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The Impact of a Material's Inherent and Process Stress on Meeting Specification and Tolerances: A Six Sigma Case Study

Brittney Jimerson[1], Yusuf Fahmy[2], Joe Fender[3], Linda Nelms[1], Ted Powell[3], and Robert Yearout[1]

[1]Department of Management & Accountancy
The University of North Carolina at Asheville
One University Heights
Asheville, NC 28804

[2]Department of Engineering-NCSU
North Carolina State University
One University Heights
Asheville, NC 28804

[3]Unison Engine Components
301 Sweeten Creek Industrial Park
Asheville, NC 28803

Corresponding author's e-mail: {Robert Yearout, yearout@unca.edu}

This Six-Sigma Case Study was conducted in a local aerospace company that produces high quality precision-machined jet engine components. These complex turbine components have thin walls that must meet tight tolerances. Disks, shafts, rotating seals, plates, and cases range in size from 3" to 80" in diameter. This case focused on a 16" (diameter) rear cooling plate whose production required 18 machining processes. The objective was to determine if it was possible to eliminate the final manual lathing process. Manual lathing was used as the last step because the material characteristics of the plate and the stress induced by the previous processes caused the final product to expand. Stress can cause unsatisfactory changes in the plate's dimensions. Stress is not only inherent in the material's internal properties but is also induced during machining. It is critical that the operator's cut is precise and does not remove too much material. During the two most critical steps of 18, measurements were taken. It was theorized that relaxing the first process tolerances could allow later processes to be numerically machine controlled to conform closer to the prescribed tolerance of the final product. Plates were tested using these revised tolerances. After the plate was shot peened (a stress redistribution process) measurements confirmed that non-conformance had been eliminated and the final machining process could be discontinued. Cost savings for eliminating the last machining and inspection process was $268 per plate or an annual saving of approximately 11% of total cost for the item studied.

Significance: This paper demonstrates the potential of Six Sigma techniques for improving the quality of a of a product's specification and tolerances and reducing overall cost.

Keywords: Six Sigma, Inherent Material Stress, Specifications, Tolerances, shot peening, and Cost Savings

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1. INTRODUCTION

A manufacturing company in Asheville, North Carolina, manufactures precision-machined jet engine components found in all-major commercial and military aircraft. This company strives to maintain continuous improvement in the production of all products. The main goal of this continuous improvements process is to use cutting-edge techniques such as broaching, curvic grinding, abrasive flow process, shot peening, abrasive waterjet cutting, and dual plane balancing to enhance efficiency, reduce turn-around time, keep cost down, and increase productivity. The company is also committed to enhancing process capabilities to better serve their customers by having more precise control on special processing along with reduced lead time. This company assures aerospace industry standards by conducting numerous tests on plates and materials before the finished products are shipped to the customer and most importantly utilize Six Sigma techniques in a lean manufacturing environment.

The rear cooling plate (Figure 1) is a component of a F404 jet engine (Figure 2) which is the power plant for Saab's JAS 39C fighter. Its production process consists of nine machining operations and one shot peening process (Figure 3). Material used in this cooling plate is premium Inconel 718 (50-55% nickel). Due to rapid hardening, this material tends to be difficult to shape and machine using traditional techniques. After the first machining, work hardening tends to elastically deform either the work piece or the tool. This is the reason age-hardening (a heat treatment technique used to strengthen malleable materials) is applied. Inconel such as type 718 are machined using an aggressive but slow cut with a hard tool, minimizing the number of processes required.

Figure 1. Rear Cooling Plate (Front View (Left) and Rear View (Right))

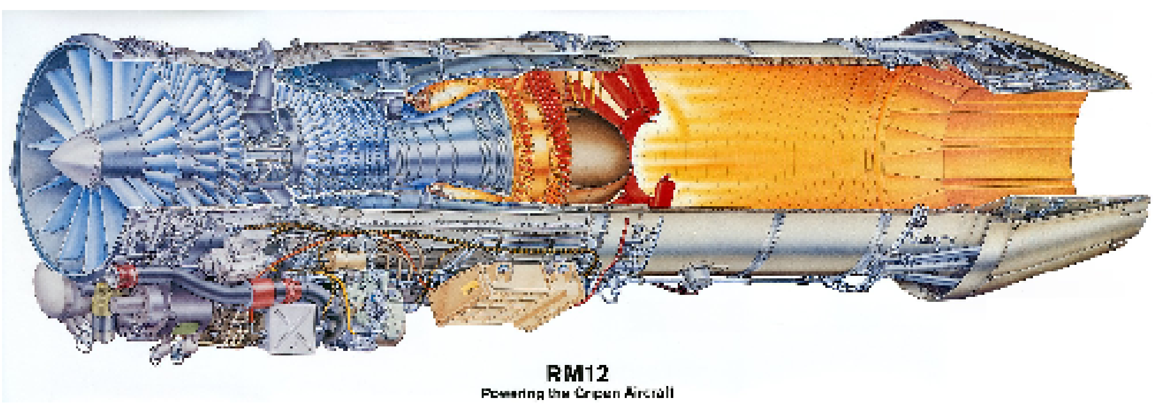

Figure 2. F404 Jet Engine

The production of this plate requires a total of eighteen steps of which ten are machining processes. The last process is a delicate and time intensive operation (step 13) that is called 'final manual lathing' - a critical step that requires a high degree of operator skill and diligence. Errors at this stage can render the entire component to scrap metal. This sole purpose of this final operation is to 'fine tune' the plate's face measurement to ensure it meets critical dimensions, within thousandths of an inch. This final fine-tuning procedure is necessary only because the previous machining operations often distort the plate and tolerances are lost. Large stresses that develop in the metal plate beneath the cutting tool during machining do not disappear entirely once the machining operation is finished, leaving behind so called 'residual stresses'. Depending on the particular machining process, these residual stresses are often significant and impart undesirable distortions and, hence, the need for the time consuming final lathing operation.

The approach was to carefully analyze the process operation just *prior* to final manual lathing (Step 13) at a stage called ***'shot peening'*** (Step 10). Shot peening is a special method of cold working metal parts. It involves the impingement of a high velocity stream of shot (spherical metal pellets, <1mm diameter) onto the exposed areas of the plate. Generally, it is used to induce a residual compressive stress on the surface of the part for the purpose of improving fatigue strength and life. This study reveals that peening can also serve a dual function i.e. that of controlling the particular *distribution* of residual surface stresses on the machined plate, especially those stressed induced by grinding. By analysis of the evolution of the dimensional changes in the plate as it was being made, the automatic numerical machine controlled shot peening system. This allows the operator to administer the peening treatment in such a way that the plate will fall within tolerances which eliminates the need for final manual lathing. Because of this latter-stage high level production control, analysis determined that tolerances during the first machining process could be even relaxed and end product non-conformance eliminated.

The objective of this study was to analyze a mechanism by which dimensional control can be increased, eliminating the final manual lathing step and, thereby, increasing manufacturing efficiency and reduce cost per plate.

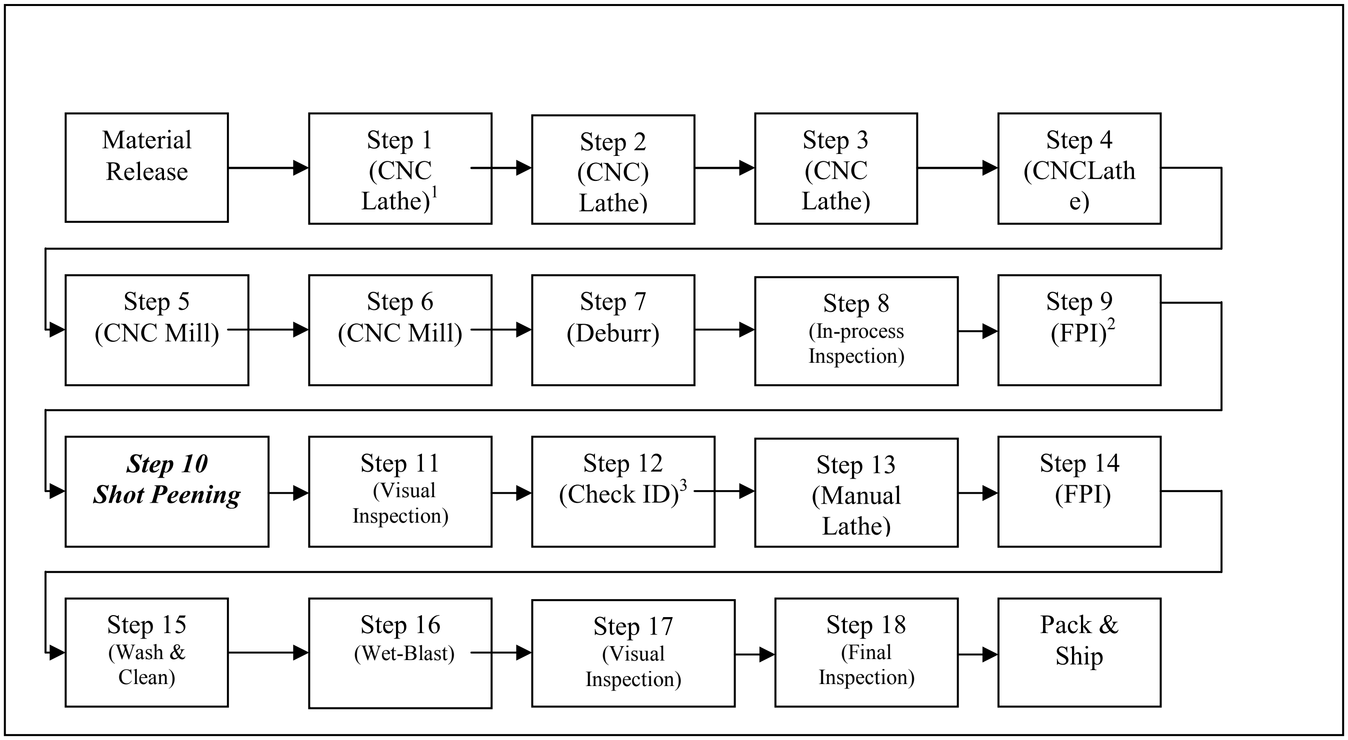

Figure 3. Process Flow Diagram

Notes: [1]CNC: Computer Numerical Control
[2]FPI: Florescent Penetrate Inspection
[3]Plate Identification and Documentation Verified

2. METHODOLOGY

The Six Sigma methodology DMAIC was used in order to identify and eliminate causes of manufacturing defects. According to the Lean Six Sigma Pocket Toolbook (George, Rowlands, Price, and Maxey, 2005), the letters are an acronym for the five phases of Six Sigma improvement: Define-Measure-Analyze-Improve-Control. There were several tools and methods used in each phase to define the problem through implementing solutions to link the underlying causes, and establish the best practices to make sure the solutions stay in place.

3. SIX SIGMA APPROACH

3.1 Phase 1: Definition of the Problem

When the study began, process engineers were setting the process target and tolerances based on individual operator's experiences with this specific plate's materials and production processes. Engineers and operators were not consistently collecting data and setting appropriate tolerances to meet the plate's specifications. However, this empirical approach was unsatisfactory because inaccurate tolerances were causing excessive rework and wasted material. Thus the company was experiencing a significant loss in time and dollars. In an attempt to correct this previous approach, Six Sigma methodology was implemented to provide a more systematic way of collecting and analyzing data. This approach would allow the engineer to determine how much stress impacted the material inherited properties and how much it caused the dimensions of the plate to enlarge.

3.2 Phase 2: Measurement

During this step data was collected on process capability, quality, and cost that were used to expose the underlying causes of the problems. The following steps were taken to accurately collect the appropriate data for the process:

a. Twenty-five plates were identified by serial number to accurately keep track each plate throughout out its total process.
b. Measurements were collected after the third lathing operation (Step 3) to insure that the plate's dimensions were within tolerances. Since the plate (Figure1) is a circular ring, measurements to insure that the plate's flatness did not exceed 0.0002 inches was required. Then four different measurements (see Figure 2) were taken at approximately 90 degree angles. The average of the four measurements was then used in determining if the plate was within specifications and tolerances.
c. This statistic was then collected at Steps 5 and 6 which was before the most crucial operation in the process (Step10 (shot peening)), to insure that these machining operations had no impact on how much the material changed under stress. Since there was not significant change in these statistics, this data was no longer collected.
d. After the plates were shot peened (Step 10), and went through appropriate inspections (Steps 11 and 12), the plates were then manually lathed (Step 13). This operation was basically a rework process.
e. Measurements were then taken to insure that the plates fell within specification and tolerances. If the plates did not meet specification and tolerances they were either reworked or scrapped.
f. The data that determined how the machining stress and shot peening contributed to the plate's dimensions was analyzed using statistical comparisons and control charts.
g. Calculations then determined that a new target (nominal) with its upper and lower allowance could be used.

3.3 Phase 3. Analysis

The objective was to eliminate the final manual lathing processes which insures that the plate's critical face measurement was within the specified 0.097 to 0.101 inches lower and upper tolerances. Data was collected on 25 plates during 2 of the most critical machining process. The flatness of each plate was checked with the expectation that it would be within a 0.001 range. The plate's dimensions were checked in four locations to collect a more accurate measurement.

<u>3.3.1. Initial Data</u>

<u>3.3.1.1 CNC Lathe (Step 3)</u>

The specification and tolerance after Step 3 (CNC Lathe) (Figure 3), the plate's critical specification and tolerance is 0.094 +/- 0.002. Measurement was taken on the face of the plate as illustrated in the not to scale sketch (Figure 4).

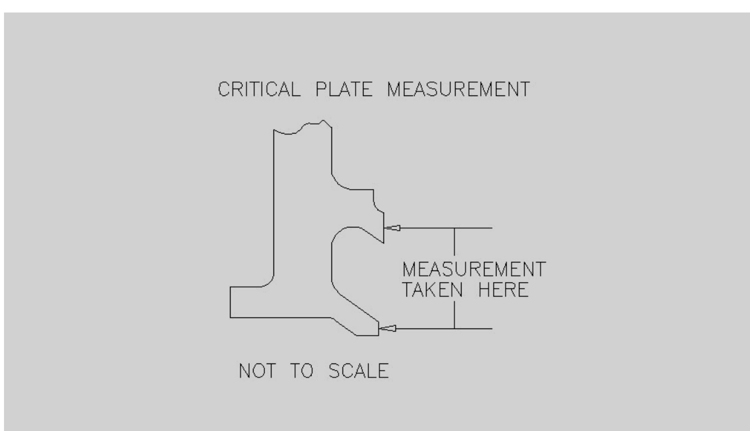

Figure 4. Location of Critical Plate Measurement (Not to Scale)

The four measurements per plate yielded an average range of 0.00078 inches and an average of the average was 0.09413 inches. An estimated standard deviation was calculated to be 0.000379 inches as prescribed by Grant and Leavenworth (1996). Since the average of the averages did not correspond with the 0.094 inch nominal, the C_{pk} (process capability index) was required (Yearout, Nelms, Lyda, and Blackwelder, 2000). The initial C_{pk} for Step 3 was 1.65 (five standard deviations). Thus the process was capable but not meeting the Six Sigma process capability criteria of 2.00 (six standard deviations).

3.3.1.2 Manual Lathe (Step 13)

At Step 13 (Manuel Lathe), the operator checks the critical dimensions of the plate to insure that it falls within the final tolerances of 0.097 to 0.101 inches.

The four measurements per plate yielded an average range of 0.001016 inches and an average of the average was 0.09586 inches. This is clearly below the final specified lower tolerance. Therefore a manual lathe operation (Step 13) is required to insure that the plate meets the specification and tolerance. When the measurements are below the lower tolerance this manual rework operation can save the plate. If the plate's measurement falls above the upper tolerance, it must be scrapped.

Of the 25 plates measured 23 plates required rework. Thus the percent requiring the manual lathing was 0.88 with a δ of 0.065.

3.3.2 Phase 4. Improved Initial Settings

The new setting was determined by taking the average part movement from the initial data (paragraph 3.3.1.1) by subtracting the Step 13 average measurements from those at Step 3. This movement value of 0.00173 inches was then subtracted from the nominal center point for the plate at Step 13. This calculation gave a proposed target for Step 3 of 0.0973 inches. Due to the expense of a plate, the authors then included a buffer by setting the target at 0.097 +/- 0.001 inches for Step 3.

3.3.2.1 CNC Lathe (Step 3)

The specifications and tolerances after Step 3 (CNC Lathe) (Figure 3), the plate's critical specification and tolerances are now 0.097 +/- 0.001. Measurements were taken on the face of the plate as illustrated in Figure 4.

The four measurements per plate yielded an average range of 0.00072 inches and an average of the average was 0.096855 inches. An estimated standard deviation was calculated to be 0.00035 inches as prescribed by Grant and Leavenworth (1996). Since the average of the averages did not correspond with the 0.097 inch nominal, the C_{pk} (process capability index) was required (Yearout, Nelms, Lyda, and Blackwelder, 2000). The initial C_{pk} for Step 3 was 0.815. Thus the process at this stage of the operation is not capable.

3.3.2.2 Manual Lathe (Step 13)

At Step 13 (Manuel Lathe), the critical dimensions of the plate were measured to insure compliance with the final tolerances of 0.097 to 0.101 inches.

The four measurements per plate yielded an average range of 0.001172 inches and an average of the average was 0.098595 inches. The estimated standard deviation was calculated to be 0.000569 inches. Since the average of the averages did not correspond with the 0.099 inch nominal, the C_{pk} (process capability index) was required (Yearout, Nelms, Lyda, and Blackwelder, 2000). The final C_{pk} just prior to Step 13 was 0.934. However, if the target had been set at 0.0973 inches rather than 0.097, then the target would have been closer to the specification mean. Thus the C_p, Process Capability Ratio using the same standard deviation would have been 2.342 (seven standard deviations). This significantly exceeds the Six Sigma criteria by one standard deviation. Therefore the potential to have a process greater than the 2.00 Six Sigma criteria is quite evident.

Of the 25 plates measured none indicated a need for rework. Thus the percent requiring the manual lathing was zero.

3.4 Phase 5. Control

The objective was to eliminate the final manual lathing processes which insures that the plate's face measurement was within the specified 0.097 to 0.101 inch tolerance. Based on the data collected and provided from the machine operators during the machining processes, the company could achieve a cost savings for eliminating the last machining and inspection process with an annual saving of approximately 11%, by relaxing the tolerances during the first machining process. Additional plates were then processed with these revised tolerances. The data was analyzed using the R-Bar and X-Bar charts. The X-Bar chart is a control chart of subgroup means and is used to track the process level and detect signs of special causes. The R-Bar chart is used to evaluate the stability of the variability within a process.

3.4.1 Observed Engineering Specification Chart

The observed engineering specification chart (Figure 5) uses upper and lower specification limits (UTL and LTL respectively) and are not calculated upper and lower control limits according to established statistical process control procedures. Intermediate limits are 1/3rd and 2/3rds the distance between the UTL and the X-Dbar, (average of the average means). When an observed engineering chart is used the investigative effect on the variation in the process, the central goal of a control chart, is nullified (McCoy, Yearout, and Patch). However, this type of chart is useful in determining by visual inspection the number and sample location of conforming and nonconforming plates (Grant and Leavenworth, 1996). As you can see after the improved target was applied to Step 3, there are no nonconforming plates.

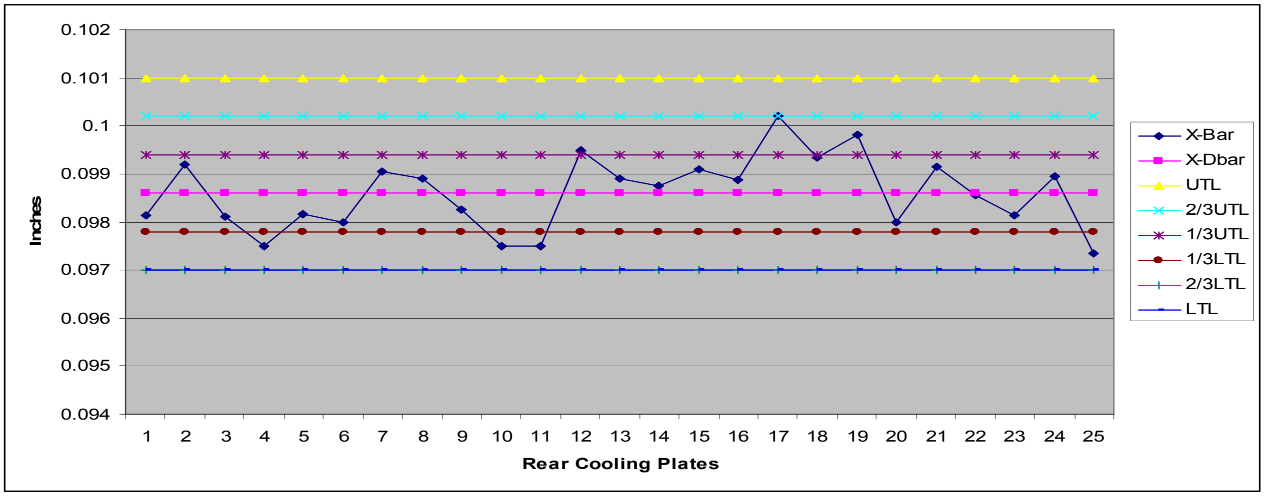

Figure 5. Observed Engineering Specification Chart

3.4.2 R Bar Chart

The R Bar chart indicates that the variation between measurements during the improved process is in control. When this chart is in control an estimated standard deviation (σ) of the process can be determined by using the following equation (equation 1) (grant and Leavenworth, 1996).

$$d_2 = \text{R-Bar}/\sigma \qquad (1)$$

Where d_2 is a Table value taken from Table C, Grant and Leavenworth (1996) using R-Bar and the number of observations in a subgroup. The standard deviation of 0.000569 inches used in calculating the C_p and C_{pk} values in paragraph 3.3.1.1. Although the first plate produced using the improved setting approaches the upper control limit, it variation is not out of controls

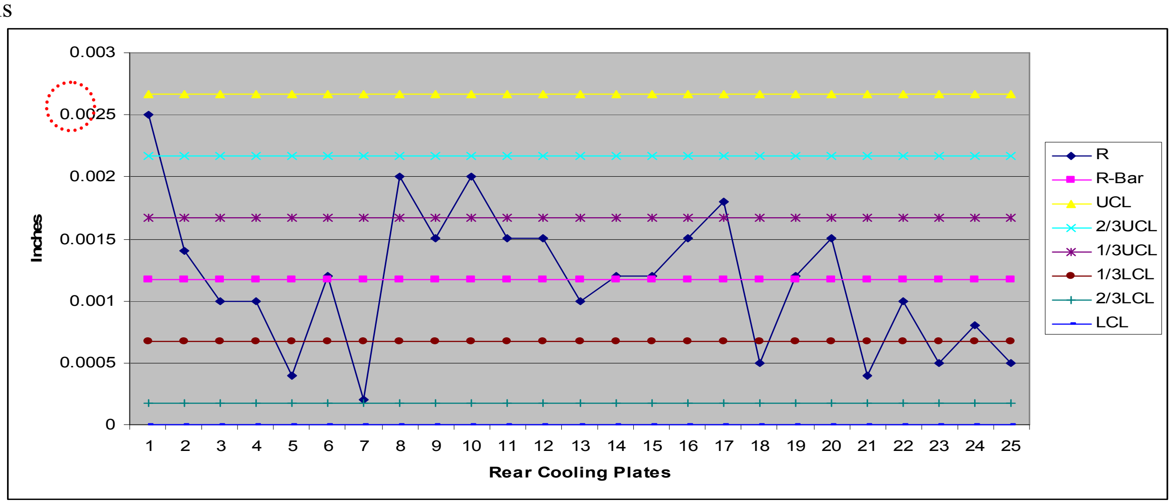

Figure 6. R-Bar Chart

3.4.3 X-DBar Chart

The X-DBar Chart illustrates that the averages of the data points taken at the four critical points on the plate are in control. However, the means on plates numbered 12 through 18 have averages that are above the averages of the means. Whenever seven successive points on a control chart are all on the same side of the X-Dbar (central) line, grounds may exist for suspicion the universe parameter has shifted (Grant and Leavenworth, 1996). However, the blank plates (un-machined) are received in batches. It appears that different operator may have programmed the settings slightly different. This is affirmed by the means for latter plates being more normally clustered around the central line.

3.5 Cost Savings

The cost of a finished rear cooling plate is $2,200.00. By eliminating Step 13 (manual lathing) and Step 14 (FPI) the saving was determined to be $268.00 per plate. Since there were no plates requiring rework, a total savings on the second lot of 25 plates that had the proposed target for Step 3 of 0.097 +/- 0.001 was $5,896.00.

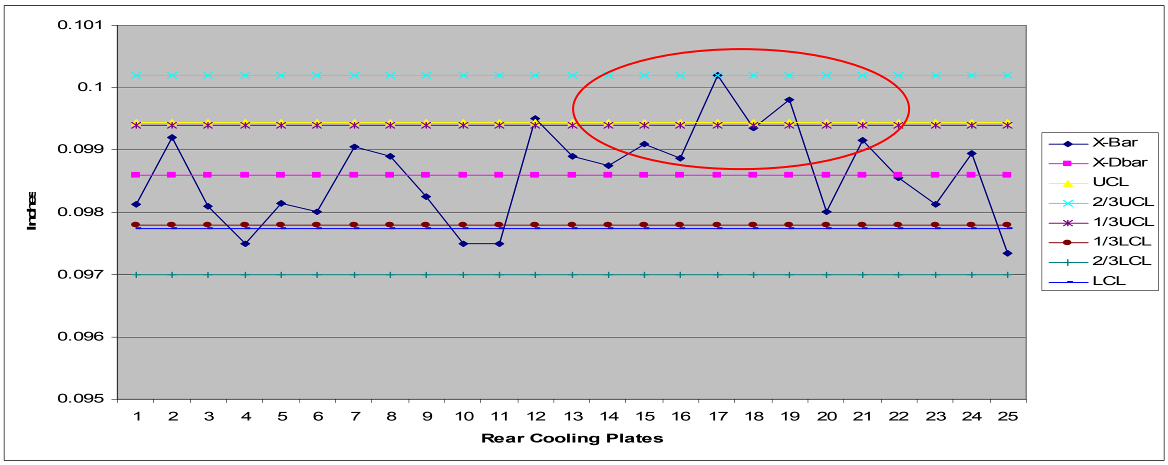

Figure 7. X-DBar Chart

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4. DISCUSSION

After the data was collected, the engineer, machine operator and six sigma coordinator, met to discuss the degree that stress had on the plate's final dimension. The data revealed that the solution to the nonconformance and the resulting rework was basically that the tolerances during the first machining process needed to be relaxed to allow the shot peening process to reverse the stress and improve fatigue stress. As a result the plates can be expected to have a longer life.

The process and quality engineers agreed that the Six Sigma problem solving approach had the potential to accurately monitor the plate's movement throughout the process. The information obtained during this analysis was essential in setting the proposed target settings. Under the initial settings 22 out of the 25 plates required rework. After the target was set to be 0.097 +/- 0.001 at Step 3 there were no plates in the 25 plate run that would require rework. Thus Steps 13 and 14 became redundant and could be eliminated. Eliminating these steps realized a $268.00 savings per plate produced. Although the C_{pk} Step 13 was calculated to be 0.93, which is significantly less than the C_{pk} 2.00 criteria, additional fine tuning to the proposed target setting to 0.0973 +/- 0.001, would result in a C_{pk} greater than 2.00. Thus the Six Sigma criteria of a process capability of 2.00 would be met.

5. CONCLUSIONS

Upon implementation of the proposed target setting to 0.0973 +/- 0.001, it was determined that this setting would result in no plates being scrapped or reworked. Thus Step 13 (manual lathing) and Step 14 (FPI) were redundant and could be eliminated. Statistical process control analysis with appropriate charts verified that the process variation was in control. Thus a cost savings was $268.00 (approximately 11%) per plate. This Six Sigma project realized a cost savings of $5,896.00 on just the improved run of 25 plates alone. The current annual contract was for an additional 30 plates, by applying this continuous monitoring and improvement, Six Sigma methodology, the potential for an additional $7,236.00 could be realized.

6. REFERENCES

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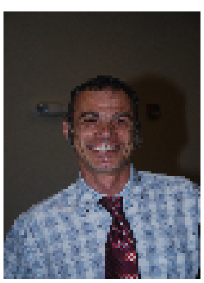
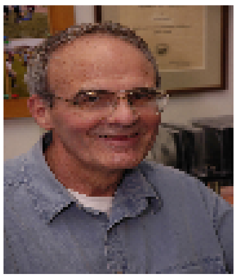
BIOGRAPHICAL SKETCH

Brittney Jimerson will graduate from the University of North Carolina Asheville (UNC Asheville) with a BS degree in Industrial Engineering Management with a minor in Mathematics. Her future plans are to secure a positron as a quality engineer and qualify as a Six Sigma Black belt. After five to ten years, she plans to attend graduate school.



Yusef Fahmy, Director, Joint NC State - UNC Asheville Engineering Programs, Teaching Assoc. Professor, Dept. Materials Science & Engineering, North Carolina State University (NCSU), BS Mechanical Engineering (NCSU), MS Materials Science & Engineering (NCSU), Ph.D., Materials Science & Engineering (NCSU). Dr. Yusef Fahmy's areas of research interest include the structure and properties of high temperature intermetallic compounds, structure and properties of nanocrystalline systems, non-equilibrium processing, mechanical behavior of structural materials and the influence of electric and magnetic fields on mechanical properties of materials. Dr. Fahmy has published in a number of peer reviewed journals including Physical Review, Journal of Materials Research, Materials Science and Engineering, Journal of Electronic Materials, Metallurgical and Materials Transactions, International Journal of Modern Physics, Hyperfine Interactions and Scripta Materialia. Dr. Fahmy has worked to bridge engineering education across disciplinary lines including integration of engineering and liberal arts in the delivery of a BS Mechatronics Engineering program at UNC-A. He is a member of Alpha Sigma Mu, Sigma Iota Rho, Sigma Xi, ASEE and a Senior Member of IEEE.

Professor of Management, University of North Carolina at Asheville (UNCA), B.A., Literature, UNCA; M.B.A., University of North Carolina at Chapel Hill. North Carolina, C.P.A., C.M.A., C.P.I.M. Mrs. Nelms awards include the Ruth and Leon Feldman Professorship for Outstanding University Service and the University Service Council Award. She has published several articles in top tier peer reviewed international journals such as The Management Accountant and conference proceedings to include the Annual International Journal For Industrial Engineering Theory, Practice, and Application Conference. Mrs. Nelms has served as the Director of UNCA's Undergraduate Research Program. Her research interests are in the areas of managerial and accounting ethics, economic analysis, inventory, and other related topics that span the gap between economics, accounting and engineering.



Robert Yearout Professor of Industrial Engineering Management, University of North Carolina at Asheville (UNCA), B.S.C.E., Virginia Military Institute, M.S.S.M., University of Southern California, M.S., Ph.D., Kansas State University. LTC (US Army Special Forces, Retired). Dr. Yearout's awards include the Ruth and Leon Feldman Professorship for Outstanding Research, Distinguished Teaching Award, UNCA Distinguished Teacher of the Year, University Service Council Award, Board of Governors of the University of North Carolina Award for Excellence in Teaching, and Annual University Research Council Award for Scholarly and Creative Achievement. Dr. Yearout has published a significant number of articles in national and international peer reviewed journals such as IEEE Transactions on RELIABILITY, International Journal of Industrial Ergonomics, and the International Journal For Industrial Engineering Theory, Application, and Practice in subject areas directly related to his teaching expertise. He is the editor for National Conferences on Undergraduate Research (NCUR) Proceedings and a member of the Editorial Board for the International Journal For Industrial Engineering Theory, Practice, and Application.