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A Material's Inherent and Process Stress
(A Six Sigma Case Study)

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Abstract

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. Measurements were taken during each of the 18 steps. 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 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 cycle or an annual saving of approximately 11% of the total cost per plate.

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

1. Introduction

1.1 six sigma

Six sigma concepts were conceived by Bill Smith, a reliability engineer for Motorola Corporation. Six Sigma is a disciplined, data-driven approach and methodology for eliminating defects (driving towards six standard deviations between the mean and the nearest specification limit) in any process -- from manufacturing to transactional and from product to service. Six Sigma is a methodology that provides business with the tools to improve the capability of their business process. The increase in performance and the decrease in process variation lead to defect reduction and improvement in profits, employee, morale, and quality of product [4]. Essentially, Six Sigma is about results – enhancing profitability through improved quality and efficiency. Improvement projects are chosen based on their ability to contribute to the bottom line on a company's income statement by being connected to the strategic objectives and goals of the corporation.

1.2 process capability

1.2.1 process capability ratio (C_p)

The Process Capability Ratio (C_p) determines if the process is capable of meeting the specifications (tolerances) [2]. If C_p is greater than 1.00, the tolerance range is greater than the range of actual process output. If C_p is less than 1.00, the process does not meet specifications, and the process will not meet the desired quality[5]. Equation 1 is the calculations for the process capability ratio.

C_p= (USL-LSL)/6σ (1)

1.2.2 process capability index (C_{pk})

C_p indicates that the process is capable when the ratio is greater than the critical value of 1.00. Many quality engineers prefer and recommend a critical value of 1.33. One must remember that satisfactory input only occurs when and if the process distribution is centered on the nominal value of the design specifications. The argument that the authors use to explain and justify the C_p assumes that the process is on target, which means that the process (μ) and the target value (Tg) or nominal value is the same. Thus the C_p ratio will only provide a good assessment of capability when the process is on target [5]. The possibility that a process will have small variability but poor proximity to the target has sparked the development of the process capability index (C_{pk}). The advantage of using C_{pk} is that it not only takes into account the process mean and deviation but includes the deviation from the target or nominal value [2]. Equation 2 is the calculation for the process capability index.

C_{pk}=Minimum of [(x-double bar - LSU)/3σ, (USL- x-double bar)/3σ)] (2)

Where x-double bar is the mean of the process output

1.3 machining process

The rear cooling plate (figure 1) is a component of a F404 jet engine, which is the power plant for Saab's JAS 39C fighter. Its production process consists of nine machining operations and one shot peening process. Material used in this cooling plate is premium Inconel 718 (50-55% nickel**).** Due to rapid work hardening, this material tends to be difficult to shape and machine using traditional techniques. After the first machining process, work hardening tends to elastically deform either the work piece or the tool during following processes. This is the reason age-hardened (a heat treatment technique used to strengthen malleable materials). 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))

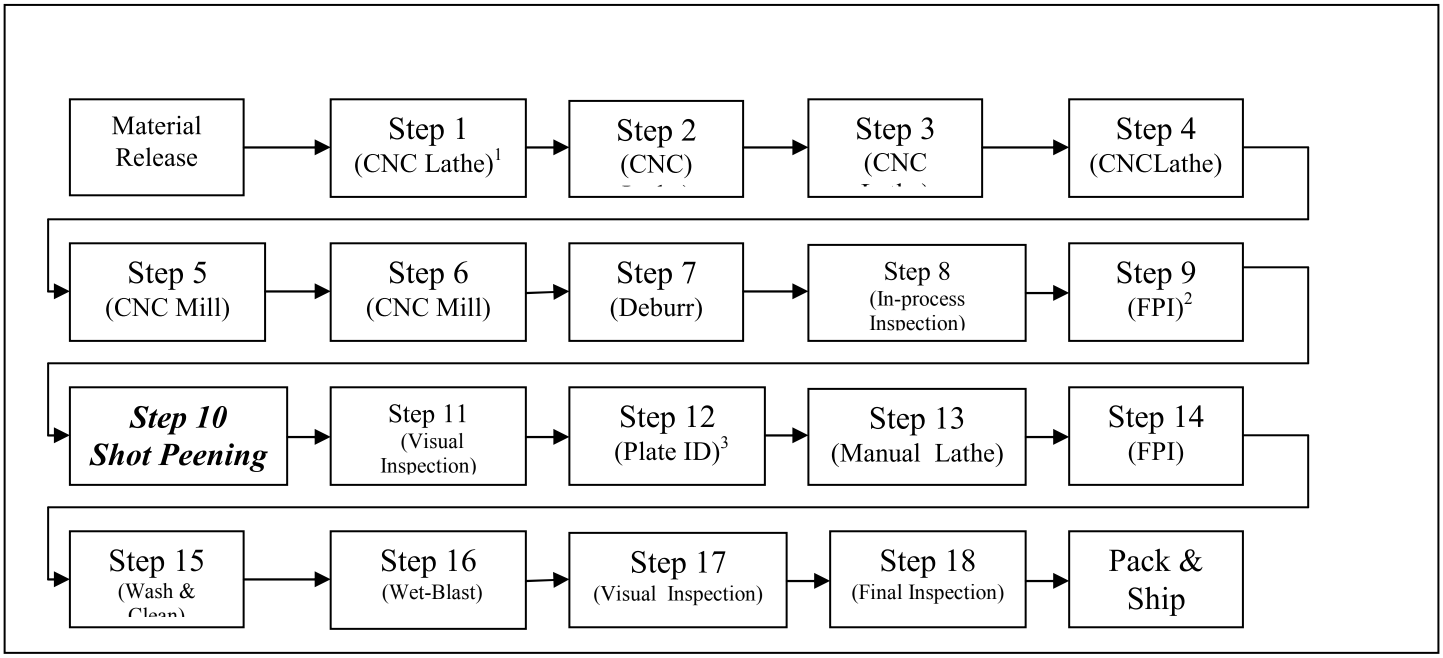

Figure 2. Process Flow Diagram

Notes: [1]CNC: Computer Numerical Control
[2]FPI: Florescent Penetrate Inspection
[3]Plate ID:

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. The 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 part 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 can be programmed to administer the peening treatment in such a way as to eliminate 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.

1.4 problem

Currently, process engineers were setting target nominal and tolerances based on individual operator's experiences with this specific part's materials and production processes. They 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 to change.

2. Methodology

The Six Sigma methodology DMAIC was used in order to identify and eliminate causes of manufacturing defects. The letters DMAIC are an acronym for the five phases of Six Sigma improvement: Define-Measure-Analyze-Improve-Control[1]. 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.

2.1 measurements

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 of 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 were taken at approximately 90 degree angles. The average of the four measurements was then used in determining specifications.

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 parts fell within specification and tolerances. If the plates did not meet specification and tolerances they were either reworked or scrapped.

f. The data was then analyzed using statistical comparisons and control charts to determine the impacts of machining stress and the shot peening contributed to the plate's dimensions.

g. Calculations then determined that a new nominal with its upper and lower allowance could be determined.

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 part was checked and indicated to be round within a 0.001 range. The parts dimensions were checked in four locations to collect a more accurate measurement.

3.1. initial data

3.1.1 cnc lathe (step 3)

The specifications and tolerances after Step 3 (CNC Lathe) (figure 2), the plate's critical specification and tolerances is 0.094 +/- 0.002.

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[2]. Since the average of the averages did not correspond with the 0.094 inch nominal, the C_{pk} (process capability index) was required [5]. The initial C_{pk} for Step 3 was 1.65. Thus the process was capable but not meeting the Six Sigma process capability criteria of 2.00.

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 specifications. 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 88% with a δ of 0.065.

3.2 new data

The new setting was determined by taking the average part movement from the initial data (paragraph 5.1) 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. The purpose of this step was to improve the production process in order to meet final specification and tolerances.

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 part 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[2]. Since the average of the averages did not correspond with the 0.097 inch nominal, the C_{pk} (process capability index) was required [5]. The initial C_{pk} for Step 3 was 0.815. Thus the process at this stage of the operation is not capable.

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 [5]. The final C_{pk} for 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 nominal specification. Thus the C_p, Process Capability Ratio using the same standard deviation would have been 2.342. 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 required rework. Thus the percent requiring the manual lathing was zero.

3.3 observed engineering specification chart for new data

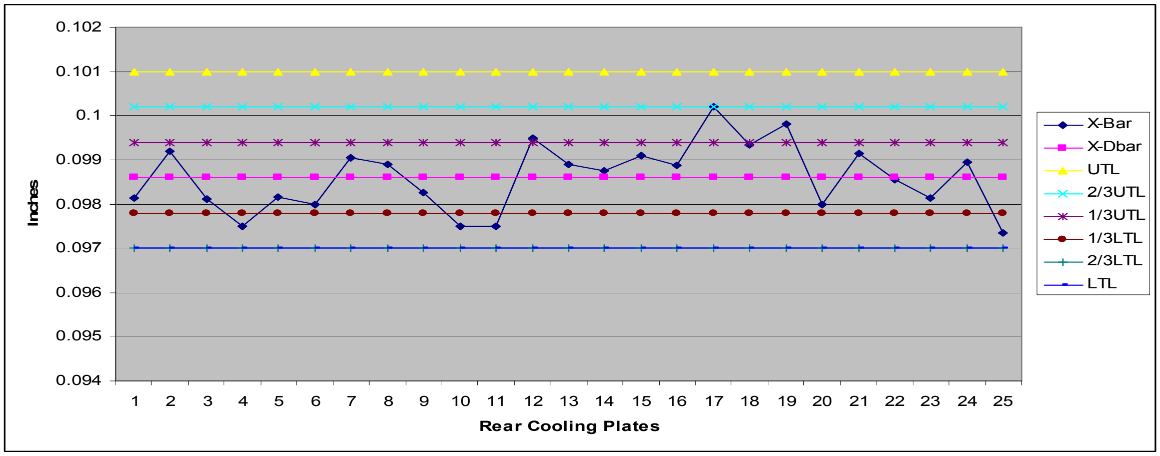

Figure 3 Observed Engineering Specification Chart

The observed engineering specification chart (Figure 3) 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 2/3^{rds} 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 in the process, the central goal of a control chart, is nullified [3]. However, this type of chart is useful in determining by visual inspection the number and sample location of conforming and nonconforming plates [2]. As you can see after the improved target was applied to Step 3, there are no nonconforming plates.

3.4 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 $13,400.00.

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 most common cause for the nonconformance and the rework process was basically that the tolerances during the first machining process needed to be relaxed.

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.

Although there may be a some future plates that will require manual lathing and FPI, the risk of producing a plate that exceeds 0.101 inch upper tolerance level which will require scrapping may increase to an unacceptable level. Since the cost of scrapping a plate is approximately $2200.00 plus an additional $2200.00 for a replacement plate, the risk of moving the target to the nominal setting at Step 3 in order to obtain a C_p of 2.00 (Six Sigma criteria) is not economically feasible.

5. Conclusion

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 $6,700.00 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 $8,040.00 could be realized.

6. References

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