Improving the Polishing Process for Rockwell Hardness Test Block

By
Mohammad Imani Nejad

M.S. Mechanical
Tehran Polytechnic University, 1998

SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
Master of Engineering in Manufacturing

AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
September 2009

Signature of Author: ________________ Department of Mechanical Engineering
August 10, 2009

Certified by: ________________ Jung-Hoon Chun
Professor of Mechanical Engineering
Thesis Supervisor

Accepted by: ________________ David E. Hardt
Chairman, Committee for Graduate Students

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Mohammad Imani Nejad

Submitted to the Department of Mechanical Engineering on Aug 12, 2009
in partial fulfillment of the requirements for the Degree of
Master of engineering in Mechanical Engineering

Abstract

Inefficiencies in a Rockwell hardness test block manufacturing process were analyzed. The polishing stage was identified to be the bottleneck with a high reworking rate. An understanding based on the physics of polishing was the first step. Then a DOE analysis was implemented to find the optimum parameters of polishing process. A range of solutions were implemented and improvements were observed. Adding compliance, introducing two stages of polishing and using a different pad and slurry were key elements in improving the polishing process. Various quality control factors were assessed. Early analysis of those optimized parameters appeared promising; where the average polishing cycle times for brass and steel were reduced from 20 minutes to less than 2 minutes and 4 minutes, respectively. Meanwhile the quality of surface finish was improved significantly.

Thesis Supervisor: Dr. Jung-Hoon Chun
Title: Professor of Mechanical Engineering

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1.1 Introduction

This thesis is sponsored by Wilson Instruments, a division of **** Inc. It is focused on improving the productivity and throughput of the production line dedicated to manufacturing metal calibration test blocks used to calibrate Rockwell hardness testing equipment. A team of 4 members was formed to tackle the project. During our first month of work we visited the Norwood calibration and packaging facility, the Binghamton production facility and key outside vendors. We interviewed and observed as many people as possible involved with producing the test blocks. Throughout this process we noticed reoccurring themes and problems.

The later stages of the manufacturing line, polishing and lapping, have substantially higher rework rates. Both operators and management complained that cycle times are erratic. Parts are often scratched during polishing or lapping which often requires them to be sent back several steps in the sequence. The polishing and lapping processes are also very operator specific processes. Some operators are able to produce consistent, high quality parts while other operators struggle to produce any good parts. We concluded that the polishing and lapping processes were poorly understood and poorly defined. This thesis will focus on polishing process and attempt to reduce the cycle time as well as reworking rate. It also deals with the quality of the polishing of test blocks and other alternative solutions.

1.2 Company Background

Wilson Instruments was a pioneer in Hardness Testing equipment and standards. The company was founded by Charles H. Wilson. In 1920 Charles Wilson collaborated with Stanley Rockwell to produce the first commercially available Rockwell hardness testing machines. The Rockwell Hardness standard has become the prominent hardness testing standard for metals. Since their original success with Rockwell hardness testers, Wilson Instruments has continued to be a market leader in hardness testing with an expanded instrument line including Micro Hardness and Brinell hardness testing equipment.

1.3 Rockwell Hardness Test Background

The Rockwell hardness scale is defined by the indentation hardness of metals. There are multiple Rockwell scales. For this project, we are focused on the Rockwell-B (HRB) and Rockwell-C (HRC) scales. In order to determine the hardness of a material, an indentation test must be performed.

The Rockwell hardness test is an indentation test that uses a calibrated machine to apply a known force to a diamond or tungsten carbide sphere-conical indenter (under a specified procedure) and measuring the difference in depth of indentation. The hardness of a specimen can be measured in three simple steps. First the indenter is brought into contact with the specimen and a force $F_0 = 10\text{Kgf}$ is applied for a certain period of time. The depth of indentation is measured either by a dial or digital gauge. Then this force is increased at a specific rate to F_1 which can be 60, 100 or 150 Kgf according to the ASTM standard for HRA, HRB or HRC, respectively. After holding this force (F_1) for a certain time, it is released and the depth of indentation is measured. The Rockwell hardness, HR, is measured by formula [1]:

$$HR = 100 - \frac{h}{0.002} \tag{1}$$

The depth, h, in Eq. (1) is in millimeter. According to the ASTM standard (E18-08a), Rockwell hardness testing machine shall be verified on a daily basis by means of standardized test blocks. These test blocks are manufactured and calibrated in accordance with ASTM E 18-08 (Appendix A). The Rockwell test blocks provide an easy and inexpensive way to verify the machine. These blocks are used as a standard reference to verify the hardness tester.

Due to the destructive nature of the Rockwell indentation test, each time a calibration block is used, a small indentation is left on the block. This means that each block can only be used 100-200 times before it must be replaced. As a result, Wilson Instruments manufactures the calibration blocks in large quantities and sells them as consumables.

1.4 Manufacturing process

The Rockwell test blocks are circular discs approximately 64 mm (2.5 inches) in diameter and 6 mm (1/4" inch) thick. The Rockwell test blocks are made from two different materials to provide a full range of hardness. Cartridge brass is used for test blocks ranging from HRB30 to HRB90, while O-1 tool steel is used for harder materials up to HRC-60. The test blocks are physically identical, regardless of material, except for the varying hardness. However, the manufacturing processes are slightly different for each material. Figure 1 shows the manufacturing process of the Rockwell test blocks.

Wilson manufactures the test blocks at ***** machine shop in Binghamton, New York. The manufacturing process is as follows:

- Brass test blocks are rough cut from 9mm (0.350 inch) brass plates by water jet. Steel blocks are rough cut with a band saw from round bar stock. Both steel and brass cutting processes are outsourced and then shipped to the Binghamton facility.

- At the Binghamton facility a CNC lathe is used to cut the final diameter, face the blocks, and chamfer the edges. This is performed in two setups. The machined blocks are then roll stamped with a unique serial number on the circumference.

- The test blocks are then sent out for heat treatment. The blocks are heat treated to full hardness and then annealed down to the desired hardness level.

- When the blocks return from the heat treating facility they have a scaled finish. The blocks are quickly bead blasted to remove this surface. The blocks are then manually buffed to remove any sharps.

- The steel blocks are surface ground to ensure proper parallelism and flatness.

- All the blocks are lapped and polished to ensure proper parallelism, surface flatness, and surface finish. However during this study it turned out that lapping and polishing is done only for cosmetic purpose.

- After passing dimensional quality control, the blocks are sent to ***** Norwood facility.

- At the Norwood facility, the hardness of every block is tested and recorded. The blocks are then packaged and shipped out.

The total annual demand is 20,000 test blocks where 12,000 of them are for steel and the rest of them are for brass. The average lead time for either test block is almost one month.

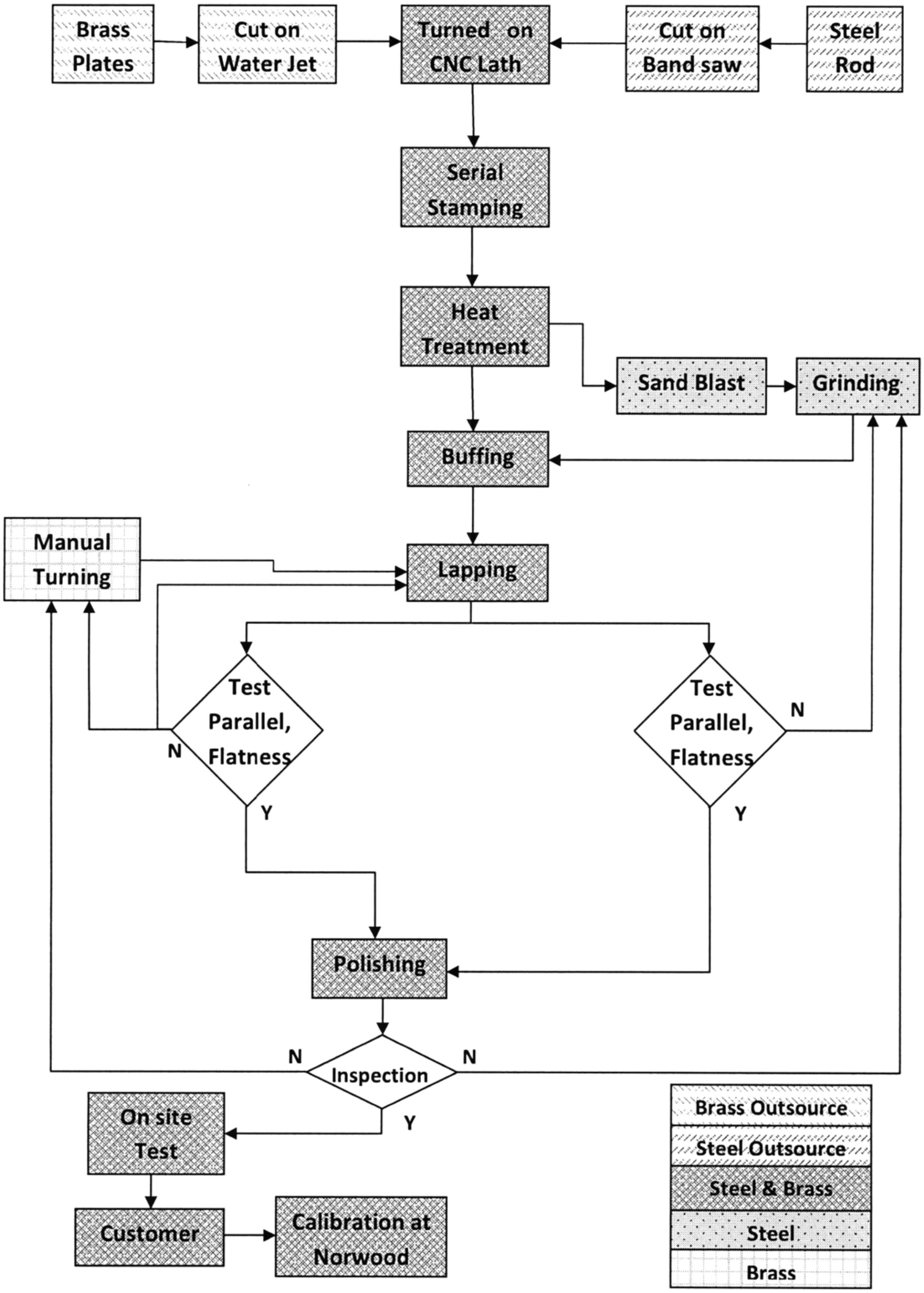

Figure 1- Manufacturing Process in Binghamton

1.5 PROBLEM STATEMENT

The manufacturing process for producing the test blocks has been suffering from different problems. Many of the steps involve high amounts of rework, parts often fail final QC, training new workers has been difficult as many of the processes are not properly understood or documented. Wilson would like to investigate the entire manufacturing process to find ways to streamline the process in order to improve productivity. After a number of visits at **** Company in Binghamton and focusing on the production process, we found out that improvement process can be identified as follows:

1- *Polishing*

Our primary findings showed that the polishing step is the main bottle neck for both materials. As it is shown in the Table 1, the production rate for polishing is far less than the other stages. Early analysis showed that this step is the main bottleneck for two reasons. First, a significant percentage of the test blocks are sent for reworking. This reworking is due to some scratches that are inspected visually. By examining 1 batch of each material (each batch consists of 200 test blocks), it was found out that most scratches have a radial pattern. Although there was a speculation that these scratches are due to raw material, it seems that since these scratches have the same shape and pattern, they are created either in the lapping or the polishing machine. The radius of scratches is within the radius of the lapping and the polishing path. Also the number and depth of scratches are proportional to the test block hardness. The softer block has more and deeper scratches. Accordingly this thesis is focused on the polishing process and will be discussed in next chapters in details. Second, the machine cycle time was long (20 minutes).

Table 1- Manufacturing process cycle time

Process	Production Rate for Steel(Block/hr)	Production Rate for Brass(Block/hr)
Turning & Stamping	18	33
Bead Blasting	50	-
Grinding	30	-
Buffing	30	67
Lapping	25	20
Polishing	16	10
Inspection	200	200

2- *Variations*

Variations were observed in the whole production line. Significant percentage of the final products was either scrapped or sent back for reworking just because of non-uniformity in hardness. Reworking was also a major problem between each stage that leads to a higher cycle time and extra cost. It appeared that reducing the variations is key element of increasing the throughput as well as cost reduction.

3- *Line balancing*

Line balancing is an effective tool to increase the throughput of the production line while reducing the man power and associated cost. Line balancing analysis can help the company to estimate the number of operators for different situations. It also reduces the unnecessary inventory and lead time. Our primary analysis showed that a line balancing analysis is necessary to provide us a big picture of whole process and see the effect of our improvements in each stage.

Chapter2. Polishing Process

2.1 Introduction

The primary objectives of this work were to reduce the polishing cycle time as well as reworking. The other goal was to increase the surface finish quality in order to enable the company to compete with the other manufacturers. A firm grasp of the physics of polishing is the key element to pinpoint the problems and specifically scratches that cause reworking. Thus in this chapter the theory of polishing is discussed for better understanding the process. However in this project experimental procedure namely DOE[1] will be used to optimize the polishing process in terms of cycle time, quality and yield. Polishing of ferrous and non-ferrous materials is different because of the physical and chemical properties; hence each material will be discussed separately.

2.2 Theory of Polishing

Polishing is the technology that has been developed along the history of humankind. This is a process that material is removed from a specimen to reach to a desired surface finish. The process of polishing has been applied to many different types of materials, ranging from metals, semiconductors and etc. The polishing technique is so useful to many industries because of its controllability over the precision. Surface finishes can be produced in the nanometer range with ultra polishing process, which makes the polishing so attractive.

Polishing is typically done at low speeds using either polishing cloths or pads, abrasive films, or specially designed polishing machines. Polishing with cloth or pads requires the free abrasive, which means that abrasive should be added separately to the system. Pad's material and structure are very critical to the final quality of specimen's surface finish. If flatness is primary concern, short nap pads such as nylon are suitable, but if the surface finish is more critical, then large nap such as Rayon or silk is used. However there are some pads that combine the best of both, to get the desired flatness and surface finish simultaneously [3].

Polishing removes materials little by little, to produce a mirror finish surface. For such a process, fine abrasives with grain size of micron and special pads are used. The abrasive particles are retained on the pad surface, and the workpiece surface is scratched microscopically. In this kind of machining the tool and workpiece are rubbed against each other under a certain pressure and the relative velocity. The material removal rate is proportional to the relative velocity, pressure and Preston constant. The Preston

[1] Design of experiment

constant includes all other parameters such as pad, slurry and etc. When a high degree of flatness is required the tool surface accuracy is important, because in deed the tool surface is transferred to the workpiece. Unlike the grinding or other machining process the surface flatness of polished specimen is determined only by the tool surface and not the tool motion.

The abrasive grains in slurry generate the chips during mechanical polishing action. When using slurry with bigger and harder particles or impurities than the primary abrasive grains or if it includes dust from room atmosphere, then there are unexpected deep scratches on the workpiece surface. It is important to note that these defects tend to increase in proportion with polishing time, because polishing machine employs a periodic motion. Therefore in order to get the mirror finish surface it is critical to use fine abrasive grains and preventing dust from contaminating [2].

In general the surface quality is determined by the following factors:

- Removing large particles and dust from slurry
- Washing workpiece and polishing jigs
- Using a dust free room
- Workers awareness about maintaining clean condition

The polishing process schematic is shown in Figure 2, where the test blocks are placed on the machine table and the excess material is removed by the slurry that is added to the pad.

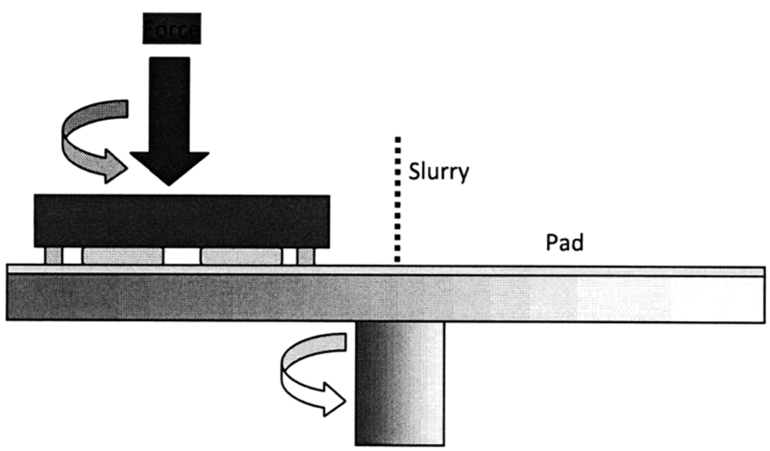

Figure 2- Schematic of Polishing

The linear material removal rate for polishing, MRR, is defined as [2]:

$$MRR = K_p P V_r \quad (2)$$

where K_p is the Preston constant, P is the normal pressure exerted to the specimen and V_r is the relative velocity between the specimen and rotary table. The Preston constant, K_p, is a function of different parameters such as pad, slurry and etc. This simple equation is important and helpful to understand the polishing process. According to Eq. (2), once the proper pad and slurry are selected, then we only need to optimize the process based on the other two parameters and time.

2.3 Polishing Machines

A polishing machine consists of a rotary table (plate) with adjustable speed. The workpiece is held by a customized jig and fixture which can be rotated by a separate mechanism or by the table itself. In order to have a uniform material removal it is essential that both table and specimen rotating at the same direction. The pressure can be applied to the specimen by means of a dead weight or pneumatic equipment. Since the pad or cloth should be changed frequently thus the pad is adhered to the main plate by special glue. Slurry is fed either manually or by automated device accordingly. Some polishing machines have a washing system that can be used to remove slurry at the end of polishing process. Figure 3 shows the polishing machine that is being used at ***** in Binghamton. This machine employs a simple mechanism for rotating the tool plate and test blocks. The tool plate is rotated by a 1hp, 1750 rpm induction motor that is connected to the plate by a 1:25 ratio gear box. Since there is no control on the speed, the rotational velocity is fixed at 70 rpm. The pressure is applied by placing some dead weight on the top of the test blocks. The operator adds slurry randomly in time with a manual sprayer.

Since the polishing machines have a relative motion mechanism, therefore uniformity of relative motion is essential for obtaining the smooth polished surface.

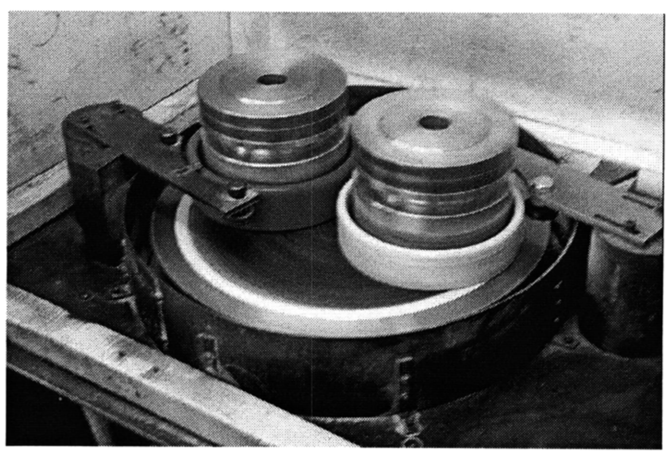

Figure3- Polishing Machine in Binghamton

The other polishing machine at ***** is located in Norwood facility made by Buehler which is shown in Figure 4. This machine accommodates a 200mm (8 inch) plate that has user controlled variable speed with ability to change the plate direction. The pressure can be controlled via a digital HMI as well. The jig and fixture for this machine is quite different from what is used in Binghamton. In Buehler polishing machine the test blocks are held and rotated by the head of the machine as well. Because of its controllability on the pressure, speed and time, this machine was used for some DOE analysis and some other tests like pad and slurry sensitivity analysis.

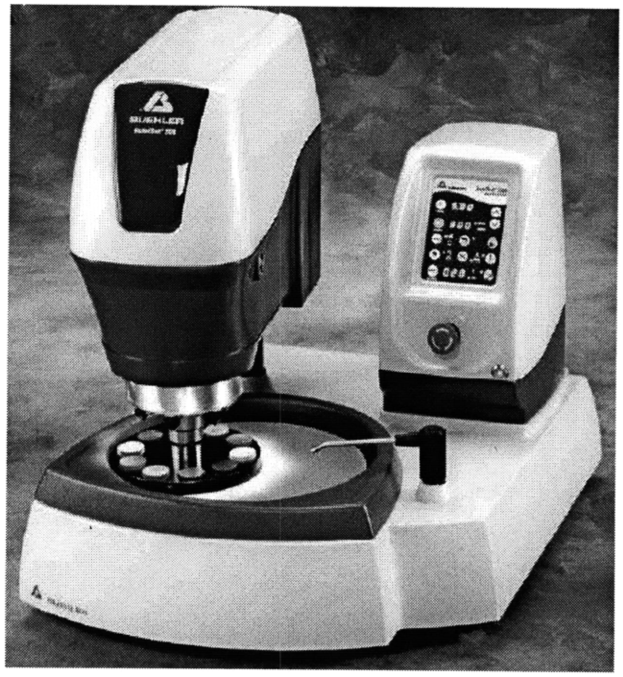

Figure 4- Polishing Machine at Norwood

2.4 Abrasive Types[2]

There are many different types of abrasive along with its associated pad or cloth to choose for polishing process; however they all can be categorized in to four main basic types:

- Silicon Carbide(SiC)
- Aluminum Oxide (Al_2O_3)
- Boron Carbide(B_4C)
- Diamond (C)

---

[2] Lapmaster

Selecting any of these abrasive depends on number of parameters such as: hardness, ultimate surface finish, material removal rate, chemical reaction and price.

SiC: SiC is hard and generally has a needle or blocky structure. SiC is used in many applications where rough lapping is required. It is seldom used for polishing or applications that require smooth surface finishes.

AL_2O_3: Al_2O_3 relatively hard and has a sharp, angular structure. Alumina is commonly used where fine surface finishes are required as it breaks down over time and gives excellent surfaces during lapping and polishing. Alumina is also relatively inexpensive.

B_4C: B_4C is harder than most other abrasives (excluding diamond) and has a blocky crystal structure. B_4C provides excellent removal rates and is typically used when fast removal with moderate surface quality is needed.

Diamond: Diamond is the hardest material known and has a sharp, angular structure. Diamond is extremely useful in lapping and polishing due to its removal rates and surface finishing qualities. Diamond can produce excellent surface finishes combined with high removal rates.

It should be noted that slurry grains are not uniform and contain different sizes. Figure 5 shows a typical polishing slurry grain distribution. As we can see for this particular slurry with grain size of 3 micron, there are some grains even with 4.5 micron.
Typical slurry consists of approximately 95% H_2O, 3% H_2O_2 and 2% Al_2O_3 particles by volume.

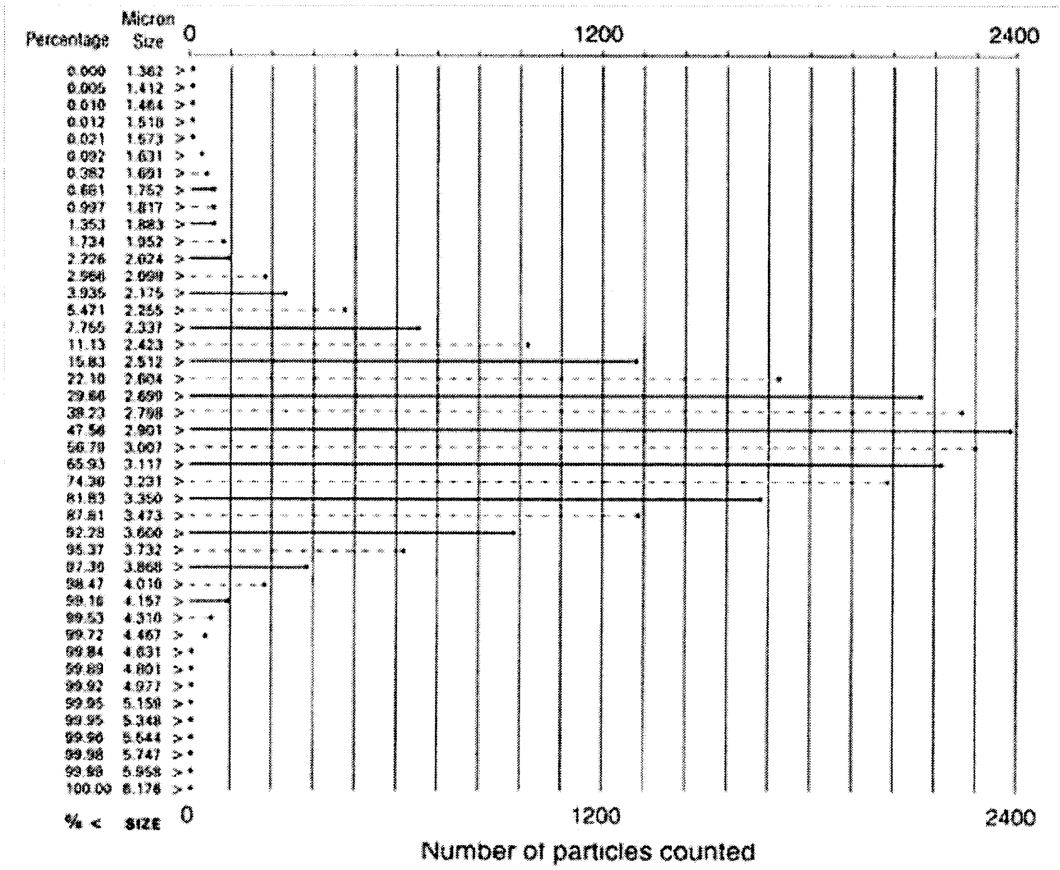

Figure5- Slurry grain distribution [4]

It is worth mentioning that before this study, Lapmaster slurry with grain size 5 micron and 3 micron were used for steel and brass, respectively.

Chapter3. Experimental Study

3.1 Identified Problems and preliminary analysis

As in all research, the first and maybe the most important step is to identify problems. Problems can come from the process itself or come from the previous stages. Thus it is important to examine carefully the whole production line and pinpoint the root cause of the problems. In this chapter, we deal with identified issues and their possible sources in polishing process.

3.1.1 lapping

As it is mentioned in Section 1.4, the ground test blocks meet the ASTM standard in terms of flatness, parallelism and surface roughness. Thus the lapping process is a non value added process to the whole system. Basically the lapping and polishing processes are done only for cosmetic purposes. Therefore if the polishing can be done without lapping the test blocks, then we can eliminate the lapping stage. It is also worth mentioning that the lapping process adds some unwanted scratches to the test blocks due to the fact that slurry is used for lapping process as well. These scratches lead to having more reworking and in turn a higher cycle time.

3.1.2 Reworking

Whenever the operator sees scratches on the test blocks, he or she send these test blocks for either lapping or even turning for brass and grinding for steel, depending on the depth of scratches. This reworking incurs extra charge to the company in many different ways. Thus it is very critical to reduce the reworking in polishing stage.

3.1.3 Jig

During work with the polishing machine, we observed that the slurry was accumulating behind the jig. As we can see in Figure 3, the jig is in contact with pad and it doesn't let the slurry go easily under the test blocks. This problem reduces the material removal rate or increases the cycle time.

3.1.4 Cleanliness

Cleanliness is a major problem in Binghamton facility. Any particle or dust in the slurry causes some scratches which lead to reworking. Not only the polishing room is not a clean room but also it opens to a corridor that goes directly to the main work shop.

Since the polishing machines for both steel and brass are located in the same room and the operator runs both types at the same time, it is quite possible that she or he spreads different slurries to each machine. For instance when the operator is running the polishing machine for steel, her hands are contaminated with slurry that is being used for steel; then she runs the machine for brass without washing her hands or changing the gloves. Under this condition, the slurry with larger grain size is mixed with the slurry for brass and causes scratches.

3.1.5 Pressure and Velocity

Since the material removal rate is proportional to pressure and velocity, Eq. (2), therefore it is important that we employ the right pressure and velocity. On the other hand the scratches are proportional to the amount of applied pressure as well [3]. Hence there is a tradeoff between the polishing cycle time and the likelihood of creating scratches. Although it seems that the decrement of material removal rate by decreasing pressure can be compensated by increasing the relative velocity; but it is not quite possible. This is because the Eq. (2) is not exactly linear (K_p), at least according to the tests that were being done in this work. In Chapter 4 it will be explained how the optimum pressure and speed were found by using DOE.

3.1.6 Proper pad and slurry (K_p)

The polishing rate and quality is highly sensitive to the pad and slurry that is being used. It seems that there have been a few attempts to try different slurries and pads at *****. As it will be discussed later in Section 3.2.4 the pad can have a great impact on cycle time reduction. It is worth mentioning that we tried some pads for brass that was recommended for ferrous materials; however it turned out to be very useful.

3.1.7 Torque

It is very important to note that all 4 machines in Binghamton have different driving system. The two machines that are being used for brass have smaller motor with improper gearbox. When those machines that are being used to polish the brass test blocks are loaded, the machine's noise and vibration increases drastically. Considering the fact that the test blocks can easily move inside the jig, extra vibration makes the test blocks vulnerable to scratches. Typically a DC motor is used to maintain constant torque regardless of load; however the motors for these machines are squirrel cage inductive AC motors. Thus the torque is not sufficient to produce a constant torque.

3.1.8 Washing Equipment

The polishing machines in Binghamton suffer from lack of washing equipment. This is important especially for brass test blocks which require washing away the slurry for final polishing step. When water based slurry like MasterPolish 2 is used for polishing, it is so helpful to have a washing system that not only cleans the test blocks but also the pad.

3.2 Process Improvements

The main objective of this project was to reduce the cycle time as well as reworking in the polishing process. The initial cycle time for polishing of both brass and steel test block was 20 minutes. This cycle time had been set based on the company experience along many years of production. The set up time for each run including cleaning and loading is almost 4 minutes. This cycle time could be even longer, if the operator found some minor scratches on the test blocks. To make matters worse, the deeper scratches cause reworking that increases the total takt time.

Although the cycle time depends on the pad, slurry, pressure and velocity directly; we should also bear in mind that these parameters can affect the cycle time indirectly as well. For instance, we know from Eq.(2) that increasing the normal applied pressure, decreases the cycle time, but at the same time it increases the likelihood of creating scratches[3], which increases the cycle time indirectly. Obviously it would be perfect, if the polishing process could happen in a clean room with high standards, but it is very expensive to make a particle free environment in a work shop like ***** in Binghamton. Therefore there is always a chance to have larger particle in slurry and thus we need to take that into account and try to resolve the problem with other technique.

3.2.1 Lapping

As it was mentioned in Section 3.1.2, the lapping is a non value added process. Thus, we tried to eliminate the lapping stage by modifying the polishing process. For this purpose, we polished a number of steel test blocks right after grinding. Depending on the test block's hardness, the polishing time can be increased by one to four minutes; however this extra time can be compensated by increasing the pressure and velocity.

3.2.2 Reworking

It was determined that by implementing the two stages polishing we can reduce the amount of reworking. In the first stage (rough polishing), the major scratches can be removed by applying high pressure. In the second stage (fine polishing), we can reach to the desired surface finish by using a new pad and slurry which is described in Section 3.2.4. By introducing this new method, we were able to remove the major scratches by polishing, instead of sending test blocks back to the other stages. This procedure is described in the recommendation section in Chapter 5.

3.2.3 Jig Design

During work with the polishing machine, we observed that the slurry was accumulating behind the jig. This problem was solved by designing a new jig which is shown in Figure 6. Several test blocks polishing were achieved under the same condition to verify the influence of the new jig. It appeared that new jig played a role to decrease the cycle time. Obviously it is because that slurry is important factor in material removal rate in polishing.

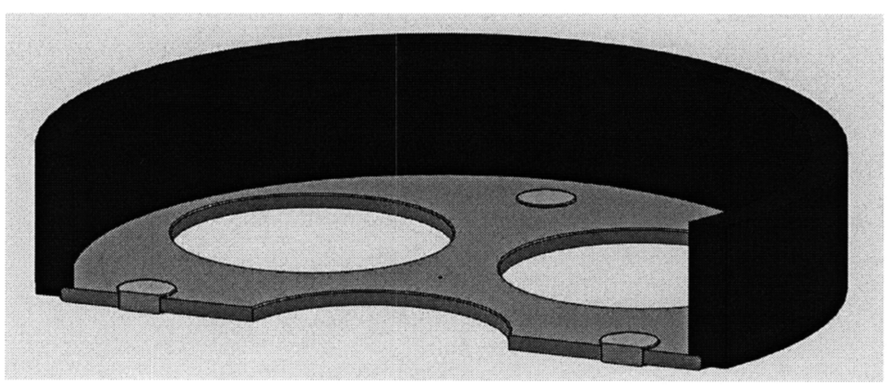

Figure6-Modified jig

Figure 7 shows a cross section of the modified part. As it is shown in the picture, by adding a counter board in the cage (blue part), the whole jig stands on the pad only on the three stands (yellow parts). Therefore there is a sufficient gap for slurry to go under the test blocks.

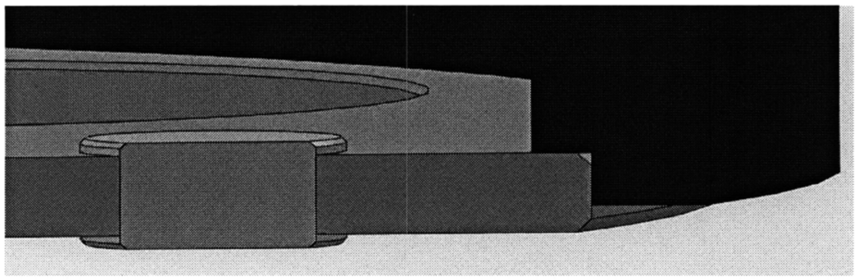

Figure 7- Modified section

3.2.4 Pad and Slurry

As we can see in Figure 5, the slurry with grain size of 3 micron has some larger particles. Therefore, if we increase the pressure, the test blocks are more vulnerable to being scratched by these larger particles. Meanwhile as it is shown in Figure 8, the slurry grain size has impact on the material removal rate. After running DOE which will be discussed in Chapter 5, the slurry for brass changed from 3 micron to 1 micron for the first stage. The Buehler MasterPolish 2 Colloidal Silica Suspension plus Hydrogen peroxide found out to be effective for the second stage. Buehler MasterPolish 2 Colloidal Silica Suspension is new slurry that is used for final polishing. The material removal rate for this slurry is considerably more than its competitors. This is shown in Figure 8.

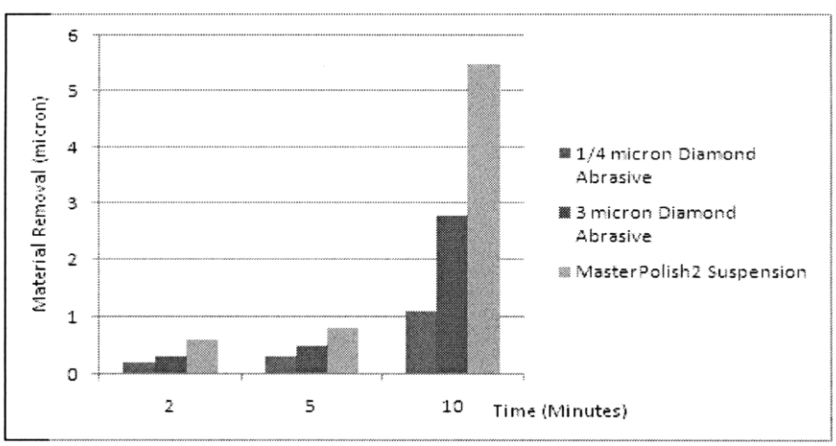

Figure8- MasterPolish 2 material removal [5]

As we can see in Figure 8, the material removal rate for MasterPolish 2 is much more than typical diamond slurries. Therefore it is a good choice for polishing the brass and soft steel test blocks. However there are some disadvantages associated with this slurry as well. This slurry is water based and when it is used for steel, the test block should be dried very soon, otherwise surface of the test blocks get stain. In addition, since it is mixed with hydrogen peroxide then it softens the surface of the test blocks which in turn make it more vulnerable to scratches. As we will discuss later in Chapter 5, this slurry will be used in the second stage for brass test blocks.

3.2.5 Steel Test Block

Although the steel test blocks are less vulnerable to scratches than the brass blocks, but still one of the main reason of long cycle time was minor scratches. To verify the sensitivity of creating scratches with applied pressure, a simple test was done by decreasing the force from 9 kg (20 lb) to 4.5 kg (10 lb). Not surprisingly, the material removal rate was decreased drastically but the good news was scratches decreased too.
To address this issue, a simple modification was done with an idea to add some flexibility to the system. As it is described in Section 2.3 the polishing machine consists of a rigid rotary plate that polishing pad is adhered on its top. The normal pressure is applied directly by adding some dead weights on the top of test blocks. In other words there is no flexibility in the contacting area. Figure 7 shows how adding flexibility can help reducing the amount of scratches. The flexible pad deforms as a larger particle touches the block surface and prevents the surface of being scratched; however it is very important to find the pressure limit. The optimum pressure which will be found by DOE enables us to decrease the cycle time as well as likelihood of creating scratches.

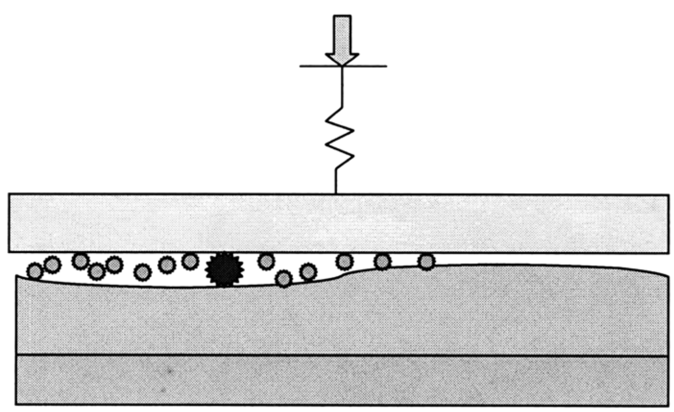

Figure 9- Polishing schematic

To add the flexibility, a rubber pad was added to the beneath of the polishing pad. By adding this rubber pad or in other words adding flexibility, we minimized the effect of existing particles. Fortunately, with such a simple modification, the polishing cycle time for steel blocks was reduced to 5 minutes or the production rate was 4 times faster than before. The production has been continuing for almost three month and according to the operator, she has seen even less reworking. Unfortunately since we were not in Binghamton for the whole project time, the amount of reduction in reworking has not been quantified. Although the three month production is not enough to prove the new methodology but it seems to be promising!

3.2.6 Brass Test Block

In general, the non-ferrous metal polishing is more challenging, not only because they are softer, but also due to their metallurgical structure and chemical properties. Polishing the brass test blocks in Binghamton is not an exception too and there is more associated reworking than the steel test blocks for the same reasons. In exploratory experiments, it was found out that polishing brass test block is highly sensitive to the pad. Although the polishing pad that was already being used, was recommended by Buehler, but in order to find out the sensitivity we used a Nylon pad (that was already being used for steel). The result was quite surprising; the material removal rate increased drastically however there were consistent scratches on the test blocks. As a result, it seemed to be logical to use Nylon pad for polishing brass test block and try to eliminate or decrease the scratches by different factors such as pressure, slurry and etc.

At this point, it was also reasonable to try the two stage polishing process for brass instead of a single stage. There were several reasons for doing so. First of all, adding extra stage enables us to use different slurry and pad with different pressure which gives us more flexibility. In second stage we can use low grain size slurry which provide much higher quality and enable us to remove the minor scratches from previous stage. Secondly, by using rough polishing in the first stage we can prevent of sending those test block with deeper scratch either to lapping or turning. This in turn helps making fewer non uniform parts, because as it was described earlier the turning process after heat treatment can deteriorate the hardness uniformity. The other advantage of this method is that we can have high force polishing in the first stage to increase the material removal rate and a low force polishing stage to remove the minor scratches. The main disadvantage of this method is adding an extra setup time for second stage.

After implementing the two stages polishing, the test block quality was remarkable. The second stage pad was Buehler TexMet and the slurry was Master met 2 suspension Buehler. As we will see in Chapter 4 the first stage cycle time reduced to only one minute and the second stage cycle time was less than one minute too. The extra cleaning and setup time was almost 4 minutes.

However, the good news is that after implementing DOE analysis and production of 96 parts, only fewer than 10 percent of the brass test blocks, needed second stage polishing. Considering the fact the Instron is going to run Tier 2 products for test blocks; it is also possible to sort high quality test blocks for Tier 1 and the rest for Tier 2.

Chapter4- Process Optimization

4.1 Design of Experiment

Most manufacturing process and improvements consist of several different variables. These variables can be either controllable or uncontrollable that can affect the design. Design of experiment (DOE) is a series of tests that is being achieved by means of changing controllable variables in order to find the optimum operating point. Along the way, we are interested in determining which variables are the most influential and what condition minimizes the effect of uncontrollable parameters.

DOE is a powerful engineering tool for improving manufacturing process. In this project we will use DOE to implement the following goals:

- Reduce variability
- Reduce cycle time
- Improve quality
- Reduce reworking
- Reduce overall cost

4.2 Factorial Design

Since we have several parameters of interest, factorial design is suitable for our application. In factorial design, all parameters are varied simultaneously to test all possible combinations of different factors. There are several advantages of factorial design in comparison with one factor variation at a time. First, it is less time consuming which in turn reduces the cost of analysis and improvement. Secondly with implementing factorial design, we are able to detect any possible interactions between factors [6]. Although it seems that there is no interaction between above aforementioned parameters, it would be worthwhile to test it.

We can summarize the DOE for our polishing system as shown in Table 2.

Table 2-Factorial design factors and levels

Material	Factors	Levels	Replicates	Run
Steel	4	2	Steel:12	$2^4 = 16$
Brass	5	2	Brass:18	$2^{5-1} = 16$

Pressure, velocity, time, slurry and pad were the inputs where yield and surface roughness were output of the DOE analysis.

The analysis of variance (ANOVA) is another key tool in factorial design process which enables us to find the level of significance of each factor. In this discussion we don't provide the theory of ANOVA analysis, and instead a commercial software was used to generate an ANOVA table and eventually a Pareto chart to find the level of significance of each factor.

4.3 Yield

The main objective of polishing at Instron like any other manufacturing process is to produce the test blocks that meet required specifications. However the variability inherent in polishing can lead to some scratches which cause painful reworking. The presence of such a disturbance which leads to test blocks rejection, is quantified by the yield. Obviously the yield is the most important factor for the company in terms of both cost and utilization.

Since there is no standard or criteria for accepting or rejecting test blocks in terms of the number or shape of scratches, we use the same convention that is already used by the operator. The judgment of rejecting or accepting a test block in terms of scratches is based on the visual inspection. The operator inspects the test block carefully for scratches that are visible.

Fortunately we were able to quantify the quality of surface roughness and set a criterion. As we discussed earlier the required surface roughness is $12\mu in$ $(0.3\mu m)$ according to ASTM standard; however the company policy is to polish the test blocks as best as they can only for cosmetic purpose. In order to quantify the accepted quality of shininess or achievable one and consider that as our target in DOE analysis, we can measure the surface roughness for a number of test blocks that already passed the QC. The average roughness for 10 random brass test blocks was $3\mu in$ $(0.07\mu m)$. Thus in our DEO analysis we can set the target surface roughness as R_a $equal\ to$ 1 μin (0.02 μm). This insures the quality improvement.

4.4 Experimental procedures

Although the major problems were solved by focusing on the physics behind the polishing, but eventually an experimental tool was used to optimize the polishing parameters. All experiments were under a typical daily condition, in order to simulate the real production. The main purpose for doing so was to minimize the effect of the uncontrollable parameters and finding the optimal factors accordingly.

In order to make sure that these tests include the human error as well; half of these tests were done by operator. The test blocks were chosen from different batches to insure that material and manufacturing variations from previous stages included.

Unfortunately, the machine's speed was limited to 70 rpm. It was determined that cycle time could be even less, if we were able to increase the speed. The polishing machine in Norwood was used later to verify this fact.

4.4.1 Steel

According to Eq. (2) and physics behind the polishing process, four factors were chosen at two levels as shown in Table 2. In a full factorial design, 16 tests with 12 replicates for each run were conducted to optimize the overall yield. The low and high levels of these factors were determined based on the previous experiments that were conducted to pinpoint the associated problems.

Table 3-Full factorial design for steel

Run Order	Slurry (μm)	Pressure (lbs)	Velocity (rpm)	Time (min)	Steel Yield%
1	1	15	40	3	8
2	3	15	40	3	16
3	1	30	40	3	25
4	3	30	40	3	16
5	1	15	70	3	30
6	3	15	70	3	33
7	1	30	70	3	87
8	3	30	70	3	83
9	1	15	40	6	30
10	3	15	40	6	33
11	1	30	40	6	83
12	3	30	40	6	75
13	1	15	70	6	87
14	3	15	70	6	87
15	1	30	70	6	91
16	3	30	70	6	87

After conducting the tests summarized in Table 3 and collecting the required data, commercial package was used for analysis. The results are shown in Figure 10 through 15. In Figure 10, Pareto chart, the ANOVA results are presented in a graphical form for simplicity. The Pareto chart of the effects is used to determine the magnitude and the importance of an effect, based on ANOVA results. Figure 10 displays the absolute value of the effects of each term. A reference line is drawn based on the Type I[3] error and any

[3] Type I error is the probability that ANOVA null hypothesis is rejected.

effect that passes this reference line is potentially important. The absolute value of the effect, determines its relative strength. The higher the value means the greater the effect on the response.

Not surprisingly the most significant factors for steel are velocity, time and pressure. However with Type I error=0.05, α, the interactions are the next significant factors. Further tests were implemented to verify the interactions and it turned out to be consistent. The importance of pressure and slurry interaction is one of the useful results that can be deduced from Figure 10. For slurry with grain size of 3 micron, increasing the pressure causes yield reduction.

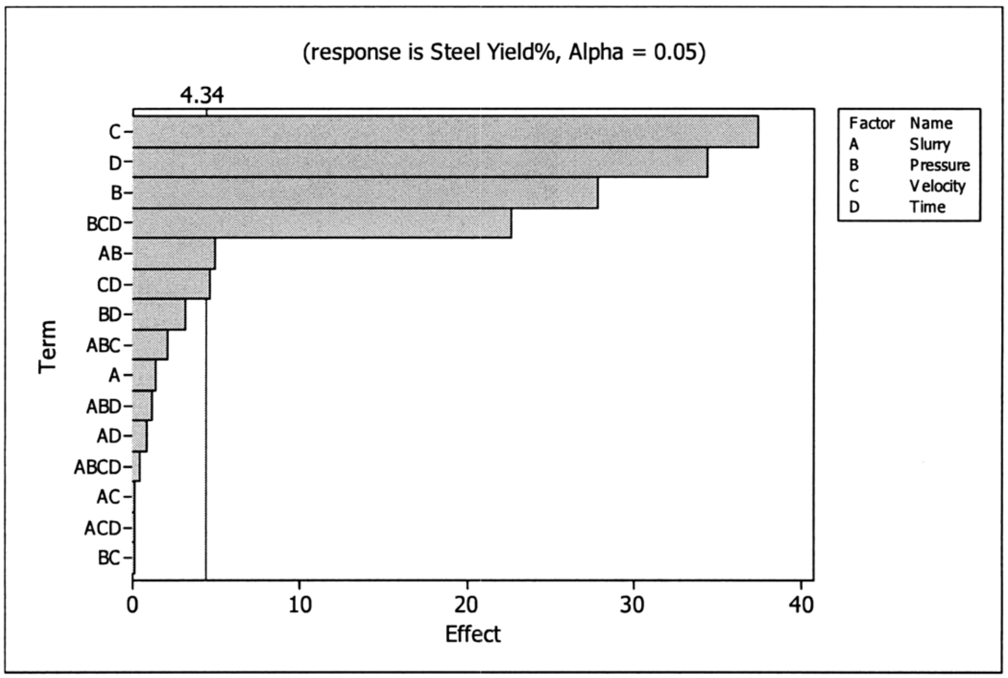

Figure 10- Pareto chart for steel yield

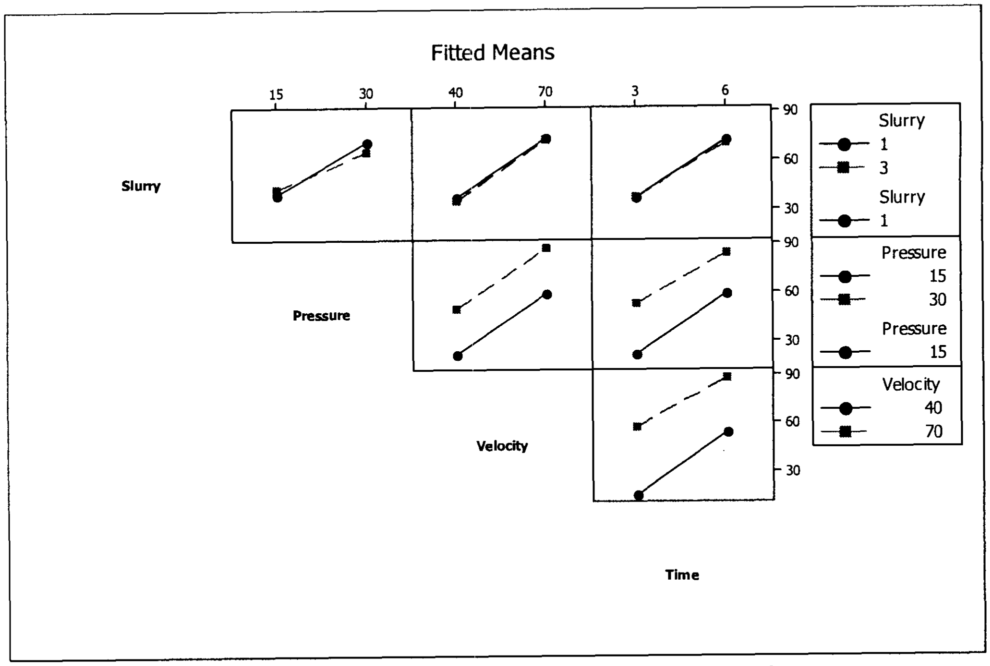

Figure11- Interaction plot for all factors (steel yield)

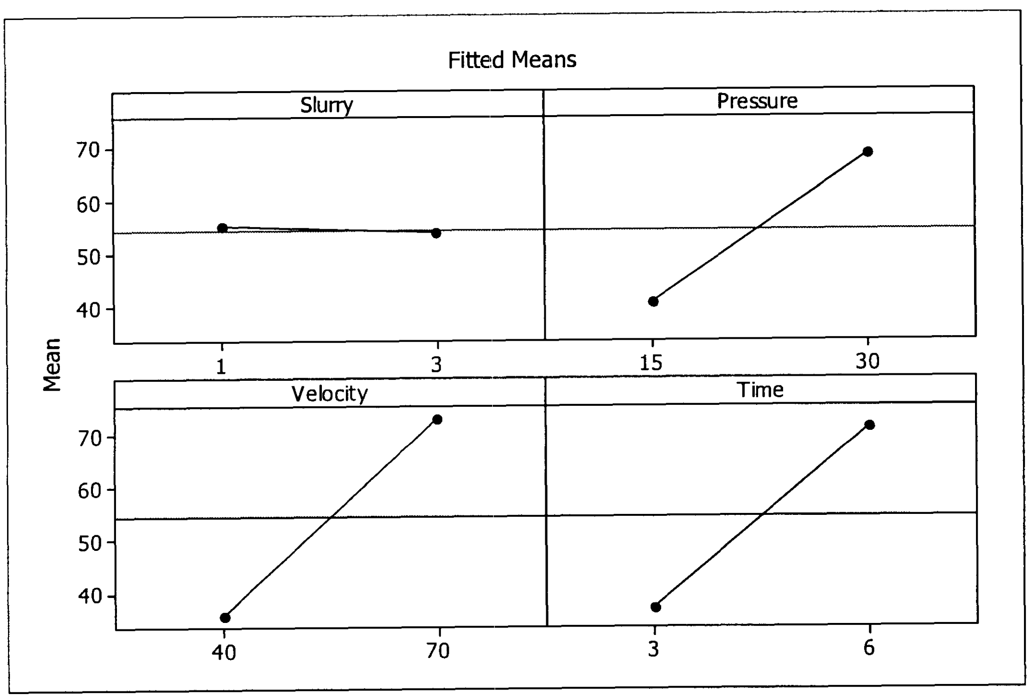

Figure12- Main effects for all factors (steel yield)

Figures 11 and 12 also show the interaction between factors and main effects of each factor on the yield. These graphs support Eq. (2), where the pressure and velocity are the most significant parameter in polishing and we can ignore their interactions.
Figures 13 and 14 show the contour and surface plot for the yield. Although the software has an option to find the optimum point with different linear programming technique; in this case it is very easy to find the optimum point from these graphs. Apparently the optimum point for the steel polishing can be found in Table 4.

Table 4- Optimum factors for steel polishing

Pressure Kg(lbs)	Velocity (rpm)	Time (Minute)	Slurry (Micron)
13.5(30)	70	5	1

One of the most important conclusions that can be deduced from Figure 14 and 15 is that, by either increasing the velocity or pressure, we are able to reduce the cycle time. Since the polishing machine in Binghamton was limited to only 70 rpm therefore a special jig shown in Appendix B was designed to polish the Rockwell test blocks with brand new Buehler machine at Norwood. The results were as we expected and it turned out the cycle time could be reduced to 3 minutes if the equivalent speed could be 120 rpm. This also shows that Eq. (2) is not linear as a function of speed; however it means that by changing the gear box of the polishing machine in Binghamton the cycle time can be reduced further. Pressure increment found out to be effective as well, but as we discussed in Chapter 3 the likelihood of having scratches increases significantly [3].

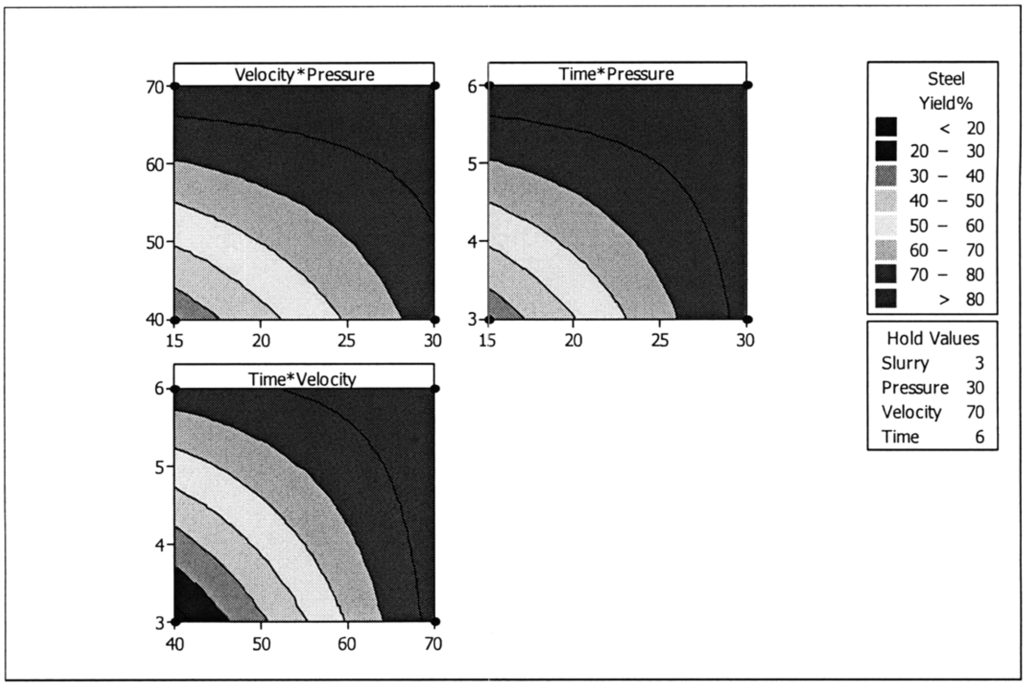

Figure 13- Contour plot for all factors for steel yield

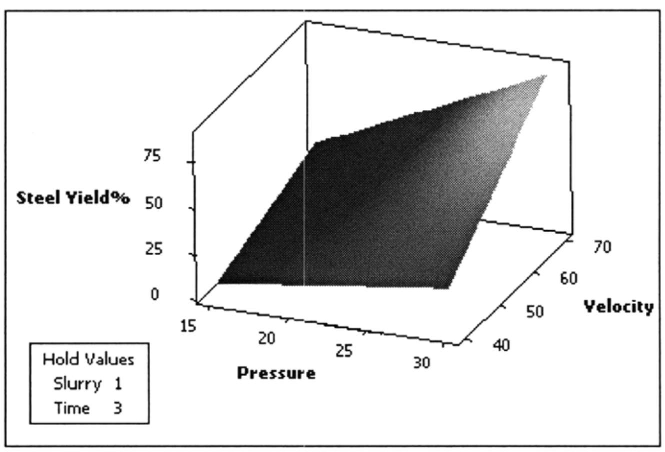

Figure14- Surface plot of Steel yield% vs. Velocity, Pressure

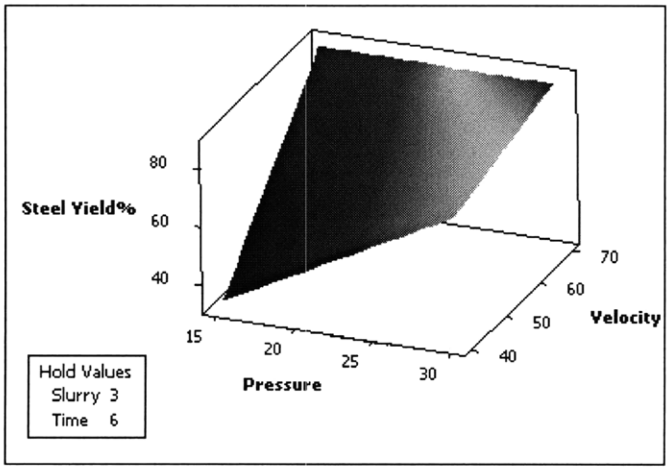

Figure 15- Surface plot of Steel Yield% vs. Velocity, Pressure

By comparison of Figures 14 and 15, one can see the effect of slurry grain size on yield. As we can see, the yield is increased by increasing the pressure and velocity when the slurry with grain size of 1 micron is used. However this is not true for slurry with grain size of 3 micron. This is actually the proof of what we discussed earlier in Chapters 2 and 3. According to Figure 5 when we use 3 micron slurry, there are some particles with almost 5 micron diameter as well. Therefore by passing the pressure limit, the test blocks are more vulnerable to being scratched by larger particles and the yield decreases. By adding a center point to the DOE, we could verify the pressure limit.

After conducting more experiments, we found out that it is even possible to reduce the cycle time to 4 minutes with acceptable quality. The DOE results were for steel test blocks with HRC>30; however for very soft steel it is better to use a second stage polishing. The final results are given in Chapter 5.

4.4.2 Brass

The polishing of non ferrous materials is more challenging in comparison with ferrous one [3]. This is not only because they are softer but also it is due to their chemical properties as well. In explanatory experiments it was found out that brass polishing is very sensitive to pad and slurry. Thus for brass DOE analysis, five factors were chosen at two levels as shown in Table 5. For the sake of time and cost; fractional factorial design with 16 tests and 18 replicates for each run were conducted to optimize the overall yield. Even without doing any analysis it is very obvious that brass polishing is highly sensitive to pad and time. Since the brass polishing behavior was different from steel and our expectations, 18 replicates were chosen for more consistency.

Table 5- Fractional factorial design for Brass

Run Order	Pad	Slurry (μm)	Pressure (lb)	Velocity (rpm)	Time (minutes)	Brass Yield %
1	Met	1	15	40	10	0
2	Nylon	1	15	40	2	16
3	Met	3	15	40	2	0
4	Nylon	3	15	40	10	8
5	Met	1	27	40	2	8
6	Nylon	1	27	40	10	8
7	Met	3	27	40	10	50
8	Nylon	3	27	40	2	75
9	Met	1	15	70	2	0
10	Nylon	1	15	70	10	0
11	Met	3	15	70	10	25
12	Nylon	3	15	70	2	75
13	Met	1	27	70	10	75
14	Nylon	1	27	70	2	91
15	Met	3	27	70	2	8
16	Nylon	3	27	70	10	0

Although the nylon pad is not recommended for brass by its producer "Buehler", in early experiments it was found out that the nylon pad has an impact on brass removal rate and quality. For this reason, nylon pad was an option in DOE analysis for brass polishing and ultimately it turned out to be the best pad in terms of quality and yield. As we can see in Figure 16, surprisingly the pad-time interaction is the most significant factor for brass polishing. Further experiments were conducted to verify this phenomenon and it turned out to be consistent.

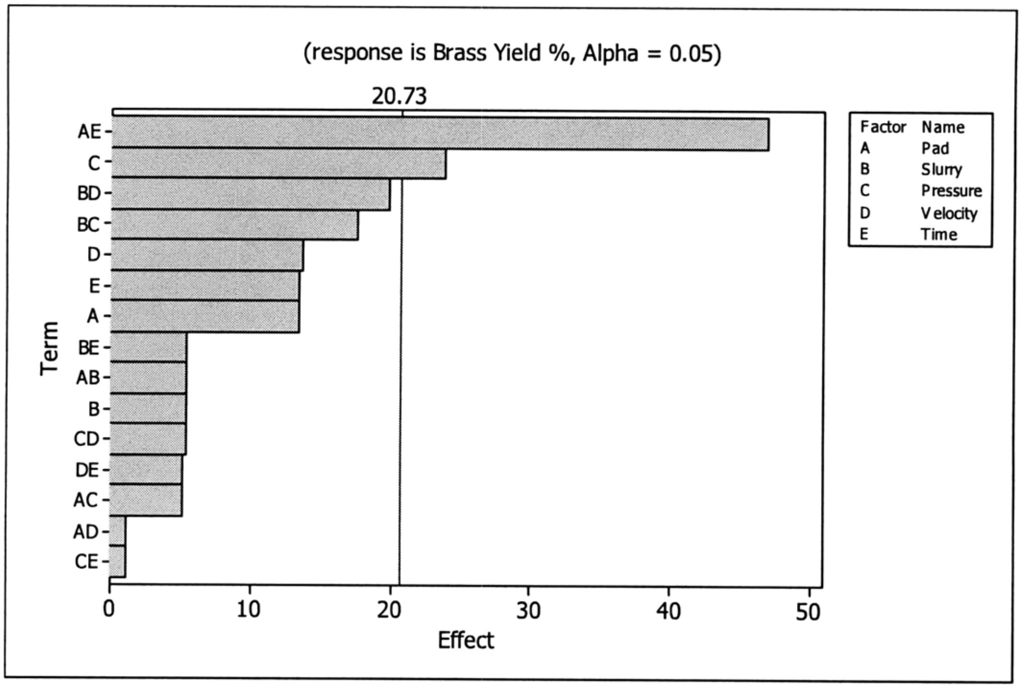

Figure 16-Pareto Chart for Brass yield

Unlike the steel, we can see major interactions between different factors for brass in Figure 17. The most important one is the interaction between time and pad and specifically for nylon pad. It was determined that the nylon pad can reduce the cycle time drastically but there were always some minor scratches consistently. After running the DOE, fortunately it was found out that by reducing time to almost 1 minute we can get rid of these scratches with remarkable yield percentage. Since the reduction in cycle time from 20 minutes to 1 minute was significant, therefore it seemed to be logical to add another step for removing the minor scratches for those rejected test blocks. This stage was also done successfully which will be discussed in recommendation section in Chapter 5.

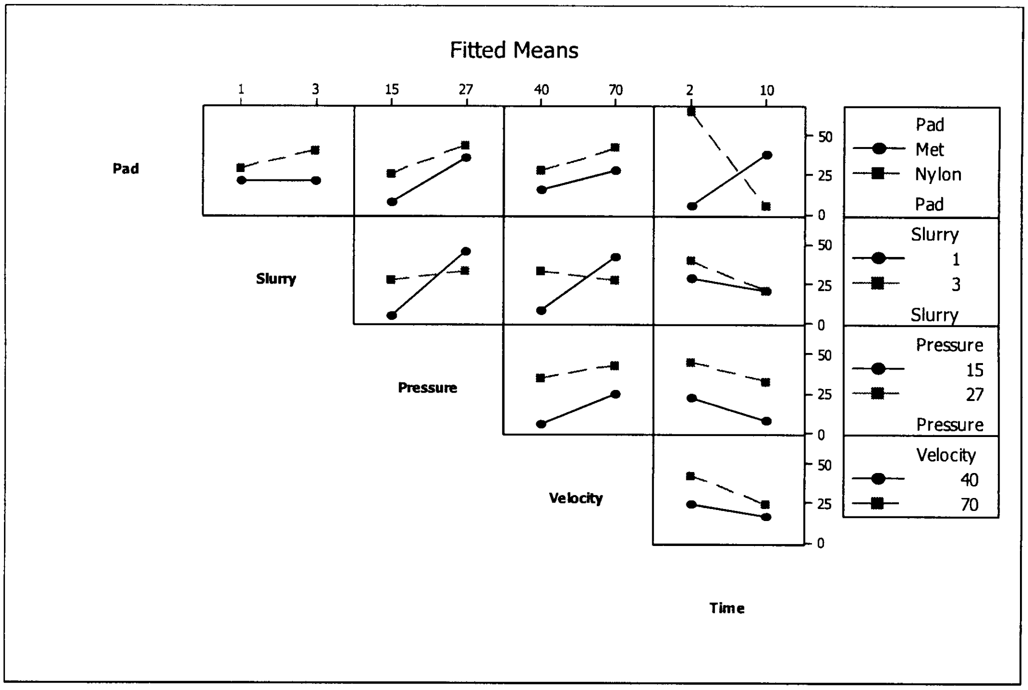

Figure 17- Interaction plot for all factors (Brass yield)

Figure 18 shows the main effect of different factors on brass polished test blocks yield. The main factors for brass test blocks, just like as steel, are pressure and velocity; however unlike the steel, the polishing time has a different effect on the yield. As we can see in Figure 18, the yield decreases significantly by increasing the polishing time from 2 minutes to 10 minutes.

In these experiments, the aluminum dioxide was used for slurry; however diamond was used in a few tests after DOE analysis, in order to see any chemical interactions. No considerable differences were observed by using the both types of slurries.

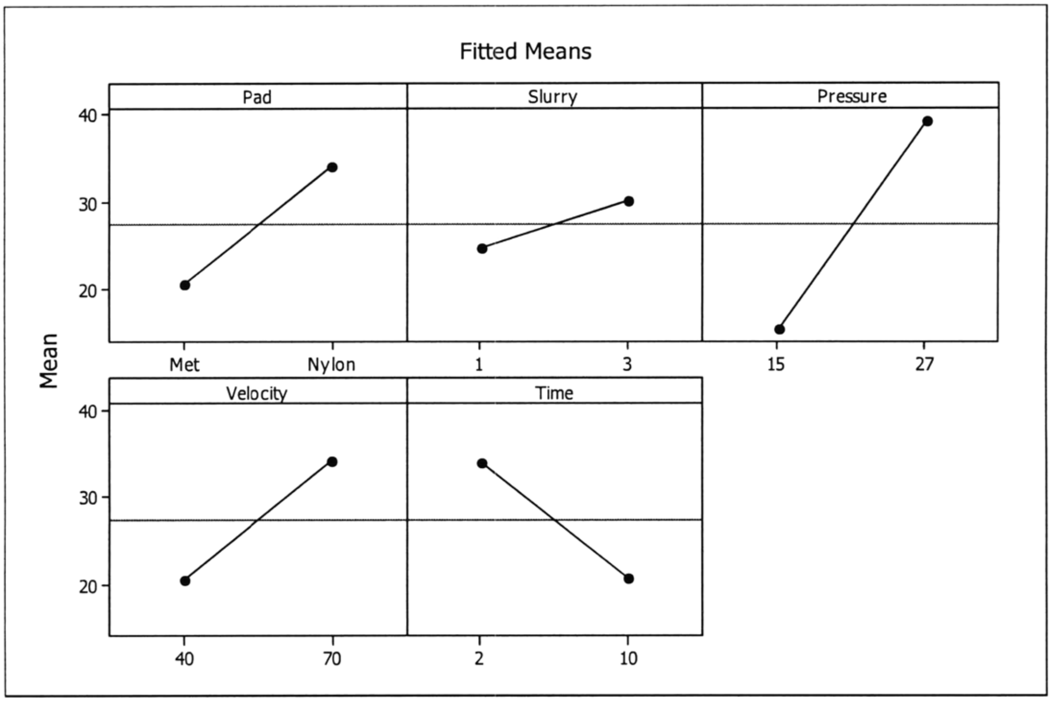

Figure 18- Main effects for all factors (Brass yield)

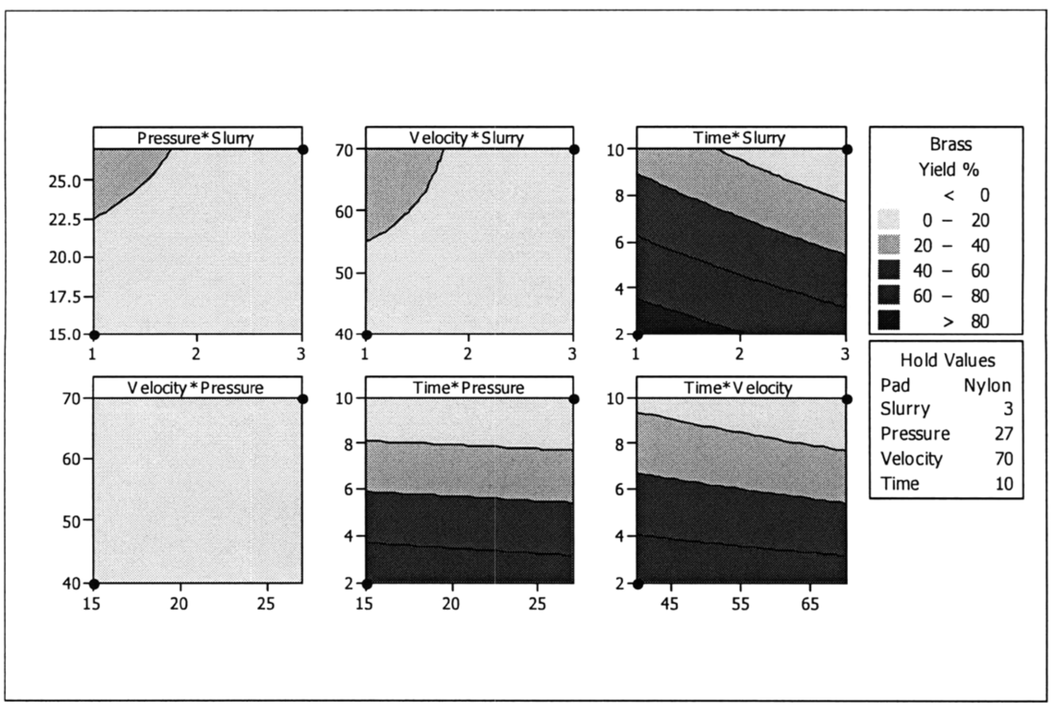

Figure 19- Contour plot for all factors for Brass yield

By using the software optimization tool or Figure 19, the optimum point for brass polishing is found as in Table 6.

Table 6- Optimum factors for brass polishing

Pressure Kg(lbs)	Velocity (rpm)	Time (Minute)	Slurry (Micron)	Pad
12(27)	70	1	1	Nylon

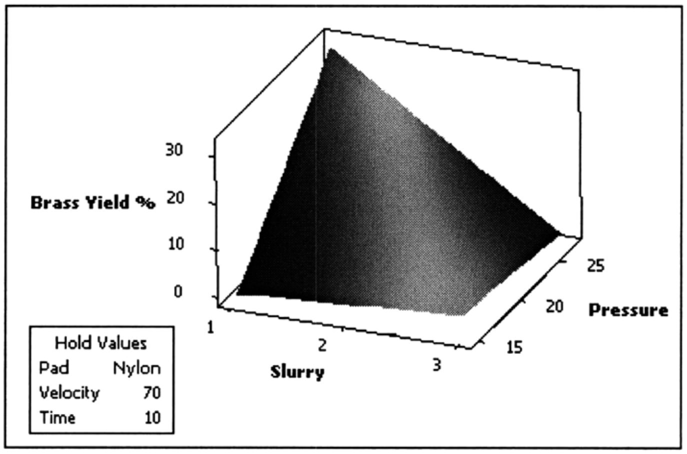

Figure 20- Surface plot of Brass Yield% vs. Pressure, Slurry

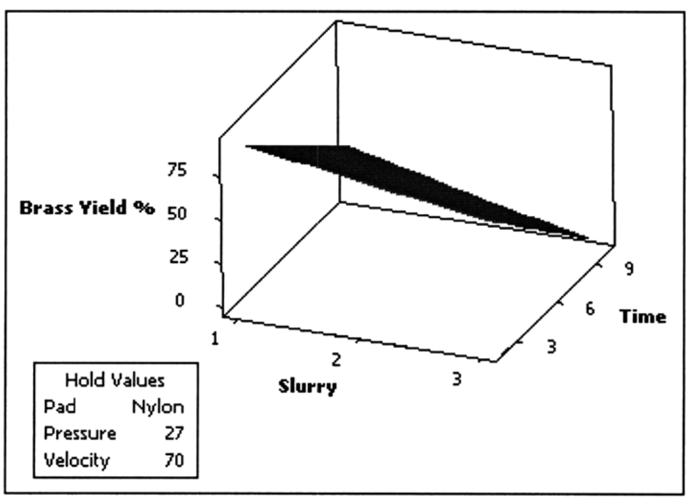

Figure21-Surface Plot of Brass Yield% vs. Time, Slurry

Figure 20 shows the effect of pressure and slurry on yield which looks like what we observed for steel. This is why that it is highly recommended to use 1 micron slurry in the recommendation section in Chapter 5. Figure 21 also demonstrates that how increasing the polishing time along with 3 micron slurry can reduce the overall yield. Further experiments were implemented for sensitivity analysis and it turned out that polishing time as well as slurry is critical for polishing efficiency.

4.5 Quality

In this work, the other major goal was improving the mirror finish quality of both test block and specially the brass one. The shininess of the test blocks is function of different factors such as surface roughness, waviness and grain structures. In this section we just compare the surface roughness of test blocks before and after this study because it was easy to measure; however the shininess quality was improved drastically.

For comparison, 10 brass test block were chosen randomly and their surface roughness was measured and compared to 10 brass test block with new polishing method. The results are shown in Table 7.

Table 7- Quality comparison before and after this study for brass

Surface Roughness	R_a $\mu in(\mu m)$	R_z $\mu in(\mu m)$	R_m $\mu in(\mu m)$
Before	3(0.09)	24(0.6)	32(0.9)
After	1(0.03)	12(0.3)	12(0.3)

Apparently the overall surface roughness was almost 3 times improved. Unfortunately we were not able to measure the surface shininess, but by comparing the test blocks, one could easily distinguish the quality improvement. The surface roughness definition is provided in Appendix C.

4.6 Eliminating the reworking (Grinding & Lapping)

Before this study, the test blocks that had scratches after polishing were being sent back either to grinding or lapping stage depending on how deep scratches are. These reworking not only increases the production cost but also increases the cycle time. Once it was found out that the Nylon pad along with increment of pressure can contribute to high material removal rate; it seemed to be logical to remove scratches in polishing stage.

For this reason, a number of steel test blocks that were already rejected, were used to re-polish them with higher pressure. After some trial and error, it was found out that the scratches were eliminated with 15kg (34 lbs) pressure and 3 minutes. Some of those test blocks that still had some minor scratches, was polished again by ordinary pressure and time and they turned out to be scratch free.
The same procedure was carried on for brass test blocks with a few exceptions. If the scratches were not very deep, which could be easily judged by a trained eye, then the TexMet pad along with new slurry (Master Met 2) was able to remove the scratches and provide a very shiny surface. The procedure is discussed in Chapter 5. If the scratches were too deep, it was only needed to re-polish the block with Nylon pad.

Chapter5. Conclusions and Recommendations

5.1 Conclusions

In this thesis, the improvement of polishing process of Rockwell hardness test block has been studied. The physics of polishing was a key element to pinpointing the problems in polishing process. Preston equation, Eq. (2), was used repeatedly to reduce the cycle time as well as to improve the quality for both brass and steel test blocks. It was determined that by adding compliance (rubber pad) to the polishing machine table, the test blocks are less vulnerable to being scratched. This enabled us to increase the pressure which in turn reduced the cycle time. At this point, the polishing cycle time for steel was reduced to 5 minutes.

On the other hand, by choosing the appropriate polishing pad and slurry not only was the reworking rate reduced but also the quality of surface finish was improved significantly. It appeared that Nylon pad has a significant impact on brass test block polishing. By using Nylon pad, the cycle time for brass test block was reduced from 20 minutes to almost 2 minutes. The surface roughness and shininess was improved drastically as well. It is worth mentioning that this pad is not recommended for non ferrous material by its producer.

A new jig was designed to facilitate a better flow of slurry under the test block and increase the efficiency of polishing process. The previous jig's rim was in contact with the polishing pad, which prevented the flow and led to the accumulation of slurry at that point.

Then the polishing factors were optimized by running a DOE analysis with 5 and 4 factors at two levels for brass and steel, respectively. The results for steel test blocks appeared to be as we expected based on Eq. (2). However the brass test block's outcome was surprising. The pad-time interaction, turned out to be the most significant factor. It was also determined that increment of polishing time, deteriorates the yield. Therefore further experiments were conducted to obtain the optimum polishing time for brass test blocks. After conducting the DOE analysis the polishing cycle time was 1 and 4 minutes for brass and steel, respectively.

Although the results appeared to be consistent for a wide range of hardness, it turned out that some accommodations are required for very soft steel and brass test blocks. As a result, a second stage polishing was introduced to address the issue. A different polishing process was developed for very soft test blocks accordingly.

The other advantage of two stages polishing was reduction of reworking. Before this study the rejected test block from polishing were sent to the previous stages. By having two stages of polishing, we were able to remove the major scratches in first stage. In this stage, the material removal rate was increased by means of applying high pressure. Then the minor scratches were removed in the second stage.

5.2. Recommendations

In this section, we summarize the results of all conclusions and provide the new recipe for the test block polishing. Some other useful recommendations that resulted from this work that can enhance the throughput will be presented as well. The other alternative that was implemented will be discussed at the end.

5.2.1 Steel polishing

We recommend the new steel polishing process with the following criteria:

1- Place a rubber pad[4] on the polishing machine table carefully such that no air bubble forms under the pad.
2- Put a Nylon pad on the top of rubber pad and again it must be such that has no air bubble in between.
3- Clean carefully the test blocks with alcohol and cotton before loading them to polishing machine.
4- Make sure to use the new modified jig as shown in figure 6.
5- For hard steel (HRC>30) the total weight is 14kg (30 lbs) and for soft steel (HRC<30) use 12kg (27 lbs).
6- Set the timer for 4 minutes for hard steel and 6 minutes for soft steel.
7- For those soft steel test block with minor scratches use second stage polishing to remove them.
8- Set the speed to the 70 rpm.
9- When the pad is new, sometimes it is necessary to re-polish the first batch.
10- If in one day different hardness test blocks are to be polished, it is better to go from soft to hard. This enlarges the pad life time and prevents of having scratches.
11- Always use 1 micron slurry for first stage.
12- If the pad is used for harder steel, then it can't be used for softer one and need to be changed.
13- Since the machine is not automated, the operator has to make sure that the pad is wet all the time.
14- Sort those test blocks with scratches and apply 15kg (34 lbs) for three minutes to re-polish them. For softer steel (HRC<40) use 14 kg (30 lbs). This step prevents sending back the test block to either grinding or lapping for reworking.
15- Whenever the unacceptable test block for each run is more than 35% change the Nylon pad with new one.

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[4] In our experiment we used the black TextMet from Buehler

16- Second stage polishing: TextMet (brown) pad and Master Met2 slurry with 4 minutes running time.

5.2.2 Brass polishing

The new brass polishing method is the same as steel except for the following items:

1- The total weight is 12kg (27 lbs)
2- Set the timer to 1 minute.
3- Sort the test blocks that have scratches. For those with minor scratch, use the Buehler TexMet pad with MasterMet 2 slurry for 1 minute or less and the test block with deeper scratch re-polish them with the same pad and slurry.
4- Change the gloves when using different slurries.

It is very important to mention again that cleanliness is the key element in scratch free polishing.

5.3 Other Solutions

5.3.1 Increase the machine speed

As it was shown in the DOE analysis and verified by the polishing machine at Norwood; cycle time can be reduced further by increasing the polishing speed. It is very easy to do this, only by means of changing the gear boxes. The gear box ratio is 1:25 for two machines and for the other two is 1:30.

5.3.2 Automation

It is highly recommended that at least automate the polishing pressure to the test blocks. It would be easy to use pneumatic jack for this purpose. It will decrease the total cycle time significantly and gives more latitude to the operator for applying different pressure for different hardness. After decreasing the machine cycle time, the overall polishing cycle time is limited to the operator performance and how fast he or she can load and unload the machine. Therefore automating the machine can be very helpful.

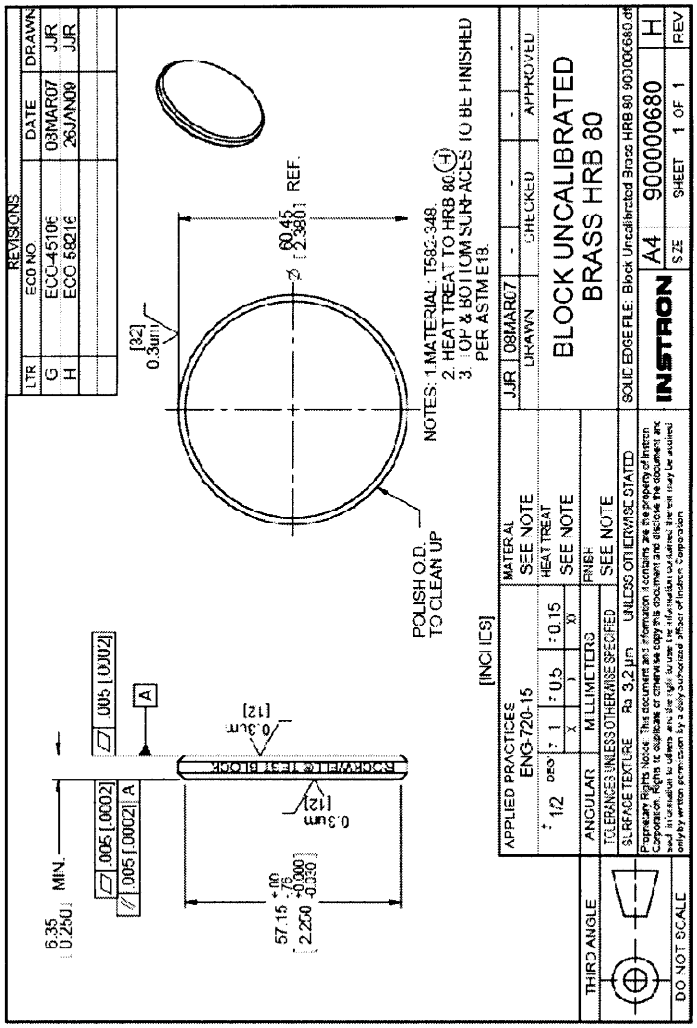
5.3.3 Watt nickel coating

As it was described earlier since the polishing is done only for cosmetic purpose and considering the fact that Rockwell hardness test is based on the depth of indentation, therefore coating seems to be a reasonable alternative. Since the R_m is only $0.5\mu m$ on average for test blocks, therefore a $1\mu m$ coating would be sufficient to cover the surface of the test block after grinding with a reasonable margin. Based on the hardness testing theory, this coating would not affect the performance of the test block. However the major issue is to control the thickness and uniformity of the coating.

A survey of another companies indicated that Watt nickel coating is a good option to address the issue. Watt nickel coating is an electro less types of coating which gives a good controllability on both thickness and uniformity.

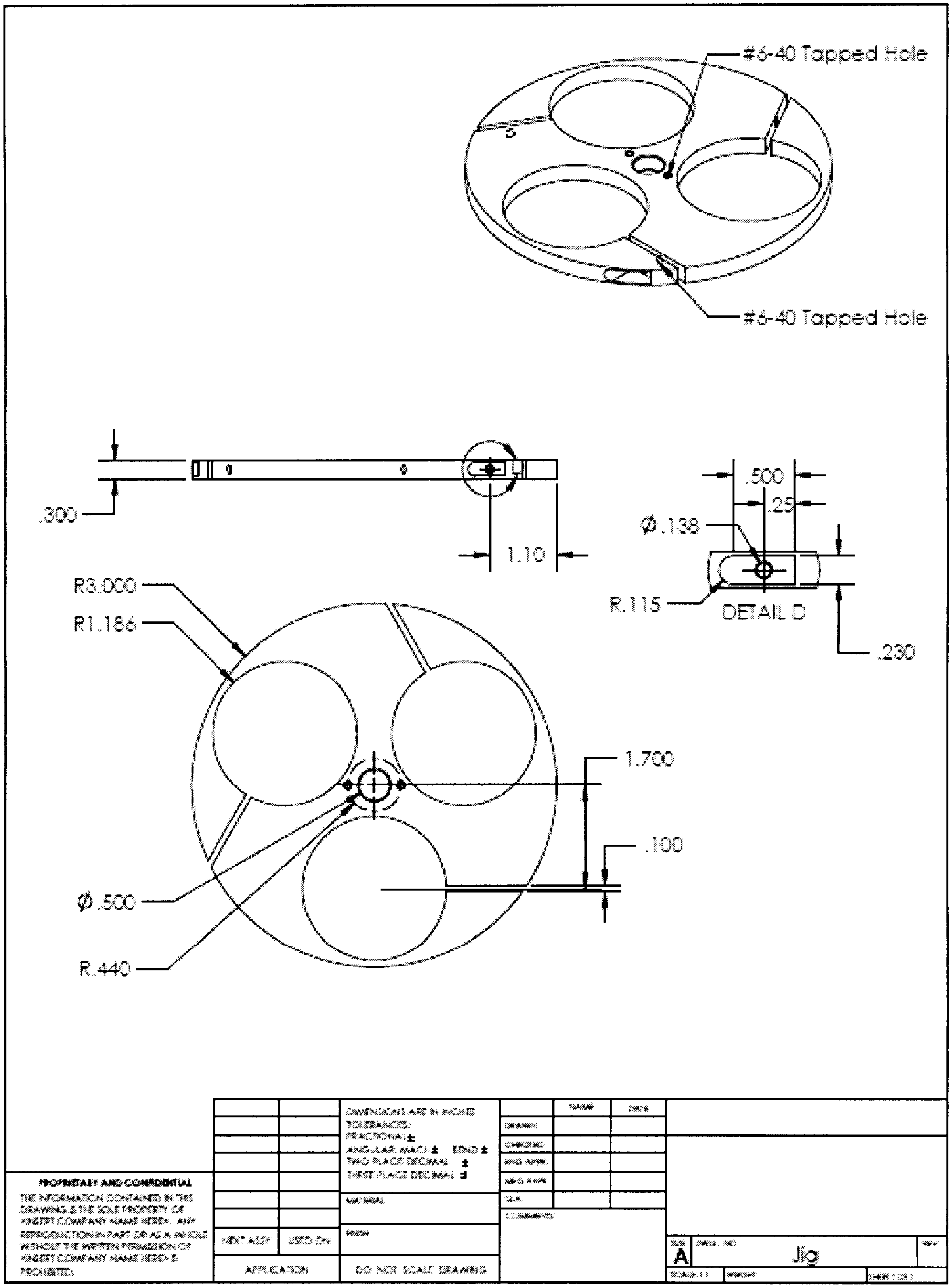
A few steel test blocks were sent to a local company for watt nickel coating and the results for the first attempt were satisfactory. Two out of five were shiny and passed the quality control test in Norwood. One of the main advantages of nickel coating is to eliminate both lapping and polishing processes. The other advantage of nickel coating is that the test block is less vulnerable to corrosion.

Appendix A. ASTM standard for test blocks (E18-08a)



Thickness	>6mm (0.236in)
	<16mm (0.630in)
Test surface area	<2600mm^2 (4in^2)
Flatness	< 0.005mm (0.0002in)
Parallelism	<0.0002 mm per mm (0.0002in per in)
Roughness	<0.003 mm (12µin)

Appendix B. Jig for Buehler polishing machine



Appendix C. Roughness Average R_a

According to ASTM standard the roughness average is defined as follows:
"The arithmetic average height of roughness irregularities measured from a mean line within the evaluation length (L)"

$$R_a = \frac{1}{L}\int_0^L |y|dx$$

$$R_a(approx.) = \frac{y_1 + y_2 + y_3 + \cdots + y_n}{n}$$

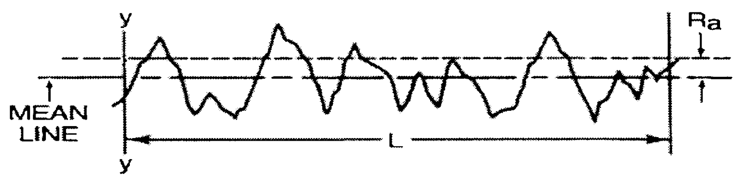


Figure 22- Roughness average [3]

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