• Division of personnel</td>
</tr>
<tr>
<td>• Mfg Engineering</td>
<td>18%</td>
<td></td>
<td>• Division of personnel</td>
</tr>
<tr>
<td>• Depreciation</td>
<td>~12%</td>
<td></td>
<td>• 10-15% plant depreciation</td>
</tr>
<tr>
<td>• Heat Treat Utils</td>
<td>9%</td>
<td></td>
<td>• 9% of total</td>
</tr>
<tr>
<td>• Maintenance</td>
<td>8%</td>
<td></td>
<td>• ~8% weld related</td>
</tr>
<tr>
<td>• Welding Supplies</td>
<td>7%</td>
<td></td>
<td>• 7% for weld wire, flux, etc</td>
</tr>
<tr>
<td>• Config. Ctrl (ECs)</td>
<td>5%</td>
<td></td>
<td>• Percentage of EC's</td>
</tr>
<tr>
<td>• Matls Ctrl Lab</td>
<td>4%</td>
<td></td>
<td>• Division of personnel</td>
</tr>
<tr>
<td>• Process Devel</td>
<td>--</td>
<td>100%</td>
<td>• 1990 budget</td>
</tr>
</tbody>
</table>

Table 4.1 - Summary of welding related overhead distribution (plant welding related overhead breakdown is not publishable)
Figure 4.2 - Relative overhead item costs for the total plant and for welding related items within the plant
The importance of Table 4.1 and Figure 4.2 is that they show both the relative importance of welding to a particular overhead function and the absolute importance of that function to the total welding overhead. The top five overhead items (excluding Process Development, which is under external control) are QA inspection, Manufacturing Engineering, Welding Supplies, Direct Supervision and Materials Handling. Together they make up over 65% of the total manufacturing overhead costs. This represents roughly half of the total costs of welding (D.L. + OH.). Thus there is a great opportunity for cost savings from attacking overhead (more so than direct labor).

4.1.1 Reducing Overhead Costs
Attacking overhead costs requires a knowledge of what drives overhead costs. If one can reduce the overhead driver, the overhead in the long run, will be reduced as well. Table 4.2 shows that currently the majority of overhead costs are allocated via direct labor dollars. If direct labor dollars were true cost drivers of overhead, then one would expect that eliminating direct labor by automation or outsourcing would be a desirable thing. But, as pointed out in Chapter 3, this often merely shifts the costs from direct costs to indirect costs and in fact will increase overhead costs.
<table>
<thead>
<tr>
<th>Overhead Activity</th>
<th>Current Basis for Allocation to B.U. (stage 1)</th>
<th>Current Basis for Allocation to Part (stage 2)</th>
<th>Proposed Basis for Allocation to Part (stage 2)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemicals</td>
<td>Direct Hrs in Cleaning</td>
<td>DL$</td>
<td>DL$</td>
<td><em>Used in pickling operations on Ti</em></td>
</tr>
<tr>
<td>Config. Control</td>
<td>DL$</td>
<td>DL$</td>
<td>DL$</td>
<td></td>
</tr>
<tr>
<td>Industrial Gases</td>
<td>Floor Space</td>
<td>DL$</td>
<td>DL$</td>
<td><em>Some B.U.'s have installed flow mtrs</em></td>
</tr>
<tr>
<td>Maintenance</td>
<td>Direct Measure</td>
<td>DL$</td>
<td>DL$</td>
<td><em>Or machine Hrs</em></td>
</tr>
<tr>
<td>Mtls Control Lab</td>
<td>DL$</td>
<td>DL$</td>
<td>Direct Matl $</td>
<td><em>MCL provides QC for incoming mats</em></td>
</tr>
<tr>
<td>Mtls Handling</td>
<td>DL$</td>
<td>DL$</td>
<td>Throughput Time</td>
<td></td>
</tr>
<tr>
<td>Mfg Engineering</td>
<td>Direct Measure</td>
<td>DL$</td>
<td>DL$</td>
<td></td>
</tr>
<tr>
<td>Q. A./ Inspection</td>
<td>Direct Measure</td>
<td>DL$</td>
<td>Throughput Time</td>
<td></td>
</tr>
<tr>
<td>Q.R. Crib</td>
<td>DL$</td>
<td>DL$</td>
<td>% of Scrap Tickets</td>
<td><em>QR's weld related % of</em></td>
</tr>
<tr>
<td>Supervision</td>
<td>Direct Measure</td>
<td>DL$</td>
<td>DL$</td>
<td><em>Case BU has indirect employees</em></td>
</tr>
<tr>
<td>Tooling/Fixtures</td>
<td>Direct Measure</td>
<td>DL$</td>
<td>DL$</td>
<td><em>Amortised over life of part</em></td>
</tr>
<tr>
<td>(design &amp; build)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waste Water Cost</td>
<td>DL$</td>
<td>DL$</td>
<td>DL$</td>
<td></td>
</tr>
<tr>
<td>Welding Supplies</td>
<td>Direct Measure</td>
<td>DL$</td>
<td>DL$</td>
<td></td>
</tr>
<tr>
<td>Process Devel.</td>
<td>DL$</td>
<td>DL$</td>
<td>DL$</td>
<td><em>R&amp;D type function</em></td>
</tr>
<tr>
<td>Heat Treat (utilities)</td>
<td>Direct Hrs, Heat Treat</td>
<td>Direct Hrs, Heat Treat</td>
<td>Direct Hrs, Heat Treat</td>
<td></td>
</tr>
<tr>
<td>Depreciation</td>
<td>Book Value</td>
<td>DL$</td>
<td>% Value of Machines</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2 - Allocation of overhead costs to Business Unit (Stage one) and from Business Unit to product (stage two). The proposed stage two allocation scheme is shown in bold.
In the second-to-last column of Table 4.2, suggestions are listed for new bases for overhead allocation to the part level that could be implemented in relatively short order. Where possible, it would be desirable to measure costs directly. For example, efforts are currently underway in one Business Unit to incorporate flow meters to monitor industrial gas usage. Other typically overhead-type costs that could eventually be measured fairly directly at the point of use include: welding supplies, materials handling, maintenance and Q.A./Inspection. One way to encourage the direct measurements, is to allow Business Units who can prove their resource usages are less than the overhead allocation says they are, to reflect the savings on their books.

Short of measuring costs directly at their point of use, there are a number of other drivers that can provide a better level of differentiation than direct labor dollars. The concept of using throughput time (cycle time) for the purpose of overhead allocation to the part level has a great appeal for many of the overhead items - especially considering that many overhead costs are intimately tied to delays in the manufacturing cycle. The two most likely candidates for the use of throughput time as a cost driver are Material handling and QA-Inspection. It seems reasonable that a reduction in throughput time would require the elimination of material movements, and the elimination of re-inspection.

One thing that is clear from a quick look at Table 4.2 is that there is nothing clear about accounting for overhead. However, with the advent of faster and faster computers, the handling and sorting of the massive amounts of data involved pose no problem. At the sponsoring company, an effort is currently
underway to directly measure many of the typically "peanut-buttered" costs and directly track setup, variance (both in production and setup), Inspection, Rework and Scrap. A weld monitoring system is also in place in one Business Unit which tracks quality problems by type of defect and distills them into easy to read Pareto Diagrams and Pie Charts. The frontier for Management Information Systems in manufacturing performance measurement and cost accounting appears boundless.

4.2 A Process Flow to Understanding Welding Costs

A logical approach to understanding where costs and wastes come into the welding process is to model costs in the framework of the process flow of the welding operation. Figure 4.3 is a simplified version of the process flow diagram shown in Chapter 2, modified to show the input of costs (and wastes) along the way. Each operation in the process has four basic categories of manufacturing cost as listed below.

1) **Direct and value adding costs (good)**
   - Direct Labor
   - Direct Materials

2) **Direct and non-value adding costs (bad)**
   - Scrap, Rework and Repair
   - Variances from Direct Labor standards
   - Direct Labor to correct flaws from prior operations
Figure 4.3 - Process flow diagram showing input of overhead costs.
3) **Indirect costs linked to value adding activities (good)**

- Supervision
- Welding supplies and industrial gases

4) **Indirect costs linked to non-value adding activities (bad)**

- Quality Assurance (Inspection)
- Configuration Control (Engineering Changes)
- Material Handling
- Setup
- Inventory Holding Costs

Figure 4.4 graphically depicts the above mental model for the assignment and allocation of welding costs from the Business Unit Level to the Part level (stage two).

![Diagram](image)

**Figure 4.4 - Mental model for assignment and allocation of Business Unit costs to the part level**

The **direct and value adding (good) costs** are simply the direct costs of Labor and Materials. These are currently accounted for in terms of direct labor standard hours (multiplied by a fringe benefit overhead rate) and material purchases (multiplied by a materials overhead rate). Since time standards seem fairly arbitrary and are changed yearly to reflect actual labor,
for the purposes of this model, the standard and variances are combined to arrive at the direct and value adding costs for each operation. Standard times can be predicted on the basis of design feature drivers such as number of welds (stops and starts), length of weld, type of joint, material type, etc. For the purposes of the model, however, it is assumed that a knowledgeable engineer would be able to predict standard times and costs to a fair degree of accuracy (this may be a good area for future work).

Currently included in the labor category are costs for correcting errors from previous production steps. In this model, these costs have been reclassified into the direct waste category (number 2 above). Also, for the purposes of this manufacturing model, all material costs are considered invariate and will not be included.

- **Direct and non-value adding (bad) costs** are represented by the obvious SR² and the not so obvious direct labor operations that include the key words - rework as-required, straighten, stress relieve, and anneal - and generally represent some correction of some previous steps in the process. These represent costs that have traditionally been hidden in operations that were created as a result of the acceptance of the flaws "inherent" to welding.

Chapter 2 pointed out that the direct costs for straightening and rework to correct flaws from previous operations was (from Table 2.3) about 27% (15% + 12%). This represents the direct labor savings potential of eliminating these process steps. Of course, eliminating variance on the value adding process steps will add to the savings, but its contribution will be relatively small.
Another look at Table 2.3 shows that the clock time (or calendar time in this case) for the non value adding activities makes up 47% (22% + 25%) of the time it takes to move a part through the welding area. This represents the savings potential for indirect costs (both "good" and "bad") that are linked to throughput time. The enormous leverage in reducing overhead costs by eliminating direct, non value adding activities exists because with each rework cycle a part goes through, it experiences not only the direct rework labor hours, but also the transfer delays and queueing delays associated with the inspection and rework process. More detailed calculations for savings potential are carried out in the following section.

4.3 ITHINK™ Conceptual Cost Model of Welding Operations
The basic cost model is made up of two components. The first is the calculation of throughput time that feeds into the cost model to enable the calculation of many of the overhead costs. The second is the cost model itself, which covers each of the four different categories (direct and indirect costs (good and bad)). Given the proper inputs for production rate, direct labor hours, wages, material costs, throughput time, and all the other components of overhead cost discussed earlier, the cost model computes the running cumulative costs of the Business Unit welding operation. For the purposes of this thesis, the inputs have been disguised to protect confidentiality.

A third component of the cost model is based on the hypothesis that reducing throughput time not only reduces overhead costs, but it increases the rate of learning in the welding organization and creates a positive feedback loop that
ever encourages continuous improvement. This discussion is presented in section 4.4.

4.3.1 Understanding the ITHINK™ model diagrams

To facilitate a discussion of the workings of the cost model, it is important to be familiar with the semantics of the ITHINK™ software, including the basic definitions of stocks, flows, converters and levels. Figure 4.5 is a generic ITHINK diagram, defining the icons and explaining the important terminology.

While, ITHINK™ is primarily designed for describing and understanding dynamic systems (business cycles, predator-prey relationships, etc.) it is also useful as a “visual spreadsheet” that illustrates structure rather than just numerical values. In the cost model stock and flow diagrams to follow, it is almost possible to surmise the relationships by examining the structure of the diagrams. This would not be possible in a typical spreadsheet application. The dynamic capabilities of the ITHINK™ software are more fully exercised in the learning model discussed in Section 4.4.
4.3.2 Throughput Time Models

Figure 4.6 shows the development of the calculation for throughput time in straightening (distortion and residual stress control). The drivers for throughput time in straightening are reject rate for each straightening operation (what percentage of parts must be straightened), number of major material moves for each straightening operation, transfer time between major moves and actual time performing the straightening operations. The assumed sensitivity relationships are shown below the figure. The main
driver for throughput time in this submodel is the percentage of parts that must be straightened (Reject Rate Distortion). The other drivers will also have an effect and their sensitivities would be a good subject for future studies.

Figure 4.7 shows the same information for the throughput time in inspection rework. The drivers in this case are similar. One notable difference is that one part may go through several inspection/rework cycles before it can proceed to the machining operations. Another difference is that the straightening throughput time model assumes that all process steps associated with distortion correction and residual stress relief may be eliminated by devising a welding process that reduces reject rates to zero. In the inspection and rework model, it is assumed that, even for very low reject rates, the parts must still pass two sets of inspections (Pre-QA and QA) before they can proceed to the machining operations. The prime focus of this submodel is the 1st pass Pre-QA inspection rejection rate. Again, the other drivers would be a good topic for further study.

Figure 4.8 compares the two components of throughput time (straightening and QA inspection) based on their respective driving reject rates. The vertical lines in the figure represent the assumed current state of affairs for the particular part studied. The data has been disguised to protect confidentiality.
No_of_Straightenings = 3  
Reject_Rate_Distortion = 
Straightening_Time = 7/80  
DOCUMENT: Assuming a 2 shift day,  man-hours is a small percentage of time

Throughput_Time_Distortion_Correction = Reject_Rate_Distortion * Transfer_Time + Straightening_Time  
Time_per_Move =  
DOCUMENT: Each of three "straightening" operations (for a current rejection ratio of 20%) requires an average of 7/3 days/ = weeks  

Transfer_Time = No_of_Straightenings * Time_per_Move  

Figure 4.6 - Throughput time for straightening and stress relief as a function of percentage of parts that must be straightened and/or stress relieved. (Note that all times and reject rates have been altered to preserve confidentiality)
Throughput Time Inspect Rework

Reject Rate 1st Pass

Reject Rate 2nd Pass

Reject Rate QA

Transfer Time PreQA

Transfer Time QA

No of Moves QA

Time per Move QA

No of Moves PreQA

Time per Move PreQA

**Figure 4.7 - Throughput time for inspection and rework as a function of 1st pass reject rate. (Note that all times and reject rates have been altered to preserve confidentiality)**
Figure 4.8 - Throughput time sensitivity relationships for 1) Straightening and 2) Q.A. Inspection rework as functions of their respective reject rates. (Note that the time axis has been altered to preserve confidentiality)

The total throughput time through welding, to be input into the cost model, is determined by summing the above two components along with the time required to get through the value adding “good” activities. The proper calculation for this component would include setup times, number of operations, number of major material moves, transfer times for moves and direct “good” labor time (a very small component). Since we are primarily concerned with the overhead cost savings potential, for the purposes of this cost model the third component of throughput time is set at a constant.

4.3.3 Cost Model
The strategy of the cost model sector is to track the progress of parts through the welding area of the Business Unit for a set period of time. Sticking with the
convention established earlier, the costs are tracked separately as direct "good" costs, direct "bad" costs, indirect "good" costs and indirect "bad" costs. Figure 4.9 and 4.10 illustrate these components of costs and Table 4.3 presents the equations and logic underlying each submodel's structure. In particular, note how the throughput times calculated in the previous section are used in the indirect "bad" cost submodel. Also note that the dollar values used in the model have been disguised to preserve confidentiality.

Figure 4.11 shows the results of the model for a 52 week period. Each of the four components of cost are tracked independently and summed to make up the grand total costs. This run was made with all the parameters adjusted to represent the actual conditions for the process (as shown in Table 4.3), except that the cost numbers have been altered. Note that the indirect "bad" costs are by far the largest source of the total costs in welding this part. From a potential cost savings perspective, this appears to be fertile ground indeed.
Figure 4.9 - Cost submodels for direct "good" and direct "bad" costs in welding
Figure 4.10 - Cost submodels for indirect "good" and "bad" costs and Grand Total costs
**Table 4.3** - The basic equations representing the underlying structure of the cost model - (The values of the variables have been deleted for the sake of confidentiality)

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Grand_Total_Costs}(t) = \text{Grand_Total_Costs}(t - dt) + (\text{Total_Costs}) \times dt )</td>
<td>INIT Grand_Total_Costs = 0 |</td>
</tr>
<tr>
<td>INFLOWS:</td>
<td>( \text{Total_Costs} = \text{Good_Direct_Costs} + \text{Bad_Direct_Costs} + \text{Good_Indirect_Costs} + \text{Bad_Indirect_Costs} )</td>
</tr>
<tr>
<td>( \text{Total_Bad_Direct_Costs}(t) = \text{Total_Bad_Direct_Costs}(t - dt) + (\text{Bad_Direct_Costs}) \times dt )</td>
<td>INIT Total_Bad_Direct_Costs = 0 |</td>
</tr>
<tr>
<td>INFLOWS:</td>
<td>Bad_Direct_Costs = Weekly_Production_Rate \times (Straightening_Time + Insp_and_Rework_Time) \times Wage_Rate</td>
</tr>
<tr>
<td>( \text{Total_Bad_Indirect_Costs}(t) = \text{Total_Bad_Indirect_Costs}(t - dt) + (\text{Bad_Indirect_Costs}) \times dt )</td>
<td>INIT Total_Bad_Indirect_Costs = 0 |</td>
</tr>
<tr>
<td>INFLOWS:</td>
<td>Bad_Indirect_Costs = Matls_Handling_BU_Load_Factor_Weld_TP_fraction + QA_Inspection_BU_Load_Factor_Weld_TP_fraction + QR_Crib \times BU_Load_Factor + Inventory_Holding \times Weld_TP_fraction + (Configuration_Control + Hazardous_Wastes) \times BU_Load_Factor</td>
</tr>
<tr>
<td>( \text{Total_Good_Direct_Costs}(t) = \text{Total_Good_Direct_Costs}(t - dt) + (\text{Good_Direct_Costs}) \times dt )</td>
<td>INIT Total_Good_Direct_Costs = 0 |</td>
</tr>
<tr>
<td>INFLOWS:</td>
<td>Good_Direct_Costs = Weekly_Production_Rate \times (Labor_per_Part) \times Wage_Rate</td>
</tr>
<tr>
<td>( \text{Total_Good_Indirect_Costs}(t) = \text{Total_Good_Indirect_Costs}(t - dt) + (\text{Good_Indirect_Costs}) \times dt )</td>
<td>INIT Total_Good_Indirect_Costs = 0 |</td>
</tr>
<tr>
<td>INFLOWS:</td>
<td>Good_Indirect_Costs = (BU_Welding_Supervision + Maintenance + Mfg_Engineering + Tooling_Fixtures + Consumables) \times BU_Load_Factor</td>
</tr>
<tr>
<td>( \text{Total_Scrap_Mfg_Costs}(t) = \text{Total_Scrap_Mfg_Costs}(t - dt) + (\text{Scrap_Costs}) \times dt )</td>
<td>INIT Total_Scrap_Mfg_Costs = 0 |</td>
</tr>
<tr>
<td>INFLOWS:</td>
<td>Scrap_Costs = Scrap_Rate \times (Good_Direct_Costs + Bad_Direct_Costs + Good_Indirect_Costs + Bad_Indirect_Costs)</td>
</tr>
</tbody>
</table>
Figure 4.11 - Cost model results for cumulative costs in each of the four categories plus grand total costs for welding. (The dollar figures have been altered to preserve confidentiality)

Figure 4.12 shows the results of the sensitivity studies for two cost drivers in the form of percentage of cost savings vs percent reduction in the cost driver. The two drivers examined in the analysis were: 1) The percentage of parts that require some straightening or stress relief - "Reject Rate Distortion" and 2) The percentage of parts that require rework after the 1st pass of welding (prior to QA) - "Reject Rate PreQA." As mentioned in the above section on the throughput time analysis, there is a larger benefit from the reduction of distortion related reject rates than for 1st pass inspection reject rates. This is due to the assumption that Pre-QA and Quality inspections will probably never go away. And these activities alone, without rework, are significant sources of throughput time (see Figures 4.6 and 4.7).
Figure 4.12 - Model predictions of potential cost savings from reduction of: 1) Percentage of parts requiring straightening (or stress relief) and 2) Percentage of parts requiring rework and re-inspection after first pass of welding.

Future work with this cost model might include additional sensitivity studies on some of the other parameters in the model. Plant layout decisions, for example, might effect transfer times and/or number of material moves to a significant extent.

4.4 Learning in the Welding Organization

The cost model as presented above, can only be used to take a "static" picture of the costs of welding if no changes are introduced - either externally by management or internally through learning in the organization. In this section, reject rates and throughput times can vary dynamically as the welding organization learns how to improve the welding processes over time.
Most learning models assume that the learning rate is a constant based on cumulative volume and is exogenous to the system. In actuality, it is very much endogenous to the system. If one assumes that learning improves throughput time (through lower rejection rates) and that shorter throughput time intensifies learning opportunities and promotes better learning, a positive feedback process is established that increases the rate of learning with time. Of course, as the quality approaches perfection, the rate of learning will again decrease, but this negative feedback loop does not pose a problem for most welding manufacturing systems where there is plenty of room for improvement. By tying in the throughput time submodels to an "Organizational Learning rate" model it is possible to see the dynamic effects of welding improvements over time.

Figure 4.13 shows the causal loop diagram that is the basis of the model. The central positive (‘+’) feedback loop is the path of continuous improvement in cycle (throughput) times, learning rate and reject rates. The secondary loop can be reinforcing (‘+’) or stabilizing (‘-’), depending on how re-investment decisions are made (that is the meaning of the +/- in the loop symbol). A focus on meeting deliveries can encourage an increase in the inspection and rework effort, rather than a more far-sighted investment in process improvement, SPC and welder training. The former "investment" will do little to enhance learning, and improvement will be slow. The latter investments will directly improve either the reject rate or the intensity of the learning opportunities and will reinforce the continuous improvement loop. The various model sectors are described in more detail below.
4.4.1 Determination of Learning Rate

In standard learning rate models, the Learning rate for a particular manufacturing process is usually set at some value established by historical observations. For example, historical evidence points to a learning rate of 95%.

---

1 The '+' sign at the head of an arrow means that the two items so linked are positively correlated, the converse is true of the '-' sign.
for welding. This means that for a doubling of volume, costs for example can be expected to decrease to 95% of the previous cost (this can also apply to reject rates, throughput time, etc.). Figure 4.14 illustrates the learning curve graphically.

![Learning Curve Diagram]

Figure 4.14 - The Learning Curve and the Learning Coefficient L

The equation used to represent the learning effect is as follows:

\[
\text{Measurement (cost, time, rejects)} = au^{-b}
\]

Where:
a = the initial measurement value
u = the number of parts produced (proportional to time, at a constant production rate)
b = -\ln(L)/\ln(2), where L is the learning coefficient\(^3\)

In addition to the volume dependent learning that represents the number of opportunities for learning, there is another effect that is dependent on the intensity of the learning opportunities. A founding hypothesis for this model is that the intensity of the opportunities (as represented by L) is directly related to the ratio of cycle (throughput) time to touchtime. Figure 4.15 shows the assumed relationship for L as a function of the cycle time relationship.

![Figure 4.15 - Effect of cycle (throughput) time on learning coefficient (L)](image)

For very long cycle times (high CT/TT ratio), L is hypothesized to be close to 1.0 (no learning). As the CT/TT ratio decreases, very little happens initially (L remains near 1.0) until the CT/TT ratio drops below 10. At that point, learning begins to intensify and L drops toward its minimum value (.65 in this case).

\(^3\) Remember that for learning, a lower L means a steeper learning curve (i.e faster learning)
As CT/TI approaches 1.0, learning may actually becomes more difficult as workers have no leisure for pondering improvements. This hypothesized increase in L is shown in the figure.

4.4.2 Learning Model Results and Discussion

Figure 4.16 is the actual ITHINK™ model used to illustrate the behavior illustrated in the causal loop diagram of Figure 4.13. The equations underlying the visual model, along with explanatory documentation, are presented in Table 4.4. As before, the data has been disguised for the sake of confidentiality. A more complete model would have used the more accurate cost model (and throughput time submodels) as presented in section 4.3.
Figure 4.16 - ITHINK™ model to illustrate learning effects on reject rates and costs in the welding organization.
Table 4.4 - Explanation of variables in ITHINK™ conceptual cost model (The values of some variables have been deleted for the sake of confidentiality)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Equation</th>
<th>INIT Condition</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulative Costs(t)</td>
<td>Cumulative Costs(t - dt) + (Costs) * dt</td>
<td>Cumulative Costs = 0</td>
<td>The Costs are proportional to the time a part takes to go through the inspection and rework cycle (which is in turn related to the number of times it must go through the cycle)</td>
</tr>
<tr>
<td>INFLOWS:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Costs</td>
<td>QA_ Insp * Cycle Time_ Insp * Rework</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DOCUMENT:</td>
<td>The Costs are proportional to the time a part takes to go through the inspection and rework cycle (which is in turn related to the number of times it must go through the cycle)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cum Volume(t)</td>
<td>Cum Volume(t - dt) + (Prod Rate) * dt</td>
<td>Cum Volume = Ref Vol</td>
<td></td>
</tr>
<tr>
<td>INFLOWS:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prod Rate</td>
<td>XX</td>
<td></td>
<td>Weekly production rate (not to be confused with cycle time)</td>
</tr>
<tr>
<td>DOCUMENT:</td>
<td>Weekly production rate (not to be confused with cycle time)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smoothed CT(t)</td>
<td>Smoothed CT(t - dt) + (Change in CT) * dt</td>
<td>Smoothed CT = 5</td>
<td>This is the starting point for the system. It defines the value of LvsCT (in this model LvsCT is fixed for the entire run - a future improvement will allow LvsCT to vary as CT varies).</td>
</tr>
<tr>
<td>INFLOWS:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Change in CT</td>
<td>(Cycle Time_ Insp * Rework - Smoothed CT) / Averaging Time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Averaging Time</td>
<td>4</td>
<td></td>
<td>The reaction to more &quot;intense&quot; learning opportunities is not instantaneous. This is the time it takes for the learning to sink in and effect the system.</td>
</tr>
<tr>
<td>DOCUMENT:</td>
<td>The reaction to more &quot;intense&quot; learning opportunities is not instantaneous. This is the time it takes for the learning to sink in and effect the system.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycle Time_ Insp * Rework</td>
<td>1 + (Reject Rate * (1))</td>
<td></td>
<td>The cycle-time is affected by the reject rate. A better form for the relationship is shown in the Throughput Time Sector, but it is not used here for simplicity's sake.</td>
</tr>
<tr>
<td>DOCUMENT:</td>
<td>The cycle-time is affected by the reject rate. A better form for the relationship is shown in the Throughput Time Sector, but it is not used here for simplicity's sake.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Learning</td>
<td>(Cum Volume/Ref Vol)^*(-(-LOGN(LvsCT)/LOGN(2)))</td>
<td></td>
<td>Learning is a combination of the effects of increasing cumulative volume (number of opportunities) and the coefficient &quot;LvsCT&quot;, which represents the &quot;intensity&quot; of the opportunities. LvsCT is the fraction by which the reject rates will decrease for every doubling of the volume.</td>
</tr>
<tr>
<td>QA_ Insp</td>
<td>1000</td>
<td></td>
<td>Assume, for illustrative purposes, that QA inspection costs $1000 per week. In actuality, the cost per week is an aggregate of all the costs shown in the Cost Model Sector.</td>
</tr>
<tr>
<td>DOCUMENT:</td>
<td>Assume, for illustrative purposes, that QA inspection costs $1000 per week. In actuality, the cost per week is an aggregate of all the costs shown in the Cost Model Sector.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ref Rej Rate</td>
<td>.45</td>
<td></td>
<td>This is the starting point for the reject rate. This, along with Ref Vol and Ref CT define the process.</td>
</tr>
</tbody>
</table>
\[ \text{Ref\_Vol} = 100 \]

**DOCUMENT**: This is the starting point for volume. (for large values of Ref\_Vol, the biggest improvements in learning have already been achieved)

\[ \text{Reject\_Rate} = \text{Ref\_Rej\_Rate} \times \text{Learning} \]

\[ \text{TouchTime} = XX \]

**DOCUMENT**: The actual LASOC (direct labor hrs) time in weeks.

\[ \text{LvsCT} = \text{GRAPH(Smoothed\_CT/TouchTime)} \]

\[
(1.00, 0.695), (10.9, 0.73), (20.8, 0.84), (30.7, 0.945), (40.6, 0.965), (50.5, 0.975), (60.4, 0.98), (70.3, 0.985), (80.2, 0.985), (90.1, 0.99), (100, 0.995)\]

**DOCUMENT**: Assumed relationship of Learning Coefficient with the ratio of cycle time/ touch time. As the ratio gets small (approaches 1.0) the opportunities for learning become more intense, and LvsCT decreases.
Figures 4.17 (a,b and c) is the "base case" (as represented in Table 4.4). The assumption for this particular run is that LvsCT does not decrease with the decrease in the throughput (cycle) time through the inspection and rework operations (recall that lower values for L mean faster learning). In other words, LvsCT is fixed, based on the initial value of CT. Figures 4.18 (a,b and c) represent the same case with the "biflow" feature enacted for the "Change_in CT" flow variable (see explanation in Figure 4.5). This allows the stock "Smoothed_CT" to decrease so that LvsCT can move along its curve (Figure 4.15). The "continuous improvements" are quite dramatic.

In addition to the base cases, sensitivity analyses can be performed on the reference volume (Ref_Vol), the initial value for the cycle time (Smoothed_CT) and the relationship of the learning coefficient (L) with the cycle time ratio (LvsCT) shown in Figure 4.15.
Figure 4.17 (a,b,c) - Base Case with learning a function of only cumulative volume.
(Note that LvsCT is constant - i.e. no dependency of learning rate on cycle time)
Figure 4.18 (a,b,c) - Base Case with learning a function of both cumulative volume and cycle (throughput) time
4.5 Recommendations for Future Model Refinements

The models currently demonstrate, based on the assumptions, that reductions in throughput time not only have a direct impact on reducing overhead costs, but also allow for increased learning, via the positive feedback loop created by increasing the intensity of the learning opportunities. Additional work with the model could help to isolate the effects of throughput time improvements in straightening operations, or Pre-QA inspection and rework operations.

Improvements to the model include the perfection of the data in the costs model and addition of the logic for an investment decisions sector. In order to expedite the process of developing the structure of the learning model, the details of the cost model were not included. With the learning model fully operational, one could see the performance of the welding organization in terms of total costs in each of the four cost categories (direct and indirect, value adding and non-value adding). With the development of the investment decisions sector, one could more easily experiment with different budget allocation schemes to gain a better understanding of their effect on the future performance of the system.

4.6 Conclusions from Part I of Thesis

The goals of part I of this thesis were 1) to explore the nature of performance measurement systems, specifically cost accounting systems, and how they can be used to effect behavior and performance of a manufacturing system (personnel and machines) and 2) to examine the cost performance of welding processes in an aerospace manufacturing environment to show an economic
justification for improvements in process technology (specifically distortion control). Some of the specific findings of the research are as follows:

• There is less than 5% touchtime in welding operations (versus ~20% in machining operations).

• Delays caused by correcting distortion and relieving residual stresses account for a 22% increase in the total throughput time in welding operations for one Business Unit studied.

• Performance measures are often ambiguous and seldom reflect the real goal of Manufacturing (to make money).

• Costs in welding (especially materials handling and Q.A. inspection) are strongly correlated to total throughput time (indirect costs) and investment decisions should be based accordingly. (i.e. - reducing direct labor content is not necessarily the best approach).

• Some approaches to reducing costs in welding include:

  i) Revise cost accounting practices to separate value-adding and non-value adding activities. This will allow management to better focus improvement efforts.

  ii) Encourage more point of use measurement of what are traditionally included in the overhead pool (e.g. - welding supplies, maintenance, etc.)

  iii) Change performance measurement system to place emphasis on throughput time reduction. (e.g. - by allocating overhead by throughput time rather than by direct labor dollars)

  iv) Invest heavily in improving process control to increase 1st pass yields and reduce Pre-QA inspection cycles (discourage the reliance on intermediate repair and rework).

  v) Invest in improving distortion/residual stress control to eliminate operations. (again, reduce reliance on rework)
vi) Introduce welding cells that include inspection immediately following welding. This will reduce materials handling and speed feedback to welders.

vii) Invest in welder incentive programs to find ways to reduce throughput times.
Chapter 5

the production cycle - from preliminary joint design and process selection through final inspection of the joint. Chapter 2 outlined many of the problems associated with the various metal joining processes used in jet engine manufacture. In the aerospace industry, because of the focus on thin, lightweight materials, distortion and its control are of paramount interest. The cost studies detailed in previous chapters along with the comments of experienced welders and the volumes of previous work in the literature all point to distortion control as an important goal for the future of welding.

This section begins with a discussion of the basics of distortion and residual stresses in welding. Next, some approaches to distortion control in welding will be discussed. The work of Q. Guan, et al [Guan, 1988], on a Low Stress Non-Distortion (LSND) welding technique will then be introduced. The bulk of this chapter will be devoted to the Finite Element Method (FEM) simulation and analytical verification of the LSND technique. The concluding remarks will introduce the use of this weld simulation technique as a welding fixture design tool and propose some future studies to enhance the simulation's capabilities.

Apart from the work presented here on weld simulation, some additional effort was put into a study of the concept of an 'intelligent' welding fixture. An intelligent fixture senses movement and forces within the workpiece during the welding operation and applies counter-measures (forces, temperatures, movements, etc.) in an intelligent manner so as to effect the desired final workpiece condition. A discussion of this hypothetical fixture, along with the results of some experimental work are presented in Appendix A.
5.2 Fundamentals of Welding Distortion

There has been a considerable amount of work dedicated to determining the causes of distortion and residual stresses during welding. Masubuchi [Masubuchi, 1980] describes six basic types of distortion (Figure 5.1):

1) *Transverse shrinkage* occurs perpendicular to the weld line

2) *Longitudinal shrinkage* occurs parallel to the weld line.

3) *Angular distortion* is rotation about the weld line caused by a non-uniform transverse shrinkage.

4) *Rotational distortion* is a rotation of the two welded plates perpendicular to the weld line in the plane of the plates.

5) *Longitudinal bending distortion* occurs because of a non-uniform residual stress distribution through the thickness of the plate.

6) *Buckling distortion* occurs when compressive residual stresses cause instability in thin plates
5.2.1 The Causes of Distortion

Perhaps the best simple explanation of the residual stress phenomenon can be made by analogy to the structure in Figure 5.2. Illustrated are three steel bars of equal length and cross sectional area connected by two rigid blocks at the
ends. If the middle bar is heated, it is prevented from expanding by the two outside bars. If the thermal stresses become large enough to exceed the yield stress of the material then plastic flow will occur to redistribute the material so that the middle bar now has a new 'natural' length that is shorter than its original length. If the structure is then allowed to cool to room temperature the middle bar will be left with a residual tensile stress. Furthermore, if the compressive stresses in the two outside bars are high enough (or the members are slender enough), then buckling will occur.

![Diagram](image)

**Center Bar is Heated causing compressive stress to the point where yield occurs**

**Natural, room temperature length of center bar is reduced because of plastic flow**

**Residual tensile stress remains after cooling**

Figure 5.2 - Residual tensile stresses occur along the weld bead as a result of constrained thermal expansion, plastic deformation and thermal shrinkage upon cooling.

In welding, the amount of restraint imposed has a significant bearing on the level of residual stress in the weldment. If the welding is carried out in a free state condition, the movement of the metal is unrestrained and therefore no
plastic deformation will occur and the residual stresses will be small. If, however, the material near the joint is restrained, either by fixturing or by the geometry of the weldment itself (as is the case when welding bosses into rigid cylinders or in circumferential welds on cylinders), compressive stresses will occur. If these compressive stresses exceed the yield strength of the material then plastic deformation, leading to tensile residual stresses, will occur.

Unfortunately, the very act of welding - joining two pieces together - creates additional restraint on the joint which will guarantee the existence of some built-in stresses.

5.2.2 Mismatch Distortion
An additional type of distortion commonly found in welding thin materials is mismatch distortion. The basic cause for mismatch distortion is asymmetric heat flow with respect to the weld line. The causes for this are illustrated in Figure 5.3. Mismatch becomes very important for load transferring joints. A discontinuity in the load path can create quite a stress riser and can lead to vastly over-built (over-designed) structures at best and in-service failures at worst. Concern over the control of this type of distortion is so pervasive at the Company that a special task force has been assembled and is actively pursuing routes to correct this this problem.
5.2.3 Control of Distortion and Residual Stresses

Several attempts have been made to identify the welding parameters that can have a significant effect on distortion and residual stresses. Table 5.1 is a compilation, from several sources\(^1\) of the parameters that effect the distortion and residual stresses in the Gas Tungsten Arc Welding process. Next to each item is a ranking that identifies the strength of the correlation with the final level of distortion (low, medium or high). Figure 5.4 shows the cause and effect relationship of distortion in the form of an Ishikawa (Fishbone) diagram. It is very evident from this illustration that the distortion phenomenon is the result of a great many parameters - most of which are difficult to control.

\(^1\) [Masubuchi, 1980], [National Materials Advisory Board, 1987], Interviews with Company experts and various theses.
<table>
<thead>
<tr>
<th>TABLE 5.1 - Parameters Effecting Distortion (and their level of effect)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>I. Welding parameters Effecting Heat Input</strong></td>
</tr>
<tr>
<td>a) Arc Current Level</td>
</tr>
<tr>
<td>- Use of pulsed vs. constant current.</td>
</tr>
<tr>
<td>b) Arc Voltage Level</td>
</tr>
<tr>
<td>c) Speed of Travel</td>
</tr>
<tr>
<td>d) Seam Tracking</td>
</tr>
<tr>
<td>e) Electrode Characteristics</td>
</tr>
<tr>
<td>high</td>
</tr>
<tr>
<td><strong>II. Weld Joint Characteristics</strong></td>
</tr>
<tr>
<td>a) Gap</td>
</tr>
<tr>
<td>b) Included Angle</td>
</tr>
<tr>
<td>c) Initial Mismatch</td>
</tr>
<tr>
<td>high</td>
</tr>
<tr>
<td><strong>III. Base Material Characteristics</strong></td>
</tr>
<tr>
<td>a) Material Properties</td>
</tr>
<tr>
<td>- Coefficient of thermal expansion</td>
</tr>
<tr>
<td>b) Geometry</td>
</tr>
<tr>
<td>- Unsymmetric heat sinks</td>
</tr>
<tr>
<td>c) Disimilar thickness</td>
</tr>
<tr>
<td>high</td>
</tr>
<tr>
<td><strong>IV. Filler Material Characteristics</strong></td>
</tr>
<tr>
<td>a) Feed rate (amount deposited effects cooling)</td>
</tr>
<tr>
<td>b) Filler metal preheat temperature</td>
</tr>
<tr>
<td>medium</td>
</tr>
<tr>
<td><strong>V. Method of Shielding</strong></td>
</tr>
<tr>
<td>a) Torch gas flow rate (effects cooling)</td>
</tr>
<tr>
<td>b) Trailing gas- flow rate and temperature</td>
</tr>
<tr>
<td>low</td>
</tr>
<tr>
<td><strong>VI. Fixture Characteristics</strong></td>
</tr>
<tr>
<td>a) Material properties</td>
</tr>
<tr>
<td>- specific heat</td>
</tr>
<tr>
<td>b) Temperature</td>
</tr>
<tr>
<td>- thermal conductivity</td>
</tr>
<tr>
<td>c) Interface properties</td>
</tr>
<tr>
<td>- thermal conductivity, coeff. of friction</td>
</tr>
<tr>
<td>d) Hold down location (proximity to joint)</td>
</tr>
<tr>
<td>e) Fixture compliance</td>
</tr>
<tr>
<td>f) Timing of clamping (clamp and release)</td>
</tr>
<tr>
<td>high</td>
</tr>
<tr>
<td>high</td>
</tr>
<tr>
<td>medium</td>
</tr>
<tr>
<td>high</td>
</tr>
<tr>
<td><strong>VII. Use of Chills</strong></td>
</tr>
<tr>
<td>a) Location relative to weld seam</td>
</tr>
<tr>
<td>b) Temperature</td>
</tr>
<tr>
<td>- heat capacity (size, cooling medium)</td>
</tr>
<tr>
<td>c) Contact points with weldment</td>
</tr>
<tr>
<td>high</td>
</tr>
<tr>
<td>high</td>
</tr>
<tr>
<td>high</td>
</tr>
<tr>
<td>medium</td>
</tr>
<tr>
<td><strong>VIII. Tack Welds</strong></td>
</tr>
<tr>
<td>a) Strength</td>
</tr>
<tr>
<td>b) Location (spacing)</td>
</tr>
<tr>
<td>c) Initial offset</td>
</tr>
<tr>
<td><strong>IX. Post Weld Heat Treatment Cycle</strong></td>
</tr>
<tr>
<td>a) Thermal cycle</td>
</tr>
<tr>
<td>- hold temperature and time</td>
</tr>
<tr>
<td>b) Heat treatment fixturing</td>
</tr>
<tr>
<td>- hold down location and force</td>
</tr>
<tr>
<td>c) Localized vs. general heat treatment</td>
</tr>
</tbody>
</table>
Figure 5.4 - Ishikawa Diagram for the Causes of Distortion in GTA Welding
5.2.4 Methods for Minimizing Distortion and Residual Stresses

Several techniques for distortion control were uncovered in the literature. The most common techniques involve careful control of the welding arc parameters along with the use of stress relieving heat treatments and straightening operations that are carried out after the welding is complete. Since this can be interpreted as treatment of the symptoms rather than the underlying causes, no further discussion of these techniques will be made.

Another commonplace approach to distortion control is presetting. Presetting is a method of fixturing which takes into account the expected deformation due to the welding process to pre-position the pieces to be welded in a manner such that after welding the weldment has the desired configuration. This method, much like straightening operations, is based on the "inevitability of distortion" and will not be discussed further.

The most interesting techniques from an overall process improvement perspective involve some kind of manipulation of the welding conditions leading to stress free weldments. Of these there are two distinct approaches. One involves the pre-application of either mechanical or thermal loads prior to welding [North Amer., 1965] and the other one utilizes in-process application of mechanical or thermal loads in an attempt to gain some control over the process. In all cases, careful control of the welding arc parameters and seam tracking is also practiced.
The difficulty of any in-process approaches to distortion control in welding is based on the fact that although Gas Tungsten Arc Welding is a process which confines itself to a very small volume of metal (at any one time), it not a "serial" process in the sense that what goes on in that little region of molten material can have an effect on the structure as a whole (e.g. residual stresses and distortion). For example, as the weld proceeds the weldment itself becomes less flexible and therefore the boundary conditions for the problem change considerably. The time lag between the application of the heat source and the final distorted result is also a large barrier to total control of the GTAW process.

It was the hope of the experimental plan, outlined in Appendix A, to correlate some in-process measurement (be it movements or forces) with the final level of distortion and residual stress. Unfortunately, because of all the inter-dependent factors which contribute to the final distortion, this was not possible under this scope of research. (Figure A1 in Appendix A is a process model view of distortion control)

One interesting technique that shows some promise for the in-process control of distortion was a hot-rolling technique immediately following welding [Kurkin, 1984]. The effect of this hot rolling is to induce a compressive stress in the weld region that both counteracts the normal residual tensile stress from the welding process and enhances recrystalization (annealing) to reduce the overall residual stress level. While the evidence in the literature suggest that this technique is very effective, it suffers the serious drawbacks of complexity and cumbersomeness.
Techniques of pre-application of mechanical or thermal loads to weld pieces to reduce stress and the ensuing distortion have been known and practiced for quite some time [Masubuchi, 1980]. The most common form of pre-application is preheating. By using our previous analogy of the three metal bars, one can see that the benefit of preheating the entire structure is that the center bar must reach a considerably higher temperature before plastic deformation can occur. Therefore, the level of plastic deformation and the resulting residual stresses occurring upon cooling is reduced accordingly. One of the difficulties associated with simple preheating is that the metallurgical side-effects (most notably, hot-cracking) can be detrimental; especially for age hardenable alloys.

In the mid-1960's, NASA's Marshall Space Flight Center carried out a number of studies on the effect of in-process cryogenic cooling on distortion in TIG butt-welded thin aluminum [North Amer., 1965]. These studies concluded that intense cooling in the vicinity of the joint had a significant positive effect on reducing distortion. Several drawbacks to the proposed system (to be used in the welding together of Saturn V tank segments) prevented the system from ever being fully implemented. One persistent problem, that was overcome finally through the use of an elaborate system of baffles, was the introduction of contamination into the weld from the cryogenic gases. Another difficulty was that the presence of such an intense cooling environment made the power requirements of the system increase dramatically. This had the effect of increasing the variability of the welding process itself - not to mention that disaster would occur if the cooling were interrupted.

The final obstacle (and the most significant) to the implementation of this technique was the sheer complexity of the apparatus which was required to
move with the weld torch. One of the attractions of welding as a joining process is its simplicity and this was defeated with this system, creating a psychological barrier to its success.

5.2.5 Combined Mechanical and Thermal Prestress
A combination of mechanical and thermal prestress loads have been used with some success in the welding of railroad boxcar roofs [Masubuchi, 1980 - pg 319]. The most interesting technique from a practical standpoint utilizes the thermal expansion properties of the weld pieces to create a thermal prestress that can be tuned to counteract the effects of welding to produce an essentially stress free weldment. It is conceivable that this tunability might be used in a more real-time fashion if the appropriate in-process measurement mentioned above can be determined. For the present, however, the tuning is accomplished by means of trial and error experiments. For complicated welds and correspondingly complex welding fixtures this tuning process can be very time consuming and costly if every experiment requires a new fixture. This reasoning was the justification for the weld simulation work to be discussed in the next chapter.

5.3 Conclusions
From the discussion in Part 1 of this thesis it is clear that there is much to be gained through the elimination of straightening and stress relieving operations in the welding fabrication of aircraft engines (up to 15% cost savings, according to the model). Clearly the focus needs to be on distortion and residual stress elimination rather than correction. This is the best way that the overhead costs associated with queuing times, and moving parts about the factory, can be addressed.
A more sophisticated closed loop feedback control of arc parameters and seam tracking (which will require a good deal of capital investment and may result in cost prohibitive equipment) shows some promise in helping to decrease distortion, but it seems clear that the fixture side of the equation needs to be addressed as well. Fixturing parameters such as thermal profile and clamping locations and forces seem to play an even more important than arc parameters in their role in distortion. The following chapter examines one possible route to distortion elimination through better fixturing.
Chapter 6

Finite Element Analysis of Low Stress Non-Distortion Welding

6.1 LSND Experimental Work

The foundation for the work presented in this section is based primarily on a paper by Q. Guan, et al [Guan, 1988] in conjunction with the Welding Institute in Cambridge, U.K. This paper outlines a technique dubbed Low Stress Non-Distortion (LSND) welding and goes on to describe a series of GTA Welding experiments that demonstrate the feasibility and viability of the technique\(^1\). The main idea of LSND welding of thin-walled structural elements is to create a stretching effect by means of a preset temperature distribution, while at the same time restricting out-of-plane movement or “transient buckling” of the workpiece. Figure 6.1 is a schematic of the LSND fixture and Figure 6.2 shows the imposed thermal distribution. The thermal stretching effect is essentially the same as for the simple preheating case except that by cooling in the vicinity of the joint the temperature of the surrounding areas can be held much lower so that metallurgical problems can be avoided. The prevention of transient buckling is important because if movement is allowed then the effects of thermal preloading will be negated.

\(^1\)An international patent (No. PCT/GB88/00136) was filed jointly by BAMTRI (Beijing Aeronautical Manufacturing Technology Research Institute) and The Welding Institute on 26 February, 1988.
Figure 6.1 - Schematic diagram of LSND welding method and fixture\textsuperscript{2}

Figure 6.2 - Thermal profile illustrating the principles of LSND welding\textsuperscript{2}.

\textsuperscript{2} From Guan, Q. [ref]
The experiments were carried out on 5083 aluminum alloy of thicknesses 0.71, 1.62 and 3.25 mm and 18-8 stainless steel of thicknesses 1.00, 1.62 and 3.25 mm. Figure 6.3 gives the basic dimensions of the test pieces and Table 6.1 gives the welding parameters.

![Dimensions in mm]

(a)

$L = 1000$

$B = 200$

Figure 6.3 - Basic dimensions and sample allocation of strain gauges for residual stress measurements

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<th>Welding voltage, V</th>
<th>Welding speed, mm/min</th>
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<td>2-pass welding</td>
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</table>

Table 6.1 - Typical welding conditions in the experiments

3 From Guan, Q. [ref]
The experimental results were quite impressive. Comparisons between conventional welding and LSND welding were given in terms of out of plane deflections as well as levels and distributions of residual stresses. The test pieces welded under LSND conditions appeared to be completely distortion-free as a result of the residual stresses being kept to a value lower than the critical buckling value for the thin specimens. Figure 6.4 shows typical results for residual stresses for 1.62 mm, 18-8 stainless steel conventionally welded and welded by the LSND technique\(^4\).

\(^4\) Conversations with David Harvey of The Welding Institute indicated that equally good results could be obtained with or without weld wire and that tacking prior to welding seemed to have a positive effect on the results.
Figure 6.4 - Residual stress distributions on SS 18-8, 1.62 mm specimens after conventional welding and LSND welding\(^5\)

\(^5\)From Guan, Q. [ref]
6.2 LSND Simulation Via Finite Element Method

The goals of the LSND simulation effort were as follows:

1) Establish a methodology for conventional and LSND weld simulation using the MARC™ finite element code.

2) Attempt to verify, by simulation, the results of one particular set of experimental results in the Guan paper.

3) Analyze sensitivities of results to changes in temperature and placement of heat zones and placement of fixturing.

4) Develop optimization procedure for an LSND fixture design based on known sensitivities.

Due to time constraints, only the first two objectives were addressed. The last two would be necessary to fully utilize the advances made in the first two. These are left as areas for future study.

A good deal of time was devoted to developing the finite element modeling technique (using the MARC™ code) by which the LSND welding method could be evaluated analytically. Although there have been significant in-roads made in simulating forging and casting processes, there are several difficulties inherent to weld simulation which make it, to-date, intractable.

In order to completely and accurately simulate the welding process, one must perform a dynamic, thermal analysis to determine the thermal gradients in the part as a function of time and then perform a structural analysis at each time step based on the material properties at the elevated temperatures. Ideally, because of the coupled nature of the analysis, it would be preferable to perform both analyses simultaneously on the same model. However, the
complexity of this fully coupled analysis is such that it becomes cost and time prohibitive for all but the simplest of problems. For this reason, the majority of thermal/structural analyses are currently performed in two distinct steps: thermal and structural. The References section contains a listing of recent papers done by the leading researchers in the field of welding simulation.

To accurately handle the analysis of GTA welding, one must be able to handle the moving heat source problem. Proper treatment of this problem requires not only a fairly refined mesh to capture the intense thermal gradients, but a three-dimensional one as well (a 2-D plane strain analysis was attempted, but failed to predict the expected residual stresses). The combination of the large model along with the time-stepping nature of the analysis can put an enormous burden on the computational capacity of any of today's most powerful computers. The thermal runs for this study initially required over 400 time steps and over 3 hours of CPU time (on a DEC-2500 workstation) to simulate 5 seconds of stationary application of the weld torch (for later runs, this was reduced to ~175 time steps).

6.2.1 Thermal Analysis

After the procedure for the analysis was determined, two thermal runs were made. The first was made under the assumptions of conventional welding which included no preheating or cooling of the test piece. In the second, the LSND thermal distribution (shown in Figure 6.2) was applied. In both cases the boundary conditions and the heat input from the arc were identical.
All of the finite element models developed for this study were constructed using PATRAN\textsuperscript{TM} pre-processor and run on the MARC\textsuperscript{TM} finite element analysis system.

6.2.1.1 Mesh and Boundary Conditions

The basic model along with the heat transfer boundary conditions for the analysis can be determined from the sample runstream given in Appendix B-1. The top surface of the plate used a free convection and radiation heat transfer assumption (a standard MARC\textsuperscript{TM} subroutine). The bottom surface was held at a constant temperature to simulate the existence of an infinite heat sink. For the case of conventional welding, the bottom temperature was set at 80 °F. For the case of LSND welding the bottom temperature was set at 500 °F between the clamps and 60 °F outside the clamps. In both cases, the clamps provide additional heat sinks at the top surface of the plate. These conditions attempt to mimic the conditions of the experiments as determined from the report [Guan, 1988] as well as conversations with individuals at The Welding Institute.

6.2.1.2 Thermal Material Properties

Thermodynamic material properties (thermal conductivity - k, specific heat - c\textsubscript{p} and latent heats for fusion and vaporization) for stainless steel at elevated temperatures were obtained from a variety of sources, including company internal material data and textbooks [Incrupera and Dewitt, 2nd Ed., page 756]. Since elevated temperature data was not available for 18-8 stainless steel (the material used in the Guan research), some of the data was for 304L stainless steel.
6.2.1.3 Thermal Loading

A gaussian distribution of heat flux was applied as the heat source for this problem. The coding used for this distribution was written by Dr. John Cowles of the University of Connecticut and is included in Appendix B-3. As a further simplification, this heat source was made to be stationary and the heat input used was on a per lineal inch basis. The arc diameter was assumed to be 0.10 inches.

6.2.1.4 Results of Thermal Analysis

Typical results for the thermal analysis (for the LSND case) are shown in Figure 6.6 through Figure 6.12. Note that the thermal profile at time t = 0.0 is identical to the profile at time t = 5.0 seconds. This is just before the final step in the thermal analysis, which applies a uniform temperature of 80°F to the entire model. Because the heat from the torch is so localized, there is no visible difference in the thermal gradients between the two cases studied.
Figure 6.6 - Initial LSND thermal profile. Time = 0.00 seconds
Figure 6.7 - Closeup of weld joint region showing temperature profile at 0.0542 seconds after application of volumetric heat source
Figure 6.8 - Temperature profile at time = 0.142 seconds after application of heat source
Figure 6.9 - Temperature profile at time = 0.283 seconds after application of heat source. Nearing peak temperature.
Figure 6.10 - Temperature profile at time = 0.817 seconds after application of heat source. Cool down has begun.
Figure 6.11 - Temperature profile at time = 1.19 seconds after application of heat source.
Figure 6.12 - Temperature profile at time = 5.0 seconds after application of heat source. Temperatures have settled to their initial values.
6.2.2 Structural Analysis

To minimize the run times, the structural analysis portion of the coupled analysis was done on roughly every fifth thermal analysis step. An attempt was made to analyze smaller time steps during the heat-up portion of the cycle to capture the steep thermal gradients. The details of the model follow.

6.2.2.1 The Mesh and Boundary Conditions

The initial trials of the analysis were run with a two-dimensional, plane strain model that was assumed to be a slice out of an infinitely long test piece. Unfortunately, this model proved to be unable to predict the expected tensile residual stresses in the out-of-plane direction at the weld joint. It was clear that a three-dimensional model was required.

A generalized three dimensional plane-strain model was then constructed to acquire the extra dimension while still maintaining reduced degrees of freedom. Additionally, the stationary heat source simplification precluded the need to remesh as the simulation proceeded. In order to speed convergence it was necessary to impose some artificial restraints along the bottom surface of the weld pieces to prevent out of plane movement. Figure 6.13 shows the details of the boundary conditions (the mesh is identical to that used in the thermal analysis). Appendix B-3 contains the listing for the MARC™ runstream that generated the structural model (sans mesh data).
- Bottom surface is suppressed in the vertical direction
- Faces are constrained to remain parallel (generalized plane strain)
- Clamps are attached to workpiece in only the vertical direction (free to slide horizontally with thermal expansion)
- Weld joint end is constrained to a plane by a symmetry condition

Figure 6.13 - Description of MARC Finite Element model of SS 304L test piece and boundary conditions.
6.2.2.2 Bandwidth Optimization

Several bandwidth optimization schemes were pursued. The best for this particular model was found to be the Cuthill-McKee algorithm.

6.2.2.3 Material Properties

In order to capture the plastic deformation of the material in and around the weld it was felt that a work hardening model should be used. Work hardening takes place when the metal is plastically deformed, making further plastic deformation more difficult. The model, coded into MARC™ subroutine WKSLPE, is shown in Appendix B-4. Unfortunately, a great obstacle to convergence was encountered when the temperature of the material in the joint region approached the melting temperature. In this regime, the mechanical properties of the metal are so degraded as to offer little resistance to even the slightest forces. This caused the material in the weld pool region to behave erratically - with distortions computed that were on the order of inches.

Because there was nothing in place to handle the liquid metal problem, it was necessary to abandon the work-hardening model in favor of an elastic-plastic model in which it was possible to “massage” the physical properties at high temperatures (i.e. the Young’s modulus and yield point) to prevent the unrealistic distortions from occurring. Yielding (plastic flow) was not allowed to occur after the material had melted (the yield point was artificially raised after 2500 °F). This led to artificially high transient elastic stresses in the weld pool, but should not contribute heavily to an error in the final residual stress (which results mainly from plastic deformation).
The assumed Young's Modulus and Yield stress as a function of temperature is given in Figure 6.14. Note that both the Young's Modulus and the Yield stress drop off as the temperature approach the melting range, but as the temperature increases further, the Young's modulus and Yield stress increase so that the material will behave as perfectly elastic.

![Assumed Elevated Temperature Mech. Properties](image)

Figure 6.14 - Assumed profile of material properties with temperature. Series 1 - Young's Modulus (E), Series 2 - Yield stress (YTS)

6.2.2.4 Structural Loading

The fixture clamping force was not considered in this model. Rather, the entire bottom surfaces of the weld pieces were held down so that no vertical (out of plane) motion could occur. The location of the clamps was modeled, however, because their contribution as heat sinks was considered to be important.
6.2.2.5 Matrix Solution

Even after all of the simplifying conditions were imposed, the run time for one of these models was over 3 cpu-hrs on the VAX-2500 workstation.

6.2.3 Analysis Results

After the thermal data bases were established, a number of structural runs were made using the thermal data as input. The purpose of the multiple structural runs was to determine the following:

1) The proper time step size for the structural analysis
2) The proper elevated temperature, structural material properties to achieve convergence
3) The proper solution parameters to guarantee a rapid convergence to a reasonable solution.

As the test pieces cool to room temperature, a uniform 80°F, there is a noticeable difference between the conventional welding case and the LSND welding case. Figures 6.15 and 6.16 show the residual Z-stresses and the residual effective stresses for the conventional welding analysis and Figures 6.17 and 6.18 show the same for the LSND welding analysis. Comparing the peak stresses, LSND welding shows a 37% improvement in the Z-stress and a 27% improvement in effective stress over conventional welding. This compares with a three-fold empirical improvement as shown in Figure 6.4 (from Guan report).
Figure 6.15 - F.E. analysis results. Conventional Welding - Residual Z-Stress
Figure 6.16 - F.E. analysis results. Conventional Welding - Residual Eff-Stress
Figure 6.17 - F.E. analysis results. LSND Welding - Residual Z-Stress
Figure 6.18 - F.E. analysis results. LSND Welding - Residual Eff-Stress
The reason for the difference from the empirical results is not known, but it is encouraging that the analytical method predicts the improvement of the LSND technique over that of conventional welding. With this starting point, goal 2 (outlined at the beginning of the section), to verify the empirical results in the Guan report, is near at hand. It also seems possible that goals 3 and 4, to develop some useful applications for this analysis, may be on the horizon as well.

6.3 Recommendations

One possible reason for the discrepancy in the analysis results and the Guan report results is the use of the elastic-plastic material assumption. With a perfected work-hardening model (one that does not blow up at high temperatures), the material is not perfectly plastic when taken beyond its yield point. This extra bit of resistance may make a large difference (on the margin) as transient stresses are reduced by LSND.

In order for the work-hardening routines to work, it must be possible to set strains to zero once the metal in the joint has melted. This will have a significant impact since residual stresses occur during the cool down from the molten state. The “massaging” of the material properties for the elastic-plastic case (shown in Figure 6.14) was a crude attempt to set the strains in the weld pool closer to zero (by raising the modulus) so that upon cooling, only elastic stresses will come into play.
One thing does seem clear from the analysis; the LSND technique bears some more looking into as a means to reduce distortion and residual stesses. It would be a worthwhile project to find a practical application for this technique and begin to experiment with LSND on real hardware.
REFERENCES


Lin, Chao-Hsiung, *Reduction of Distortion in Welded Aluminum Structures by Differential Heating*, Massachusetts Institute of Technology Master's Thesis, Naval Arch. and Marine Eng., 1977. (works if distortion prediction can be perfected - otherwise it's trial and error)


Appendix A

Intelligent Fixturing and Some Experiments in Measuring Distortion In-Process

With the recent push toward flexible manufacturing and quick setup times, the concept of flexible fixturing in manufacturing has been a subject of intense interest. Most of the effort in this area seems to have centered around fixtures for machining that are somehow reconfigurable and are easily adaptable to a variety of parts. (Two approaches used are the low melting temperature fixture, which conforms perfectly to any workpiece shape while in the liquid phase, and the ‘Lego’ or building block approach which utilizes a combination of simple pins and holes to allow basic fixture elements to be shifted to achieve the desired configuration.) The concept of “intelligent” fixturing takes flexible fixturing one step further into the dynamic regime.

An intelligent fixture senses movement and forces within the workpiece during the processing operation and applies counter-measures (forces, temperatures, movements, etc.) in a reasonable manner so as to effect the desired final workpiece condition. One example of such a fixture is being studied at Sikorsky Helicopters for the machining of precisely shaped doors and windows into a flexible composite fuselage. The tradeoff here is whether to machine the openings in a partially flattened configuration using a simple tool, taking into account the distortion that will occur when the hull is allowed to return to its rounded shape, or to machine the openings in the rounded shape condition using a very complicated NC machine tool.
If the goal is to control final shape of the weldment, it is conceivable that the movement of the weld pieces can be detected and a "brute force" correction can be made by the fixture to return the weldment to the straight condition. If, on the other hand, the desire is to minimize residual stress in the weldment (which is often more important for thin materials and from the perspective of stress corrosion or fatigue resistance), the task is much more difficult. Direct measurement of residual stress by nondestructive methods (such as X-ray diffraction) is currently unreliable and very cumbersome. This means that indirect methods of measurement combined with a physics-based model of the process must be used as the input to the control box.

Control of the process is made more difficult because the residual stresses in a weldment are generally macroscopic in nature, and not subject to changes within a local region. Figure A1 is a process model view of distortion in GTA welding.
Figure A1 - Process Model view of distortion in GTAW welding
Experiments with In-process Distortion Measurement

The purpose of the experiments was to determine if it was possible to measure something (be it movements, forces, etc.) which would give an indication of the level of distortion in the part. Figure A-2 attempts to highlight the various correlations needed to fully understand the cause and effect relationships in welding.

The test pieces used were roughly 8 x 3 inches by .032 thick. Figure A-3 shows the typical after-welding shape and the locations for measurements. The measurement used to follow distortion, was the movement of the AVC (arc voltage control) as picked up by LVDT's in the fixture (see below). Figures A-4 to A-8 show the results of the experiments. They show that, indeed, the LVDT's can pick up the movement of the AVC, but the after-released distorted shape bore little resemblance to the measurements. This is because the distortions measured were primarily due to compressive buckling, which can go in either direction.
A2 - SCHEMATIC REPRESENTATION OF EXPERIMENTAL PROGRAM TO CORRELATE IN-PROCESS (TRANSIENT) METAL MOVEMENT WITH DISTORTION IN GTA WELDING OF THIN MATERIALS

Experimental Program

Arc Parameters
- Welding Speed
- Thickness
- Gapping
- Tacking

INITIAL WELDING CONDITIONS

IN-PROCESS METAL MOVEMENT
- Vertical Movement/Force
- Transverse Movement/Force

AS CLAMPED DISTORTION
- 3 Vertical Displacements
- 3 Transverse Displacements

FINAL DISTORTION
- 5 Out-of-plane Measurements
- 3 Transverse Measurements

Data Analysis

- Correlation 1
- Correlation 2
- Correlation 3
- Correlation 4
- Correlation 5
- Correlation 6

☆ - Correlations of specific interests
A3 - EXPERIMENT: DISTORTION IN GTA WELDED THIN MATERIALS
Measurements to Characterize Distortion

Stop Weld

Start Weld

Scribed Lines (2)

1  2  3  4  5  6  7  8
Data from "EXP#1 data"

Data from "EXP#2 data"
Data from "EXP*70.data"

Data from "EXP#8.data"

-147-
APPENDIX B

APPENDIX B1 - MARC Runstream for thermal analysis (LSND3DT.DAT)
APPENDIX B2 - Subroutine FLUX for volumetric heat generation from arc
APPENDIX B3 - MARC Runstream for structural analysis with Work-Hardening (LSND3DSW.DAT)
APPENDIX B4 - Subroutine WKSLP to define work-hardening slope as a function of Total equivalent plastic strain
APPENDIX B1 - MARC Runstream for thermal analysis (LSND3DT.DAT)

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3.03E-4, 980.6
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3,
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-150-
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CONTINUE
APPENDIX B2 - Subroutine FLUX for volumetric heat generation from arc

SUBROUTINE FLUX(F, TEMFLU, MIBODY, TIME)
DIMENSION MIBODY(1), TEMFLU(1)

ROUTINE WRITTEN FOR KIP POOL FOR 3D WELDING WITH VOLUMETRIC HEAT
GENERATION FOR POWER INPUT TO MODEL. ONLY ARC INPUT COMES INTO PLAY
IN THIS ROUTINE. ALL RADIATION AND FREE CONVECTION SHOULD BE DONE IN
ROUTINE FILMS

* * * * *
CALLED BY CONSB, CONS D, CONSH, CONS I

* * * * *
USER SUBROUTINE FOR NON-UNIFORM FLUX INPUT.

F FLUX VALUE
TEMFLU(1) ESTIMATED TEMPERATURE
TEMFLU(2) PREVIOUS VOLUMETRIC FLUX
TEMFLU(3) TEMPERATURE AT BEGINNING OF INCREMENT
TEMFLU(4, 5, 6) INTEGRATION POINT COORDINATES
MIBODY(1) ELEMENT NUMBER
MIBODY(2) FLUX TYPE
MIBODY(3) INTEGRATION POINT NUMBER
TIME TIME

* * * * *
CALL MTRACE(6HFLUX, 1, 0) TR
CALL MTRACE(6HFLUX, 2, 0) TR

ARC PARAMETERS
REAL A/0.05/
REAL NARCH/0.8/
REAL NARC
REAL QARC/14.2/
REAL QPOWER
REAL THICK/0.064/
REAL ARVCVEL/0.22/
REAL TMAX

! 2 SIGMA RADIUS OF ARC (IN)
! MAXIMUM ARC EFFICIENCY
! ARC EFFICIENCY
! PEAK ARC INPUT POWER (VOLTAGE*CURRENT) IN BTU/S
! ARC POWER SCALED BY TIME FACTOR
! THICKNESS OF PLATE (IN)
! ARC VELOCITY (IN/S)
! TIME THAT ARC WILL BE TURNED ON

*** MARC COMMON BLOCKS ***

*** INITIALIZE ***

WRITE (6,998) MIBODY(1), MIBODY(3), TEMFLU(4), TEMFLU(5), TEMFLU(3)
998 FORMAT (1X, 'ELEM ', I4, ' INT POINT ', I1, ' XPOS ', F15.5, ' YPOS ', F15.5, ' TEMP BEGIN ', F15.5)

F = 0.

*** CHECK CODE FOR FLUX TYPE, 3 == VOLUMETRIC GENERATION FROM ARC

XINT = TEMFLU(4)
YINT = TEMFLU(5)
ZINT = TEMFLU(6)

XMAX = A*SQRT(YINT/THICK)
TMAX = 2/A/ARVCVEL

IF (XINT .LE. XMAX AND TIME .LE. TMAX) THEN
  IF (TIME .LE. TMAX/2.) THEN
    QPOWER = QARC*2.*TIME/TMAX
  ELSE
    QPOWER = QARC*2.**(TMAX-TIME)/TMAX
  ENDIF
ENDIF

*** CALCULATE ARC EFFICIENCY
IF (TEMPFLU(3) .GT. 2500.) THEN
   NARC = NARCMAX * EXP(-((TEMPFLU(3) - 2500.) / 300.))
ELSE
   NARC = NARCMAX
ENDIF

F = NARC * 2.5 * QPOWER / (A * A * THICK) * (YINT / THICK) *
   EXP(-3. * (XINT / A) ** 2 * THICK / YINT)
ENDIF

RETURN
END

SUBROUTINE FILM (H, TINF, TS, N, TIME)

******************************************************************************
* FREE CONVECTION AND RADIATION *
******************************************************************************

REAL H     ! FILM COEFFICIENT (W/M * K)
REAL TINF   ! AMBIENT TEMPERATURE (DEG F)
REAL TS(6)  ! TNEW, TOLD,, INTEGRATION POINT COORDS
INTEGER N(3) ! ELEMENT, CODE, INTEGRATION POINT ID
REAL TIME   ! CURRENT TRANSIENT TIME (SECONDS)

*** RADIATION TRANSFER PARAMETERS ***

REAL SIG/3.414E-15/  ! STEFAN BOLTZMANN CONSTANT (BTU/(SEC*IN**2*F**4)
REAL EPS/0.80/       ! SURFACE EMISSIVITY

* USER MUST DEFINE THE FOLLOWING VALUES BEFORE RUNNING NARC *

TINF=80.0

*** RADIATION COEFFICIENT ***

TEMPR = TS(2) + 460.0
TINFR = TINF + 460.0
HRAD = SIG * EPS * ((TEMPR**2 + TINFR**2) * (TEMPR + TINFR))

*** CONVECTION COEFFICIENT ***

FROM THERMODYNAMICS AND HEAT POWER, GRANET AS A FIRST CUT TAKE AN APPROXIMATE
VALUE FOR FREE CONVECTION COEFFICIENT FOR GASES.

PAGE 631 -- RANGE FROM 1.9E-7 TO 9.65E-6 BTU/S/IN**2/F

CHOOSE 5.0E-7

HCONV = 5.0E-7

H = HRAD + HCONV

RETURN
END

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APPENDIX B3 - MARC Runstream for structural analysis with Work-Hardening (LSND3DSW.DAT)

COMMENT -MAG PATMAR VERSION 3.2
COMMENT Tues Dec 4 16:34:54 1990
TITLE LSND VERIFICATION ANALYSIS
SIZING, 1500000,
ELEMENTS, 7,
ALIAS, 1, 43, 7
THERMAL
SETNAME, 50,
ALL POINTS
END
RESTART
1, 10,
DEFINE ELEMENT SET ALLELEMS
1 TO 138
DEFINE NODE SET ALLNODS
1 TO 392
OPTIMIZE, 1,
50,
CONTROL
300.10, 1, 3,
0.10,
POST
11, 1, 1, 19, 1,
1, XX STRAIN
2, YY STRAIN
3, ZZ STRAIN
4, XY SHEAR STRAIN
11, XX STRESS
12, YY STRESS
13, ZZ STRESS
14, XY SHEAR STRESS
17, VON MISES
9, TOTAL TEMPERATURE,
23, ZZ TOTAL PLASTIC STRAIN
ISOTROPIC
1
1 VON MISES ISOTROPIC
31.0000+6.0.305000, 0.283000, 6.4700-6, 121530.00, 1,
ALLELEMS
COMMENT PROPORTIONAL LIMIT DATA
TEMPERATURE EFFECTS, DATA
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102070., 600.000,
91590., 800.000,
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0.2846E+08, 500.000,
0.2788E+08, 600.000,
0.2728E+08, 700.000,
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-157-
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APPENDIX B4 - Subroutine WKSLP to define work-hardening slope as a function of Total equivalent plastic strain

```fortran
SUBROUTINE WKSLP (SLOPE, EBARP, DT, IFIRST)

C**********************************************************************************************
C Owner: (Mfg. Analysis)
C Purpose:
C This subroutine defines the work-hardening slope for 1 material as a function of the current Total Equivalent Plastic Strain and Temperature for...
C Notes:
EBARP, DT, IFIRST should not be altered in this routine
SLOPE, STYRT must be defined in this routine
C Data Input procedure:
3D array with the following components
1 - STRESS - KSI
2 - STRAIN - percent
   ISTRN = 0 - Input PLASTIC strain
   ISTRN = 1 - Input TOTAL strain = ELASTIC + PLASTIC
3 - TEMP - deg F
C Description of Variables Referenced in Subroutine Call:
SLOPE - work-hardening slope defined as dSTYRT/dEBARP
EBARP - current total equivalent plastic strain
DT - current total temperature
IFIRST - is passed in as 1 for initial yield
         2 for the 10th cycle yield curve when ORNL constitutive theory is flagged
C Description of GLOBAL COMMON Variables:
M - current element number
STYRT - current yield stress
C Description of LOCAL Variables:
C Common Statements:
COMMON /FAR/DUM(17), M
COMMON /STRXIE/STRYT
C Declarations of Variables Referenced in Subroutine Call:
REAL SLOPE, DT, EBARP
INTEGER IFIRST
C Declarations of Local Variables:
REAL*8 DSTRYT, DSLOPE
INTEGER M
REAL*8 T, S, STRL, STRU, DELT, TT, DELSTR
PARAMETER (NTEMP = 11, NDATA = 26)
REAL X1 (NTEMP, NDATA, 3)
PARAMETER (NROW = 50, NCOL = 50, N3D = 3, N2D = 2)
REAL X (NROW, NCOL, N3D)
REAL P (NROW, NCOL, N2D)
INTEGER ISTRN, IPRNT1, IPRNT2, LGDSP
```

START MATERIAL DATA:
Stress vs Plastic strain by Temperature

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<tr>
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</tr>
<tr>
<td></td>
<td>&lt;</td>
<td>0.1,0.01,1.E-4,</td>
</tr>
</tbody>
</table>

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0.60E-2, 0.60E-2, 0.60E-2, 0.60E-2, 0.60E-2, 0.60E-2, 
0.60E-2, 0.60E-2, 0.60E-2, 0.60E-2, 
0.80E-2, 0.80E-2, 0.80E-2, 0.80E-2, 0.80E-2, 0.80E-2, 
0.80E-2, 0.80E-2, 0.80E-2, 0.80E-2, 
0.10E-1, 0.10E-1, 0.10E-1, 0.10E-1, 0.10E-1, 0.10E-1, 
0.10E-1, 0.10E-1, 0.10E-1, 0.10E-1, 
0.15E-1, 0.15E-1, 0.15E-1, 0.15E-1, 0.15E-1, 0.15E-1, 
0.15E-1, 0.15E-1, 0.15E-1, 0.15E-1, 
0.20E-1, 0.20E-1, 0.20E-1, 0.20E-1, 0.20E-1, 0.20E-1, 
0.20E-1, 0.20E-1, 0.20E-1, 0.20E-1, 
0.25E-1, 0.25E-1, 0.25E-1, 0.25E-1, 0.25E-1, 0.25E-1, 
0.25E-1, 0.25E-1, 0.25E-1, 0.25E-1, 
0.30E-1, 0.30E-1, 0.30E-1, 0.30E-1, 0.30E-1, 0.30E-1, 
0.30E-1, 0.30E-1, 0.30E-1, 0.30E-1, 
0.40E-1, 0.40E-1, 0.40E-1, 0.40E-1, 0.40E-1, 0.40E-1, 
0.40E-1, 0.40E-1, 0.40E-1, 0.40E-1, 
0.50E-1, 0.50E-1, 0.50E-1, 0.50E-1, 0.50E-1, 0.50E-1, 
0.50E-1, 0.50E-1, 0.50E-1, 0.50E-1, 
0.70E-1, 0.70E-1, 0.70E-1, 0.70E-1, 0.70E-1, 0.70E-1, 
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0.90E-1, 0.90E-1, 0.90E-1, 0.90E-1, 0.90E-1, 0.90E-1, 
0.90E-1, 0.90E-1, 0.90E-1, 0.90E-1, 
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0.15, 0.15, 0.15, 0.15, 0.15, 0.15, 
0.15, 0.15, 0.15, 0.15, 
0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 
0.2, 0.2, 0.2, 0.2, 
0.3, 0.3, 0.3, 0.3, 0.3, 0.3, 
0.3, 0.3, 0.3, 0.3, 
0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 
0.5, 0.5, 0.5, 0.5, 
0.7, 0.7, 0.7, 0.7, 0.7, 0.7, 
0.7, 0.7, 0.7, 0.7, 
0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 
0.9, 0.9, 0.9, 0.9, 
32.0, 200.0, 400.0, 600.0, 800.0, 1000.0, 1200.0, 1800.0, 
2500.0, 2700.0, 10000.0, 
260*0.0/

END MATERIAL DATA:

Set Options
ISTRN = 0
IPRT1 = 0
IPRT2 = 0
LGDSP = 0

Load working array X, with proper material data
DO I=1, NTEMP
  DO J=1, NDATA
    X(I,J,1) = X1(I,J,1)
    X(I,J,2) = X1(I,J,2)
    X(I,J,3) = X1(I,J,3)
  ENDDO
ENDDO

Material Data has been loaded, start calculations

Initialize slope/intercept array
DO I=1, NRROW
  DO J=1, NCOL
    DO K=1, NZD

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P(I,J,K)=0.0
ENDDO
ENDDO
ENDDO

C Convert from KSI & percent strain
DO I=1,NTEMP
  DO J=1,NDATA
    X(I,J,1) = X(I,J,1) * 1000.
    X(I,J,2) = X(I,J,2) * 0.01
    X(I,J,3) = X(I,1,3)
  ENDDO
ENDDO
WRITE(6,*) 'NDATA = ',NDATA

C Print out the input data if selected by user
IF (IPRNT1.EQ.1) THEN
  WRITE(6,*)'
  WRITE(6,*)'Input Material Properties'
  WRITE(6,*)'
  DO I1=1,NTEMP
  DO I2=1,NDATA
  WRITE (6,FMT=("3(1X,E10.4)")) (X(I1,I2,I3),I3=1,3)
  ENDDO
ENDDO
ENDIF

C Convert to large displacement values of stress-strain
C if large displacement flag set to 1
C Per MARC section 3.6-1
C STRESS = STRESS / (1.0 + STRAIN)
C STRAIN = STRAIN * (1.0 + 0.5*STRAIN)
IF (LDISP.EQ.1) THEN
  DO I1=1,NTEMP
  IF(IPRNT1.EQ.1)WRITE (6,*)'Large Disp. Correction Applied'
  DO I2=1,NDATA
  X(I1,I2,1) = X(I1,I2,1) / (1.0 + X(I1,I2,2))
  X(I1,I2,2) = X(I1,I2,2) * (1.0 + 0.5*X(I1,I2,2))
  IF(IPRNT1.EQ.1) THEN
  WRITE (6,FMT=("3(1X,E10.4)")) (X(I1,I2,I3),I3=1,3)
  ENDDO
ENDDO
ENDIF

C If stress/strain zero point exists in data use it
C otherwise calculate it
C P(1,1) - Slope  P(1,2) - Intercept
DO L=1,NTEMP
  IF (X(L,1,2) .NE. 0.0) THEN
   P(L,1,1) = X(L,1,1) / X(L,1,2)
   P(L,1,2) = X(L,1,1) - P(L,1,1) * X(L,1,2)
  IF(IPRNT1.EQ.1) THEN
  WRITE (6,3000)L,P(L,1,1),P(L,1,2).
  3000 FORMAT(1X,'Calculating ZERO point',/,'Temp/Slope/Intercept = ',I5,2E15.5)
  ENDDO
UX
ENDIF
ENDDO

C Extract plastic strain from TOTAL strain if input that way
IF (ISTRN.EQ.1) THEN
  DO L = 1,NTEMP
  DO N = 1,NDATA

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IF (P(L,1,1) .NE. 0.0) THEN
   X(L,N,2)=X(L,N,2)-X(L,N,1) / P(L,1,1)
ENDIF
ENDDO
ENDIF
ENDIF

C Calculate the slope/intercept for the stress-plastic strain curve
DO L=1,NTEMP
   DO N=2,NDATA
      IF ( X(L,N,1) .NE. 0.0) THEN
         MMM = N - 1
         IF (X(L,N,2) .EQ. X(L,MMM,2)) THEN
            P(L,N,1)=0.0
         ELSE
            P(L,N,1)=((X(L,N,1)-X(L,MMM,1))) / ((X(L,N,2)-X(L,MMM,2)))
         ENDIF
         P(L,N,2)=X(L,N,1) - P(L,N,1) * X(L,N,2)
      ENDIF
      IF (IPRNT1 .EQ. 1) THEN
         WRITE (6,4000)L,P(L,1,1),P(L,1,2)
      ENDIF
   ENDDO
4000 FORMAT(1X,' Curve/slope/intercept ',I5,2E15.5)
ENDIF
ENDIF
ENDDO
ENDIF

C IF (IPRNT1 .EQ. 1) THEN
   WRITE (6,*),' Stress vs. Plastic Strain Used in Calcs'
   WRITE (6,*),' DO I1=1,NTEMP'
   DO I2=1,NDATA
      WRITE (6,FMT=('(3(1X,E10.4))') (X(I1,I2,I3),I3=1,3)
   ENDDO
   ENDDO
   WRITE (6,*)' '
ENDIF

C Set up interpolator
C T is TEMP
C S is STRAIN
C  T=DT
C  S=EBARP

C Bound temperature 1st
DO L=2,NTEMP
   IF (T .LT. X(L,1,3)) GO TO 60
ENDDO
CONTINUE

60 ITL = L-1
ITU = L

C Extrapolate on last straight line
C Bound strain to determine which linear fit to use
DO L=2,NDATA
   IF (X(ITL,L,2) .EQ. 0.0) GO TO 79
   IF (S .LT. X(ITL,L,2)) GO TO 80
ENDDO
CONTINUE

79 IF (X(ITL,L,2) .EQ. 0.0) L = L-1
80 CONTINUE
  ISLL = L-1
  ISUL = L
C DO L=2,NDATA
   IF (X(ITU,L,2) .EQ. 0.0) GO TO 94
IF (S .LT. X(ITU,L,2))  GO TO 95
ENDDO
94 CONTINUE
IF(X(ITU,L,2).EQ. 0.0) L = L-1
95 CONTINUE
ISLU = L-1
ISUU = L

C-----------------------------------------------------------------------
C Calculating Interpolate Temperature
C Calculate bounding stresses (lower & upper)
   STRL = (P(ITL,ISUL,1) * S) + P(ITL,ISUL,2)
   STRU = (P(ITU,ISUU,1) * S) + P(ITU,ISUU,2)
C
C Take linear percentage
   DELT = X(ITU,ISUU,3) - X(ITL,ISUL,3)
   TT = T - X(ITL,ISUL,3)
   FACTOR = TT / DELT
   DELSTR = STRU - STRL
C
C Interpolate yield stress
   DSTRYT = STRL + (DELSTR * FACTOR)
   STRYT = DSTRYT
C
C Interpolate work-hardening slope
   DSLOPE = P(ITL,ISUL,1) + FACTOR * (P(ITU,ISUU,1) - P(ITL,ISUL,1))
   SLOPE = DSLOPE
C
C Print out calculated values if selected
   IF(IPRINT .EQ. 1) THEN
      WRITE(6,1000)M,DT,DSTRYT,DSLOPE
   1000 FORMAT(1X, 'Work Hardening Slope',
   > '/ Element ', IS,
   > '/ Temp ', E15.5,
   > '/ Stress ', E15.5,
   > '/ TanMod ', E15.5)
      ENDIF
      RETURN
   END
C
SUBROUTINE INTCRD(M,NN,XINTP,NCRD)
C * * * * * * * * * * * * * * * * * * * * * *
COMMON/HEATTM/CUTIME,DUTIME
COMMON/CREEPS/ICREEP,ITHERM,CPTIM,ICPTIM,
1 ICETE,ICFST,ICFEQ,ICFTM,
2 ICETEM,CREASEP(33),TIMINC,MCREEP,JCREEP,
3 ICFA,ICFTMP,ICFSTR,ICFQCP,ICFCPM,ICRFPR
TIMING = DUTIME
RETURN
END