Development of a Robust Heat Treating Process for Rockwell B-scale Hardness Test Blocks

by

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

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ABSTRACT

Robust process design methods are applied to a heat treating process used in the manufacture of Rockwell B-scale hardness test blocks. Experimentation efforts indicate that the existing heat treating process produces hardness test blocks with a uniformity that is very near the optimum achievable. Several control factors including soak temperature, soak time, cooling method, and a secondary heat treatment are included in a set of screening experiments. The effects and interactions of control factors are studied using analysis of means and a static S/N ratio. The significance of control factor effects and interactions are computed using analysis of variance (ANOVA) techniques.

The philosophy behind and methodology of Taguchi's parameter design method is presented in terms of robust process design applications. Taguchi's contributions to the field of quality engineering, including the Quality Characteristic, Signal-to-Noise (S/N) Ratio, and Orthogonal Arrays are discussed.

A summary of metallurgical information pertinent to heat treating copper-based alloys is given. Partial annealing processes used to control the properties of cold-worked metals are discussed.

The challenge of implementing Taguchi methods in a manufacturing environment are discussed and a structured procedure for their implementation is presented.

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Kenneth C. Russell, Professor of Metallurgy, Professor of Nuclear Engineering

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Part 1: Introduction

1.1 Background

The Wilson Instruments Division of Instron is the leading manufacturer of Rockwell hardness testing equipment and is credited with having established the Rockwell hardness test over 75 years ago. The work contained in this thesis is based on the optimization of a heat treating process used by Wilson Instruments in the manufacture of B-scale standard hardness test blocks. Standard hardness test blocks are used to monitor and calibrate Rockwell hardness testers during tester commissioning and maintenance programs. They are also used to maintain Wilson Instrument's internal hardness standards.

Wilson Instruments is at the leading edge of Rockwell hardness testing equipment. Most recently, their introduction of the Wilson 2000 series of hardness testers marked a leap ahead of the competition in quality and value. The introduction of the Wilson 2000 series answered the increasing demand of hardness tester users for improved accuracy and repeatability. In support of the customer's demands, Wilson Instruments has also focused considerable efforts on improving the quality of their standard hardness test blocks.

The quality of Wilson's Rockwell C-scale test blocks was improved through the efforts of a Leaders for Manufacturing (LFM) internship completed one year ago. In fact, as a results of those, and previous improvement efforts, the National Institute of Standards and Technology currently purchases, calibrates, and re-sells Rockwell C-scale test blocks manufactured by Wilson Instruments. The quality of Rockwell B-scale test blocks, which are manufactured from copper alloys, as opposed to steels, however, had not been the subject of quality improvement efforts for several years.

To improve the quality of Rockwell B-scale standard hardness test blocks the Wilson Instruments Division sponsored a second LFM internship. The primary goal of the internship was achieved as the uniformity of the B-scale test blocks was improved by approximately

35%. The enhanced uniformity of the test blocks was achieved by implementing new process control procedures and by improving raw material supplies. Following the primary efforts performed during the LFM internship, an effort to optimize the heat treating process used in the manufacture of B-scale test blocks was performed. The methodology and results of the heat treating process optimization efforts are the subject of this thesis.

1.2 Scope of Thesis

This thesis is limited to the heat treating process used to manufacture B-scale test blocks. It does not discuss the process control procedures or material improvements made over the course of the LFM internship as they are critical to Wilson Instrument's continued leadership in the hardness testing marketplace. Likewise, the exact materials and process parameter settings used in the heat treating process optimization are not provided in the thesis.

1.3 Goals of Thesis

The primary goal of the thesis is to provide the Wilson Instruments Division of Instron with a greater understanding of the B-scale test block heat treating process. A secondary goal is to teach the quality philosophy and quality engineering methods commonly referred to as Taguchi methods to the employees of the Instron Corporation. Instron has an excellent reputation for the quality of their products and, I believe, that their quality efforts could be further improved through the use of Taguchi methods in their manufacturing process and product development efforts.

Part 2 Background

Rockwell hardness tests are used in research, standardizing, and industrial applications. In all applications there is constant incentive to increase the accuracy and repeatability of hardness testing. In particular, consider the implications of erroneous hardness tests in high-volume manufacturing process control applications. Errors in such applications can be extremely costly and can only be avoided by increasing the quality of the entire hardness testing system.

2.1 Rockwell Hardness Testing System

Hardness is loosely defined as a material's ability to resist deformation. A Rockwell hardness test is a destructive test that determines the hardness of a material by pressing a object of known geometry, called an indentor into the material. For the Rockwell B-scale the indentor is a 1/16" steel sphere. A hardness tester is used to press the indentor into the material using a sequence of known loads. The hardness tester also records the depth of penetration achieved by the indentor. For the Rockwell B-scale the hardness test sequence is as follows:

I. application of minor load:

   A. a 10 kgf load is applied to seat the indentor

   B. the start or reference depth of penetration, y_{start}, is measured

II. application of major load:

   A. a 100 kgf load is applied to cause an inelastic deformation of the material

III. application of minor load:

   A. the load is returned to 10 kgf allowing elastic recovery to occur

   B. the final depth of penetration, y_{final}, is measured

The hardness tester records the two depth of penetration measurements and then calculates the material's hardness using the following relationship:

Hardness, HRB = $130 - [(y_{final} - y_{start})/2\ \mu m]$

There are many different Rockwell hardness scales which are used to accommodate materials of varying hardness and thickness. The Rockwell scales all use a similar testing method with significant differences arising only in the types of indentors and magnitudes of loads applied.

2.2 Hardness Test Blocks

The primary physical components in the hardness testing system include the hardness tester, indentor, and hardness test block. The hardness test block is used to calibrate hardness testers in commissioning, service, and maintenance applications. In use, the test block is tested using the hardness tester that is undergoing evaluation. If the hardness reading produced by the hardness tester does not match the known hardness of the test block (within a certain measurement tolerance), the hardness tester is adjusted accordingly.

Each hardness test block is calibrated and stamped with a known hardness by Wilson Instruments. The calibration is performed by measuring the hardness of the test block six times. One of several standardizing hardness testers in the Wilson Instruments Standards Laboratory is used for the calibration measurements. The standardizing testers are monitored and maintained to produce accurate and precise hardness readings. The mean and range of the six readings, and the individual readings themselves, are recorded on a calibration certificate that is shipped with the test block. The mean hardness and a standard measurement tolerance is imprinted on the side of each test block.

The primary problem with B-scale hardness test blocks is that the variation in hardness across the surface of each individual test block is larger than desired. Ideally, the variation in hardness would be zero. Hardness variation effects both the end user of the test blocks and Wilson Instrument's manufacturing operations. For the end users, be they external customers or Wilson Instruments service people, test block hardness variation can decrease the accuracy of tester calibrations and increase the time required to complete the calibration procedures. For Wilson Instrument's manufacturing operations, test block variation reduces the manufacturing yield because calibration requirements dictate that any test block with a range of calibration readings greater than a prescribed value must be discarded. The reduction of test block variation then produces three primary benefits:

1. increased hardness tester calibration accuracy
2. decreased hardness tester calibration efforts
3. increased manufacturing yields

There is an additional benefit to decreasing the variation in hardness test block readings. Since the creation of the Rockwell hardness measurement standard, Wilson Instruments has set the de facto standard for Rockwell hardness. Maintenance of the standards requires the use of hardness test blocks. The use of more uniform test blocks in the standards maintenance process would create a more stable and easier to maintain standard.

Additionally, two years ago, the National Institute of Standards and Testing (NIST) began issuing standard test blocks for the Rockwell C-scale. Wilson Instruments supplies uncalibrated C-scale test blocks to NIST who then calibrates them using a highly accurate and precise deadweight hardness tester. NIST also plans on issuing standard test blocks for the Rockwell B-scale as well. Wilson Instruments, by improving the uniformity of their B-scale hardness test blocks, could be in a very good position to supply NIST with the uncalibrated test blocks for the national Rockwell B-scale hardness standard.

2.3 Manufacture of B-Scale Hardness Test Blocks

B-scale hardness test blocks are produced from a copper alloy using a combination of machining, heat treating, and calibration operations. A block diagram representation of the manufacturing process is given in Figure 1 below. In the figure, the manufacturing steps completed by outside vendors are indicated in italics. Because a substantial portion of the manufacturing process is completed by outside vendors, Wilson Instruments must maintain open and clear channels of information with their vendors. The focus of this thesis is on the heat treating process which is performed by a vendor. A detailed description of the manufacturing process steps depicted in Figure 1 is not within the scope of the thesis, however; a summary account is presented in the following paragraphs.

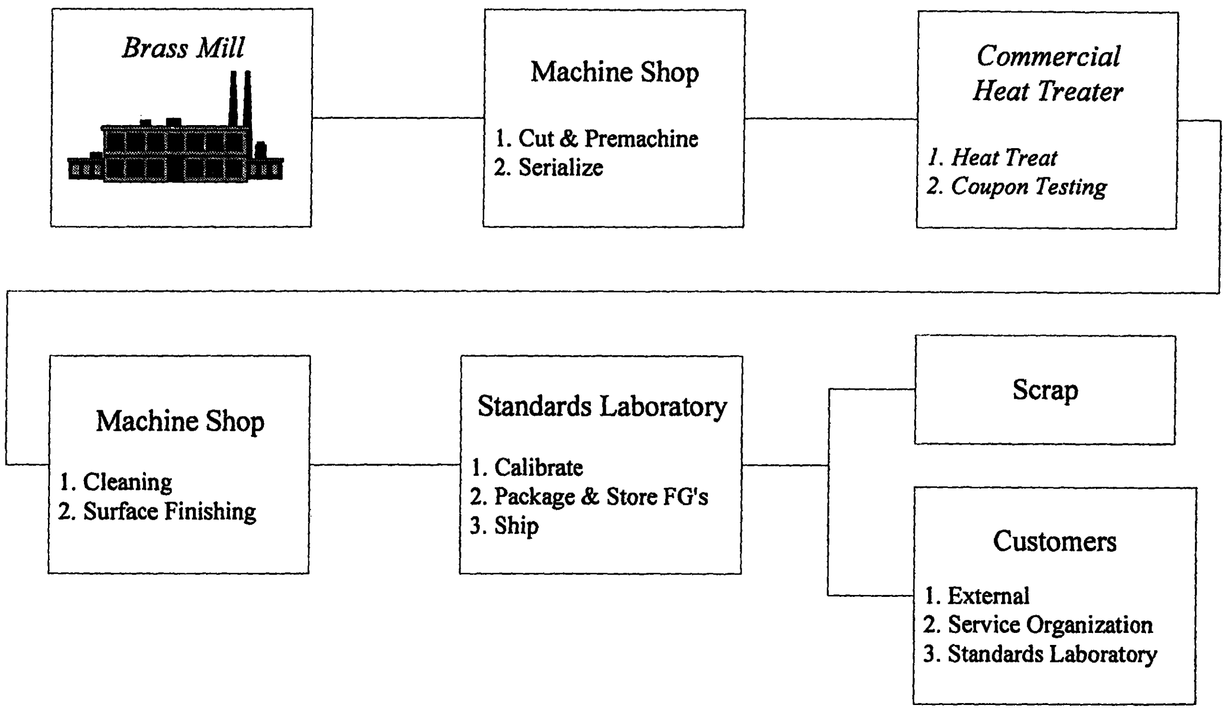

Figure 1, Manufacturing Process for B-scale Hardness Test Blocks

The ***brass mill*** is responsible for producing the raw material used in the manufacturing process. The raw material must have uniform and stable hardness characteristics which dictate that the material must be uniform in chemical composition and microstructure, and free of chemical impurities and mechanical defects. The brass mill melts the required metallic elements, casts the melt into an ingot, hot-rolls the ingot into sheet, and then anneals and cold rolls the material into a sheet with the desired physical and material characteristics. The brass mill also performs machining processes to the material so that it fits Wilson Instrument's machine tools and so that it has a reasonably smooth surface finish.

The Wilson Instruments **Machine Shop** is responsible for completing machining operations before and after the heat treating process. Prior to heat treating, the Machine Shop cuts the copper alloy plate into approximately 2 $^{1}/_{4}$" diameter blocks(they are referred to as "blocks" as opposed to "discs" because the blocks were originally produced in a rectangular shape), faces the blocks' top and bottom to establish flat and parallel surfaces, chamfers the edges of the blocks, and then stamps each block with a unique serial number. After heat treating, the blocks are returned to the Machine Shop. The Machine Shop removes heat treat scale from the blocks and then laps them to achieve a high level of surface flatness and parallelism. Finally, the block's top surface is polished to a mirror-like finish. Before delivering the test blocks to the Standards Laboratory, the machine shop inspects the test blocks for surface flatness, parallelism, and finish.

The ***heat treating vendor*** is responsible for heat treating the test blocks to one of several hardness levels specified by Wilson Instruments. The heat treater places a group of blocks into a gas-fired furnace at a set temperature for a fixed period of time. The blocks are removed from the furnace and allowed to air cool. After the blocks have been allowed to cool several coupon test blocks are tested to determine the mean and variation of hardness on each coupon block's surface. The coupon blocks act as an indicator of the mean and uniformity of hardness achieved by the heat treating process.

The **Standards Laboratory** is first responsible for inspecting the test blocks for cosmetic flaws. The Standards Laboratory then calibrates the test blocks using standardizing hardness testers. Standardizing hardness testers are specially constructed and maintained to furnish precise and accurate hardness measurements. Each test block is tested for hardness six times. The individual hardness measurements, mean, and range of the six readings are recorded on a calibration certificate. If the range of hardness on a block is greater than the maximum value specified by a given standardizing body, such as the values provided in ASTM E-18, the test block must be scrapped. After successful calibration the blocks are packaged, placed in finished goods inventory, and, finally, shipped to customers as required.

It should be noted that the uniformity of hardness on a test block is determined primarily by the Brass Mill and Heat Treater. If the Machine Shop provides smooth, flat, and parallel surfaces, and the Standards Laboratory properly maintains their standardizing testers and test procedures, the remaining sources of variation in hardness are a function of the block's metallurgical condition. The block's metallurgical condition is dependent almost entirely on the processes used by the Brass Mill and Heat Treater. The manufacture of quality hardness test blocks is then very much dependent on the outside vendors used by Wilson Instruments. With a considerable dependence on its vendors it then becomes critical for Wilson Instruments to maintain good relationships with their vendors. Wilson Instruments must simultaneously maintain a knowledge base that allows them to understand their vendor's manufacturing processes as they will dictate the metallurgical condition of the test blocks and thus the test blocks' uniformity of hardness.

It should also be noted that the primary inspection point in the manufacturing process occurs at the very end of the process. Because the inspection does not occur until the blocks reach the Standards Laboratory, a great deal of manufacturing value is lost when a block is scrapped. In addition, because the primary inspection point is at the end of the manufacturing process it becomes difficult to determine the root cause of quality problems. Although inspections may be performed in the manufacturing steps prior to the Standards Laboratory, the accuracy of these tests is difficult to establish primarily due to the fact that the block surfaces are not as smooth, flat, and parallel as they are after the final lapping and polishing operations are performed. Standard material inspection and operating procedures were developed during the LFM internship and their implementation will reduce the risk of introducing quality problems during the manufacturing processes.

Part 3: Introduction to Taguchi Methods

3.1 History and Current Use of the Taguchi Method

Taguchi Methods are a system of quality engineering techniques that focus on utilizing engineering knowledge to create the best product or process at the lowest possible cost. Dr. Genichi Taguchi began developing the methods while working to repair Japan's postwar phone system. During the postwar period, the Japanese industries were faced with a shortage of both raw materials and capital and, therefore, were forced to translate their raw materials into useful products as efficiently as possible. Dr. Taguchi combined his knowledge of statistics and engineering into a system that would provide superior outputs while requiring minimal inputs.

Quality methods may be thought to operate in two realms; on-line and off-line. On-line quality methods enhance production output quality by maintaining process control, predicting out-of-control conditions, indicating the root causes of production problems, and measuring production quality. Traditional on-line quality methods include feedback control, statistical process control, and recording of data. Using on-line quality methods to drive continuous improvements in quality can be costly or downright impossible.

Off-line quality methods can be used to develop or design products and processes with high quality performance characteristics before they are put into full-scale production. Off-line quality activities allow for potentially greater quality improvements because they are less subject to the immediate constraints of production schedules and capital investments.

The quality efforts employed by many U.S. manufacturing firms over the past 50 years have been primarily on-line methods. On-line quality methods control or inspect quality into a product or process whereas off-line quality methods strive to design products or processes such that they will produce high quality without the need for tightly controlled conditions of customer usage or manufacturing operations.

Taguchi methods are off-line quality methods. They have been widely used by Japanese manufacturing firms with great success. The methods optimize product and process functional performance by identifying sources of variation and adjusting product and process parameters to suppress the proliferation of variation into a product or process' key functional characteristics. Taguchi's definition of quality may be interpreted as the ability of a product or process to meet its intended performance requirements while being exposed to a broad range of operating conditions. Instead of controlling the operating conditions, Taguchi suggests that the product or process be designed such that changes in operating conditions yield little effect on the intended performance of the product or process.

Taguchi methods have a unique set of basic premises which are not generally included in traditional quality techniques. The Taguchi Method foundations include:

- the costs of quality can be quantified and must include manufacturing costs, life-cycle costs, and losses to society(i.e. environmental impact)
- quality costs are directly related to the variation in functional performance of a product or process
- engineering rather than scientific or statistical methods should be emphasized when completing design and optimization activities
- the effects of uncontrollable variation(noise) on the performance of a product or process should be explicitly included in design and optimization procedures

Through these basic premises, the Taguchi methods provide an engineering approach to product and process design and development that yields high quality systems in a timely manner. Taguchi Methods have achieved wide acceptance by manufacturing companies worldwide. According to the American Supplier Institute[1], Taguchi Methods are used primarily to improve existing products and processes. Additional applications which are quickly gaining increased acceptance include new product and process design, flexible technology development, and on-line process control rationalization. The successful use of Taguchi methods in U.S. manufacturing firms to date has been attributed to the fact that the methods:

1. merge the engineering and statistical communities in a useful manner
2. provide a means of quantifying and communicating to management the costs of variability in product or process performance
3. necessarily employ a cross functional team that yields quicker and more effective solutions
4. employ approaches to experimentation that produce results that are more easily interpreted and communicated to others while requiring less time and resources

This thesis is focused on the design of a process and will, therefore, not always refer to both product and process design when speaking generally about the Taguchi methods. Please be aware that the concepts and methods described can be deployed to develop, design, and/or optimize existing and/or new, processes or products.

3.2 The Loss Function

High quality is freedom from costs associated with poor quality.[2]

Taguchi's loss function is useful due to its simplicity and its ability to bring together both economic and engineering concepts. The quality loss function establishes the

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[1] American Supplier Institute, World Wide Web Page, http://www.amsup.com/taguchi/ , January 12, 1997.

[2] Fowlkes, W.Y., Creveling, C.M., Engineering Methods for Robust Product Design - Using Taguchi Methods in Technology and Product Development, Addison-Wesley, Reading, MA, 1995.

approximate loss to manufacturers and consumers due to a deviation in process performance from the intended target. A generic quadratic loss function is shown in Figure 2 below.

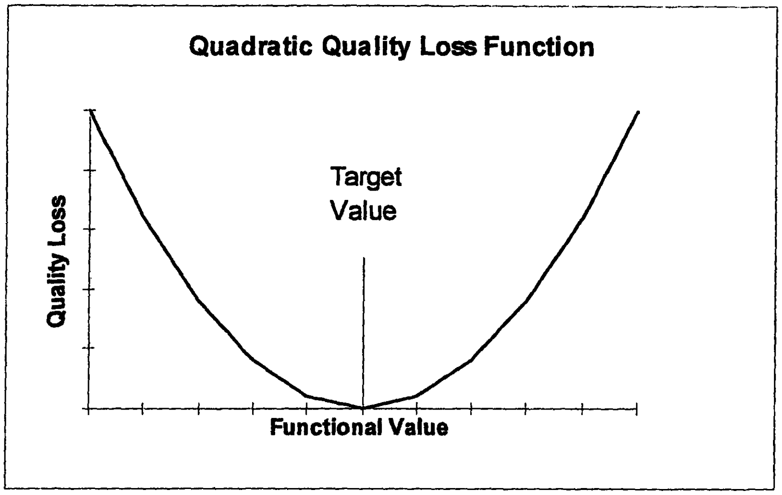

Figure 2, Generic Quadratic Loss Function

The standard loss function is a quadratic function that has the following form:

$L(y) = k(y\text{-}m)^2$

where:

L= loss to society, \$

k = quality loss coefficient, \$

y = actual performance

m = target value

Clearly, when the actual performance, y, is equal to the target value, there is no loss. As the deviation from the target increases the loss to society increases by the square of the deviation. Although it may be argued that the shape of the curve is not necessarily quadratic, the parabolic shape has been proven to closely approximate the shape found in situations with substantial sample sizes.

The quality loss coefficient is determined by the following equation:

$k = A_o/(\Delta_o)^2$

where:

Δ_o = 50% customer tolerance limit

A_o = total losses to manufacturer, customer and society at Δ_o, \$

The 50% customer tolerance limit is the point at which 50% of the customers would take some form of economically measurable action due to a product's poor quality. Typical actions might include sending the product back for repair, making a warranty claim, or flat-out refusing to accept the product at the time of delivery. A_o, is calculated by summing the total economic costs incurred at the 50% customer tolerance limit. A_o would then include all material, labor, transportation costs, and other costs due to repair, loss of use, and replacement.

Taguchi's loss function demonstrates a significant philosophical difference between traditional quality methods in manufacturing firms and the Taguchi method. The traditional method of measuring quality relies on engineering specification limits. Under the traditional methods, quality is improved by producing a greater percentage of output that falls within the specification limits for a given production effort. The loss function, on the other hand, suggests that quality is increased only by reducing deviation from the desired target performance.

Consider the specification limits that are used to accept or reject a ball bearing. The longest bearing life would be realized if the ball bearing were perfectly round. However, to account for the realities of production, an engineering specification limit is set to accept or reject ball bearings based on their roundness. The bearing customer would value a ball bearing that is just barely within the specification limits more or less the same as a bearing that is just barely out of the specification limits. The arbitrary setting of the specification limits clouds the most important quality issue, that is; the customer derives the most value from a ball bearing that is perfectly round. The loss function demonstrates that there is measurable value to achieving the target performance of perfect roundness, as opposed to just falling within the specification limits.

In a manufacturing firm, the loss function can act as the central means of communicating on-target quality efforts. It is easily communicated throughout an organization due to its simplicity and graphical nature. The loss function unites the concepts of cost and quality together so that both engineering and management teams can see the benefit of variation reduction efforts. The loss function also supplies its users with a view into the long term costs of quality because it includes both the explicit and implicit costs incurred by the manufacturer, their customers, and the society as a whole.

3.3 Noise and Robustness

The loss function establishes the idea that deviation from intended performance is measurable and costly. Noise and robustness are concepts which may be used to describe a means by which the deviation from intended performance can be reduced. Noise is defined as anything that causes a system's functional characteristic or response to deviate from its intended target value. Sources of noise are those sources of variation that are either impractical or too costly to control. Robustness is the property a product or process must enjoy if it is to perform at its intended target value in the presence of noise factors. Put another way:

> *"A product or process is said to be robust when it is insensitive to the effects of sources of variability, even though the sources of variability have not been eliminated."*[3]

The concepts of noise and robustness can be clearly conveyed by modeling a system as a "black box". Consider two systems that are represented in Figure 3 below. Each system has the same noise inputs. The noise inputs are working to cause variability in each system's output (functional performance or response). The output from system 1 appears to have significantly more variation than system 2. System 2 is more robust that System 1 and we would expect that its quality would be correspondingly higher according to the loss function.

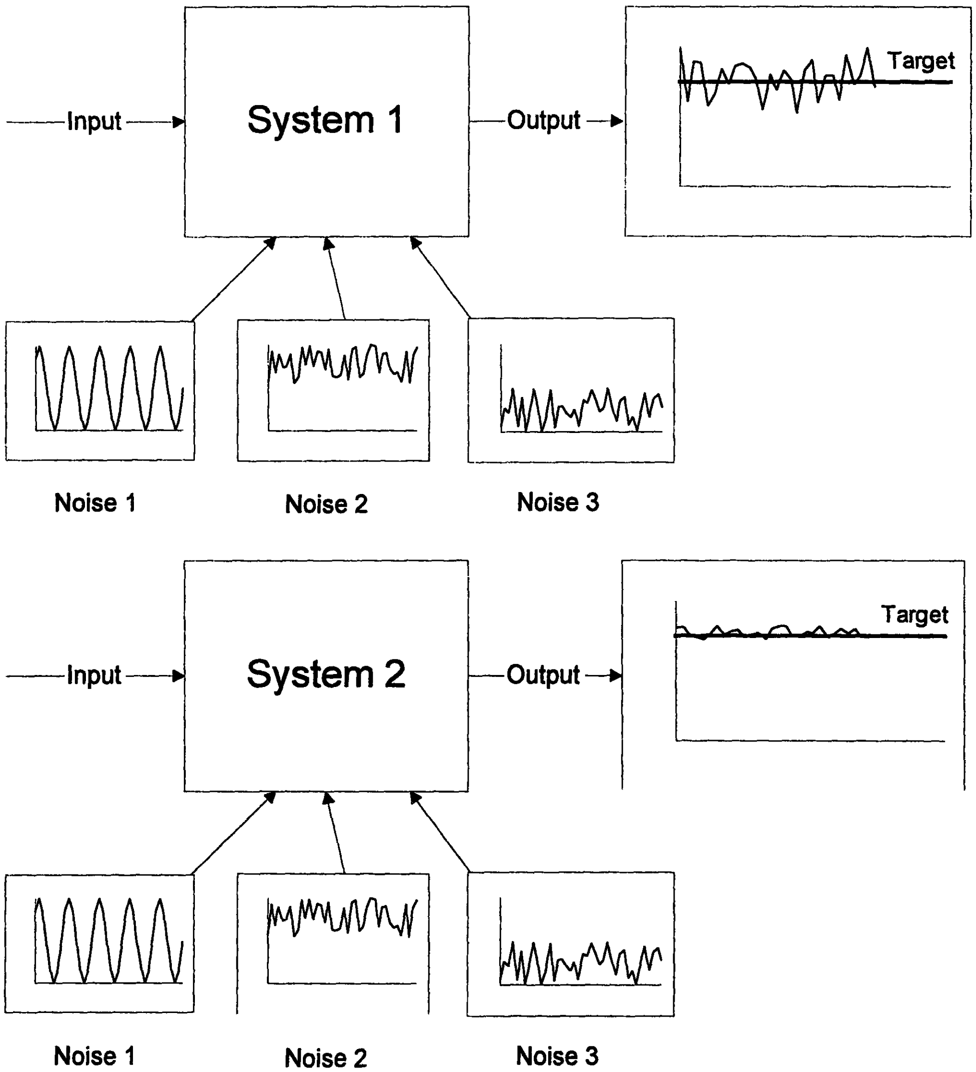

Figure 3, Demonstration of Robustness

Although there are seemingly endless sources of noise that can effect a system, all noise factors can be categorized into three categories, external, deterioration, and unit-to-unit.

[3] Fowlkes, W.Y., Creveling, C.M., Engineering Methods for Robust Product Design - Using Taguchi Methods in Technology and Product Development, Addison-Wesley, Reading, MA, 1995.

External noise factors are sources of variability that come from outside a process. Deterioration noise factors are sources of variability that occur due to a change within a process. Unit-to-unit noise factors are sources of variability that stem from the inability to produce any two identical items in a production process.

If a simple machining process is considered, the three types of noise factors could be represented as shown in Table 1 below.

Noise Factor Type	Machining Process Noise
External	*environmental conditions:* as the temperature of the machine shop changes over the course of the day, the machine may undergo thermal expansion/contraction
Deterioration	*wear:* as the cutting tool wears the resulting part dimensions will change
Unit-to-Unit	*material:* due to differences in the material hardness no two parts will be the same

Table 1, Machining Process Noise Factors

The Taguchi methods use designed experiments and engineering knowledge to determine those noise factors which have an effect on a process. Once the significant noise factors have been identified, further experimentation and engineering is utilized to produce a process design that is robust, that is; the design must be such that it is insensitive to the noise factors which effect the system.

3.4 Parameter Design

Parameter design is used to determine process parameter settings that yield the most robust process at the lowest possible cost. Parameter design considers two types of factors: noise factors and control factors. External, internal, and unit-to-unit noise factors represent the uncontrollable sources of variation that effect the process output. Control factors are those factors which can be controlled at a reasonable cost. The interaction between noise and control factors is determined using specially designed experiments. By studying the interaction between the control and noise factors, the control parameter settings that result in the most uniform process output may be identified.

Parameter design is often completed in two steps. First, experiments are used to identify the sources of noise that effect the process most significantly. Second, experiments are completed to gain information about the process control factors. Control factors that have a significant effect on the variability of the process output are set such that the output variation is minimized. Control factors that effect the mean response of the system but have little effect on the process output variation are called scaling factors. Once the control factors are set to levels that reduce the process output variation, scaling factors may be used to adjust the process output to the desired target. A visual representation of the two step parameter design process is shown in below.

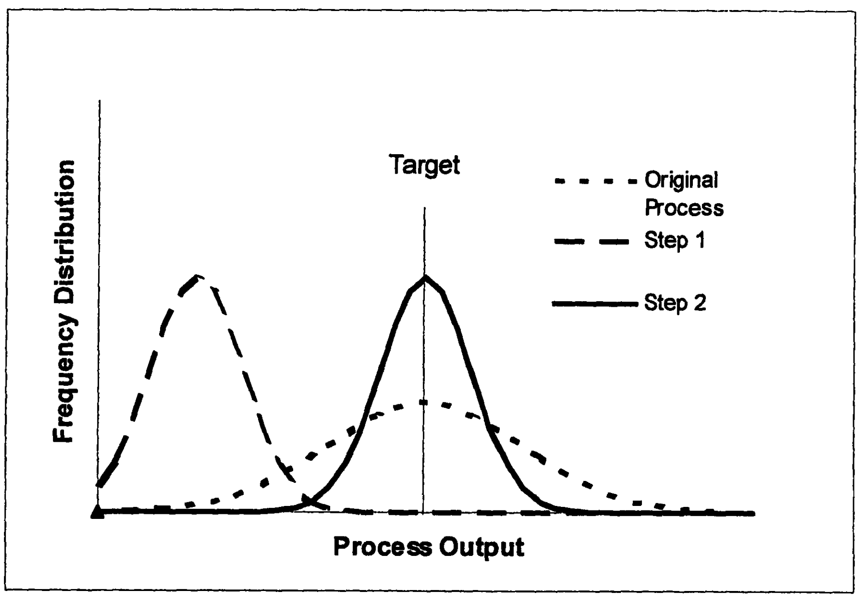

Figure 4, Two Step Parameter Optimization Process

Dr. Taguchi developed a number of tools that make the parameter design method efficient, flexible, and, perhaps most importantly, relatively easy to communicate to those without intimate engineering knowledge. The most widely used tools in parameter design are the quality characteristic, signal-to-noise (S/N) ratio, and orthogonal array. The quality characteristic represents the measured output of a process. The S/N ratio is a measure of robustness that may be specially designed to accommodate many different types of processes and analysis methods. The orthogonal array is a design of experiments array that maximizes the amount of information obtainable from an experiment with an important caveat being that complementary engineering knowledge is available.

3.4.A Quality Characteristic

The quality characteristic is the measured response of a process. Selection of the quality characteristic must be done carefully. Determining how to measure the output from a process may appear to be an artless activity, however, Dr. Taguchi's son cautions users of parameter design in stating:

> *In parameter design, the most important job of the engineer is to select an effective characteristic to measure as data... We should measure data that relate to the function itself and not the symptoms of variability...Quality problems take place because of variability in the energy transformations. Considering the energy transformation helps to recognize the function of the system.*[4]

Engineers should not be tempted to measure the quality characteristic in terms of existing quality or accounting metrics. If the metrics chosen for the quality characteristic do not correspond to the process' energy transformation, the engineer will have little success in understanding how the control and noise factors actually effect the process. Measures used for the management of production operations such as yield or defects per unit generally make poor quality characteristics. Measures that relate to the energy transformation such as geometric dimensions, material properties, or temperature provide more useful information about how the control and noise factors effect a process.

[4] Nair, V.N., "Taguchi's Parameter Design: A Panel Discussion." Technometrics 34, 1992.

The quality characteristic must also be selected such that it reduces the chance of measuring interactions between control factors. An interaction between control factors occurs when the effect of one control factor is dependent on another control factor. As will be discussed in section 3.4.C, Taguchi's parameter design experiments are most effective when interactions between control factors are eliminated through the use of sound engineering judgment. Dr. Taguchi states:

> *The efficiency of research will drop if it is not possible to find characteristics that reflect the effects of individual factors regardless of the influence of other factors.*[5]

Often the quality characteristic can be chosen such that interactions are avoided. Minimizing the effects of interactions simplifies the experimental and analysis efforts required in a parameter design. By eliminating interactions, the process under consideration becomes easier to understand and control. A process that does not have significant interactions can be engineered for additivity. Additivity in the process means that the effects of each control factor on the process output is independent of other control factors. Because their are no interactions between the control factors there is no need for multiplicative cross terms when predicting or analyzing the system's response.

Parameter design may be used to optimize a wide array of processes. Accordingly, several different types of quality characteristics have been developed. The types of quality characteristics and examples of their use are shown in Table 2 below.

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[5] Taguchi, G. System of Experimental Design, Vols. 1 and 2. ASI and Quality Resources

Quality Characteristic Type	Description	Examples
Dynamic	Process is optimized over a range of output values	speed on an electric mixer volume on a stereo amplifier temperature in an oven
Nominal-the-best	Process is optimized for one particular output value	dimension of a part mixture of a chemical solution electrical resistance of a resistor
Smaller-the-better	Process is optimized for an output value that is as near to zero as possible	wear of a cutting tool shrinkage in casting power loss through a powertrain
Larger-the-better	Process is optimized for an output value that is as large as possible	efficiency of a furnace strength of a structure fatigue resistance of a weld

Table 2, Types of Quality Characteristics

Dr. Taguchi believes that the most powerful type of characteristic is the dynamic type. He has been quoted as saying "*the adoption and continued utilization of the dynamic approach represents the path that virtually all world-class organizations will take to establish themselves as leaders in their industries.*"[6] The dynamic characteristic can be applied to processes where the output of the system changes as the input to the system is adjusted. The dynamic method optimizes a process over a range of expected outputs, whereas the other quality characteristics optimize the process at a fixed output level only.

3.4.B Signal-to-Noise (S/N) Ratio

The S/N ratio is used to measure the robustness of a process. The "signal" (numerator) represents the response of the process as measured by the quality characteristic. The "noise" (denominator) represents the magnitude of the uncontrollable sources of variability in the process. The S/N ratio is calculated in a different manner for each type of quality characteristic. However, regardless of the type of process being studied, when the S/N ratio is maximized, the robustness of the process is also maximized. A custom S/N ratio can be developed for unique processes, however all S/N ratios should:

1. measure the process output variability that is caused by noise factors
2. be independent of shifting the mean response of the process to its target
3. be a relative measure so that it can be used for comparative purposes
4. reduce the potential for interactions between control factors

One of the most common S/N ratios is the static, nominal-the-best type. In the nominal-the-best case the process is optimized for a known target response value. For the static, nominal-the-best quality characteristic, the S/N ratio is defined as:

$$S / N = 10\log\left[\frac{\bar{y}^2}{s^2}\right]$$ where: $\bar{y}$ = mean process output and s^2 = process output variance

It can be seen that an increase in the signal, $\bar{y}^2$ or a decrease in the noise, s^2 causes the S/N ratio to increase. Intuitively, this makes sense as an increase in "signal" or a decrease in "noise" should be considered a move in the right direction for the process if it is to be made more robust. Also note that the equation does not contain the target value; this is because the S/N ratio is independent of shifting the mean response of the process to the target value.

The base 10 log function puts the S/N ratio into decibel units. The log transformation is accepted as standard Taguchi method procedure and grew out of Dr. Taguchi's work in the communications industry. However, use of the log function is more than just a relic because it "makes the metric more additive in the statistical sense."[2] To see why the log function promotes additivity one needs only to look at one of the log function's basic properties, that is, log(A x B) = log A + Log B. Given two control factors, A and B, and an interaction

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[6] Wilkens, J., "Introduction to Quality Engineering and Robust Design." American Supplier Institute, 10th annual Taguchi Symposium, 1992.

between the two, A x B, then the log of the response, log (A x B), becomes additive in that it may be treated as log A + log B.

The S/N ratio is frequently plotted together with the mean response of the process to demonstrate the effects of an individual control factor. Figure 5 shows two combinations of S/N ratio and mean response that could be encountered while analyzing a parameter design experiment. The top two plots represent the mean response and S/N ratio of a control factor that could be used as a scaling factor. Note that in the top plots the mean process output can be shifted (presumably to the desired target value) without causing a decrease in the S/N ratio and, hence, process robustness is maintained. The bottom plots demonstrate a control factor that should be set at its higher level in order to increase process robustness. In the bottom plots there would be serious loss of process robustness if the control factors low setpoint were used.

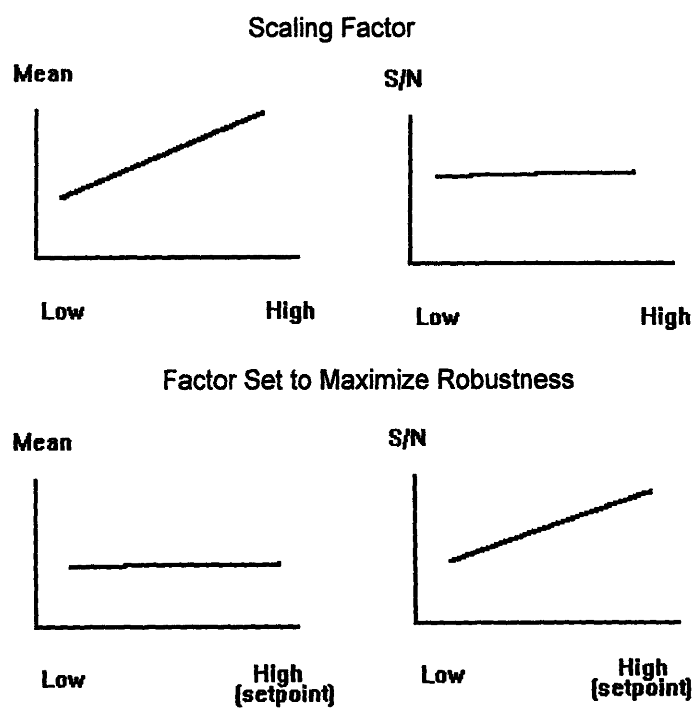

Figure 5, Typical Control Factor Types

There are numerous possible combinations of mean response and S/N ratio. A control factor that has little effect on either mean response or the S/N ratio may be adjusted to the most economical level. In order to locate those control factors that are useful for shifting the mean response to the target and increasing robustness, it is common to include as many control factors in the parameter design process as is practical.

3.4.C Orthogonal Arrays

To reduce the experimentation effort required in his parameter design work, Dr. Taguchi adopted the use of orthogonal arrays. Orthogonal arrays are designed experiment arrays that have the property of orthogonality; that is, the factors in the array are balanced and statistically independent. The basic terminology used to indicate an orthogonal array is L_x, where L indicates that array is orthogonal and x dictates the number of individual experiments in the array. An example of and L_8 array is shown in Table 3 below.

Run	1	2	3	4	5	6	7
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

Table 3, Standard Two-Level L8 Orthogonal Array

In many Taguchi applications the orthogonal array is used in an inner and outer array configuration. The inner array generally contains the control factors while the outer array contains the noise factors. The inner array provides information regarding the effects of control parameters and generates the "signal" in the S/N ratio. The outer array acts to stress the system giving the necessary "noise" in the S/N ratio.

The total experimental effort can be considerable when both inner and outer arrays are of significant size. For example, if an experiment were to use and L_8 inner array and a L_8

outer array, the total effort would require 64 experiments. Each of the control factor settings dictated by the inner array would have to be repeated for each of the eight noise factor settings required for the outer array. To reduce the experimental effort, the noise array can be minimized by confounding or combining the noise factors. Preliminary experiments are used to provide the information necessary for confounding the noise factors and the resulting outer array becomes an L_2. By confounding the noise factors the total test effort becomes sixteen noise and sixteen main experiments for a factor of two savings. Confounding can not always be used; however, in most parameter design efforts it is extremely useful for reducing the experimental efforts required.

For parameter design the orthogonal array is preferred to other experimental arrays because it provides a great deal of useful information while using the least possible number of experiments. An orthogonal array that can test the effects of seven parameters is shown in Table 3. Testing of seven parameters with a traditional full-factorial experiment would require 128 experiments, an order-of-magnitude greater effort.

Although the orthogonal arrays decrease the experimentation resources required for parameter design, the real benefit offered by orthogonal arrays is their balance. Balance in the array can be seen by noting that within every column each factor level is used the same number of times. Balance between the factors is also evident by noting that for a given factor held at one level, each and every other factor occurs at its two respective levels the same number of times. For example, when factor 1 is held at level 1, factor 3 has the pattern 1, 1, 2, 2, while factor 5 has the pattern 1, 2, 1, 2, (see Table 3 above). Each of the factor levels occur twice although there are differences in pattern.

Balance, or orthogonality, in the array isolates the effects of individual parameters making them easier to analyze and control. For example, when a factor level is found to produce a change in the process output, be it measured as the mean response or S/N ratio, the change can be directly attributed to that factor alone and not the other factors. The effects of the other factors need not be accounted for because each of the other factors occur an equal number of times at both their levels and; therefore, their factor level effects cancel one another out.

The weakness of orthogonal arrays is that they cannot be used if the experimenter does not have a good understanding of the process under consideration. Traditional experimental design arrays are powerful in that they are able to quantify interactions in a process. If interactions are present and not accounted for in an orthogonal experiment, the array will produce useless or misleading information. Generally speaking, interactions are avoided in parameter design; however, if they are unavoidable, modified orthogonal arrays may be used to accommodate them.

One final benefit that is frequently noted about the orthogonal array is that they are relatively easy to manipulate. Traditional experimental design arrays can be difficult to work with for engineers who do not have rigorous statistical backgrounds. Because the orthogonal arrays are more easily applied, the parameter design engineers can presumably spend more time on engineering and experimentation than on manipulation and analysis of the experimental arrays. The combined simplicity of the orthogonal array and the emphasis on eliminating interactions makes the output of the orthogonal array more easily communicated throughout a cross-functional organization.

The information presented in the last few sections of this paper contains a recurring theme; that is, engineering knowledge is necessary to employ Taguchi methods successfully. In fact, Dr. Taguchi has recommended that 80% of a parameter design team's efforts be spent before any experiments are actually completed. A failure to plan for interactions is cited as being the largest cause of failure in use of the Taguchi Method experiments. In following with Dr. Taguchi's advice, a search of available information on related heat treating processes and Taguchi method applications was completed. The results of this search are the subject for the following section of this thesis.

Part 4: Engineering Knowledge of Related Heat Treating Processes and Taguchi Method Applications

Before the Taguchi methods are applied to the hardness test block heat treating process, a study of related heat treating and Taguchi methods applications is necessary. A review of the available literature will provide information that would otherwise have to be re-learned through costly experimentation.

4.1 Purpose of Heat Treating Hardness Test Blocks

The purpose of heat treating B-scale hardness test blocks is to reduce the test block's hardness. By using the heat treating process Wilson Instruments is not required to hold raw material inventory for all the hardness ranges they produce (see Table 4). It is possible to use brass plate with a hardness of HRB 80 or greater for all the B-scale test blocks offered by Wilson except for the HRB 95 test block. The HRB 95 test block is produced from steel.

Nominal Hardness (HRB)	Hardness Range (HRB)	Material
0	Below 5.0	Copper alloy
10	5.0 - 14.9	‖
20	15.0 - 24.9	‖
30	25.0 - 34.9	‖
40	35.0 - 44.9	‖
50	45.0 - 54.9	‖
60	55.0 - 64.9	‖
70	65.0 - 74.9	‖
80	75.0 - 89.9	‖
95	Above 90.0	Steel

Table 4, B-Scale Test Block Hardness Ranges and Materials

The heat treating process used by Wilson Instruments is called annealing. In general, annealing refers to any heat treating process wherein a metal is brought to an elevated temperature, held at the temperature for a pre-determined time, and then cooled to ambient conditions in order to reduce hardness. The annealing process used for test blocks is called a partial annealing process. The partial annealing process must be controlled to yield two important results, they are:

1. on-target average hardness of the test blocks
2. high uniformity of hardness on each test block

As will be discussed in the following section, a partial anneal is difficult to control. The changes which occur in the metal's structure during a partial anneal are both heterogeneous and rapid. In addition to being difficult to control, there is very little information published on partial annealing. In fact, the published literature advises that partial annealing be avoided in commercial applications.

4.2 Commercial Annealing Processes

4.2.A Purpose of Commercial Heat Treating Processes

Commercial annealing processes are performed on metals to facilitate subsequent cold working, improve mechanical, electrical or thermal properties, enhance machinibility, and/or stabilize part dimensions. Annealing processes are used for both ferrous and non-ferrous metals; however, only non-ferrous annealing processes will be discussed in this document. To further limit the discussion of annealing processes, only those metal products and processes which are closely similar to those used in the manufacture of B-scale test blocks will be considered. That is, the information will be focused on annealing processes that are used in the manufacture of wrought copper alloy products.

4.2.B Brass Strip: An example of Cold Work and Annealing

In the manufacture of wrought copper alloy products the annealing process is used primarily to facilitate cold-working processes. As an example, consider the production of 0.04 in. brass strip. The metal may begin the cold rolling process at some thickness which is considerably greater than the final thickness, say 0.40" thick. When the material is cold rolled both its strength and hardness increase as is indicated in Figure 6. These properties increase because the strain placed into the material increases the density of dislocations in the material's metallic structure. The dislocations act as barriers to further strain in the material and thereby increase both its strength and hardness.

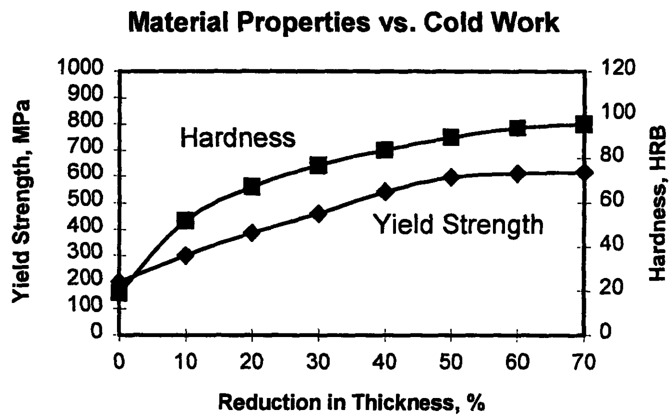

Figure 6, Material Properties vs. Cold Work for a Copper Alloy

When the strength and hardness of the metal increases it becomes more costly to deform the metal. In addition, the metal may become brittle with high levels of cold work, potentially leading to fracture and a stalled production line. To reduce the strength and hardness of the heavily cold-worked metal strip it is subjected to an annealing process. A typical non-ferrous alloy's properties will change during the annealing process according to the curves shown in Figure 7 below.

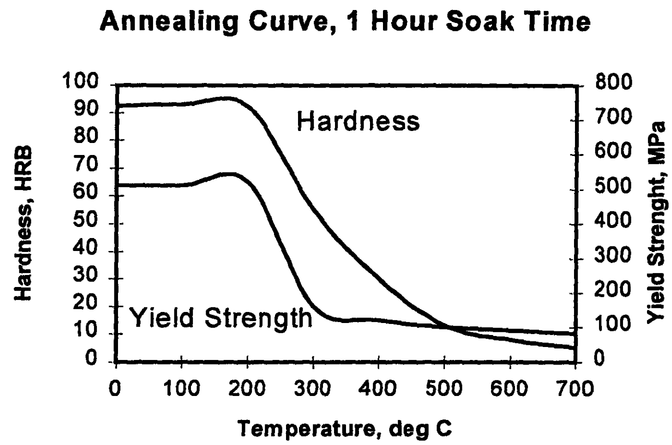

Figure 7, Typical Annealing Curve for a Copper Alloy: Hardness, Yield Strength vs. Temperature

In a step-wise manner the rolling and annealing functions are performed until the strip is reduced to a thickness that is close to its final desired thickness. For continuous products, such as strip, wire, and sheet, annealing is frequently done in a continuous process where the metal is passed through a annealing furnace. The temperature of the furnace and the speed at which the material passes through the furnace are controlled to produce the desired results. Other products, such as slabs, plates, and heavy sections are batch annealed. To produce the desired results in batch annealing the furnace temperature, soak time, and furnace load must be controlled. The inter-process anneals are controlled to yield the desired material properties at the lowest possible manufacturing cost.

4.2.C Full vs. Partial Annealing

Wrought copper alloys are produced at numerous tempers. The product's temper designates its material properties and is set according to American Society for Testing and Materials (ASTM) specifications. For example, yellow brass (UNS No. 26800), is produced according to ASTM B36/B36M with the temper designations and material property requirements as shown in Table 5 below.

Temper Designation		Tensile Strength, MPa	Rockwell Hardness, HRB, for > 0.036" thick
M20	As hot-rolled	275-345	N/A
H01	Quarter-hard	340-405	44-65
H02	Half-hard	380-450	60-74
H03	Three-quarter hard	425-495	73-80
H04	Hard	470-540	78-84
H06	Extra-hard	545-615	85-89
H08	Spring	595-655	89-92
H10	Extra Spring	620-685	90-93

Table 5, Temper Designations for Yellow Brass, UNS 26800[7]

A product's temper is generally determined by final processing steps that add cold work to the material. The tempers are determined by cold working, as opposed to annealing, for two reasons:

1. it requires less energy and fewer process steps to cold work the material to its final dimensions and material properties
2. it is relatively difficult to control the material properties resulting from an annealing process

When an annealing process is used to produce a product with specific material properties, the annealing process is called partial annealing or annealing to temper. Commercial heat treaters generally avoid these processes as the resulting on-target success rates are quite poor. In fact, and American Society of Metals publication states, "It is impracticable to anneal for definite properties of tensile strength or hardness between the normal cold worked and fully recrystallized or softened range because of the extremely rapid change of properties with only a small change in metal temperature."[8]

[7] American Society for Testing and Materials, Designation B 36/ B 36M, Standard Specification for Brass Plate, Sheet, Strip, and Rolled Bar, 1995.
[8] American Society for Metals, Source Book on Copper and Copper Alloys, Section VIII: Heat Treating, Metals Park, OH, 1979.

There are several variables which effect the outcome of the annealing process including, but not limited to:

1. furnace temperature
2. time the product spends in the furnace
3. degree of cold-work in the material
4. furnace load(utilization)
5. product dimensions
6. material chemical composition

To avoid the cost of controlling the above variables, the common practice is to use full anneal processes. A full anneal brings the material to its minimum strength and hardness. In Figure 7, a full anneal would correspond to the portion of the curve above approximately 500 °C. In this region of the annealing curve the material properties are less sensitive to variations in the time and temperature process parameters. In full annealing the material approaches a state of equilibrium. When a partial anneal is performed the dynamics of the process are much faster than when a full anneal is used. Consequently, the material properties are highly sensitive to the variables listed above and considerable efforts must be made to control the process variables in order to produce consistent on-target results. The next section will discuss technical information regarding the annealing process.

4.3 Annealing: Technical Details

4.3.A Reference Literature on Annealing

To this day, the mechanics of annealing processes are not fully understood. The available literature on the subject is difficult to use for one of the following two reasons:

1. the information relies on experimental data that is strictly context dependent
2. the information is in the form of theoretical dissertations that are complex and unproven in practical applications

The most informative annealing references located by the author are a recently published monograph[9], compiled by Mr. John Humphreys and Mr. Max Hatherly, and The American Society of Materials(ASM) Handbooks, Volumes 2[10] and 4[11]. A summary of information applicable to the heat treating of copper alloys will be presented in this section. At this point, however, it is worth quoting the preface of the Humphrey and Hatherly monograph:

> It is not easy to write a book on recrystallization, because although it is a clearly defined subject, ***many aspects are not well understood and the experimental evidence is often poor and conflicting.*** It would have been desirable to quantify all aspects of the phenomena and to derive the theories from first principles. However, this is not yet possible, and the reader will find within this book a mixture of relatively sound theory, reasonable assumptions and conjecture. There are two main reasons for our lack of progress. First, we cannot expect to understand recovery and recrystallization in depth unless we understand the nature of the deformed state which is the precursor, and that is still a distant goal. Second, although some annealing processes, such as recovery and grain growth are reasonably homogenous, others, such as ***recrystallization and abnormal grain growth are heterogeneous, relying on local instabilities and evoking parallels with apparently chaotic events such as weather.***
> (emphasis by the author)

The published technical information, albeit sparse, provides a useful basis for the experimental efforts presented in later sections of this thesis.

4.3.B Steps in the Annealing Process

There are a number of process steps that occur during the annealing process. The steps are described in Table 6 and their positions on a typical annealing curve are illustrated in Figure 8.

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[9] Humphreys, F. J., Hatherly, M., *Recrystallization and Related Annealing Phenomena,* Pergamon, Elsevier Science Ltd., Tarrytown, NY, 1995.

[10] ASM Handbook, Formerly Tenth Edition, Metals Handbook, Volume 2, Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, ASM International, 1995.

[11] ibid.

Sequence	Step Name	Description of Annealing Step
1	Recovery	Microstuctural changes in the dislocation structure of the material partially restore the material's properties to what they were prior to deformation, hence the name recovery. Hardness of copper based alloys may actually increase during this step because the dislocation structures become more stable.
2	Recrystallization	Small crystals nucleate at areas of high dislocation density. The small crystals have a dislocation density similar to the material prior to cold working and, therefore, the material's strength and hardness decrease. New crystals form and grow until the cold worked crystals are replaced.
3	Normal Grain Growth	The new crystals formed during recrystallization grow and combine with one another. The increased grain-boundary area in the material further decrease its strength and hardness, although to a lesser degree than recrystallization.
4	Abnormal Grain Growth	The larger of the new grains may grow more rapidly than the small grains, thereby creating a structure with greatly varying grain sizes.

Table 6, Steps in the Annealing Process

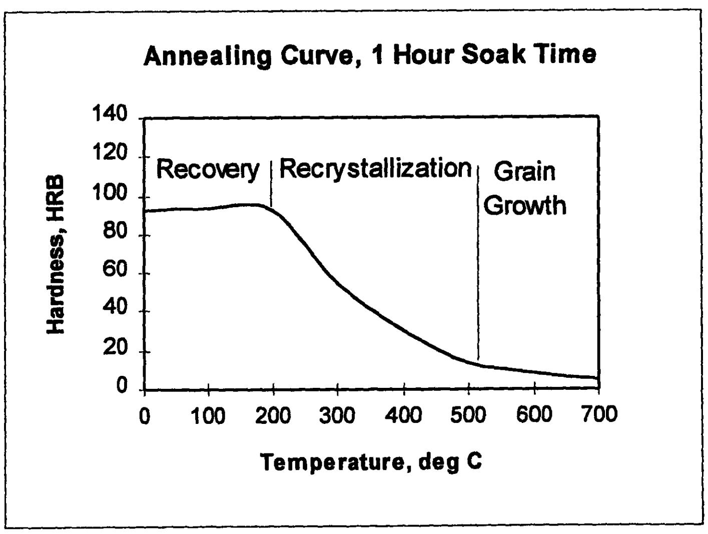

Figure 8, Steps in the Annealing Process for a Copper Alloy

It should be noted that the annealing steps may overlap significantly. In practice, making a distinction between the steps is difficult. For the purposes of heat treating copper alloy hardness test blocks it is deemed most important to concentrate on the recrystallization process. However, there are a number of relevant observations that can be made about the other steps:

1. *Recovery:* At high temperatures and heating rates the effects of recovery are minimal in comparison to those of recrystallization. For single phase copper alloys, recovery is significant only when heat treating is used to incur very small changes in hardness(i.e. one or two points in hardness on the Rockwell scale).
2. *Normal Grain Growth:* Normal grain growth is a homogeneous process and, therefore, should not significantly decrease the uniformity of hardness in an annealed material.
3. *Abnormal Grain Growth:* Abnormal grain growth is a heterogeneous process that generates a wide distribution of grain sizes in a material. Grain size can be correlated to hardness and; therefore, a material with a wide distribution of grain sizes will have a wide distribution of hardness. Abnormal grain growth should be avoided in the annealing process for test blocks.

4.3.C Recrystallization

In the annealing of hardness test blocks a copper alloy is heated to a temperature that is greater than its recrystallization temperature. The recrystallization temperature is the temperature at which the formation of a new, low-strain crystalline structure emerges in a cold-worked material in a given amount of time, typically one hour. When the material takes on a crystalline structure with a reduced level of strain, the hardness of the material decreases. In short, the dislocations that increased the material's strength and hardness during the cold working processes are removed during recrystallization.

The recrystallization process consists of two primary mechanisms. There is a nucleation process where the new crystals are formed and a growth process where the new crystals replace the deformed material. Nucleation and growth may occur at the same time in the material. The process is considered to be analogous to a phase transformation, such as the solidifying of a molten metal. In recrystallization, the driving force for the changes is the stored energy due to cold working and the activation is triggered by thermal energy.

There are a set of recrystallization laws which govern the basic behavior of recrystallization processes[12]. The laws are as follows:

1. A minimum deformation is needed to initiate recrystallization.
2. The temperature at which recrystallization occurs decreases as the time of anneal increases.
3. The temperature at which recrystallization occurs decreases as strain increases.
4. The recrystallized grain size depends primarily on the amount of deformation, being smaller for large amounts of deformation.
5. For a given amount of deformation the recrystallization temperature will be increased by a larger starting grain size and a higher deformation temperature.

The laws of recrystallization indicate that the results of the annealing process are largely a function of the:

1. deformed state of the material that enters the annealing process
2. temperature at which the material is annealed
3. length of time over which the material is annealed

4.4 Applicability of Literature to Taguchi Method Experiments

The information provided in the preceding sections summarizes the key energy transformation that occurs during the heat treating of B-scale hardness test blocks. Although the information promotes a basic understanding of the energy transformation, it does not provide any direct information regarding interactions. Based on the character of the energy transformation the greatest potential interaction is believed to be between annealing temperature and soak time.

Only one source of information regarding the potential for a relationship between time and temperature was located[13]. The information is specific to a pure copper and a 5% zinc content brass (C21000, Gilding Metal). The source indicates that there is no significant

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[12] Humphreys, F. J., Hatherly, M., *Recrystallization and Related Annealing Phenomena*, Pergamon, Elsevier Science Ltd., Tarrytown, NY, 1995.

[13] ASM Handbook, Formerly Tenth Edition, Metals Handbook, Volume 4, Heat Treating, ASM International, Figure 16, pg. 830, 1995.

interaction between time and temperature. An adaptation of the data for one of the alloys is presented in Figure 9. In the figure it can be seen that there is an interaction between time and temperature at the beginning and end of the recrystallization phase of the annealing process. The interaction is demonstrated by the fact that each curve has a different slope. However, in the region where recrystallization occurs, the annealing curves for short, medium, and long soak times all have nearly the same slope. The similarity in slope of the curves indicates that the interaction between time and temperature is minimal in this region.

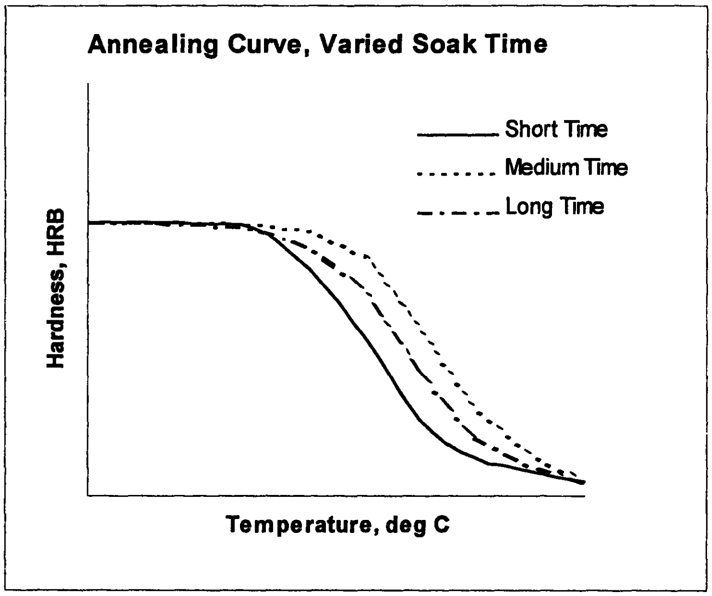

Figure 9, Interaction Between Time and Temperature for Annealing a Wrought Copper Alloy

In practice, the test blocks are annealed by a process that falls within the recrystallization region and it would be expected that no significant interaction between time and temperature would occur. Although the available data is not for an alloy currently used by Wilson Instruments, most of the single-phase, wrought copper alloys are governed by the same annealing processes. Based on the information available regarding interactions, it would be expected that interactions between time and temperature are weak.

4.5 Benchmarking of Related Taguchi Method Applications

Further research was completed to gain information regarding the application of Taguchi methods to hardness test blocks or other applicable heat treating processes. Two useful papers were located that offer useful information to the manufacturing process used for hardness test blocks. Interestingly enough, both papers were authored by the same group and both addressed the manufacture of products used to transfer standards for material property measurement systems.

Both of the papers were written by a team of Japanese engineers. The cross functional approach of their efforts may be clearly noted by reviewing the members of the team; an engineer from heat treating and metal products manufacturing company, a scientist from a national standardization laboratory, an engineer from a bearing inspection association, and a university professor of Taguchi methods. Although the papers demonstrate that the Taguchi methods can be used to create dramatic improvements in heat treating processes, both papers address the heat treating of steel which is not directly analogous to the heat treating of copper alloys. Nonetheless a review of the papers provides useful insight into the problem at hand.

4.5.A Paper Review: "Development of Heat Treatment Technology for the Standard Hardness Test Blocks"

In this paper the authors discuss the use of Taguchi methods in developing a manufacturing process for Rockwell C-scale (steel) hardness test blocks. It is interesting to note that none of the team members had any prior experience in manufacturing hardness test blocks. The published results of the paper indicate that the team was able to develop high quality test block across the entire C-scale within a reasonable amount of time. Based on the fact that heat treating is often considered as much an art as a science, the team's results indicate that the Taguchi methods can be used to quickly develop strong internal process knowledge and capability in an organization.

The paper indicates that the authors first used a screening experiment with a large number of control factors. Screening experiments are used when little information is known about a system. In the words of the authors

> "The reason so many control factors are selected is that a person who manufactures a hardness test block for the first time does not know which factors influence the uniformity of the test block the most, nor the trends among the various levels of factors.

In order to make these points clear, a screening experiment is conducted as a first step..."[14]

A screening process contains only an inner array and as such does not provide the "noise" portion of the S/N ratio. However, in the paper the authors show that the S/N ratio may be used to assess the effects of the control factors on the quality characteristic regardless of the absence of intentionally induced noise factors. Hardness was used as a measure of a static, nominal-the-best quality characteristic. Analysis of variance (ANOVA) of the experimentally derived S/N ratios was used to predict the effect each control factor had on the uniformity of hardness. Based on the results of the experiment a prediction of the optimum control factor settings and a confirmation experiment was performed. The confirmation experiment indicated that the system model was additive by showing that the predicted optimum system output from the screening experiment was in agreement with the confirmation experiment's results.

Given the positive results of the screening experiment the team proceeded by employing a dynamic type quality characteristic. As was discussed in section 3.4.A, the dynamic type quality characteristic is the most powerful because it may be used to optimize a process over a controllable range of outputs, as opposed to optimizing the system for a single output value. Unfortunately, the authors did not publish any information about their dynamic experiments besides the results which, as mentioned earlier, indicate that they were quite successful.

It is useful to examine the results shown for the control factors that are not entirely specific to the manufacture of C-scale hardness test blocks. Three control factors related to finishing of the test block surface were included in their study. The results of the screening experiment are as shown in Table 7 below. The results show that the surface finish control factors had relatively little effect on the system's response. The conclusion that their effects

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[14] Nakai, I., Inoue, I., Ishida, H, Yano, H., "Development of Heat Treatment Technology for the Standard Hardness Blocks", 9th Annual Taguchi Symposium, American Supplier Institute, 1991.

are minimal is supported by the fact that the relative effect of the experimental error was estimated at 10.7%. Wilson Instruments has also found that surface finishing methods have a relatively small effect on hardness uniformity for standard Rockwell tests. The same conclusion does not necessarily hold true for superficial and micro-hardness tests where smaller load applications and indentors are used. Wilson Instruments prefers to put the highest quality surface finish on all their test blocks both for marketing purposes and so that any test block can be used for any type of Rockwell test.

Factor	Level 1	Level 2	Units	Relative Effect of Factor, (%)
Method of Surface Grinder	Reciprocating type table	Rotary type table	n/a	9.6
Grain Depth of Grinding	2	6	μm	negligible
Lapping Time	10	20	min.	2.1

Table 7, Surface Finish Control Factors

In addition to the information regarding the surface finishing of hardness test blocks the methodology described in the paper is considered valuable. By demonstrating that the methods can be used successfully, confidence in the efforts to optimize the B-scale hardness test block manufacturing process may be increased.

4.5.B Paper Review: "Development of Charpy Impact Test Piece"

In this paper the same team that optimized the manufacturing process for hardness test blocks uses Taguchi methods to optimize the manufacture of Charpy impact test pieces. As with the previous paper, the material used for the Charpy impact test pieces is steel and; therefore, the data presented in the paper is not applicable to B-scale hardness test blocks. However, the methodology used in the paper and the success of the team's efforts are worth noting.

A dynamic quality characteristic was employed in the Charpy experiments. The paper notes that a significant portion of the knowledge collected during the C-scale hardness test block efforts was applied to the Charpy test piece efforts. With this knowledge base, the team was able to conduct a dynamic experiment without expending resources on noise or screening experiments. The team used an experimental plan consisting of an L_8 inner array with six control factors, and a L_9 outer array containing both signal and noise factors.

The results of the dynamic optimization process was that the standard deviation in energy absorbed was cut in half across the product range of Charpy impact test pieces. The duration of the team's efforts was stated to be six months whereas the team spent one and one half years optimizing the C-scale hardness test blocks. The primary lesson demonstrated in the paper is that the Taguchi methods can become much more powerful when significant engineering knowledge of the system under consideration is available. Having delivered the information contained in this chapter of the thesis, optimization of B-scale test block heat treating process may be discussed.

Part 5: Application of Taguchi Methods to the B-scale Test Block Heat Treating Process

5.1 The Parameter Diagram for B-scale Block System

In the past chapter a significant amount of engineering knowledge was presented regarding the heat treating process. However, before advancing to an optimization of the heat treating process it would be useful to assess the myriad of control and noise factors in the whole test block system. Clearly, the variability in hardness on a test block as measured by the test block user is only partially attributable to the heat treating process.

A useful tool for analyzing the control and noise factors involved in a process is the parameter diagram or P-diagram[15]. The P-diagram was developed by Madav S. Phadke, a one-time co-worker of Dr. Taguchi, and pioneer of Quality Engineering applications in the United States. A generic version of the P-diagram is presented in Figure 10. The P-diagram is used to classify the parameters, also called factors, involved in the parameter optimization process. In short, signal factors are used to dynamically adjust the process response value; noise factors represent the sources of uncontrollable variability; and control factors are process parameters that may be set by the engineer to produce a process that is insensitive to noise; that is, a robust process.

[15] Phadke, Madav S., Quality Engineering Using Robust Design, AT&T Bell Laboratories, Prentice Hall, Englewood Cliffs, NJ, 1989.

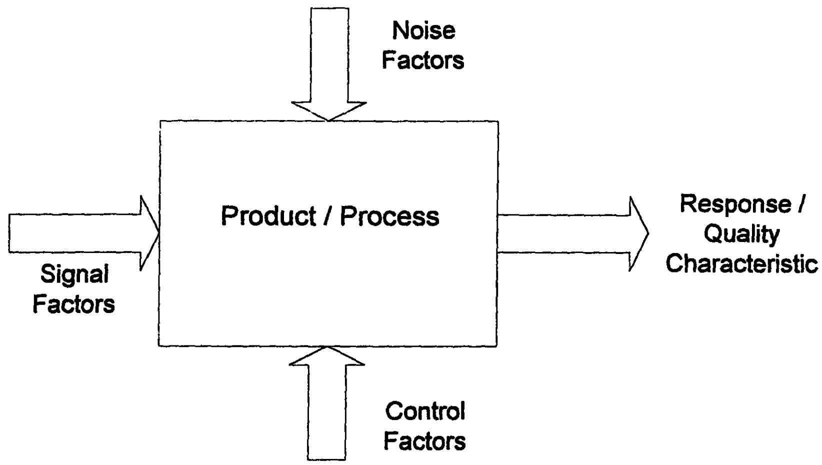

Figure 10, Generic P-diagram

A illustrative P-diagram for the entire B-scale test block system is included in Appendix 1. The P-diagram for the process as a whole is not comprehensive because the author's engineering knowledge for all the process steps is incomplete. Based on the knowledge available at the time, however, the P-diagram indicates that at least eighteen noise factors and eleven control factors are associated with the system. The experimental effort required to test this number of factors would be quite large.

Ideally the whole test block system would be subjected to a dynamic optimization process. However, the resources required to conduct such an effort would be tremendous. There are also practical limitation in that several of the factors in the diagram are associated with the Brass Mill. The Brass Mill would not be willing to experiment with those factors due to economic considerations. Likewise, several of the factors associated with the Customer would be difficult to evaluate in parameter design experiments. Based on the engineering knowledge and experience available, it was deemed most important to concentrate the parameter optimization efforts on the heat treating process alone.

5.2 *Optimization Procedure for the Heat Treating Process*

A straightforward, proven method of optimizing the heat treating process through parameter optimization was proposed. The steps in the optimization process were to be:

1. Creation of P-diagram
2. Quality Characteristic Selection
3. Noise Experiment and Confirmation
4. Control Factor Experiment and Confirmation
5. Analysis of Results and Planning of Future Efforts

However, the results of the noise experiments demonstrated that more information was required to fully understand the heat treating process and that the proposed optimization procedure shown above was accordingly modified. Instead of completing a control factor experiment, a screening experiment with replication was used. As discussed in Section 3.5.A, screening experiments are used to gather information about a process when a Taguchi practitioner has an insufficient understanding of the process under consideration. The actual procedure used to investigate the heat treating process is as follows:

1. Creation of P-diagram
2. Quality Characteristic Selection
3. Noise Experiment and Reflection
4. Screening Experiment and Confirmation
5. Analysis of Results and Planning of Future Efforts

A description of each of the steps will now be presented in turn.

5.3 Creation of the P-diagram

The P-diagram for the heat treating process was developed based on the engineering knowledge discussed in Part 4 and conversations with the Commercial Heat Treater. The P-diagram for the heat treating process is presented in Figure 11.

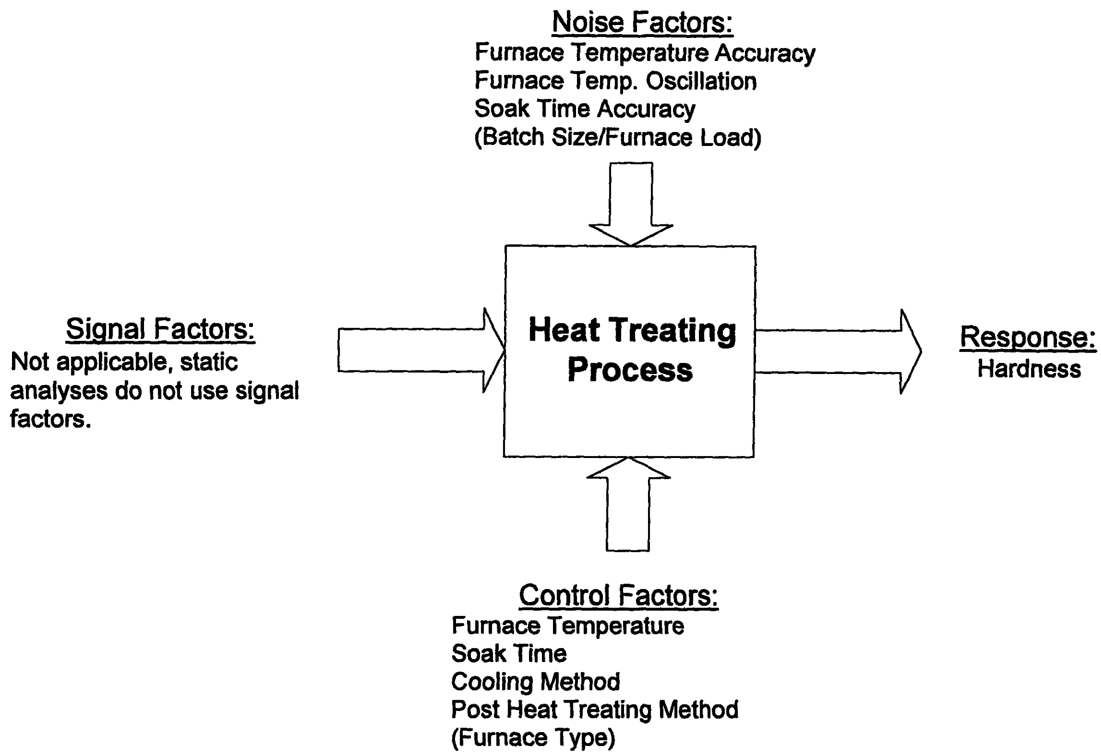

Figure 11, Heat Treating Process P-diagram

Due to economic and practical constraints, the parameter optimization could not be performed using the Commercial Heat Treater's facilities or similar equipment. Instead, the commercial heat treating process was simulated using experimental heat treating equipment. The advantage of the experimental equipment was that it was less expensive, more precise and more accurate. The increased precision and accuracy of the experimental equipment allowed the noise found in the commercial heat treating equipment to be simulated in a controlled manner.

The disadvantage of the experimental heat treating equipment was that several of the factors identified in the P-diagram could not be studied. Two factors (identified in parentheses in Figure 11) were; therefore, eliminated from the parameter optimization process. Furnace load measures the utilization of a furnace. It is common practice for commercial heat treaters to maximize their capacity utilization by combining several heat treat jobs in one furnace. Wilson Instruments requires that a single furnace be dedicated to their heat treating jobs so that the only variation in furnace load is the number of test blocks in a heat treat batch. The mass of the test blocks in one batch is relatively small in comparison to the capacity of the commercial furnaces and; therefore, the effect of furnace load on test block variation is probably negligible.

The furnace type used in commercial heat treating is different from that used in the parameter optimization experiments. The primary difference in the two furnaces is the part heating rates. Experience gained over the course of the LFM internship indicates that the effect of part heating rate on the variation of hardness in a test block is negligible. All of the other noise and control factors shown in the P-diagram could be analyzed with the experimental heat treating equipment.

5.4 Selection of the Quality Characteristic

The measured response for the process output was chosen to be hardness. Hardness is believed to be a good quality characteristic because it is directly related to the energy transformation that occurs during the heat treating process. As per the discussion presented in Section 4.4, it was also believed that hardness would not be prone to significant interactions between control factors. A static, nominal-the-best approach to the optimization was used. It was determined that too little knowledge about the process was available to embark on a more comprehensive dynamic analysis. As a starting point for the parameter optimization a known time and temperature combination was chosen that produced a test block of adequate quality.

5.5 Noise Experiment

A noise experiment is the first step in the two step parameter optimization process (see Section 3.4). The objective of a noise experiment is to determine how the noise factors effect the process mean output. After the effect of each noise factor is determined, the noise factors can be combined into a single confounded noise factor. As discussed in Section 3.4.C, by using a confounded noise factor, the experimental effort can be significantly reduced.

5.5.A Noise Factors and Test Plan

The noise factors used in the experiment are described as follows:

1. *Accuracy of temperature* accounts for difference between the temperature control setting and the true mean temperature achieved. The difference could be due to calibration.
2. *Oscillation of temperature* represents the variation in temperature due to the inherent control characteristics of the furnace. The oscillation could also be caused by opening and closing the furnace door to insert parts.
3. *Accuracy of soak time* characterizes the event of having the actual soak time differ from the scheduled soak time. The accuracy could be reduced by operator error in inserting or removing parts from the furnace.

The noise factor levels for the experiment are shown in Table 8. The noise factor levels were arranged such that a high level on the noise factors would theoretically produce an increase in the hardness of the test blocks. An L4 orthogonal array was used to assess the effects of the noise factors on the hardness of the test blocks. The experimental array for the noise experiment is provided as Table 9.

	Level		
Noise Factor	Low	High	Unit
Accuracy of Temperature	+ 30	- 30	°F
Oscillation of Temperature	+/- 15	+/- 3	°F
Accuracy of Soak Time	+ 15	- 15	minutes

Table 8, Noise Factor Names and Levels

Run Number	Accuracy of Temperature	Oscillation of Temperature	Accuracy of Soak Time	Block Serial Numbers
1	nominal +30 °F	+/- 15 °F	nominal +15 min.	I50869, I50864, I50342
2	nominal +30 °F	+/- 3 °F	nominal - 15 min.	I50863, I50867, I50311
3	nominal -30 °F	+/- 15 °F	nominal - 15 min.	I50325, I50300, I50340
4	nominal -30 °F	+/- 3 °F	nominal +15 min.	I50324, I50876, I50336

Table 9, Noise Experiment Orthogonal Array

5.5.B Noise Experiment Procedure

In all of the experiments three test blocks were heat treated at one time. One block in each run was fitted with a thermocouple to measure the actual temperature of the test block throughout the heat treating process. The thermocouple data was collected through the use of PC-based software and examples of the data are provided in Appendix II. The thermocouple data provided a means to verify that the experimental heat treating equipment was operating at the correct temperatures throughout the experiments.

After the noise experiments were completed the test blocks were sent to the machine shop where their surfaces were made flat, parallel, and smooth. The same lapping and polishing procedures that are currently used for production test blocks was used for all of the experimental test blocks. To reduce the potential for biased results, care was taken to randomize the selection of test block material and the order of experimental runs and measurements.

The hardness of each test block was measured in the Wilson Standards Laboratory using a certified standardizing machine. Twelve hardness measurements were made on each test block. A test pattern that broke the disc into four quadrants and three radial layers was used. The measurement subdivisions on the disk were of equal area. The results of the hardness measurements are tabulated in Appendix III.

For the sake of this investigation, the hardness tester and indentor are held constant and all efforts are focused on studying the hardness test blocks. During Wilson Instrument's previous LFM internship, Mr. Hans Laudon clearly demonstrated that the ability to measure the variation in Rockwell C-scale test blocks is limited by the measurement variation of the Wilson 600 series hardness tester[16]. While it is recognized that a significant portion of the measured hardness is attributable to the hardness tester no information or resource is available to quantify this source of variation. For the time being, the measured variation is treated as if it were entirely attributable to the hardness test blocks themselves.

5.5.C Noise Experiment Analysis

An analysis of means (ANOM) of the noise experiment data was completed using the software package WinRobust© Version 1.0. An ANOM calculates the effect each noise factor has on the mean response of the heat treating process. The calculations performed in the ANOM are actually quite simple. Take for example the mean response for setting the Accuracy of Temperature at its lower level of "nominal + 30 °F". To calculate the mean response for this factor at the low level, the average hardness of all the test blocks processed at the low level (runs 1 and 2 in Table 9) is calculated. The calculation is as shown in Table 10.

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[16] Laudon, Hans J., "Statistical Characterization and Control of Variation in the Manufacture of Standard Test Blocks used for Rockwell Testing", Massachusetts Institute of Technology Masters Thesis, May, 1996.

Run Number	Serial Number	Mean Hardness
1	I50869	61.67
1	I50864	60.61
1	I50342	61.73
2	I50863	60.09
2	I50867	60.79
2	I50311	64.13
	Mean Response	61.50

Table 10, ANOM Sample Calculation

The results of the ANOM are graphically represented in Figure 12 . The use of a graphical representation for the ANOM results is generally preferred because is allows the results to be more easily understood. By displaying the effects of multiple noise factors side-by-side it also shows the relative strength of the noise factors.

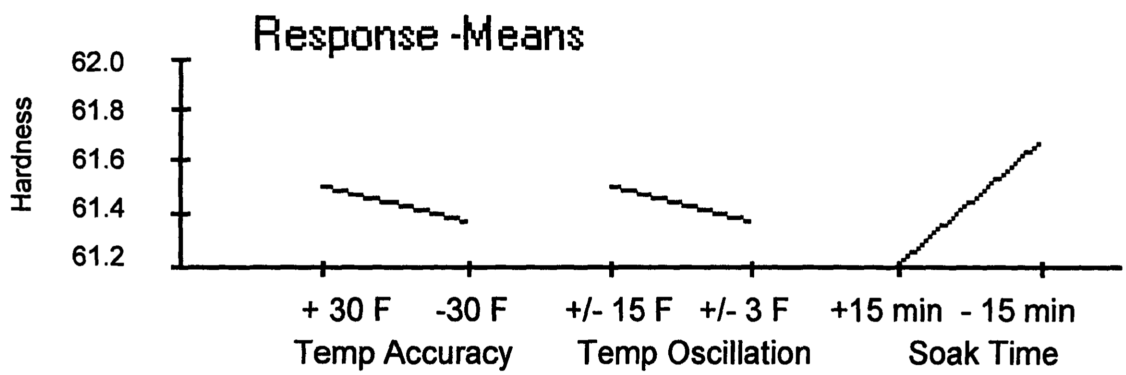

Figure 12, Noise Experiment ANOM Plots

The ANOM plots do not behave as expected. When the temperature of the soak is at the + 30 °F level the mean response is actually lower than at the -30 °F level. The opposite effect is expected as the hardness of the test blocks should decrease when the temperature of the soak is increased. The basic annealing curve shown in Figure 7 clearly demonstrates that as the anneal temperature increases, the hardness of the metal should decrease.

The effect for soak time does behave as expected. When the soak time is at the +15 minute level the mean hardness is lower than when it is at the -15 minute level. It makes sense that the hardness increases with decreasing soak time because the annealing process is allowed to act for a longer period of time. The effect of temperature oscillation is considered irrelevant based on the contradictory findings of the noise experiment.

The behavior demonstrated in the noise experiments is probably caused by a noise factor that is not accounted for in the experiment. The author believes that the unaccounted for noise factor is variation in hardness of the raw material plate stock. The brass plates that are shipped to Wilson Instruments are cut from much larger plates at the brass mill. It is likely the hardness of the larger plates vary significantly from the middle of the plate to the outer edges of the plate. There may be a similar distribution of hardness from the head to the tail of the larger production plates. Unfortunately, there is no way of knowing the orientation of the raw material plate stock with regards to the larger production plates, and it is, therefore, impossible to study.

It is known that the distribution of hardness across the raw material plate stock has a range of approximately two Rockwell points. This information is based on data collected from the production of a range of test blocks that do not require heat treating. Please note that the variation being discussed here refers to the difference between the mean hardness on one raw material plate versus another raw material plate, not across an individual test block. The results of the noise experiment show that the noise conditions were not strong enough to overcome the effect of the raw material's inherent hardness distribution. In essence, the effects of the noise factors are not believed to be measurably significant.

Two conclusions are made based on the results of the noise experiment. The first is that the hardness characteristics of the raw material, both mean and variation, have a dominant effect on the hardness characteristics of the test blocks. The second conclusion is that the contradictory results of the noise experiment warrant a deviation from the standard parameter optimization process.

5.6 *Screening Experiment*

In an attempt to better understand the heat treating process, a screening experiment is conducted. The screening experiment is an orthogonal array experiment that does not intentionally include noise factors. The absence of noise factors generally allows the experimental effort associated with a screening experiment to be reduced. By reducing the experimental effort general information about a process can be learned at relatively low cost.

5.6.A Experimental Error and Interactions

In this case, the experimental effort is actually doubled because a replicate is performed for each experimental run in the screening array. The replication is performed in an attempt to understand the magnitude of experimental error in the experiments. It is likely that a great deal of the experimental error can be attributed to the variation in raw material hardness. By gaining a reasonably accurate assessment of the experimental error, an analysis of variance will show whether or not the control factors investigated in the screening experiment are truly significant.

The screening experiment is also designed to reveal information about the interaction between soak time and temperature. The screening experiment uses an L8 (2^{4-1}), Resolution IV orthogonal array. The array is given in Appendix IV. The L8 (2^{4-1}), Resolution IV orthogonal array was chosen because it allows four factors and three two-way interactions to be studied. The three two-way interactions are not confounded with the main control factor effects in the L8 (2^{4-1}) array.

5.6.B Control Factors and Test Plan

The experimental plan for the screening experiment is given in Table 12.

	Factor Level		
Factor	Low	High	Units
Soak Temperature	nominal +100	nominal -100	°F
Soak Time	nominal +30	nominal -30	minutes
Cooling Method	Slow	Fast	n/a
Secondary Heat Treatment	Yes	No	n/a

Table 11, Screening Experiment Control Factors

	Factors					
Run Number	A Soak Temperature (°F)	B Soak Time (minutes)	C Cooling Method	D Secondary Heat Treatment	Block Serial Numbers	Random Test Sequence
1	nominal +100	nominal +30	Slow	No	I50862, I50872, I50345, I50346, I50860, I50314	16 9
2	nominal +100	nominal +30	Fast	Yes	I50875, I50313, I50343, I50329, I50304, I50305	14 3
3	nominal +100	nominal - 30	Slow	Yes	I50321, I50323, I50857, I50335, I50309, I50341	1 7
4	nominal +100	nominal - 30	Fast	No	I50877, I50320, I50870, I50318, I50302, I50334	10 12
5	nominal -100	nominal +30	Slow	Yes	I50855, I50868, I50865, I50879, I50332, I50326	4 8
6	nominal -100	nominal +30	Fast	No	I50308, I50338, I50333, I50859, I50322, I50856	5 6
7	nominal -100	nominal - 30	Slow	No	I50853, I50858, I50880, I50317, I50327, I50331	11 13
8	nominal -100	nominal - 30	Fast	Yes	I50349, I50312, I50319, I50328, I50348, I50871	2 15

Table 12, Screening Experiment Orthogonal Array

5.6.C Screening Experiment Procedure

As in the noise experiment, three test blocks were heat treated at a time for each screening experiment run. During each run one test block was fitted with a thermocouple so that the true temperature of the test blocks could be monitored. Samples of the thermocouple data for two of the screening runs are included in Appendix V. The sequence of the experiments and the assignment of block serial numbers was randomized to reduce the risk of introducing experimental bias. After the heat treating process the blocks were surface finished according to Wilson Instrument's standard procedures.

The screening experiment test blocks were tested for hardness using one of Wilson Instrument's standardizing hardness testers. As in the noise experiment, each test block was divided into twelve sections of equal area. One hardness measurement per subsection was made. The results of the hardness tests are included in Appendix VI. For each experimental run a grand mean and standard deviation were calculated. A combined mean and standard deviation are calculated by averaging the grand means and standard deviations from each of the two experimental runs. The combined means and standard deviation are used to analyze the control factor effects.

5.6.D Screening Experiment Analysis

The screening experiment data is interpreted using analysis of means (ANOM), S/N ratio analysis, analysis of variance (ANOVA), and analysis of two-way interactions. The ANOM measures the effect each control factor has on the mean response of the process. The S/N ratio analysis indicates how the control factors effect the robustness of the process. The ANOVA reveals the significance of each of the control factor effects. Finally, the analysis of two-way interactions investigates the relationship between pairs of control factors.

ANOM

The screening experiment ANOM was performed using the WinRobust© software package. Graphical results of the ANOM are presented in Figure 13 and tabular results are given in Table 13. The mean response of each control factor can be calculated due to the balance of the orthogonal array. That is, for each distinct setting of a control factor, every other control factor occurs at its respective levels an even number of times; therefore, the effects of the other control factors have a canceling effect.

As an example, the mean response for setting the soak temperature at the nominal +100 °F level is calculated as follows:

$$Effect_{SoakTemp,no\min al+100F} = \frac{1}{4}\left(\overline{\overline{y_1}} + \overline{\overline{y_2}} + \overline{\overline{y_3}} + \overline{\overline{y_4}}\right)$$

$$= \frac{1}{4}(46.60 + 46.15 + 57.65 + 60.07)$$

$$= 52.62$$

where:

$\overline{\overline{y_i}}$ = combined mean(see Appendix VI) for the i^{th} control factor combination in the experimental array

An interpretation of the ANOM results will be given below as it is useful to jointly review the mean response and S/N ratio effects when assessing the characteristics of a control factor.

S/N Ratio Analysis

An introduction to the S/N ratio was presented in section 3.4.B of this thesis. The S/N ratio measures robustness in parameter optimization. In a standard parameter optimization procedure a process is intentionally subjected to large doses of noise through the use of noise factors. The S/N ratio indicates the robustness of the process in light of the disturbances embodied in the noise factors. In the screening experiment used for the B-scale hardness test blocks, no noise factors are included and, as such, the S/N ratio used for the screening experiment is not a traditional Taguchi S/N ratio. However, the S/N ratio may be used as a measure of process robustness without intentionally including noise factors in an experiment. There are noise factors present in any experiment regardless if they are intentionally included or not.

The S/N ratio calculation is based on the variance of a process's output. To calculate a variance, sufficient degrees of freedom in the experiment must be allocated. In a traditional parameter design experiment noise factors provide the degrees of freedom needed to calculate a variance. In screening experiments, replication provides the degrees of freedom needed to calculate the variance.

The successful use of S/N ratios in screening experiments is documented in the two papers reviewed in sections 3.5A and 3.5.B of this document. In the paper concerning steel hardness test blocks a static, nominal-the-best S/N ratio is used. This type of S/N ratio assumes:

1. the quality characteristic is continuous and non-negative
2. the variation of the quality characteristic scales proportionally with the mean

Given that the Rockwell B-scale is the chosen quality characteristic, the first assumption is acceptable but the second is not. There is no indication that the variation in hardness is proportional to mean hardness. Indeed, it is certain that when the hardness of a test block is zero the variation in hardness is not zero, which is what the assumption implies. In fact, conventional wisdom shows that the variability in hardness of B-scale test blocks gradually decreases with increasing hardness.

There is a less frequently used static, nominal-the-best S/N ratio that could be applied to the screening experiment. The ratio is called the nominal-the-best type II or the signed-target S/N ratio. The signed-target type ratio assumes:

1. the quality characteristic is continuous and either positive or negative
2. the variation of the quality characteristic does not scale with the mean

The signed-target S/N ratio may be calculated as follows:

$$S/N_{signed-target} = -10\log_{10}\left(S^2\right)$$

where S^2 = measured population variance or:

$$S^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2$$

For a hardness test block it is of paramount importance to minimize the variation in hardness across the face of each test block. Every test block is individually calibrated and the critical function of the test block is purely that all hardness readings made on the test block fall within a tight distribution around the block's calibration value. The variation of mean hardness between test blocks within a production batch is not of critical importance. The mean hardness of the test blocks are bounded by a relatively large range (see Table 4) without incurring any quality loss to the customer, manufacturer or society.

There are two groups of three test blocks associated with each combination of control factor levels. The S/N ratio that is calculated for each control factor combination must represent the variance measured on each of the six test blocks, not the variance between the means of the six test blocks. (Please note that this differs from most Taguchi analyses. A standard approach would calculate the S/N ratio using a population variance representing variation between the six test blocks' mean hardness.) Accordingly, the S/N ratio for each control factor combination level, for each group of three test blocks, is calculated using the average within block variance as follows:

$$S/N_{signed-t\arg et} = -10\log_{10}\left(S_{average}{}^2\right)$$

where six test blocks are used with twelve measurements per test block:

$$S_{average}{}^2 = \frac{\left[S^2_{block1} + S^2_{block2} + S^2_{block3}\right]}{3}$$

and:

$$S^2_{block1} = \frac{1}{11}\sum_{i=1}^{12}(y_i - \bar{y}_{block1})$$

and for any given test block:

$$\bar{y} = \frac{1}{12}\sum_{i=1}^{12} y_i$$

A spreadsheet was used to perform the signed-target S/N ratio calculations because the WinRobust© program did not support calculating an S/N ratio in this way. The spreadsheet is given in Appendix VII and the results are summarized in Figure 13 and Table 13. The response effects for the S/N ratio are calculated using the same process as is used in the ANOM. The S/N ratios for the replicates are averaged to yield the control factor effects.

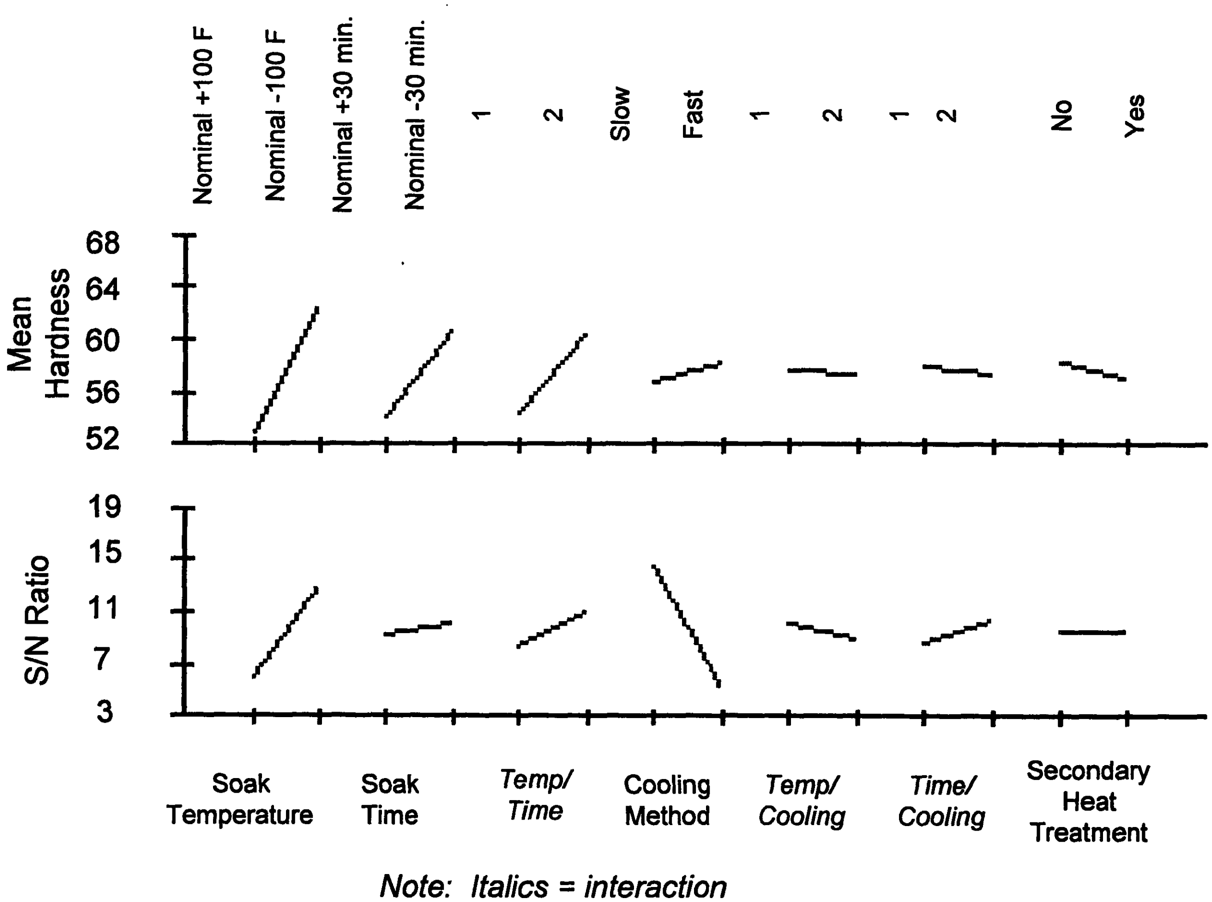

Figure 13, Screening Experiment Factor Effect Plots

		Response	
Control Factor	Level	Mean Hardness	S/N Ratio
Soak Temperature	nominal +100 °F	52.62	4.94
	nominal -100 °F	62.35	11.95
Soak Time	nominal +30 min.	54.19	8.02
	nominal -30 min.	60.78	8.88
Time/Temperature Interaction	1	54.54	7.16
	2	60.43	9.74
Cooling Method	Slow	56.79	13.18
	Fast	58.18	3.72
Temp/Cooling Interaction	1	57.69	9.03
	2	57.28	7.86
Time/Cooling Interaction	1	57.67	7.67
	2	57.30	9.22
Secondary Heat Treatment	No	58.01	8.42
	Yes	56.96	8.47

Table 13, Control Factor Effects

An assessment of the control factors can be made using the data provided in Figure 13 and Table 13 as follows:

1. *Soak Temperature:* In agreement with Figure 7, lowering the soak temperature increases the mean hardness of the test blocks. Lowering the soak temperature creates a significant increase in the S/N ratio and, therefore, process robustness.
2. *Soak Time:* In agreement with Figure 9, lowering the soak time increases the mean hardness of the test blocks. The effect of soak time on the S/N ratio is minimal indicating that it could be used as a tuning factor, that is, the mean hardness of the process could be put on target by varying the soak time without increasing the variability of hardness on a test block.
3. *Cooling Method:* The fast cooling method causes a slight increase in mean hardness but a significant decrease in the S/N ratio. The slow cooling method is preferred because it increases the S/N ratio significantly.
4. *Secondary Heat Treatment:* The secondary heat treatment causes a slight decrease in mean hardness and has little effect on the S/N ratio. The secondary heat treatment should not be used because it produces virtually no effect on the process.

The factor effect plots also indicate that the interaction between soak temperature and soak time is significant with regards to the mean hardness. Figure 14 illustrates the interaction between soak temperature and soak time. The interaction plot shows that the effect of soak temperature has a greater effect when the soak time is increased to the nominal +30 minutes soak time level. An interaction between time and temperature was anticipated but it was not expected to be so strong. It is fortunate that it was accounted for in the experimental array. The interaction should be included in any predictive equations for the mean response.

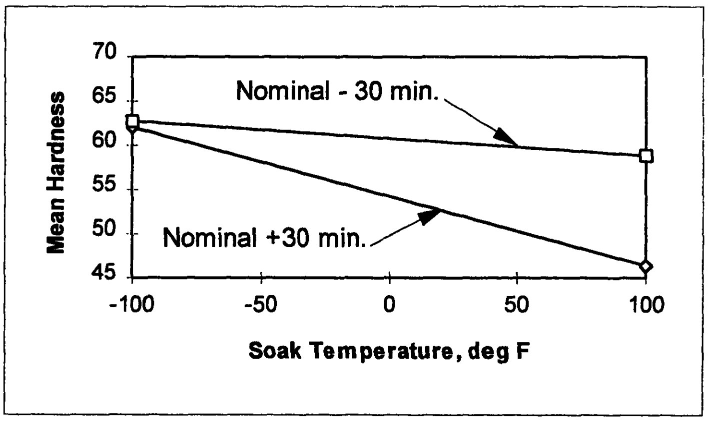

Figure 14, Soak Temperature/Time Interaction Plot for Mean Hardness

ANOVA

Analysis of variance(ANOVA) provides a means of determining significance of control factor and interaction effects on either the mean response or S/N ratio. The ANOVA provides a means of determining whether the effects of control factors are truly important or simply the product of random experimental effects. The significance of the effects is measured by comparing the ratio of the mean square due to a control factor or interaction to the mean square due to experimental error and/or unaccounted for interactions. The statistic that measures the significance of an effect is called the F-ratio and it is defined as follows:

$$F - ratio = \frac{MS}{S_e^2}$$

where:

MS = mean square due to a control factor or interaction(accounted for in the experiment)

= (factor effect sum or squares) / (factor degrees of freedom)

S_e^2 = mean square due to experimental error and/or interactions(not accounted for)

= (error sum of squares) / (error degrees of freedom)

As discussed in Sections 5.4.C and 5.5.A, replication was used in the screening experiment to get an estimate of the experimental error. In parameter design the error variance is usually estimated by pooling the effects of weak control factors. The pooling method yields an estimate of the experimental error without adding additional experimental effort. Pooling is considered to be an approximate estimate of the true experimental error and given the spurious results of the noise experiment, it was determined that a more direct measurement of the experimental error would be prudent. Using the replicates, the error variance for each experimental run is calculated as follows:

$$S_e = \frac{1}{r-1}\sum\left(S/N_j - \overline{S/N_R} \right)^2$$

where:

r = the number of replicates

S/N_j = S/N (or mean) value for each of the replicates

$\overline{S/N_R}$ = average of all the S/N (or mean) values

The experimental errors for both the mean response and S/N ratio are then estimated by averaging the error variances from each control factor combination in the array. The error variance calculations are given in Appendix VIII.

With an estimate of the error variance, the WinRobust© software package is then used to calculate the control factor and interaction sum of squares and the corresponding F-ratios.

Adaptations of the WinRobust© output are given in Appendix IX and a summary of the results are shown in

Table 14. The F-ratio is used to rank the significance of control factor effects as prescribed by the following guidelines[17]:

- F>4 The control factor is strong compared to experimental error and is clearly significant.
- F<1 The experimental error outweighs the control factor effect; the control factor is insignificant and indistinguishable from the experimental error.
- F≈2 The control factor has only a moderate effect compared to experimental error.

The results of the ANOVA show that all of the control factors have significant effects on the mean hardness of the test blocks. The soak time and temperature interaction also has a significant effect on the mean hardness. With respect to the S/N ratio, soak temperature, cooling method, and the soak time and temperature interaction have significant effects. Soak time, secondary heat treatment, and the other interactions have an insignificant effect on the S/N ratio.

Factor	Mean Hardness F-ratio	Hardness S/N Ratio F-ratio
Soak Temperature	416.8	22.7
Soak Time	196.8	*(0.4)*
Time/Temp Interaction	156.7	3.1
Cooling Method	9.3	41.3
Temp/Cooling Interact.	*(0.5)*	*(0.6)*
Time/Cooling Interact.	*(0.8)*	*(1.1)*
Secondary Heat Treat	5.5	*(0.0)*

Table 14, ANOVA F-ratios

The interaction between soak time and temperature on the S/N ratio is shown below in Figure 15. The interaction plot shows that the S/N interaction behaves similarly to the mean hardness interaction. That is, the effect of soak temperature on the S/N ratio is greater when the longer soak time is used. The interactions indicate that soak time and temperature can not be considered independent of one another. The key energy transformation at work in the heat treating process is clearly a function of time, temperature, and the combination of time and temperature. The time and temperature relationship shown in Figure 9 does not hold for the copper alloy currently being used for the hardness test blocks.

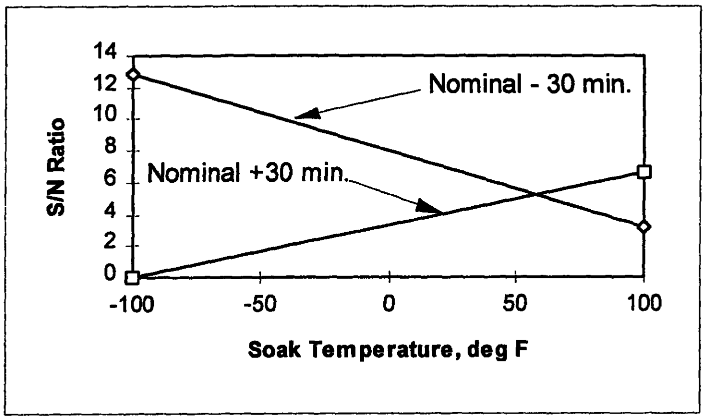

Figure 15, Soak Temperature/Time Interaction Plot for S/N Ratio

5.6.E Parameter Optimization, Prediction and Confirmation

The two-step parameter optimization process prescribes that the process output variation be reduced to a minimum before the mean response is put on target. The process variation is reduced by setting the control factor levels such that the S/N ratio is maximized. After determining the optimum control factor levels a prediction of the process mean response and S/N ratio is made. To confirm that the assumptions made about control factor interactions is correct a confirmation experiment is generally performed. If the results of the confirmation experiment agree with the performance prediction, it may be concluded that no significant interactions went unaccounted for in the parameter design experimental array.

The optimum control factor levels are chosen based on the information provided in Figure 13. To achieve the maximum S/N ratio, soak temperature is set to the nominal -100°F level and the slow cooling method is used. The other control factors do not have a significant

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[17] Fowlkes, W.Y., Creveling, C.M., Engineering Methods for Robust Product Design - Using Taguchi Methods in Technology and Product Development, Addison-Wesley, Reading, MA, 1995.

effect on the S/N ratio and their levels may be selected based on cost. The secondary heat treatment should not be performed because it requires effort while producing no significant value. The soak time is shown to have an insignificant effect on the S/N ratio and could be set to either level. The longer soak time would produce a test block with a mean hardness closer to the target hardness without causing an increase in variation.

In most parameter optimization experiments the control factors are engineered so that no interactions are present. When no interactions are present the optimum performance prediction can be made using additive models. In the case of the hardness test block screening experiment used in this study, interactions were accounted for in the experimental array and the significant interactions must be accounted for in the prediction model. The optimum performance prediction is made by adjusting the total experimental mean according to the factor effect responses. The mean and S/N response values for the significant factors at the optimum factor levels are shown in Table 15.

Factor	Optimum Level	Mean Response	S/N Response
Soak Temperature	nominal -100°F	62.35	11.95
Soak Time	nominal +30 min.	54.19	not significant
Cooling Method	slow	56.79	13.18
Secondary Heat Treatment	no	58.01	not significant
Time/Temperature Interaction	2	60.43	9.74

Table 15, Optimum Factor Responses

The mean hardness and S/N ratio at the optimum factor levels are calculated as follows:

$$\bar{Y}_{optimum} = 57.51+(62.35-57.51)+(54.19-57.51)+(56.79-57.51)+(58.01-57.51)+(60.43-57.51)$$

$$= 61.7 \text{ HRB}$$

$$\overline{S/N}_{optimum} = 8.45+(11.95-8.45)+(13.18-8.45)+(9.74-8.45)$$

$$= 17.97$$

The WinRobust© software can also be used to perform the calculation and, in addition, provides a 90% confidence interval for the prediction. The confidence interval for the mean response is found to be +/-2.3 HRB while the confidence interval for the S/N ratio is +/- 3.4.

Confirmation experiments for the optimum factor level set points were not performed due to time and material constraints. However, a review of the experimental array indicates that a factor level combination similar to the optimum was performed in the screening experiment itself. In most parameter optimization experiments the optimum factor level combinations are not found in the main experiment array because the orthogonal arrays are very "lean". The L8 (2^{4-1}), Resolution IV, orthogonal array used in the screening experiment contains more factor level combinations than are usually used. In fact, screening experiment run number 5 (see Table 12) has the optimum control factor settings. The resulting mean hardness and S/N ratio for the experiment is 60.75 HRB and 16.20, respectively. The results are within the 90% confidence interval provided by the prediction.

The mean hardness prediction is even more accurate if the effect of the secondary heat treatment, which was included in run 5, is backed out of the prediction estimate. The adjusted estimate would then be 61.2 HRB (61.7-(58.01-57.51)= 61.2). Note also that run 7 in the screening experiment produces a high S/N ratio indicating that a change in the soak time does not significantly affect the hardness variation on the test blocks.

The screening experiment provides useful information about the effects of the chosen control factors and their interactions. However, the optimum control factor settings determined by the screening experiment do not produce test blocks of much better uniformity than the HRB 60 test blocks currently produced with Wilson Instrument's commercial heat treating process. (Recall that the screening experiments were conducted with a static target hardness of HRB 60.) At the hardness ranges lower than HRB 60, the commercial process does not yield test blocks as uniform as at the HRB 60 range indicating that efforts could be made to optimize the heat treating process for the lower hardness ranges.

Part 6: Management and Implementation of Taguchi Methods in the Manufacturing Organization

6.1 Change in the Manufacturing Organization

Implementing Dr. Taguchi's Parameter Design methods in a manufacturing organization presents problems because doing so requires a deviation from the status quo. As stated by one Taguchi expert, "Change is a tough gig. It's vexing, wrenching, and risky."[18] But, as is well accepted by today's manufacturing firms, change is required to remain viable because competitive demands increase indefinitely. The current trend in competition requires that manufacturing firms generate new processes and products with more frequency, increased quality, and decreased cost. There is sufficient evidence which demonstrates that companies who adopt Taguchi methods as part of their standard process and product development efforts gain a competitive advantage over those companies who do not and, therefore, it is important to explore the means by which Taguchi methods can be implemented in a manufacturing environment.

The use of Taguchi's Parameter Design methods have been associated with significant product and process design improvements within Japanese manufacturing companies for many years. Within these firms the use of Parameter Design is very much internalized and Taguchi's basic philosophy of variation reduction is instilled in the minds of employees at all levels of the organization. Adoption of the methods by U.S. manufacturing companies has resulted in some success stories but most of the success has been limited to specific projects, not corporate wide. This trend is not difficult to believe. In fact, many of the contemporary manufacturing change initiatives, such as Total Quality Management, Concurrent Engineering, Business Reengineering, and Lean Manufacturing are accepted by companies as worthy pursuits but their implementation is not always successful. For example,

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[18] Bebb, Barry B., "Structured Implemtation of Robust Design", American Supplier Institute, 12th annual Taguchi Symposium, 1994.

approximately 25% of the efforts to implement Total Quality Management in U.S. companies succeed.

Some common examples of barriers to change that are encountered in a manufacturing environment include:

- Naysayers at all levels of the company emerge to resist change if support from top management is not secured and generously displayed.
- The payback from implementing changes is difficult to quantify, must be discounted in value because it occurs in the future, and involves significant levels of risk whereas the costs of the implementation efforts are current and more easily quantified.
- Resources allocated to implementing changes cause immediate strains on operations that must support current customer demand.
- Opponents argue that the changes may have worked at other firms but probably won't work for theirs, also known as the "not-invented-here" syndrome.

In order to overcome the barriers to change, any initiative must have:

- long term support from upper management
- champions within the working ranks to generate project level success through technical and organizational leadership
- ample resources for research and development, training, and new process/product implementation

6.2 Challenges Specific to Corporate Wide Implementation of Taguchi Methods

Implementing Taguchi methods in a manufacturing environment is not vastly different from implementing other initiatives that require operational and philosophical changes within a firm. However, Taguchi methods are thought of as technical solutions whereas Total Quality Management, Concurrent Engineering, Business Reengineering, Lean Manufacturing, and many other change initiatives are accepted as being organizational in character. The point is this; there is a tendency for upper level management to be more understanding of initiatives that are organizational in nature than those that are technical in nature. The tendency appears natural because management spends much more of its time and effort dealing with complex organizational issues.

Because Taguchi methods are highly technical in nature it is likely that their champions will come from middle managers whose daily work contains a great deal of exposure to technical matters. The challenge placed on the champion is trebled as they must simultaneously seek upper management's support, deal with the technical challenges of implementing the methods on a project basis, and maintain satisfactory performance of normal business operations. A closed-loop cycle associated with initiating change in an organization can be drawn to show the importance of upper management support. The loop is shown in Figure 16.

Middle management can take on the role of champion and generate some successful projects. If presented to management successfully, management may lend its support to the change initiative based on the success of these projects. However, building management support in this fashion can be a slow process. Resources will be scarce at first, and there is a risk of total implementation failure if some early projects do not reap large enough benefits. One means of gaining management support early in the process is to teach management the value of the changes before large scale benefits are available in their own firm. In the case of Taguchi's Parameter Design methods, the successes achieved at Kodak, AT&T, Ford, and Xerox could be brought to management's attention in order to engender their support.

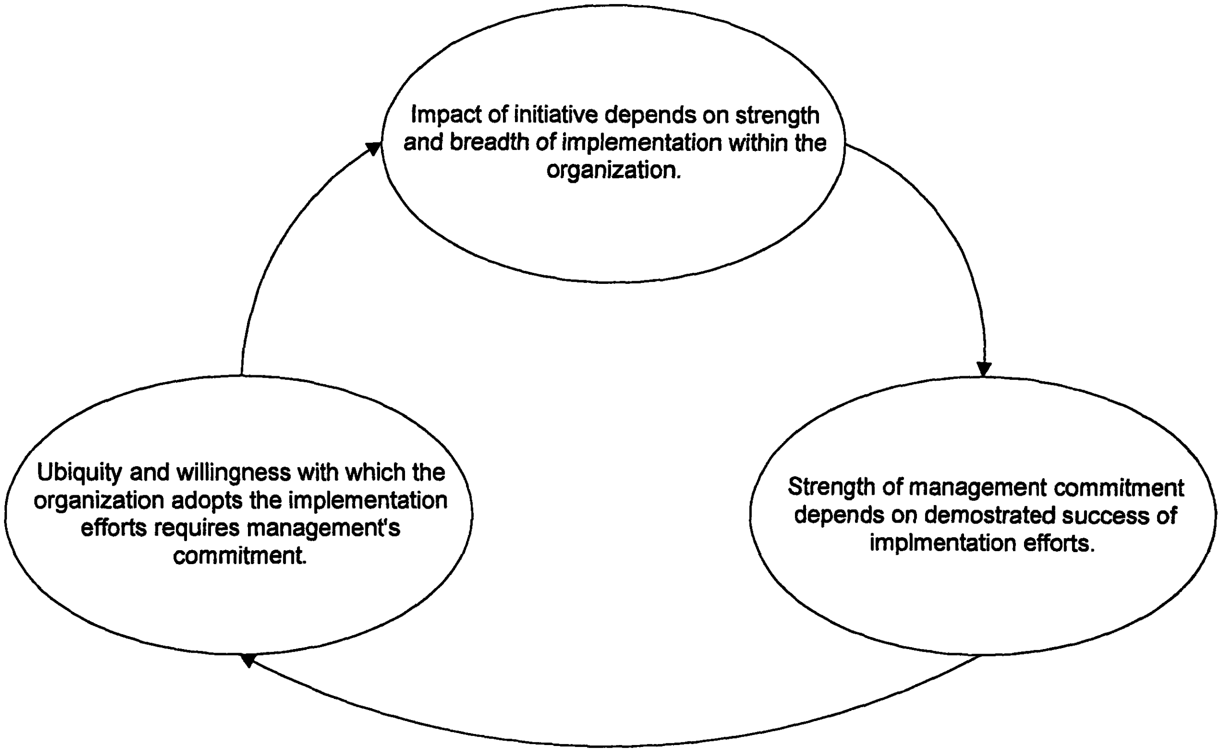

Figure 16, Management Support of Change Implementation

6.3 Implementation of Taguchi Methods on a Project Basis

6.3.A The PDCA Structure

The successful implementation of a Parameter Design process on a project basis requires significant physical and technical resources. The efficient use of these resources can be accomplished by following a structured approach called PDCA which stands for:

1. **P**lanning the experiment
2. **D**esigning the experiment
3. **C**onducting the experiment
4. **A**nalyzing the experiment

The Robust Design PDCA cycle should not be confused with the Plan, Do, Check, Act cycle so frequently used in Total Quality Management (TQM) circles, but interestingly enough, many of the TQM tools are useful in the planning stages of the Robust Design PDCA cycle. The designing, conducting, and analyzing portions of the PDCA cycle have been thoroughly discussed in Parts 3 and 5 of this thesis and, therefore, only the planning cycle will be discussed at this time.

6.3.B Planning a Taguchi Method Experiment

According to Dr. Taguchi, approximately 80% of the resources dedicated to a Taguchi project should be spent in the planning stage. This should not come as a surprise as one of the fundamental Taguchi principles is to reduce experimental efforts by applying engineering knowledge. By utilizing engineering and other available knowledge, combinations of parameter settings that knowingly yield poor results and/or interactions can be accounted for in the design of the experiment. Additionally, running the experiments and accounting for the impact of changes in processes or products requires the input of a rather wide range of functional groups thereby increasing the time required for planning.

Cross-functional Teams: To accommodate the input of the wide range of functional groups needed for a Taguchi Method process, a cross-functional team approach is suggested. Representatives of the team and the reasons for including them as members of the team, are shown in Table 16. In addition to those groups represented in the table, a team leader must be chosen. Ideally, the leader will have thorough knowledge of both Taguchi methods and the process under consideration. The leader must take on the role of manager, motivator, teacher, and corporate liaison in order to ensure success of the project.

Relation to Project	Functional Group	Contribution to the Team
Knowledge of process technical details.	Process and Product Engineers	Technical information specific to the process or product.
	Quality Engineers and Technical Supervisors	Real-life operations information that may be technical in nature but not well documented.
	Technical Experts, i.e. statisticians, chemists...	Strong understanding of process physics or analysis techniques.
Involved in the process.	Line Operators and Inspectors	Practical knowledge about the process and physical skills to conduct the experiments.
Support the process.	Production Planners	Timely completion of experiments while fulfilling immediate production demands.
	Purchasing Agents	Timely supply of material for conducting experiments. Information regarding variability of material inputs.
	Upper Management	Resources, credibility, and motivation.
Impacted by the process.	Customers	Information regarding the impact of process variability.
	Marketing	Identification of process attributes and value added.
	Manufacturing Management	Relevancy of process changes to operations.

Table 16, Members of the Cross-functional Team

Project Goals: Either before, or immediately following the formation of a cross-functional team, the overriding goal of the project must be determined. The goal of the project demonstrates the need for conducting the experiment to both upper management and those who will be affected by the project. Typical goals for parameter design experiments include increasing process quality, increasing process flexibility, and reducing process costs. Once a goal has been established, the goal must be broken down into a more manageable format.

Focused Objectives: By using a combination of team-based, TQM techniques, the project goal should be distilled down to focused objectives. The focused objectives allow the team to spend its time studying the root causes of the problem that was identified in its project goal. For example, the goal of the LFM internship on which this thesis was based was to reduce the variation of hardness on Rockwell B-scale test blocks by 30%. A cross-functional team comprised of company and academic members developed a set of objectives that portrayed the principle sources of variation on a Rockwell B-scale test block. One of the objectives identified by the team was the heat treating process. Other objectives that were identified were also studied and/or adjusted to benefit the overall goal of the project.

There are several methods that can be used to help determine focused objectives. Particularly useful techniques include process flow diagrams, brainstorming, Pareto diagrams, KJ diagrams[19], and Ishikawa (fish-bone) diagrams. Detailed description of these methods may be found in Shoji Shiba's book, "A New American TQM"[20] and Richard DeVor's text, "Statistical Quality Design and Control."[21]

I would suggest that the first step in determining focused objectives is to develop a process flow diagram that depicts all steps in the process through raw material manufacture to customer use. The P-diagram shown in Appendix I was developed based on a process flow diagram for the test block manufacturing process. The process flow diagram allows all of the members in the team to contribute their knowledge about specific portions of the process thereby creating a sense of commitment. It also serves to educate members in the team about other areas that they are not familiar with, thereby generating respect for fellow workers and a sense of cooperation among team members.

Once the team understands the process, brainstorming, Pareto diagrams, KJ diagrams, and Ishikawa diagrams can be used to focus in on the root causes of the problems the team must solve. Typically, a combination of these tools is used, however, the discretion of the team is needed to determine the extent of their use. In addition to the TQM-based techniques, statistical methods can also be employed when data relating process parameters to process

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[19] Shiba, S., "Step by Step KJ Method", Tsukuba University and The Center for Quality Management, CQM document No. 2P, 1991.

[20] Shiba, S., Graham, A., Walden, D., A New American TQM:Four Practical Revolutions in Management, Productivity Press, Portland, OR, 1993.

[21] DeVor, R., Tsong-how, C., Sutherland, J., Statistical Quality Design and Control, Contemporary Concepts and Methods, Macmillan Publishing Company, New York, NY, 1992.

output is available. A statistical analysis can provide useful information about the root causes of problems as well as information about the relationship between process parameters.

The main objective of determining the project's focused objectives is to break the problem down into manageable and discrete segments. Once these segments have been identified, the parameter design experiment may be designed specifically to address them thereby increasing the overall efficiency of the project. In addition to increasing the project efficiency, requiring the team to step through several of the TQM-based processes decreases the chance that important knowledge held by individual team members is not considered.

Part 7: Summary, Conclusions and Recommendations for Future Efforts

7.1 *Summary of Noise Experiment*

The noise experiment indicates that the hardness characteristics of the test block raw material have a very strong effect on the post-heat treating hardness characteristics of the test blocks. This observation is based on the fact that the known theoretical behavior of the copper alloy was found to be violated, that is, when soak temperature was increased, measured hardness did not decrease. It was determined that small increases in the soak temperature actually produced insignificant changes in hardness thereby indicating that the initial state of the raw material was more important than previously recognized.

The noise experiment also demonstrated that the Taguchi methods can be ineffective when specific engineering knowledge is not available to the Taguchi engineer. Although a substantial volume of theoretical knowledge was accumulated (see Part 4) for the noise experiment, the results of the experiment were unsatisfactory. In lieu of completing a full-fledged parameter design process, which relies on the successful completion of a noise experiment, a screening experiment was deemed to be a more effective means of improving the test block heat treating process. The screening experiment was designed as a compromise between optimizing the process and generating further knowledge about the process.

7.2 *Summary of Screening Experiment*

The screening experiment indicates several important lessons about the heat treating process for B-scale hardness test blocks, they are as follows:

1. A slower cooling rate yields lower hardness variation on the test blocks.
2. A secondary heat treatment does not significantly effect test block hardness variation.
3. There is a significant interaction between time and temperature with respect to both mean hardness and hardness variation.

The lessons shown above are useful in that they represent new knowledge which can be applied to future heat treating optimization efforts. However, the optimum hardness variation indicated by the experiments ($\sigma = 0.15$) is not significantly better than that currently achieved in the production of the nominal Rockwell HRB 60 test blocks. The Taguchi efforts would have been more rewarding if one of the new control factor levels (fast cooling or secondary heat treatment) had produced significant and positive effects on the hardness uniformity of the test blocks. Although the process optimization efforts did not produce a substantial improvement in hardness uniformity, the methods used were successful in that they provided a better understanding of the process in a relatively short period of time.

The screening experiment efforts indicate that further improvements in B-scale hardness test block uniformity are likely to come from outside the heat treating process. Improvements could be made in the uniformity of the raw material. However, material improvements can only be realized by working closely with the brass mills. This is a daunting task because the brass mills are not receptive to experimenting with their manufacturing processes. The brass mills are not willing to experiment with their manufacturing processes because they must achieve high equipment utilizations due to the high cost of their capital equipment. In addition, Wilson Instruments has very little purchasing power because they have low usage requirements and brass plate is a commodity product.

7.3 Summary of Implementation Issues

The implementation of Taguchi methods in a manufacturing environment requires significant resources and a structured approach. We have concluded that middle managers must champion the implementation efforts and that the speed and long term success of their efforts is greatly influenced by the support of upper management. On a project basis, the implementation efforts must follow a planning, designing, conducting, and analyzing (PDCA) structure that emphasizes the planning phase. A cross-functional team approach that employs accepted TQM techniques to develop focused project objectives is highly recommended for the planning phase.

7.4 Conclusions

The following conclusions are offered regarding the application of Taguchi methods to the heat treating process used in manufacturing Wilson Instrument's Rockwell B-scale hardness test blocks:

Noise Experiment:

- Test block hardness uniformity is highly dependent on the hardness characteristics of the raw material used in their manufacture.
- Taguchi methods can be difficult to apply when specific engineering knowledge is not available to the Taguchi practitioner.

Screening Experiment:

- Soak temperature has a significant effect on test block hardness uniformity. Soak temperature should be set at the lowest possible temperature to increase test block uniformity.
- The effect of soak time on test block uniformity is minimal, therefore, the mean hardness of test blocks can be controlled by varying the soak time without substantially affecting test block uniformity.
- Rapid cooling of test blocks causes decreased uniformity; therefore, the test blocks should be cooled to ambient conditions slowly.
- A secondary heat treatment should not be applied to the test blocks as it yields virtually no effect on the process and requires substantial effort.
- Further increases in test block hardness uniformity may be achieved by improving raw material hardness uniformity.

7.5 Recommendations for Future Efforts

7.5.A Quantify Components of Variation not Attributable to Test Blocks

In conducting this thesis the variation measured on the test blocks was attributed to the test blocks alone. As is indicated in Appendix I, there are many sources of variation in a Rockwell hardness test. Other sources of variation include the indentor, pedestal, and hardness tester. The operating parameters of the hardness test, such as indentation velocity and hold time of loads, are also potential sources of variation. Taguchi methods could be used to explore the additional components of variation using parameter design experiments. Before completing such an experimentation effort it would be advisable to benchmark the variation of several B-scale hardness test blocks using the National Institute of Standard's deadweight hardness tester. This tester was used to estimate the variation in hardness attributable to the hardness tester for Rockwell C-scale test blocks in a previous LFM internship project.[22]

7.5.B Exploration of Time and Temperature Interaction

A significant interaction between soak time and temperature was demonstrated in the screening experiments. It would be of interest to build upon the current understanding of this interaction. In addition, it would be useful to gain a better understanding of any non-linearity in the time and temperature effects on hardness. The most effective means of collecting such information would not necessarily be through the use of Taguchi methods. It would probably be more effective to use a more traditional design of experiments approach to solving this problem. In completing this work it would be important to carry out the investigation across a wide range of times and temperatures. I would also suggest using more than three levels for both time and temperature so that any non-linearity could be accurately determined.

7.5.C Application of Dynamic Quality Characteristic to the Heat Treating Process

As stated in earlier parts of the thesis, the most powerful application of Taguchi methods comes in the form of dynamic analyses. A dynamic analysis in Taguchi's sense refers to an analysis that optimizes a process over a range of outputs. In the work performed for this thesis, the output of the process was fixed at a nominal hardness of HRB 60. A dynamic analysis on the other hand would seek to optimize the process over the full range of hardness test blocks produced by the heat treating process. However, a dynamic analysis should not be conducted until further information regarding the soak time and temperature effects and interactions are known.

The screening experiment demonstrated that the HRB 60 test blocks currently being produced by Wilson Instruments have the best uniformity achievable given the existing raw material and heat treating process. However, the HRB 60 production test blocks currently have the highest uniformity of hardness in the entire range of production hardnesses and it is probable that the uniformity of the other hardness ranges could be improved using a dynamic analysis approach.

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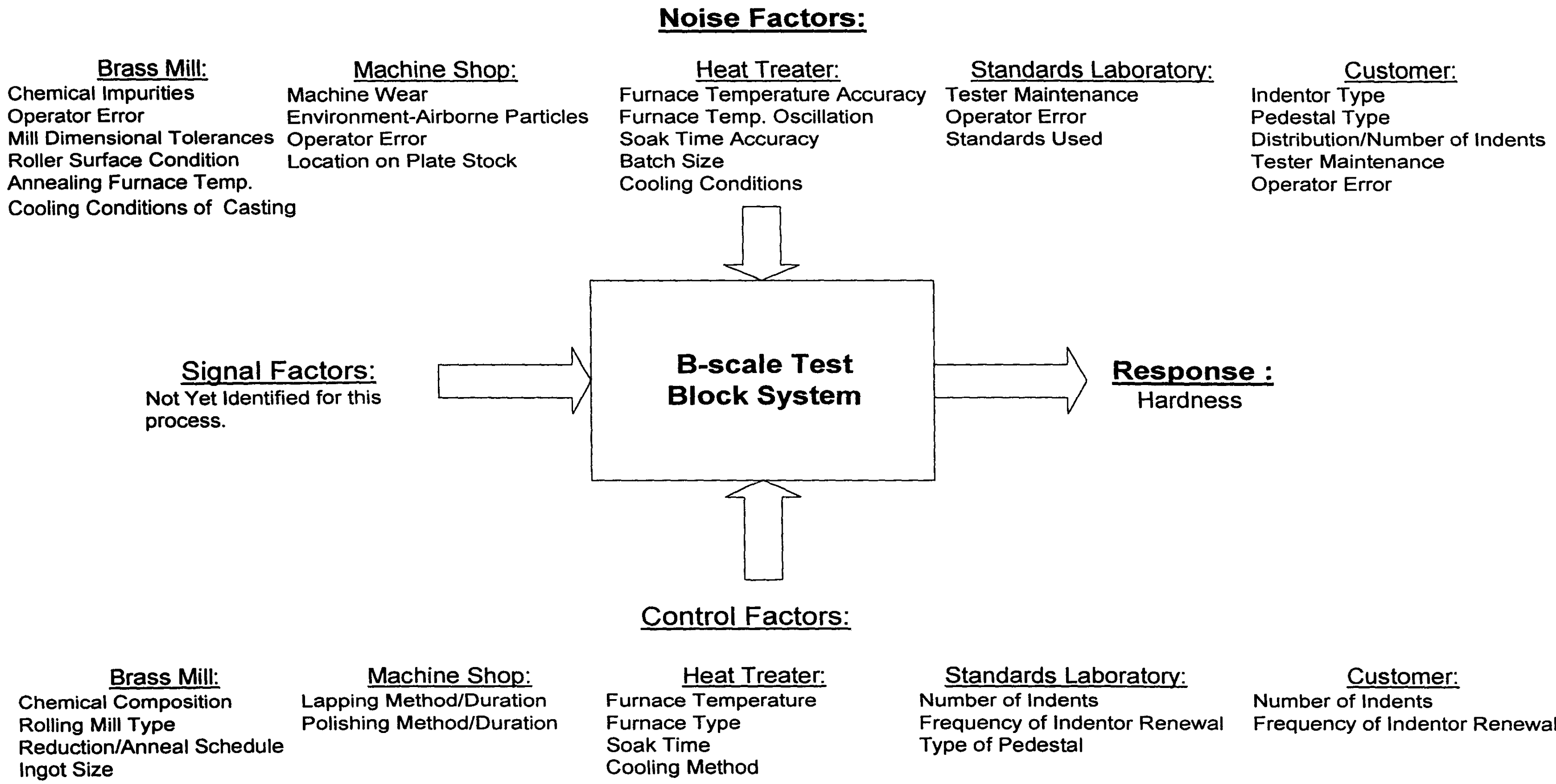
[22] Laudon, Hans J., "Statistical Characterization and Control of Variation in the Manufacture of Standard Test Blocks used for Rockwell Testing", Massachusetts Institute of Technology Masters Thesis, May, 1996.

Appendix I *P-diagram for B-scale Test Block Manufacturing Process*

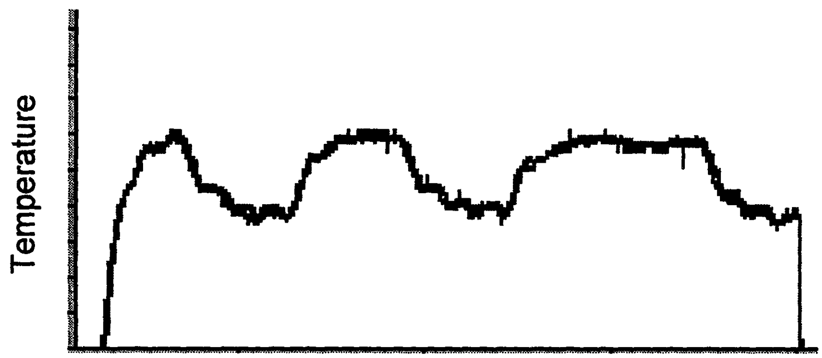


Appendix 1, P-Diagram for B-scale Test Block Manufacturing Process

Appendix II ***Noise Experiment Sample Thermocouple Data***

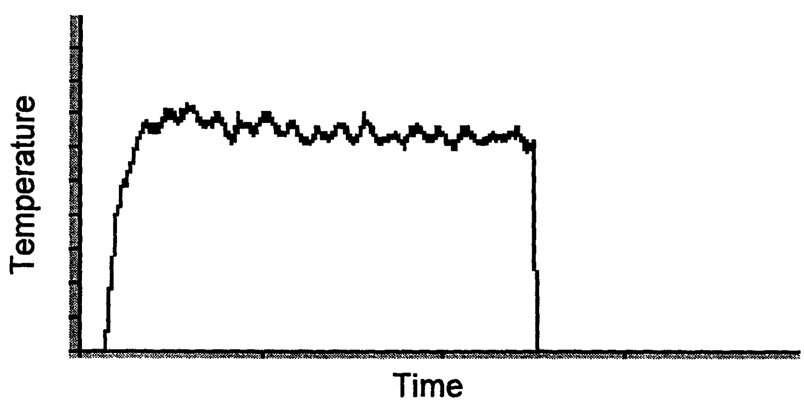
Run Number 1:

Temperature:	nominal +30 °F
Oscillation:	+/- 15 °F
Soak Time:	nominal +15 min.



Run Number 2:

Temperature:	nominal +30 °F
Oscillation:	+/- 3 °F
Soak Time:	nominal -15 min.



Appendix III *Noise Experiment Hardness Measurement Data*

	Block Serial Number											
	I50300	I50311	I50863	I50340	I50324	I50876	I60867	I60864	I50869	I50336	I50342	I50325
Hit No.	Rockwell B-scale Hardness Measurements											
1	61.62	64.15	60.31	62.02	62.51	61.96	60.78	60.68	61.71	59.11	61.71	61.25
2	61.63	64.29	60.10	61.99	62.54	61.72	60.67	60.48	61.80	59.26	61.67	61.13
3	62.35	64.44	60.41	62.12	62.49	61.98	60.84	60.64	61.48	59.04	61.64	61.28
4	61.77	63.82	60.05	61.86	62.50	61.75	60.90	60.61	60.92	58.84	62.05	61.12
5	61.76	64.21	60.27	61.96	62.34	61.73	60.96	60.62	61.68	59.25	61.53	61.24
6	61.93	63.57	60.09	61.92	62.73	61.77	60.76	60.42	62.09	58.46	61.95	61.32
7	61.53	64.08	59.54	61.95	62.38	61.42	60.56	60.16	61.89	58.90	61.53	61.38
8	62.13	64.48	60.21	62.12	62.47	61.76	60.60	60.95	61.71	59.04	61.77	60.93
9	62.10	64.32	60.18	62.20	62.38	61.63	60.83	60.66	61.61	58.87	61.69	61.26
10	61.52	63.88	60.01	61.86	62.45	61.69	60.92	60.83	61.68	59.27	61.83	60.97
11	61.59	64.14	59.81	62.13	62.58	61.78	60.49	60.57	61.88	59.09	61.72	61.19
12	61.79	64.12	60.04	62.00	62.65	61.70	61.15	60.70	61.59	59.13	61.67	61.38
Average	*61.81*	*64.13*	*60.09*	*62.01*	*62.50*	*61.74*	*60.79*	*60.61*	*61.67*	*59.02*	*61.73*	*61.20*
Std. Dev.	*0.27*	*0.26*	*0.23*	*0.11*	*0.11*	*0.14*	*0.19*	*0.20*	*0.29*	*0.23*	*0.15*	*0.14*
Range	0.83	0.91	0.87	0.34	0.39	0.56	0.66	0.79	1.17	0.81	0.52	0.45

L8 (2^{4-1}), Resolution IV Orthogonal Array:

Run	1 A	2 B	3	4 C	5	6	7 D
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

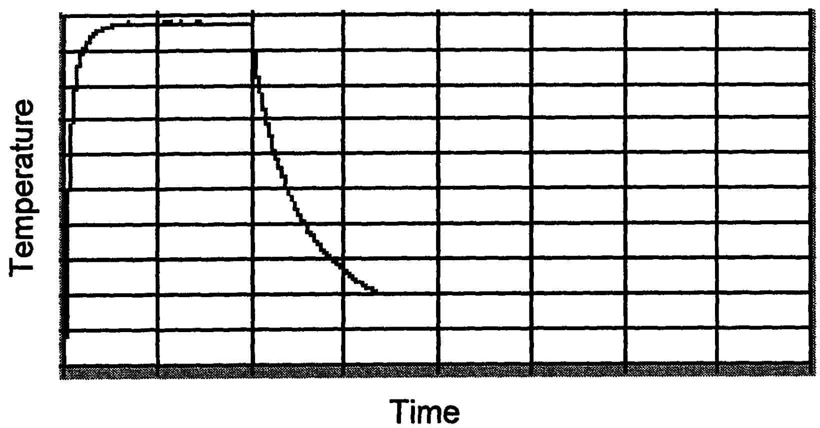
Interactions:
Column 3: 1 x 2
Column 5: 1 x 4
Column 6: 2 x 4

It is assumed that factor D has a negligible interaction with factors A, B, and C.

Appendix V Screening Experiment Sample Thermocouple Data

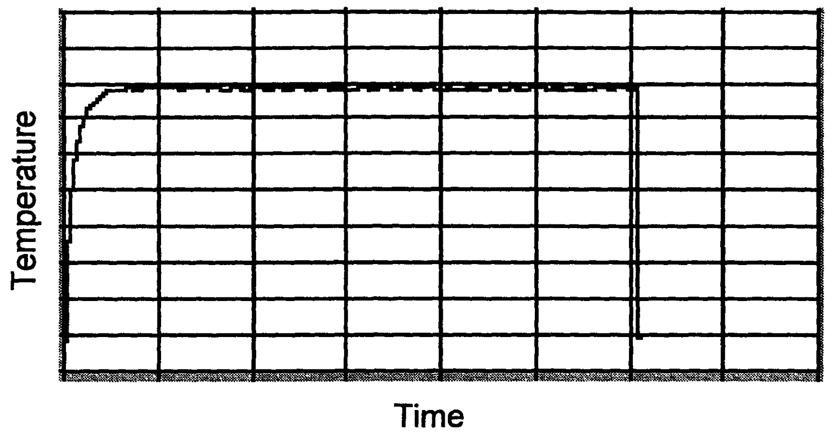
Screening Test 3B Temperature Profile:

Soak Temperature: nominal +100 °F
Soak Time: nominal - 30 minutes
Cooling Method: Slow
Secondary Heat Treatment: Yes



Screening Test 6A Temperature Profile:

Soak Temperature: nominal - 100 °F
Soak Time: nominal + 30 minutes
Cooling Method: Fast
Secondary Heat Treatment: No


Temperature
Time

Appendix VI *Screening Experiment Hardness Measurement Data*

Control Factor Settings:	
Run Number:	*1A and 1B*
Soak Temperature:	*nominal + 100 F*
Soak Time:	*nominal + 30 minutes*
Cooling Method:	*Slow*
Secondary Heat Treatment:	*No*

		1A				1B		
Block Serial No.:		**150862**	**150872**	**150345**		**150346**	**150860**	**150314**
Hit #:	1	48.22	45.65	46.70		45.79	45.49	46.42
	2	48.05	45.78	46.39		45.57	46.05	46.85
	3	47.96	45.65	47.25		45.55	45.86	47.50
	4	46.91	45.55	46.64		45.41	45.59	47.89
	5	47.76	45.63	46.34		45.29	45.70	47.86
	6	48.13	45.41	47.71		45.54	45.84	47.95
	7	48.68	45.55	46.69		45.64	45.94	49.12
	8	48.95	45.85	46.89		45.55	45.94	48.14
	9	48.23	45.83	46.84		45.51	45.84	47.73
	10	46.33	45.70	47.04		45.41	45.78	47.73
	11	49.91	45.40	47.62		45.31	46.07	47.70
	12	48.06	45.63	46.13		45.43	45.68	47.33
	Average	48.10	45.64	46.85		45.50	45.82	47.69
	Std. Dev.	0.91	0.14	0.49		0.14	0.18	0.67
	Range	3.58	0.45	1.58		0.50	0.58	2.70
			Run Grand Mean	46.86			Run Grand Mean	46.33
			Run Avg. Std. Dev.	0.51			Run Avg. Std. Dev.	0.33
			Run Avg. Range	1.87			Run Avg. Range	1.26
						Combined Mean:	46.60	
						Combined Avg. Std. Dev.	0.42	
						Combined Avg. Range	1.57	

Control Factor Settings:									
	Run Number:		*2A and 2B*						
	Soak Temperature:		*nominal + 100 F*						
	Soak Time:		*nominal + 30 minutes*						
	Cooling Method:		*Fast*						
	Secondary Heat Treatment:		*Yes*						
				2A				2B	
Block Serial No.:			**I50875**	**I50313**	**I50343**		**I50329**	**I50304**	**H50305**
Hit #:	1		48.20	47.01	49.05		45.47	47.89	46.48
	2		44.35	45.36	48.56		44.03	47.70	43.82
	3		43.64	48.77	47.99		43.38	47.60	43.40
	4		44.01	48.63	45.39		43.56	48.22	43.72
	5		45.47	46.90	46.78		45.41	46.89	45.08
	6		46.88	45.73	49.02		46.22	47.35	46.34
	7		46.93	45.29	49.17		45.62	47.71	46.63
	8		45.66	46.23	46.77		44.91	47.97	44.47
	9		43.43	46.40	46.91		44.27	47.94	43.63
	10		43.78	46.60	46.41		42.27	48.17	43.76
	11		46.44	47.50	47.93		43.85	47.47	44.34
	12		46.09	47.96	48.56		45.50	45.82	45.76
	Average		45.41	46.87	47.71		44.54	47.56	44.79
	Std. Dev.		1.56	1.17	1.23		1.17	0.66	1.22
	Range		4.77	3.48	3.78		3.95	2.40	3.23
				Run Grand Mean	46.66			Run Grand Mean	45.63
				Run Avg. Std. Dev.	1.32			Run Avg. Std. Dev.	1.02
				Run Avg. Range	4.01			Run Avg. Range	3.19
						Combined Mean:		46.15	
						Combined Avg. Std. Dev.		1.17	
						Combined Avg. Range		3.60	

Control Factor Settings:									
	Run Number:		*3A and 3B*						
	Soak Temperature:		*nominal + 100 F*						
	Soak Time:		*nominal - 30 minutes*						
	Cooling Method:		*Slow*						
	Secondary Heat Treatment:		*Yes*						
				3A				3B	
Block Serial No.:			**150321**	**150323**	**150857**		**150335**	**150309**	**150341**
Hit #:	1		55.67	58.30	59.13		56.60	57.08	59.14
	2		56.11	58.22	59.04		56.59	57.01	58.97
	3		55.81	58.10	59.09		56.60	57.82	58.94
	4		55.94	58.03	58.94		56.64	58.09	59.24
	5		55.59	57.91	59.22		56.38	58.37	59.27
	6		55.36	58.09	58.89		56.56	58.20	59.26
	7		55.22	58.43	58.47		56.76	57.37	59.02
	8		55.56	58.26	58.59		56.69	57.57	59.05
	9		55.43	58.27	58.92		56.63	57.73	58.96
	10		55.26	57.86	58.81		56.52	57.52	58.84
	11		55.42	57.72	59.04		56.55	57.63	59.23
	12		55.28	57.86	58.77		56.56	57.46	59.22
	Average		55.55	58.09	58.91		56.59	57.65	59.10
	Std. Dev.		0.28	0.22	0.22		0.09	0.42	0.15
	Range		0.89	0.71	0.75		0.38	1.36	0.43
			Run Grand Mean		57.52		Run Grand Mean		57.78
			Run Avg. Std. Dev.		0.24		Run Avg. Std. Dev.		0.22
			Run Avg. Range		0.78		Run Avg. Range		0.72
					Combined Mean:			57.65	
					Combined Avg. Std. Dev.			0.23	
					Combined Avg. Range			0.75	

Control Factor Settings:									
	Run Number:		*4A and 4B*						
Soak Temperature:			*nominal + 100 F*						
	Soak Time:		*nominal - 30 minutes*						
	Cooling Method:		*Fast*						
Secondary Heat Treatment:			*No*						
				4A				4B	
Block Serial No.:			**I50877**	**I50320**	**I50870**		**I50318**	**I50302**	**I50334**
Hit #:	1		60.99	59.45	58.82		61.87	60.26	59.04
	2		59.81	60.58	57.88		61.47	58.69	58.18
	3		58.89	59.48	58.24		59.86	59.69	59.55
	4		59.14	60.26	58.81		60.45	60.54	59.88
	5		60.00	59.63	57.67		63.01	59.71	60.45
	6		61.36	60.67	58.03		61.38	60.35	59.11
	7		61.09	59.75	58.07		61.26	59.85	59.03
	8		59.85	59.00	58.91		60.94	62.69	60.83
	9		58.68	60.00	58.08		60.15	63.06	59.42
	10		59.14	61.64	60.04		60.46	61.49	59.56
	11		59.27	60.35	59.79		63.29	62.88	59.47
	12		60.94	60.79	59.72		61.27	61.13	60.27
	Average		59.93	60.13	58.67		61.28	60.86	59.57
	Std. Dev.		0.95	0.73	0.81		1.05	1.41	0.72
	Range		2.68	2.64	2.37		3.43	4.37	2.65
			Run Grand Mean		59.58		Run Grand Mean		60.57
			Run Avg. Std. Dev.		0.83		Run Avg. Std. Dev.		1.06
			Run Avg. Range		2.56		Run Avg. Range		3.48
					Combined Mean:			60.07	
					Combined Avg. Std. Dev.			0.95	
					Combined Avg. Range			3.02	

Control Factor Settings:							
Run Number:	*5A and 5B*						
Soak Temperature:	*nominal - 100 F*						
Soak Time:	*nominal + 30 minutes*						
Cooling Method:	*Slow*						
Secondary Heat Treatment:	*Yes*						
		5A				5B	
Block Serial No.:		**150855**	**150868**	**150865**	**150879**	**150332**	**150326**
Hit #:	1	60.05	60.90	62.21	60.86	59.09	60.74
	2	60.11	60.85	62.27	61.43	59.01	60.75
	3	60.21	60.73	62.44	61.34	59.15	60.73
	4	60.27	60.95	62.70	61.16	59.05	60.93
	5	60.27	60.65	62.48	61.46	58.91	60.88
	6	60.41	60.53	62.50	61.55	58.67	60.52
	7	60.14	60.85	62.51	61.37	58.95	60.63
	8	60.25	60.74	62.50	61.40	58.90	60.86
	9	60.28	60.95	62.43	61.41	59.08	60.63
	10	60.24	60.79	62.40	61.44	58.88	60.73
	11	60.29	61.05	62.30	61.58	58.91	60.67
	12	60.41	60.85	61.96	61.42	58.79	60.44
	Average	60.24	60.82	62.39	61.37	58.95	60.71
	Std. Dev.	0.11	0.14	0.19	0.19	0.14	0.14
	Range	0.36	0.52	0.74	0.72	0.48	0.49
			Run Grand Mean	61.15		Run Grand Mean	60.34
			Run Avg. Std. Dev.	0.15		Run Avg. Std. Dev.	0.16
			Run Avg. Range	0.54		Run Avg. Range	0.56
					Combined Mean:	60.75	
					Combined Avg. Std. Dev.	0.15	
					Combined Avg. Range	0.55	

Control Factor Settings:									
	Run Number:		*6A and 6B*						
	Soak Temperature:		*nominal - 100 F*						
	Soak Time:		*nominal + 30 minutes*						
	Cooling Method:		*Fast*						
Secondary Heat Treatment:			*No*						
				6A				6B	
Block Serial No.:			**I50308**	**I50338**	**I50333**		**I50859**	**I50322**	**I50856**
Hit #:	1		62.70	63.52	65.11		63.02	62.76	62.23
	2		62.92	63.02	65.94		62.54	62.46	62.19
	3		62.49	63.04	64.08		62.87	62.80	62.22
	4		62.58	63.99	64.96		62.59	62.39	62.45
	5		63.60	63.31	65.46		62.43	62.64	62.20
	6		62.77	62.89	65.82		62.59	63.35	62.29
	7		62.54	63.64	66.15		62.52	62.67	62.08
	8		63.16	63.51	65.70		62.95	62.44	62.41
	9		62.87	63.07	65.28		63.10	62.62	62.59
	10		63.46	63.44	65.06		62.39	62.49	62.73
	11		63.31	63.87	65.46		62.45	62.68	62.07
	12		62.44	63.89	65.61		62.50	63.27	62.66
	Average		62.90	63.43	65.39		62.66	62.71	62.34
	Std. Dev.		0.39	0.37	0.55		0.25	0.31	0.22
	Range		1.16	1.10	2.07		0.71	0.96	0.66
				Run Grand Mean	63.91			Run Grand Mean	62.57
				Run Avg. Std. Dev.	0.44			Run Avg. Std. Dev.	0.26
				Run Avg. Range	1.44			Run Avg. Range	0.78
							Combined Mean:	63.24	
							Combined Avg. Std. Dev.	0.35	
							Combined Avg. Range	1.11	

Control Factor Settings:									
	Run Number:		*7A and 7B*						
Soak Temperature:			*nominal - 100 F*						
	Soak Time:		*nominal - 30 minutes*						
	Cooling Method:		*Slow*						
Secondary Heat Treatment:			*No*						
				7A				7B	
Block Serial No.:			**I50853**	**I50858**	**I50880**		**I50317**	**I50327**	**I50331**
Hit #:	1		62.42	62.49	61.81		61.81	62.04	62.34
	2		62.79	62.43	61.61		61.66	62.02	63.14
	3		62.48	62.27	61.66		61.56	62.02	63.10
	4		62.46	62.21	61.74		61.98	61.86	62.91
	5		62.46	62.09	61.66		61.58	61.20	62.84
	6		62.53	62.05	61.70		61.79	61.67	62.86
	7		62.59	62.30	61.61		62.19	61.63	63.02
	8		62.47	62.21	61.57		61.73	61.76	62.90
	9		62.48	62.12	61.62		61.90	61.86	62.79
	10		62.35	62.40	61.63		61.79	61.86	63.06
	11		62.61	62.34	61.53		61.74	61.79	63.01
	12		62.51	61.94	61.44		61.84	62.00	62.99
	Average		62.51	62.24	61.63		61.80	61.81	62.91
	Std. Dev.		0.11	0.17	0.10		0.17	0.24	0.21
	Range		0.44	0.55	0.37		0.63	0.84	0.80
				Run Grand Mean	62.13			Run Grand Mean	62.17
				Run Avg. Std. Dev.	0.12			Run Avg. Std. Dev.	0.21
				Run Avg. Range	0.45			Run Avg. Range	0.76
							Combined Mean:	62.15	
							Combined Avg. Std. Dev.	0.17	
							Combined Avg. Range	0.60	

Control Factor Settings:								
	Run Number:	*8A and 8B*						
	Soak Temperature:	*nominal - 100 F*						
	Soak Time:	*nominal - 30 minutes*						
	Cooling Method:	*Fast*						
	Secondary Heat Treatment:	*Yes*						
			8A				8B	
Block Serial No.:		**I50349**	**I50312**	**I50319**		**I50328**	**I50348**	**I50871**
Hit #:	1	62.15	64.22	63.14		64.17	66.03	63.26
	2	61.73	63.91	62.12		62.69	65.18	63.37
	3	61.98	62.60	61.75		63.20	65.69	62.83
	4	62.03	62.27	61.80		63.82	64.68	63.52
	5	62.00	63.34	61.67		64.33	64.88	64.17
	6	61.92	63.10	62.99		64.29	65.35	63.72
	7	61.98	62.78	62.54		63.64	65.84	63.71
	8	61.61	63.58	62.28		63.17	64.83	63.90
	9	61.45	62.76	61.34		63.92	64.95	62.72
	10	61.83	62.45	62.71		64.28	65.25	62.68
	11	62.05	62.78	61.82		64.49	65.36	62.76
	12	62.20	63.98	61.69		63.77	65.52	62.78
	Average	61.91	63.15	62.15		63.81	65.30	63.29
	Std. Dev.	0.22	0.65	0.58		0.56	0.42	0.52
	Range	0.75	1.95	1.80		1.80	1.35	1.49
			Run Grand Mean	62.40			Run Grand Mean	64.13
			Run Avg. Std. Dev.	0.48			Run Avg. Std. Dev.	0.50
			Run Avg. Range	1.50			Run Avg. Range	1.55
						Combined Mean:	63.27	
						Combined Avg. Std. Dev.	0.49	
						Combined Avg. Range	1.52	

Appendix VII Screening Experiment Mean and S/N Ratio Table

	Run 1			Run 2				
Run Number	Grand Mean	Grand Std. Dev.	S/N Ratio	Mean	Std. Dev.	S/N Ratio	Combined Mean	Combined S/N
1	46.86	0.51	5.85	46.33	0.33	9.63	46.60	7.74
2	46.66	1.32	-2.41	45.63	1.02	-0.17	46.15	-1.29
3	57.52	0.24	12.40	57.78	0.22	13.15	57.65	12.77
4	59.98	0.83	1.62	60.57	1.06	-0.51	60.28	0.56
5	61.15	0.15	16.48	60.34	0.16	15.92	60.75	16.20
6	63.91	0.44	7.13	62.57	0.26	11.70	63.24	9.42
7	62.13	0.12	18.42	62.17	0.21	13.56	62.15	15.99
8	62.4	0.48	6.38	64.13	0.5	6.02	63.27	6.20
						Average =	**57.51**	**8.45**

Calculations were performed on the data given in Appendix VI as follows:

Experimental Run:

$$S/N_{signed-target} = -10\log_{10}\left(S_{average}^{\ 2}\right)$$

where three test blocks are used per run with twelve measurements per test block:

$$S_{average}^{\ 2} = \frac{\left[S_{block1}^2 + S_{block2}^2 + S_{block3}^2\right]}{3}$$

and:

$$S_{block}^2 = \frac{1}{11}\sum_{i=1}^{12}(y_i - \bar{y}_{block})$$

and for any given test block:

$$\bar{y} = \frac{1}{12}\sum_{i=1}^{12} y_i$$

Appendix VIII Error Variance Calculations

	Run 1			Run 2						
Run Number	Grand Mean	Grand Std. Dev.	S/N Ratio	Mean	Std. Dev.	S/N Ratio	Combined Mean	Combined S/N	**Mean Error Variance**	**S/N Error Variance**
1	46.86	0.51	5.85	46.33	0.33	9.63	46.60	7.74	**0.14**	**7.15**
2	46.66	1.32	-2.41	45.63	1.02	-0.17	46.15	-1.29	**0.53**	**2.51**
3	57.52	0.24	12.40	57.78	0.22	13.15	57.65	12.77	**0.03**	**0.29**
4	59.98	0.83	1.62	60.57	1.06	-0.51	60.28	0.56	**0.17**	**2.26**
5	61.15	0.15	16.48	60.34	0.16	15.92	60.75	16.20	**0.33**	**0.16**
6	63.91	0.44	7.13	62.57	0.26	11.70	63.24	9.42	**0.90**	**10.44**
7	62.13	0.12	18.42	62.17	0.21	13.56	62.15	15.99	**0.00**	**11.81**
8	62.4	0.48	6.38	64.13	0.5	6.02	63.27	6.20	**1.50**	**0.06**
								Average =	**0.45**	**4.33**

Appendix IX ANOVA Tables

Mean Hardness				
Factor	Sum of Squares	degrees of freedom	Mean Square	F-Ratio
Soak Temperature	187.55	1	187.55	416.8
Soak Time	88.54	1	88.54	196.8
Time/Temp Interaction	70.54	1	70.54	156.7
Cooling Method	4.18	1	4.18	9.3
Secondary Heat Treat	2.48	1	2.48	5.5
Time/Cooling Interact.	0.36	1	0.36	0.8
Temp/Cooling Interact.	0.26	1	0.26	0.5
error	0.45	1	0.45	n/a

Hardness S/N Ratio				
Factor	Sum of Squares	degrees of freedom	Mean Square	F-Ratio
Cooling Method	44.7	1	44.7	
Soak Temperature	24.57	1	24.57	
Time/Temp Interaction	3.34	1	3.34	
Time/Cooling Interact.	1.20	1	1.20	
Temp/Cooling Interact.	0.68	1	0.68	
Soak Time	0.38	1	0.38	
Secondary Heat Treat	0.00	1	0.00	
error	1.08	1	1.08	