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Machining process changes as a function of surface roughness, specific to machining cylindrical bores

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MACHINING PROCESS CHANGES AS A FUNCTION OF SURFACE ROUGHNESS, SPECIFIC TO MACHINING CYLINDRICAL BORES

An Abstract of a Thesis
Submitted
In Partial Fulfillment
of the Requirements for the Degree
Master of Arts

Thomas Patrick Olsen
University of Northern Iowa
December 2007

ABSTRACT

Manufacturing professionals are challenged everyday to produce products to higher quality standards in a way that is economical and efficient. Manufacturing needs to minimize non value added costs such as reducing inventory, (non machined and finished goods), reduce work in process, and most of all eliminate waste. To exist, customers must be satisfied at the time of purchase and throughout the products lifecycle. To be competitive and remain a world class manufacture, companies must be flexible and be willing to change. Single point flexible manufacturing versus fixed spindle rigid machining greatly improves the ability to make changes. If a process demands tighter tolerances special equipment may still be required. Unfortunately, this may drive a company to purchase a dedicated machine, thus going away from flexible machining, which will result in higher capital and expense investment costs.

This research focused on the process of finishing roller follower bores in a cast iron six cylinder diesel engine, specifically improving the surface roughness of follower bores. The machining process studied was a non flexible dedicated station, which was part of a transfer line. Station studied had one head that contained twelve fixed spindles. Each spindle was tooled with a finished reamer dedicated to producing a hole that satisfied size, roundness, taper, and surface roughness specifications. The ultimate goal with this research was to improve part quality while maintaining current production costs and supportive resources as apposed to changing process adding costs associated with capital, expense, supporting resources, and process complexity.

The heart of this research concentrated on performing a tool performance comparison between two types of finish reamers, controlled and experimental. The controlled reamer was the existing reamer currently used in production while the experimental reamer was a new design made from solid carbide, consisting of combination left hand spiral and straight cutting edges. The dependent variable was the resultant surface roughness of finished reamed follower bores. Applying standard F and T tests to resultant data, the research proved there was a significant difference in variance and means between controlled and experimental tools. A process capability analysis was applied to both controlled and experimental tools and proved that the experimental tool performed superior over the controlled reamer.

The process that analysis was based involved finish reaming twelve roller follower bores utilizing six controlled and six experimental finish reamers. Forty one parts were randomly selected during a three thousand piece production run. Parts were cleaned and moved to a special investigative lab. A surface roughness gauge was used to measure each of the twelve bores and resulting surface roughness were recorded in tabular form.

Along with the analysis of tools the research examined a superior finishing process called, super abrasive reaming. This would be the alternative reaming process if experimental reamers did not perform well enough to meet customer specifications.

In summary, by performing F, T, and process capability analysis, this research did prove there was a significant difference in variances and means between the controlled and experimental reaming tools. The process capability of the experimental reamer was superior over the controlled reamer.

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This Study by: Thomas Patrick Olsen

Entitled: MACHINING PROCESS CHANGES AS A FUNCTION OF SURFACE ROUGHNESS, SPECIFIC TO MACHINING CYLINDRICAL BORES

has been approved as meeting the thesis requirement for the Degree of Master of Arts in Industrial Technology.

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12-1-07 Date	Dr. Ronald E. O'Meara, Thesis Committee Member
12/14/07 Date	Dr. Sue A. Joseph, Interim Dean, Graduate College

DEDICATION

This Thesis paper is dedicated to all people associated with manufacturing and developing new technology. Not only do you have people who operate machines, who become experts over time, you have support people that have the knowledge to keep machines running optimally. Process Engineers spend numerous hours fine tuning processes with the goal of maximizing return on investment, improving productivity, efficiency, and reducing waste. You have people who work in mills and foundries that supply world class castings. If castings do not meet customer specifications then machining will not be cost effective. I can't begin to express my thanks and gratitude to everyone involved in this research. People involved made this research possible; ultimately driving success.

As a special dedication I want to thank my dad, Robert R. Olsen. My dad took over my grandfathers manufacturing business, Rhinevault Olsen Machine and Tool, in 1951. Rhinevault Olsen is a small specialty job shop where I developed the passion for manufacturing. My father told me that "the customer always comes first; for if a customer is not happy, then we will not survive." He also knew that no one is perfect and that it was only through making mistakes that one truly became a master. My dad passed away in March of 2004. He will be missed.

ACKNOWLEDGMENTS

The great company, John Deere, was very supportive and helped make this thesis a reality. It was through the world of John Deere manufacturing that I was able to perform research. I would like to extend my thanks to the following people:

- Paul Mason, Manager of Machining, John Deere Engine Works, for his continued support, and allowing me to use this subject for my Masters Thesis
- Lloyd Calease, Quality Engineer, for his knowledge in the quality field and his assistance and coaching with analyzing data
- Floyd Fagle, Machine Operator, who makes dreams come true with his expertise and great understanding of machines and manufacturing
- Larry Sands, Tool Investigator, who made sure tools used during research were qualified to part print tolerances and verified tools were properly set
- Darrell Wachtendorf, Tooling Engineer, Master Programmer, for his vast knowledge in the field of tool design and his helpful suggestions throughout the project

I would also like to express a special thanks to the people who work with Northern Tool Sales and Service Company. Northern Tool designed and manufactured experimental reamers used in research. It was because of their knowledge and skill that I had an experimental tool to study. I would like to recognize the following people from Northern Tool:

- Chris Schulte, President of Northern Tool, who knows the importance of putting forth nothing less than the best effort

- Paul Schulte, Tool Design Engineer, who provided the idea and design for experimental tooling used in research
- Nick Mendella, Sales engineer, whom I have come to respect greatly for all the years of knowledge he brought to the table as well as his respectful approach when working with people

Finally, I would not have been able to work on my Masters, or this Thesis, without the support of my wife Jan, and my children, Erik and Kelly. They have been very patient during times I spent away taking classes or working on research. They have always inspired me to persevere.

It should be noted that information presented in this study has been changed. This was done to avoid any damage to Deere & Company Worldwide Operations.

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CHAPTER 1

INTRODUCTION

Today, manufacturing professionals are challenged to produce products to higher quality standards in way that is economical and efficient. Manufacturing goals include minimizing non-value added costs such as raw inventory, work in-process, finished goods, and waste. To exist in a world market today customers must be satisfied. Customers must be satisfied when they purchase a product and throughout that products lifecycle. This is the only way to retain and grow business. To be both competitive and a world class manufacturer requires the ability to change. The ease with which change can be made becomes very important. If processes are flexible making changes can be done easily, versus, non flexible, change can be difficult and associated costs will be greater.

The machining process in this research examined a non flexible machine with one head that contained twelve fixed spindles. Each spindle was tooled with a finished reamer dedicated to producing a hole that satisfied size, roundness, taper and surface roughness specifications. This machine was an integral part of a transfer line as opposed to a single point flexible machine. In a transfer line, all stations must perform operations within a predetermined time known as the transfer line station cycle time. If for any reason a stations cycle time is increased above transfer line cycle time, then that station will become the bottleneck of transfer line. Therefore, it is especially important when change is made to stay within process cycle time. Previous processes before finish reaming of roller follower bores were drilling and semi-finish reaming. Drilling and semi-finish reaming pre-processes were controlled and satisfied customer specifications so that optimal finish reaming results were achieved.

Impacts of change can have huge ramifications in the manufacturing world. It is only through justifying processes economically that manufacturers will remain competitive and will continue to exist. With the advent of out sourcing came a new dimension to our manufacturing industry. Out-sourcing challenges the security of many jobs associated with manufacturing.

This research examined the effects on a process when surface roughness quality requirements were changed from 3.2 to 0.8μm Ra, specifically in the finishing of cylindrical follower bores in a grey cast iron six cylinder diesel engine. The actual challenge was to determine following: If current process could be used without change, or, if current process could be used with changes made only to finish reaming tooling, or, if current process could be used with the addition of a new machine to refine and improve overall surface roughness results of roller follower bores.

The heart of this research concentrated on performing a tool performance comparison between two types of finish reamers: controlled and experimental. The controlled reamer was the existing reamer currently used in production while the experimental reamer was a new design made from solid carbide consisting of combination left hand spiral and straight cutting edges. The dependent variable was the resultant surface roughness of finished reamed follower bores. Standard F and T tests, along with performing a process capability analysis on experimental and controlled tools determined if there was a significant difference in variances, means, and process capabilities.

The process that analysis was based, involved finish reaming twelve roller follower bores with six controlled and six experimental finish reamers. Forty one parts were randomly selected during a three thousand piece production run. Parts were cleaned and moved to a special investigative lab. A surface roughness gauge was used to measure each of the twelve bores. Resulting surface roughnesses were recorded in tabular form.

Along with the analysis of tools the research examined a superior finishing process called super abrasive reaming. This would be the alternative reaming process if experimental reamers did not perform well enough to meet customer specifications.

In summary, by performing F, T, and process capability analysis on resultant experimental and controlled data, this research did prove there was a significant difference in variances, means, and process capabilities. The experimental reamer did in fact perform better than the controlled reamer. Through constructive communication between manufacturing and engineering a decision was made not to adopt a super abrasive process which saved between one and three million dollars. This decision was based on raising the upper tolerance limit of surface roughness from 0.8 to 1.55μm.

Exact costs associated with controlled and experimental tools, new machines, and specific process's, were withheld in this paper because of possible negative impacts that could result during current and future purchasing negotiation phases with suppliers.

Statement of Problem

The problem addressed in this study is stated in the following question. What machining process changes are required when surface roughness specifications for cylindrical follower bores, (CFB), change from 3.2 to .8μm?

Statement of Purpose

The purpose of this research was to determine actual machining process changes resulting from changing cylindrical follower bore surface roughness from 3.2 to .8μm.

Statement of Need

The most significant reason to research this topic was to understand the process changes that are required when changing surface roughness of CFB, from 3.2 to 0.8μm. Research will focus on process impacts in machine tool application, tooling, part quality, and manufacturing process capability. Another very important aspect of this research will focus on testing a new type of finish reamer, (experimental). If experimental tool performs satisfactorily, then outcome of research will have a positive impact on industry. Companies would experience a positive impact in areas of saving money by not having to invest in new expensive machinery, tooling, and gauging. This would also preserve the process cycle time which in-turn will not impact customer delivery and costs. Doing this will also keep process less complex, thus preventing increased supportive costs.

Statement of Hypotheses

Hypothesis one: The null hypotheses of study: H_{01} is that there is no significant change in process, (independent variables), when surface roughness requirements, (dependent variable), for a cylindrical bore, are changed from 3.2μm to 0.8μm.

Research question one: The first research question of study is: what process changes are required as a result from changing surface roughness of cylindrical follower bore from 3.2μm to 0.8μm?

Research question two: The second research question of study is: will there be a statistical difference between using experimental versus controlled standard production finish reamer?

Assumptions / Requirements

Below are assumptions and requirements that were made before, during, and after research was being performed. All assumptions and requirements below are variables that can influence the outcome of research if not maintained or qualified. Proving all assumptions and requirements goes beyond the scope of this research. It can be confidently stated that all assumptions and requirements listed meet or exceed requirements for performing research.

1. Material used in research, in an as-cast condition, is grey cast iron with a hardness specification falling in the range of 207 to 275 BHN. Castings used in research satisfy casting quality and material specifications.
2. Pre-machining processes satisfy part print specifications. Pre-machining in question are machining of manufacturing dowels that locates part in fixture, during drilling, semi-finish reaming, and finish reaming of cylindrical follower bores.
3. Pre-drilled and semi-finish reamed holes are round, straight, and are machined to proper sizes.
4. Part is located properly in machine fixture during machining process.
5. Machine head that contains spindles is aligned properly to fixture bar containing finish reamer guide bushings. Machine accuracy provides the foundation for tools to perform at their optimal level.
6. Coolant used in finish reaming process is clean and satisfies coolant specifications.

7. Running temperature of reaming process is stable.
8. Gauges and measuring devices have been verified.
9. Operator running machine is qualified and understands machining process.
10. Special investigators performing measurements of features are qualified and trained to perform their job of measuring and recording results.
11. Parts measured have been cleaned, providing the best chance for accurate measurements.
12. All finish reamers have been checked to verify that tool geometry is correct and satisfies tooling specifications.
13. Temperature within plant is held to 70 deg F, plus or minus 2 degrees.
14. Machining process during testing is the same as during regular production.
15. Part fixture clamping restricts part movement through machining process.

Limitations / Delimitations

The following is a list of limitations that need to be recognized. These limitations placed constraints on research flexibility and control of independent variables.

1. Machine used to drill follower bores speeds and feeds are constant and can not be changed.
2. Machines used to semi and finish ream follower bores are constant feed and have variable speed control. Feed can not be changed.
3. Since we are testing tools in a production state, speeds and feeds of all machines can not be changed.
4. Type of coolant used during finish ream process can not be changed.
5. Test reamer used is a developmental tool and is under patent review. Strict confidentiality should be observed at all times. Information presented in this study can not be duplicated, re-used, or copied, without written permission from author of research or authorization from John Deere.
6. Machines used are production machines. During study, machines will be in production so limitation to perform changes, such as changing tools, will have to be coordinated with production breaks or other factors that would allow freedom to make necessary changes or process adjustments.
7. The study will only machine Gray Cast Iron.

CHAPTER 2

REVIEW OF LITERATURE

Through review of literature the author developed a better understanding of the function of a roller follower in a diesel engine, as well as broadened his knowledge of how follower bores are machined, measured, and validated to given quality specifications. There are seven major topics found in this chapter followed by a section titled definition of terms.

Follower Bore Functionality

What is the functionality of a follower bore? Figure 1 shows a picture of follower bore, roller follower, push rod, rocker arm, valve springs, and valve assembly. As the camshaft rotates, rotational motion is transformed into linear motion by means of the cam lobe contacting follower. As a result, the follower moves up and down. The follower is supported by the follower bore. The follower bore provides stiffness and support necessary to maintain functionality throughout the roller follower's life. As roller follower moves, this causes push rod to push on one end of rocker arm. When rocker arm pivots, this causes the valve to open and close.

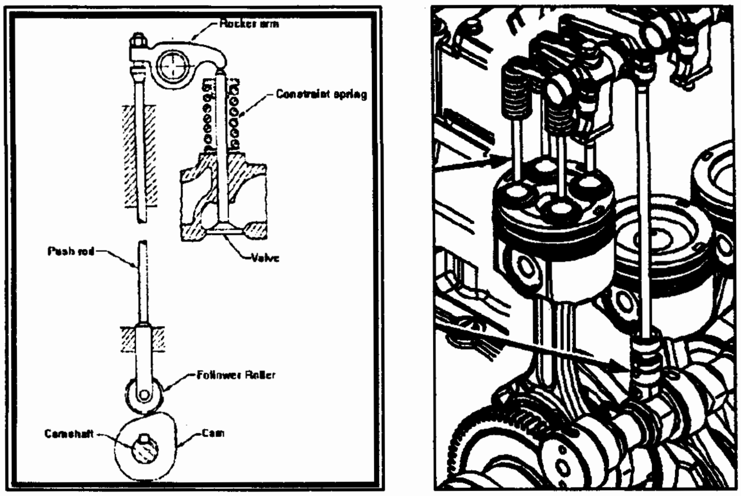


Figure 1. Rocker Arm Assembly. (*John Deere Power Tech Plus^{TM} 9.0L Tier 3/StageIIIA OEM Diesel Engines – Base Engine Technical Manual*)

The sole purpose for the rocker arm assembly is to control valve timing. The valve opens to allow a mixture of fuel and air into the combustion chamber. After combustion occurs, the valve allows burnt fuel and exhaust to vent out of the combustion chamber before process repeats (Smith, 2006).

Reasons Follower Bores Need to be Machined to Tight Tolerances

It is imperative that the follower bores meet roundness, straightness, and size specifications so that follower is supported properly. If specifications are satisfied, then pre-mature wear on follower and cam lobe can be minimized. Nagaraj, who studied *Predictions of Cam Follower Wear in Diesel Engines*, stated "forces to open the intake and exhaust valve train system are strongly influenced by the stiffness and damping of the valve seat, masses, geometries, and frictional behaviors of contacting elements of valve train components" (Nagaraj, Lakshminarayanan, Gajendra & Dani, 2005). Friction becomes an element that can and will influence the life and efficiency of valve train operation. Size difference, surface roughness, and lubrication between follower and follower bore all directly influence the amount of friction in the joint.

Definition of Surface Roughness

It is important that surface roughness (Ra), be discussed to understand boundary conditions and limitations that are dependent upon surface roughness. Surface roughness: "The finer irregularities of the surface texture that usually result from the inherent action of the production process or material condition" (ASME B46.1-2002 Standard, 2002). In other words, surface roughness is inherent imperfections left behind from cutting tools. Figure 2 represents the surface of a machined part.

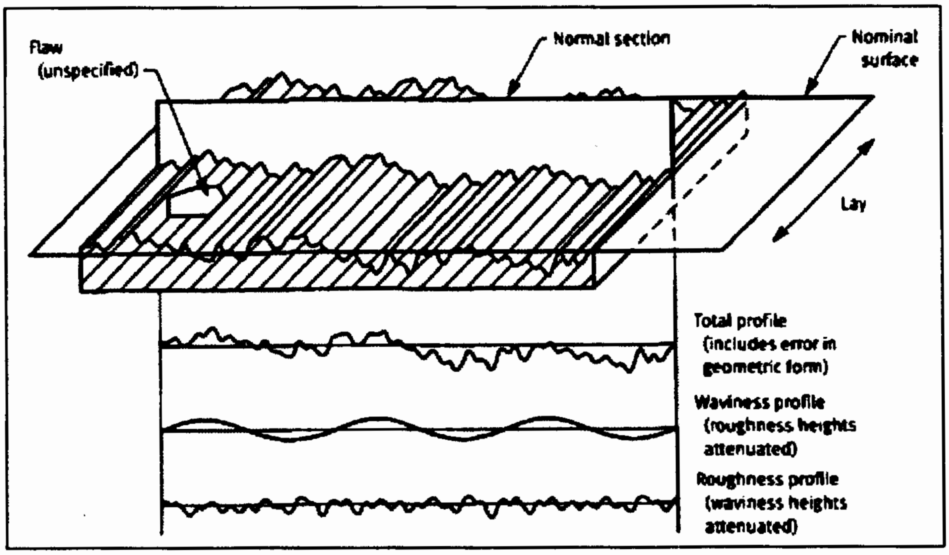


Figure 2. Duplicated from the ASME B46.1-2002 Standard.
Schematic diagram describing surface characteristics

Surface roughness is the arithmetic average of the absolute values associated with the measurement of the peaks and valleys in the material surface over a given distance (ASME B46.1, 2002).

Reasons for Changing Surface Roughness of Follower Bore

Why change surface roughness? One reason would be to reduce friction. Today designers are challenged with producing products that operate more efficiently. Mechanical devices operate more efficiently when parts work together fluidly and friction is minimized. If friction is not controlled, friction will increase, generating heat, causing wear, which will lead to premature failure (*Lubrication Principles,* 1999). "Because heat and wear are associated with friction, both effects can be minimized by reducing the coefficient of friction between contacting surfaces" (*Lubrication Principles,* 1999). Improving surface finish, roughness, will reduce friction. Improving surface characteristics can also improve several important engineering aspects of product design. They are: fatigue strength, reduce residual stress, and improve retained strength (ASM Handbook, 1995).

Another key factor that will cause wear and decrease mechanical efficiency would be to remove lubrication from mating dynamic joints. The Machinery's Handbook points out four basic sliding friction laws for lubricated surfaces.

1. If a surface has a constant oil film thickness, then frictional resistance is almost independent of the resultant pressure between surfaces.
2. Friction varies directly as the speed, at low pressures; but for high pressures the friction is very great at low velocities, approaching a

minimum at about two feet per second linear velocity, and afterwards increasing approximately as the square root of the speed.

3. For well lubricated surfaces, the frictional resistance depends on temperature, partly because of the change in viscosity of the oil and partly because of the differences in thermal growth between dissimilar materials. This can cause added pressure between parts.
4. If bearing surfaces are flooded with oil, the friction is almost independent of the nature of the material of the surfaces in contact. As lubrication is reduced, the coefficient of friction becomes more dependent upon the material of the surfaces (Oberg, Jones & Holbrook, 1982).

The particular valve follower assembly shown in Figure 1 is vertical so that when we look only at the interface between follower and follower bore there is no resisting forces acting on follower except for the frictional component and pressure between two surfaces. Looking at F=ma where m=W/g, W being the weight of follower in lbs, and g being gravity 32.2 ft/sec^2, then F=W because g = a (Oberg et al., 1982). With lubrication and focusing on frictional component, the force to move follower equals F=uW. The coefficient of friction, (u), between steel and cast iron is 0.2 (Shigley & Mischke, 1986). Therefore F=.2W. For the follower to move down would take a minimum of 20% of its own weight to overcome friction. Without lubrication the force needed to move follower would almost double to approximately 40% of weight of follower.

Current Processes Used to Achieve Surface Roughness of 3.2μm

Process development begins with understanding what machining processes are available to achieve targeted surface roughness. Specific processes produce different surface characteristics with distinct surface roughness (ASM Handbook, 1995). Figure 3 shows various surface roughnesses produced by common production methods. A finer surface finish usually demands a larger investment and greater support. The chart below identifies processes that fall within 0.8 to 3.2μm surface roughness ranges. They include: reaming, grinding, honing, and not listed super abrasive.

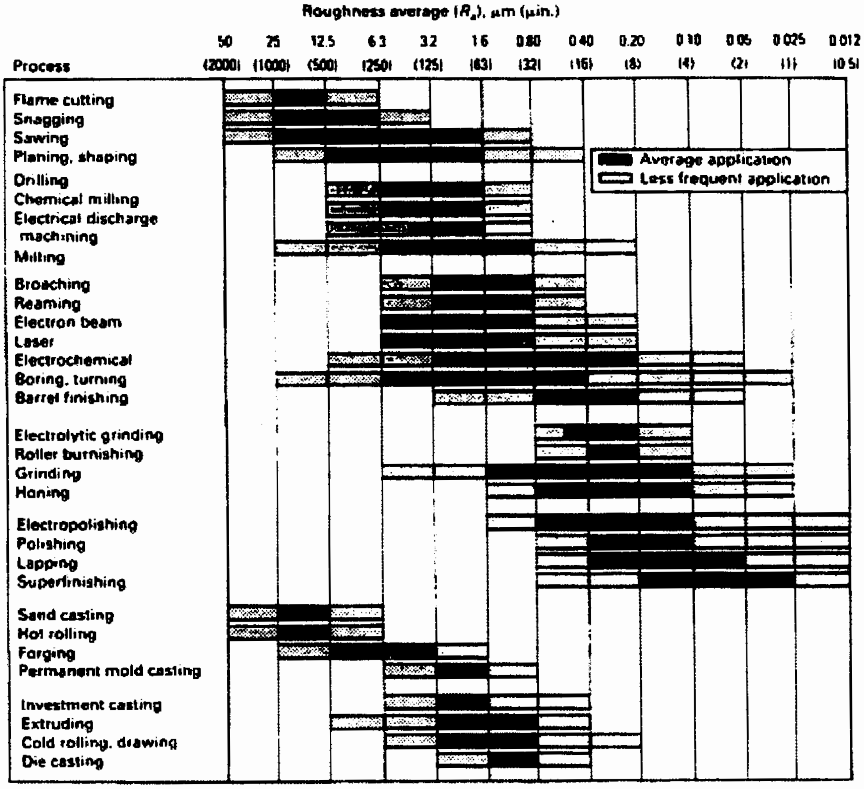


Figure 3. Surface roughness produced by production methods (ASM Handbook, 1995).

Current process explanation: This process, as well as many others producing precision bores, begins with a first pass drill operation, followed by a semi-finish end-cutting reamer, and the third and final pass is a finish ream. The drilling process removes large amounts of material while the semi-finish and finish ream passes take very little material. The drill used in this particular process is a four flute solid carbide drill with an outside diameter of 27.43 mm. The semi-finish-reamer, or end-cutting reamer, which may have either straight or spiral flutes, has no chamfer on the end for use as a lead; instead, the end has cutting edges at right angles to the reamer axis (ASM Handbook, 1995). Figure 4 shows the basic geometry for an end-cutting reamer. The diameter of the semi-finish reamer is 27.915 mm.

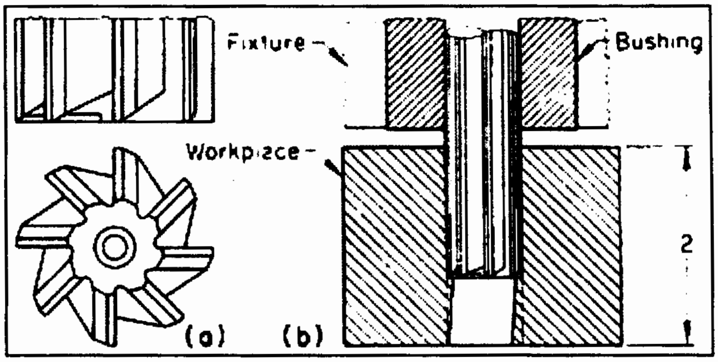


Figure 4. End-cutting reamer. (a) A common type of end-cutting reamer used for finishing blind holes. (b) When guided in a bushing, an end-cutting reamer can correct dimensional deviations in through holes (ASM Handbook, 1995).

Typically an end-cutting reamer will remove (0.018 to 0.020 in) material on diameter. The finish reamer will not be end-cutting and will typically remove (0.020 to 0.025 in) material on diameter. Most finish reamers are "Spiral-fluted and differ from straight-flute reamers only in that their flutes are milled in a helix" (ASM Handbook, 1995). Figure 5 is an example of a spiral finish reamer. It is recommended to use Spiral-flute reamers for reaming holes that cross-drilled intersecting holes. The spiral cutting edges bridge irregularities, minimizing chatter, surface roughness, and size variation.

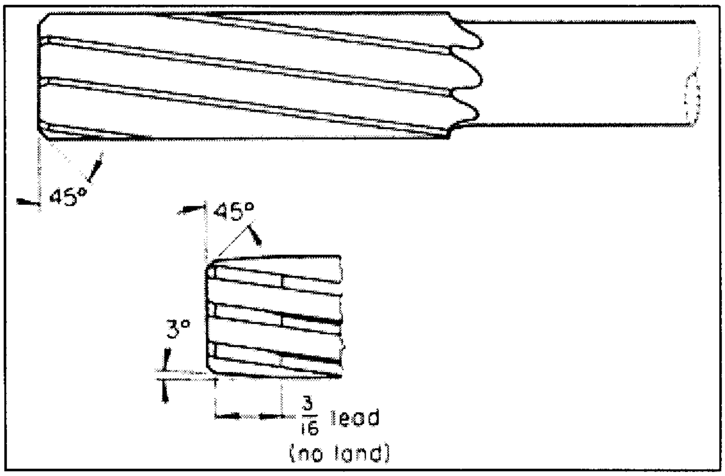


Figure 5. Spiral flute finish reamer (ASM Handbook, 1995).

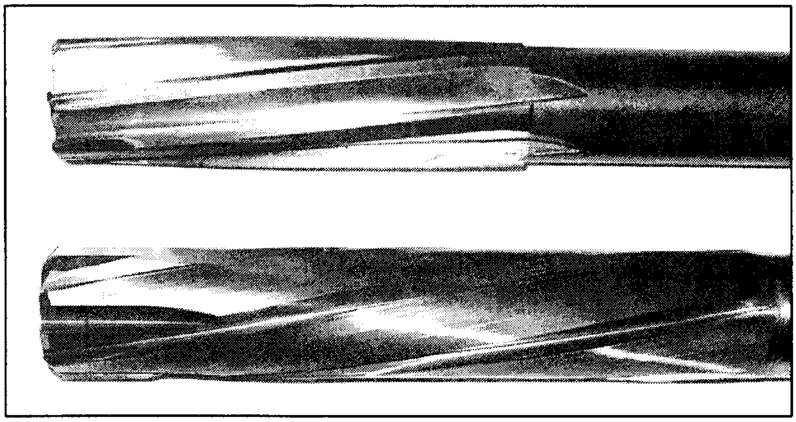


Figure 6. Controlled and experimental finish reamers. Top reamer, used in current manufacturing process (controlled), bottom reamer, is experimental reamer, combination spiral straight reamer. Note: The straight flute.

Reaming is a metal removal process and produces a very fine chip. If not enough stock exists for reamer to cut, the reamer will burnish the surface and as a result the life of the reamer will be reduced. The minimum amount of material to remove when reaming soft materials is 0.008 thousands of an inch (ASM Handbook, 1995). Figure 7 shows a picture of the finish reaming station that all cutting tests will be performed.

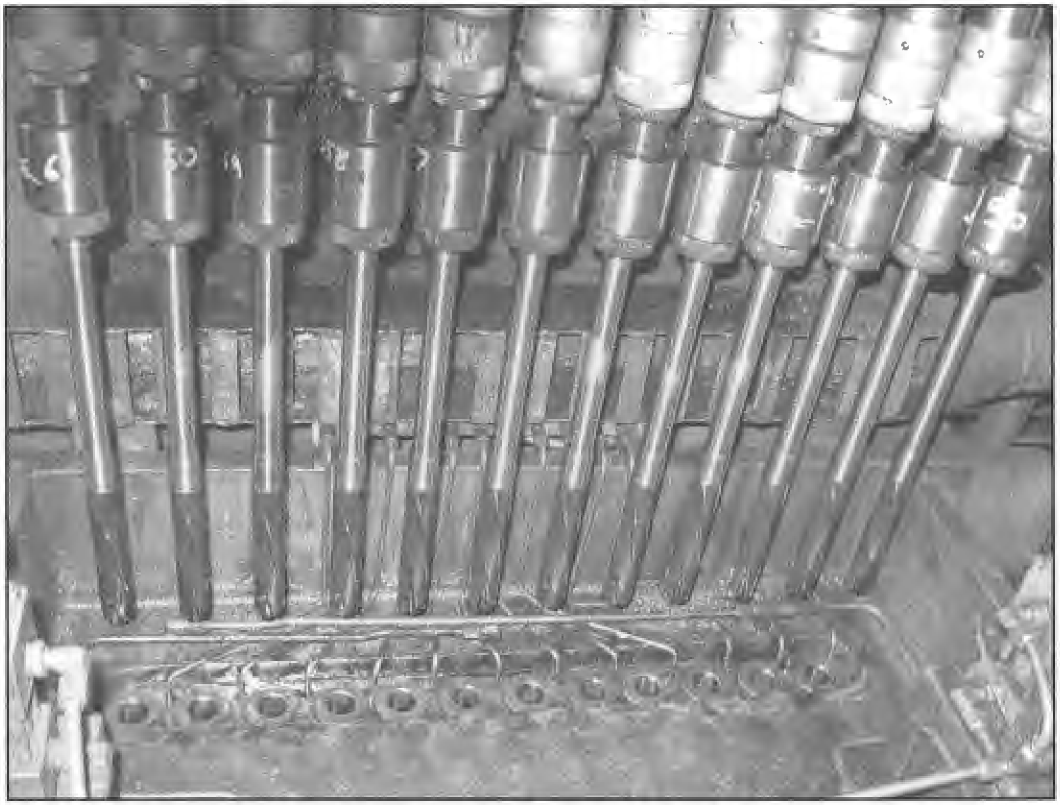


Figure 7. Twelve Spindle finish ream station loaded with test reamers.

Processes Used to Achieve Surface Roughness of 0.8μm

"Super abrasive reaming process can produce bores which are accurately sized, round, and cylindrical to the order of 0.001 micrometer or better. The surface finish resulting from super abrasive reaming usually ranges from 0.025 to 0.25µm and is largely independent of process parameters such as speed, feed, depth of cut, and abrasive grit size. Diametrical stock removal in abrasive reaming is typically no more then 30µm, so size tolerance on previous bores must be of the order of 10µm" (Arunachalam & Rajendran, 2005). Super abrasive reaming combines conventional reaming processes, identified earlier in paper, and adds one more process, an additional single pass using a super abrasive tool. This could mean for a process in place that uses fixed non-flexible multi-spindles; a new piece of machinery would have to be added to accommodate the super abrasive process. If machines are flexible it is possible to satisfy specifications by adding new tooling. Figure 8 and Figure 9 are examples of super abrasive tools.

Figure 8. Examples of super abrasive tools (Arunachalam & Rajendran, 2005).

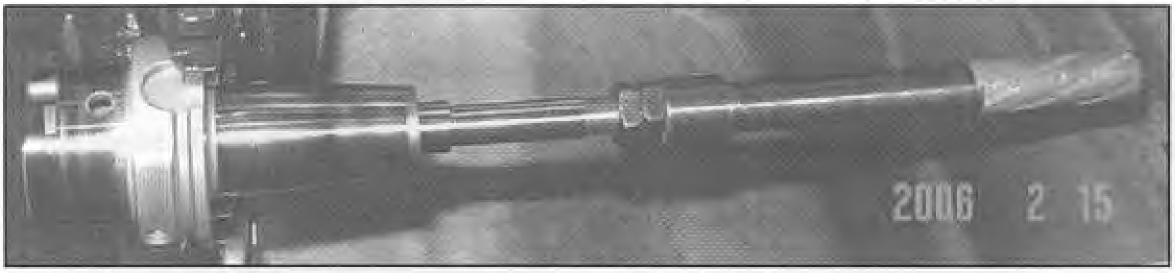


Figure 9. Example of a super abrasive tool used in machining center.

"A super abrasive tool consists of a tapered, helically barrel shaped sleeve on a tapered arbor. The diameter of reamer is adjusted by axial movement of the sleeve along the arbor. The sleeve is electroplated with abrasive particle commonly cubic boron nitride or natural diamond" (Arunachalam & Rajendran, 2005).

Increased Strain on Meeting Part Quality

In today's competitive manufacturing and design arenas, quality is the number one reason for keeping the customer happy. One area that is affecting manufacturing is the challenge of meeting tighter tolerances, assuring that all parts satisfy specifications. With the advent of trying to achieve zero defects, manufacturers are challenged to meet a capability index, (Cpk) of 1.67. In some cases this may mean making additional investments in equipment and tools. Is meeting capability really worth making additional investments? Enter the utilization of the super abrasive tool. As a result, processes must have minimal variability. Variables can impact process if not functioning properly. Delays affect process capability as well as drive up operating costs which reduce overall profit. Applications that typically require a higher level of surface control to perform optimally are bearings, pistons, and gears. (ASME B46.1-2002 Standard, 2002).

Validating surface roughness can be difficult, especially when surface roughness is reduced, along with the challenge of physically measuring actual features. The backbone of this research is based on finding a process that can generate a surface with a maximum roughness of 0.8um and continue meeting specification time and time again. If process is to meet 1.67 Cpk on surface roughness then that means that surface must have an actual surface roughness of approximately 0.47μm. Process variability must be held to a minimum. The smallest change in process will have unacceptable results. Variability may occur in areas of tool geometry, tool setting, tool life, machine reliability, maintainability, tool changes, chip removal, coolant filtration, change in temperature, and others. Validating surface finish becomes increasingly difficult. To begin with, parts need to be free of contamination such as coolant, small reaming chips, oils, and other chips from previous processes. Once part is clean, and part temperature has equalized to ambient temperature, it is ready to be inspected. It is interesting to note that there is little information on how to study surface roughness from a capability perspective. Relying on the Surface Texture ASME standard, the normal approach to determining if surface in question meets specifications is by implementing an inspection comparison process. ASME B46.1 permits considerable latitude in the method of producing and inspecting a surface, it specifies limits on the characteristics of measuring instruments, roughness, comparison specimens, and precision reference specimens. These specifications are essential for the reliable measurement of surface parameters and are necessary for establishing and maintaining control of surface texture. The roughness comparison specimens allow engineers or designers to obtain an approximate idea of the surface textures produced by various machining processes. The instruments permit the accurate measurement of characterization parameters for surfaces generated in production. The precision reference specimens provide an accurate means of calibrating the measuring instruments (ASME B46.1-2002 Standard, 2002).

One of the methods of control and inspection covered in ASME B46.1 is the use of pilot specimens. These specimens are actual parts from production that conform to specified surface requirements listed on part print. Once specimens have been validated using calibrated measuring instruments, they can be used to control process. Because specimens are of the same size, shape, material, and have the same physical characteristics as production parts, it is often possible for the operator to determine by sight or feel when production parts deviate significantly from pilot specimen (ASME B46.1-2002 Standard, 2002).

Definition of Terms

Listed definitions are useful for helping reader to understand presented literature and experimental research.

Brinell Hardness Number: (BHN) refers to measured value of an indentation in the surface of the material based on a specific load and size of ball being forced into material (ASM Handbook, 1995). Formula for calculation BHN is:

P=Force (kgf), D=Diameter of indenter (mm), d=Diameter of indentation (mm)

$$\boxed{\mathrm{BHN} = \frac{2P}{\pi D(D - \sqrt{(D^2 - d^2)})}}$$

Control Charts: A control chart is a chart with upper and lower control limits on which actual values results from a series of samples or subgroups are plotted. The chart frequently shows a central line to help detect a trend of plotted values to either the upper or lower control limits (Summers, 2003).

Cp: Capability Index, A capability index is equal to 1.00 then the process is feasible. If the capability index is greater then 1.00 then process is capable and is desirable (Summers, 2003). The greater the value the better

Cpk: A process capability index by which process capability can be benchmarked (Summers, 2003). Formulas for calculating Cpk are:

$$\boxed{\begin{aligned} \hat{C}_p &= \frac{USL - LSL}{6 \times \hat{\sigma}} \\ \hat{C}_{p.lower} &= \frac{\hat{\mu} - LSL}{3 \times \hat{\sigma}} \\ \hat{C}_{p.upper} &= \frac{USL - \hat{\mu}}{3 \times \hat{\sigma}} \\ \hat{C}_{pk} &= \min\left[\frac{USL - \hat{\mu}}{3 \times \hat{\sigma}}, \frac{\hat{\mu} - LSL}{3 \times \hat{\sigma}}\right] \end{aligned}}$$

Evaluation Length: Evaluation length is the actual length of surface measured during traversing stylist across surface. From this length data will be collected (*Phase Two, The Source of Quality,* 2006).

Friction: The rubbing of objects against another. Friction is also the resistive force between two objects that resists relative motion between the two objects (Merriam-Webster Online Dictionary, 2006).

Friction Coefficient: Is the ratio of the frictional resistance force to the normal force which presses the surfaces together (Oberg et al., 1982).

Gauge R&R: Gauge repeatability and reliability is the evaluation of a particular gauge to determine its accuracy. This is done by taking multiple measurements of one object, usually operated by three different people, to determine how repeatable and reproducible the gauge is over that particular period (Summers, 2003).

LSL: Lower spec limit, lower process limit (Summers, 2003).

Process Capability: Is the ability a manufacturing process can perform day in and day out based on meeting specifications set by the customer or designer (Summers, 2003).

Profilometer: A Profilometer is a laboratory measuring instrument that uses a stylus to measure a feature's surface finish. This devise strokes the surface determining length or depth of surface (*Phase Two, The Source of Quality,* 2006).

Ra: Ra is the arithmetic average of the absolute values of the roughness profile ordinates, also known as arithmetic average (AA) or center line average (CLA). The average roughness is the area between the roughness profile and its mean line, or the integral of the absolute value of the roughness profile height over the evaluation length (*Phase Two, The Source of Quality,* 2006).

Reaming: Reaming is a machining process in which a tool with two, four, or six sharp edges is rotated in a round hole. While tool is rotating it is removing a very small amount of material. This process will improve roundness, ovality, and size of the hole as well as improve surface roughness. Most reamers have two or more flutes either parallel to the tool axis or in a helix. Finish reaming process typically removes 0.020 in stock per diameter (ASM Handbook, 1995).

Sampling Length: Sampling length is the distance measured when scanning surface for roughness evaluation. Its length is equal to the cutoff wavelength (*Phase Two, The Source of Quality,* 2006).

Surface Finish: A part surface has two important aspects that must be defined and controlled. The first: geometric irregularities of the surface, and the second, metallurgical alterations of surface and surface layer. This second aspect has been termed surface integrity. Both surface finish and surface integrity must be defined, measured, and maintained within specified limits in the processing of any product. Standards have been adopted for surface finish and are available in ANSI/ASME B46.1-1985. A companion standard for surface texture symbols is ANSI Y14.36-1978. The standard for surface integrity is ANSI B211.1-1986 (ASM International Handbook, 1998).

Traversing Length: Traversing Length is the overall length traveled by the stylus when acquiring the traced profile (*Phase Two, The Source of Quality,* 2006).

USL: Upper spec limit, upper process limit (Summers, 2003).

CHAPTER 3

RESEARCH DESIGN AND METHODOLOGY

Research Design

The critical fact that research will prove through quantitative experimental research is that the experimental reamer, combination solid carbide spiral straight flute finish reamer, performs superior over current controlled spiral carbide tipped reamer. The dependent variable, which is the resultant surface finish of roller follower bores, (Ra), is the subject of this quantitative research study. It should be noted that all independent variables will be held constant with the exception of the difference in design of the controlled and experimental reamers. Six experimental reamers, (spindles 50 through 55), and six controlled reamers, (spindles 56 through 61), will be tooled in the twelve spindle finish reamer station. These tools will be left in the finish ream station for over three thousand cycles. A minimum of 32 pieces will be randomly pulled immediately after finish reaming process, washed, neutralized, and delivered to the special investigation surface finish laboratory. Special attention will be taken to identify parts when processed to determine if usage and age of tool impacts surface finish.

In the laboratory, a qualified special investigator (SI) will use a calibrated profilometer to measure the surface finish of each of the twelve follower bores. The resultant measurements will be recorded in a table developed by the SI. The SI will use a pencil to populate table as measuring proceeds. Data will then be analyzed using standard statistics found in the basic Excel statistics package. It is critical to note that part cleanliness is a major concern. Extra attention will be taken to clean each bore assuring no contamination or small debris will be found in bores. Debris found in bores will add variability to measurements causing readings to be inaccurate. It is also important that the part being measured be neutralized and maintains a temperature of 70 degrees F, plus or minus 2 degrees. Finally, and most importantly, the operator performing measurements must have patience and be trained on how to use measuring instrumentation. Proper placement of stylus on surface of bore is an important step and needs to be optimized each and every time. It may take several tries to find the optimal spot in bore. This position will provide the best opportunity and results when taking measurements. Figure 10 and Figure 11 show actual measurement setup.

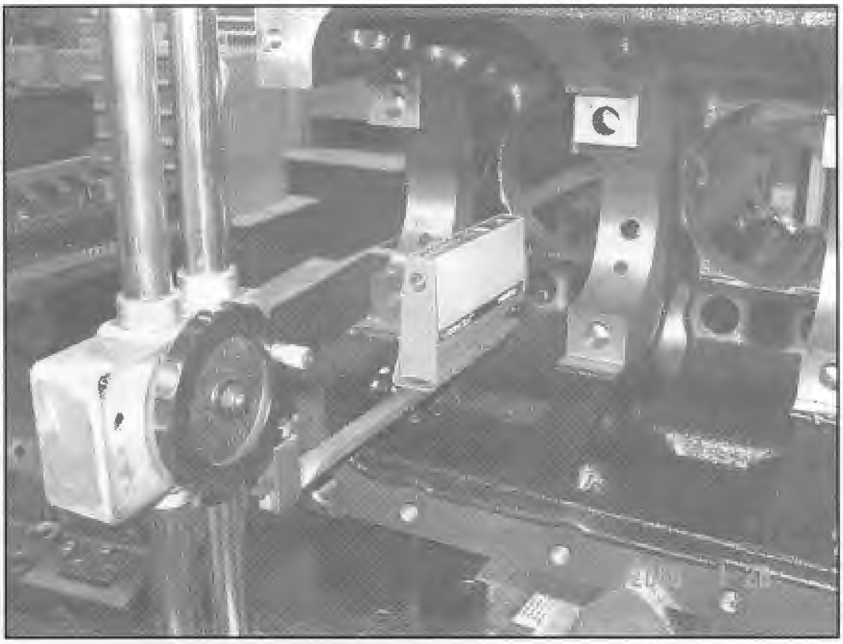


Figure 10. Surface roughness gauge set-up

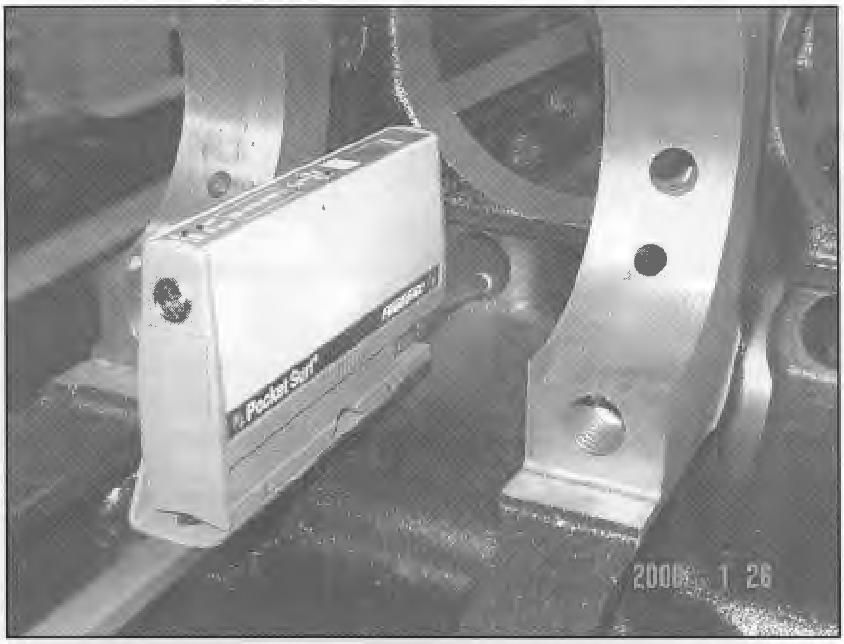


Figure 11. Surface roughness gauge set-up

The photo above shows the part resting on its side with pan rail facing operator. The instrument used to measure surface roughness is called a Pocket Surf, manufactured by Mahr. The instrument was fixtured on a stand that allows the special investigator freedom to adjust height and reposition instrument left and right.

Machine Operating Parameters / Independent Variables

It is important to mention the conditions testing will be performed and specific machine parameters. Prior to any testing, it is necessary to fill out a tool trial evaluation sheet. This document lists all machine specifics such as speeds, feeds, type of tool, etc. This also documents dates and times that test was performed. Figure 12 is an example of the form used during research.

Dept 524
Machine 4493
Operation 1190
Part Name Block, Cylinder
Material Cast Iron
Trial Start 25-Apr-08
Tool Description Finish Reamer
Vendor Northern Tool
Present Tool
Trial Tool
Test Data
Reason for Trial To test new type of reamer. Will determine if surface finish improves as a result of new tool.
Results of Trial
Machine Type
Coolant
Cutting Parameters
Chip Load
Test Procedure

Figure 12. Tool evaluation sheet identifying independent variables.

Highlighted in Figure 13 are independent variables that are most important to research. Independent variables must be known and controlled at all times. If any of these parameters were to change, then there could be an effect on the dependent variable, surface roughness of the roller follower bore. Uncontrolled variability is not acceptable and will cause less than desirable results.

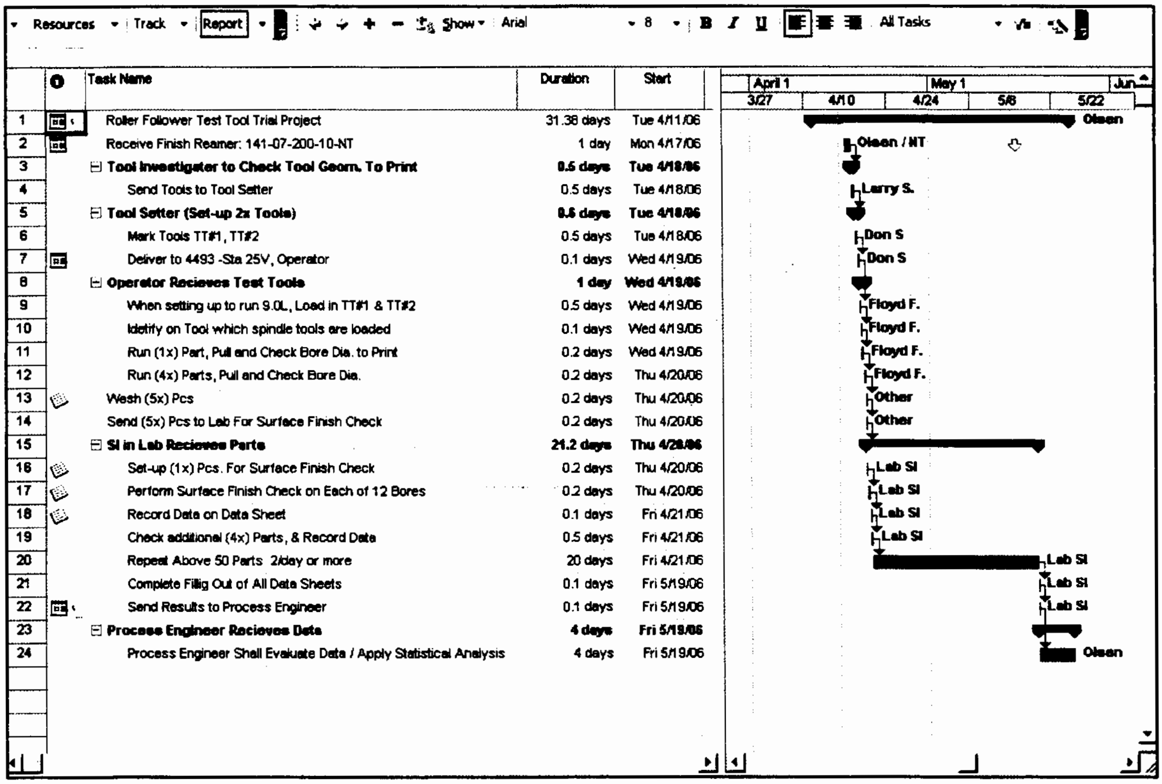
Tool Information	in
Tool Diameter	1.125
Tool Length	21
Cutting Parameters	
RPM	388
SFPM	114.22
IMP	3.104
IPR	0.008

Figure 13. Machine operating parameters

The machine used during research was a twelve spindle finish reaming station and has both lower guide and upper whip bushings. The feed rate during reaming remained constant and retraction feed was double the in-feed. Cutting fluid used was honing grade oil. This was used for lubricating and cooling of tool, as well as evacuation of small chips.

Project Schedule

A project schedule was developed to identify critical path as well as act as a management tool that highlighted activities and responsibilities of individuals who were involved during experimentation. Figure 14 is a copy of the project schedule that was developed in the planning phase of research.



	Task Name	Duration	Start
1	Roller Follower Test Tool Trial Project	31.38 days	Tue 4/11/06
2	Receive Finish Reamer: 141-07-200-10-NT	1 day	Mon 4/17/06
3	**⊟ Tool Investigater to Check Tool Geom. To Print**	**0.5 days**	**Tue 4/18/06**
4	Send Tools to Tool Setter	0.5 days	Tue 4/18/06
5	**⊟ Tool Setter (Set-up 2x Tools)**	**0.5 days**	**Tue 4/18/06**
6	Mark Tools TT#1, TT#2	0.5 days	Tue 4/18/06
7	Deliver to 4493 -Sta 25V, Operator	0.1 days	Wed 4/19/06
8	**⊟ Operator Recieves Test Tools**	**1 day**	**Wed 4/19/06**
9	When setting up to run 9.0L, Load in TT#1 & TT#2	0.5 days	Wed 4/19/06
10	Idetify on Tool which spindle tools are loaded	0.1 days	Wed 4/19/06
11	Run (1x) Part, Pull and Check Bore Dia. to Print	0.2 days	Wed 4/19/06
12	Run (4x) Parts, Pull and Check Bore Dia.	0.2 days	Thu 4/20/06
13	Wash (5x) Pcs	0.2 days	Thu 4/20/06
14	Send (5x) Pcs to Lab For Surface Finish Check	0.2 days	Thu 4/20/06
15	**⊟ SI in Lab Recieves Parts**	**21.2 days**	**Thu 4/20/06**
16	Set-up (1x) Pcs. For Surface Finish Check	0.2 days	Thu 4/20/06
17	Perform Surface Finish Check on Each of 12 Bores	0.2 days	Thu 4/20/06
18	Record Data on Data Sheet	0.1 days	Fri 4/21/06
19	Check additional (4x) Parts, & Record Data	0.5 days	Fri 4/21/06
20	Repeat Above 50 Parts 2/day or more	20 days	Fri 4/21/06
21	Complete Fillig Out of All Data Sheets	0.1 days	Fri 5/19/06
22	Send Results to Process Engineer	0.1 days	Fri 5/19/06
23	**⊟ Process Engineer Recieves Data**	**4 days**	**Fri 5/19/06**
24	Process Engineer Shall Evaluate Data / Apply Statistical Analysis	4 days	Fri 5/19/06

Figure 14. Project schedule

Material

Material used during study was gray cast iron. Gray cast iron is considered the most versatile of all foundry metals. The ease of melting, casting, and machining is due to high levels of carbon. A couple characteristics that make gray cast iron a primary choice for material are low shrinkage rates and the fluidity of material during casting process. By modifying material during casting process, one can achieve a large range of tensile strengths; from 20,000 to over 60,000 pounds per square inch (psi). Material hardness can also vary from 100 to 300 BHN in an as-cast condition (Krause, 1969).

Data Description

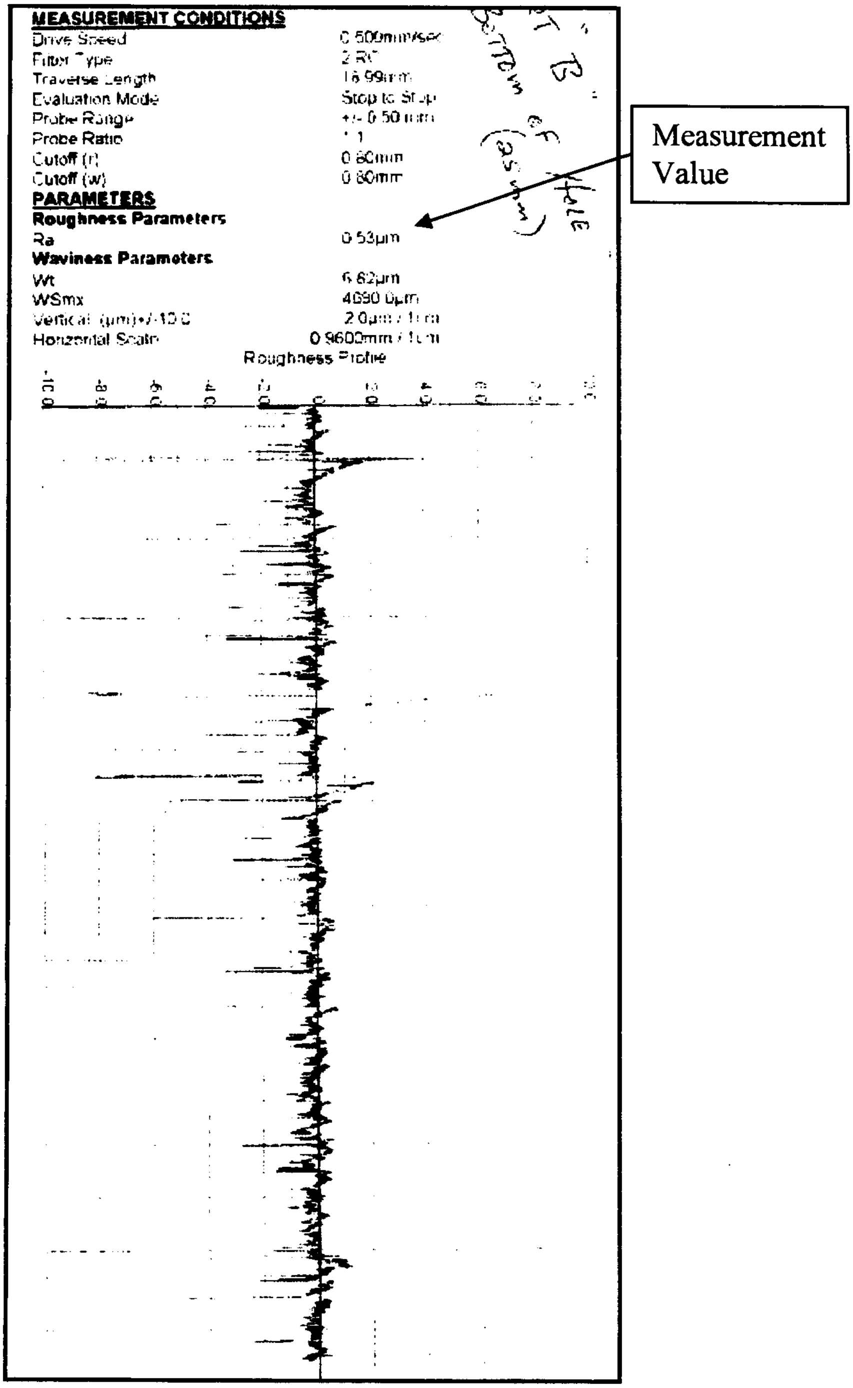
Research depends heavily on the accuracy and reliability of the surface roughness gauge. Figure 15 highlights actual specifications for instrument used.

Pocket Surf Unit Specifications:	
Unit: Pocket Surf	PDR-8
Measuring Range:	
Ra	0,03um to 6,35 um
Ry	0,2um to 25,3 um
Rmax	0,2um to 25,3 um
Rz	0,2um to 25,3 um
Disply Resolution	0.01um
Measurment Accuracy	Meets ASME B46.1, ISO, and Din Standards
Traverse Length	2 mm
Evaluation Length	0.8mm
Cutoff Position	1
Probe Type	Piezoelectric
Max Styles Force	15.0 mN
Operating Temp	10 to 45 C

Figure 15. Surface roughness gauge specifications

It is important to highlight units of measurement used during measuring of samples. The unit of measurement is metric and designated as μm, meaning micrometer. One micrometer equals one millionth of a meter or one thousands of a millimeter.

Figure 16 is an example of an actual strip chart with resultant surface roughness measurement data.



MEASUREMENT CONDITIONS

Drive Speed	0.500mm/sec
Filter Type	2 RC
Traverse Length	16.99mm
Evaluation Mode	Stop to Stop
Probe Range	+/- 0.50 mm
Probe Ratio	1:1
Cutoff (r)	0.80mm
Cutoff (w)	0.80mm
PARAMETERS	
Roughness Parameters	
Ra	0.53µm
Waviness Parameters	
Wt	6.62µm
WSmx	4690.0µm
Vertical (µm)+/-10.0	2.0µm / 1mm
Horizontal Scale	0.9600mm / 1mm

Roughness Profile

Measurement Value

Figure 16. Sample Strip Chart from Research

Data Collection

41 total parts were randomly selected over a three thousand part production run. There are twelve bores per engine, six will be reamed using experimental reamers, and the other six will be reamed using the controlled production reamers. After parts were machined, they were sent to the SI lab where a special investigator measured surface roughness of each bore. The part fixture was mounted to a granite base and was used to secure parts during measuring. The fixture remained set-up until all parts had been measured. Data collected during the measurement process was recorded and saved in a Microsoft Excel spreadsheet. Specific Microsoft Excel statistical modules were then used to analyze data, specifically the F and T-Tests. Another important part of this research was to determine if tools used satisfied process capability requirements. A capability index target of 1.67 was used to compare all data. Because resultant data did not resemble a normal distribution, data was converted to log normal format. Once in log normal format, standard capability calculations were used to calculate the 95% log normal value. This value was then converted back to normal format from which the capability of process was determined. Control charts along with histograms were used to help describe research results.

CHAPTER 4

DATA ANALYSIS

Data gathered during experiment was collected from two populations. The first population, produced by the experimental combination spiral straight finish reamer, consisted of measured surface roughness found in follower bores 50 through 55. The second population, produced by the controlled spiral finish reamer, consisted of measured surface roughness found in follower bores 56 through 61. The number of sample parts measured totaled 41.

Experimental Data

Tables 1 and 2 contain reflected collected data, experimental and controlled data respectively. Combination Spiral Straight, (CSS), refers to the six experimental reamers, and Standard, (STD) refers to the six controlled current production reamers. Table 1 represents non converted normal data and table 2 represents normal data converted to log normal format.

Table 1

Surface roughness measurements recorded during research

Part #	CSS Hole 50	CSS Hole 51	CSS Hole 52	CSS Hole 53	CSS Hole 54	CSS Hole 55	AVG Holes 50-55	STD Hole 56	STD Hole 57	STD Hole 58	STD Hole 59	STD Hole 60	STD Hole 61	AVG Holes 56-61
1	0.48	0.79	0.70	0.36	0.52	0.77	0.60	0.69	0.91	0.64	1.21	0.50	0.59	0.76
2	0.58	0.85	0.59	0.84	0.35	0.66	0.65	0.54	0.95	0.41	0.55	0.41	0.58	0.57
3	0.76	0.91	0.85	0.56	0.57	0.50	0.69	0.81	0.96	0.75	1.43	0.43	0.87	0.88
4	0.55	0.84	0.85	0.37	0.55	0.67	0.64	0.51	0.59	0.48	0.80	0.74	0.75	0.65
5	0.53	0.85	0.85	0.34	0.69	0.67	0.66	0.45	0.74	0.51	0.91	0.35	0.93	0.65
6	0.31	0.69	0.76	0.36	0.61	0.84	0.60	0.91	0.83	0.75	1.59	0.40	0.64	0.85
7	0.31	0.59	0.80	0.39	0.70	0.74	0.59	1.14	0.88	0.47	1.15	0.46	0.64	0.79
8	0.30	0.85	0.83	0.35	0.97	0.65	0.66	1.54	0.73	0.48	0.69	0.38	1.13	0.83
9	0.33	0.49	0.88	0.38	0.44	0.81	0.56	0.61	0.86	0.53	0.84	0.34	0.76	0.66
10	0.34	0.87	0.74	0.40	0.76	0.54	0.61	0.56	0.62	0.43	0.69	0.33	0.79	0.57
11	0.37	0.85	0.73	0.49	0.47	0.73	0.61	0.75	0.96	0.45	0.95	0.41	0.68	0.70
12	0.34	0.59	0.41	0.45	0.64	0.35	0.46	1.46	0.65	0.63	1.10	0.39	0.83	0.84
13	0.35	0.53	0.52	0.36	0.39	0.60	0.46	0.84	0.67	0.69	1.06	0.35	0.83	0.74
14	0.38	0.35	0.50	0.43	0.37	0.49	0.42	0.98	1.16	0.86	0.54	0.47	0.84	0.81
15	0.36	0.41	0.40	0.24	0.61	0.50	0.42	1.05	0.46	0.63	0.68	0.49	1.25	0.76
16	0.29	0.78	0.57	0.33	0.67	0.87	0.59	1.00	0.93	0.45	1.22	0.27	1.08	0.83
17	0.45	0.52	0.37	0.31	0.70	0.82	0.53	0.70	0.80	0.47	0.81	0.46	0.92	0.69
18	0.51	0.44	0.41	0.55	0.85	0.71	0.58	0.80	0.73	0.65	0.62	0.85	1.06	0.79
19	0.40	0.48	0.47	0.31	0.73	0.69	0.51	1.19	0.94	0.55	0.71	0.55	1.25	0.87
20	0.70	0.52	0.59	0.57	0.59	0.75	0.62	0.90	0.86	0.41	1.16	0.55	1.04	0.82
21	0.34	0.43	0.52	0.55	0.72	0.75	0.55	0.87	0.70	0.81	1.06	0.54	1.13	0.85
22	0.38	0.46	0.43	0.35	0.45	0.61	0.45	0.95	0.96	0.64	0.97	0.53	1.04	0.85
23	0.64	0.79	0.44	0.45	0.34	0.50	0.53	0.73	0.81	0.47	1.04	0.48	0.96	0.75
24	0.43	0.55	0.26	0.53	0.45	0.58	0.47	0.61	0.86	0.38	0.65	0.34	1.38	0.70
25	0.45	0.51	0.38	0.49	0.29	0.64	0.46	0.70	0.98	0.81	0.44	0.40	1.15	0.75
26	0.40	0.36	0.37	0.53	0.31	0.45	0.40	1.13	0.72	0.73	1.00	1.34	1.02	0.99
27	0.47	0.67	0.62	0.73	0.54	0.65	0.61	0.83	0.94	0.73	0.78	1.57	1.48	1.06
28	0.63	0.49	0.53	0.53	0.31	0.58	0.51	0.86	1.54	0.78	0.99	0.67	1.11	0.99
29	0.33	0.31	0.20	0.30	0.54	0.52	0.37	0.58	1.05	0.53	0.91	0.71	1.00	0.80
30	0.49	0.32	0.36	0.33	0.33	0.59	0.40	0.79	1.22	0.41	0.52	0.33	1.15	0.74
31	0.47	0.51	0.31	0.50	0.50	0.50	0.47	0.68	0.55	0.80	1.35	0.35	1.22	0.83
32	0.44	0.29	0.36	0.36	0.40	0.69	0.42	0.59	0.69	0.62	0.55	0.33	1.04	0.64
33	0.44	0.33	0.52	0.30	0.30	0.42	0.39	0.88	1.10	0.53	1.06	0.38	1.13	0.85
34	0.41	0.42	0.39	0.29	0.43	0.44	0.40	0.84	0.97	0.52	0.64	0.41	0.91	0.72
35	0.45	0.27	0.63	0.55	0.30	0.52	0.45	0.44	1.33	0.46	0.78	0.36	1.03	0.73
36	0.47	0.32	0.28	0.35	0.23	0.44	0.35	0.72	0.74	0.52	0.94	0.47	1.35	0.79
37	0.35	0.36	0.35	0.41	0.34	0.68	0.42	0.54	0.91	0.64	1.26	0.50	0.75	0.77
38	0.47	0.57	0.35	0.37	0.53	0.82	0.52	0.68	1.19	1.26	1.37	1.51	1.55	1.26
39	0.69	0.49	0.25	0.46	0.29	0.45	0.44	0.75	0.55	0.48	0.93	0.35	1.02	0.68
40	0.44	0.52	0.23	0.33	0.55	0.59	0.44	0.91	1.14	0.96	0.78	0.39	1.20	0.90
41	0.67	0.34	0.54	0.47	0.40	0.61	0.51	0.51	0.93	0.57	0.71	0.48	0.94	0.69

Table 2

Surface roughness data converted to log normal format

Part #	CSS Hole 50	CSS Hole 51	CSS Hole 52	CSS Hole 53	CSS Hole 54	CSS Hole 55	AVG Holes 50-55	STD Hole 56	STD Hole 57	STD Hole 58	STD Hole 59	STD Hole 60	STD Hole 61	AVG Holes 56-61
1	-0.73	-0.24	-0.36	-1.02	-0.65	-0.26	-0.51	-0.37	-0.09	-0.45	0.19	-0.69	-0.53	-0.32
2	-0.54	-0.16	-0.53	-0.17	-1.05	-0.42	-0.44	-0.62	-0.05	-0.89	-0.60	-0.89	-0.54	-0.60
3	-0.27	-0.09	-0.16	-0.58	-0.56	-0.69	-0.37	-0.21	-0.04	-0.29	0.36	-0.84	-0.14	-0.19
4	-0.60	-0.17	-0.16	-0.99	-0.60	-0.40	-0.45	-0.67	-0.53	-0.73	-0.22	-0.30	-0.29	-0.46
5	-0.63	-0.16	-0.16	-1.08	-0.37	-0.40	-0.42	-0.80	-0.30	-0.67	-0.09	-1.05	-0.07	-0.50
6	-1.17	-0.37	-0.27	-1.02	-0.49	-0.17	-0.52	-0.09	-0.19	-0.29	0.46	-0.92	-0.45	-0.24
7	-1.17	-0.53	-0.22	-0.94	-0.36	-0.30	-0.53	0.13	-0.13	-0.76	0.14	-0.78	-0.45	-0.31
8	-1.20	-0.16	-0.19	-1.05	-0.03	-0.43	-0.42	0.43	-0.31	-0.73	-0.37	-0.97	0.12	-0.31
9	-1.11	-0.71	-0.13	-0.97	-0.82	-0.21	-0.59	-0.49	-0.15	-0.63	-0.17	-1.08	-0.27	-0.47
10	-1.08	-0.14	-0.30	-0.92	-0.27	-0.62	-0.50	-0.58	-0.48	-0.84	-0.37	-1.11	-0.24	-0.60
11	-0.99	-0.16	-0.31	-0.71	-0.76	-0.31	-0.50	-0.29	-0.04	-0.80	-0.05	-0.89	-0.39	-0.41
12	-1.08	-0.53	-0.89	-0.80	-0.45	-1.05	-0.77	0.38	-0.43	-0.46	0.10	-0.94	-0.19	-0.26
13	-1.05	-0.63	-0.65	-1.02	-0.94	-0.51	-0.78	-0.17	-0.40	-0.37	0.06	-1.05	-0.19	-0.35
14	-0.97	-1.05	-0.69	-0.84	-0.99	-0.71	-0.87	-0.02	0.15	-0.15	-0.62	-0.76	-0.17	-0.26
15	-1.02	-0.89	-0.92	-1.43	-0.49	-0.69	-0.87	0.05	-0.78	-0.46	-0.39	-0.71	0.22	-0.34
16	-1.24	-0.25	-0.56	-1.11	-0.40	-0.14	-0.54	0.00	-0.07	-0.80	0.20	-1.31	0.08	-0.32
17	-0.80	-0.65	-0.99	-1.17	-0.36	-0.20	-0.64	-0.36	-0.22	-0.76	-0.21	-0.78	-0.08	-0.40
18	-0.67	-0.82	-0.89	-0.60	-0.16	-0.34	-0.55	-0.22	-0.31	-0.43	-0.48	-0.16	0.06	-0.26
19	-0.92	-0.73	-0.76	-1.17	-0.31	-0.37	-0.67	0.17	-0.06	-0.60	-0.34	-0.60	0.22	-0.20
20	-0.36	-0.65	-0.53	-0.56	-0.53	-0.29	-0.48	-0.11	-0.15	-0.89	0.15	-0.60	0.04	-0.26
21	-1.08	-0.84	-0.65	-0.60	-0.33	-0.29	-0.59	-0.14	-0.36	-0.21	0.06	-0.62	0.12	-0.19
22	-0.97	-0.78	-0.84	-1.05	-0.80	-0.49	-0.81	-0.05	-0.04	-0.45	-0.03	-0.63	0.04	-0.19
23	-0.45	-0.24	-0.82	-0.80	-1.08	-0.69	-0.64	-0.31	-0.21	-0.76	0.04	-0.73	-0.04	-0.34
24	-0.84	-0.60	-1.35	-0.63	-0.80	-0.54	-0.76	-0.49	-0.15	-0.97	-0.43	-1.08	0.32	-0.47
25	-0.80	-0.67	-0.97	-0.71	-1.24	-0.45	-0.78	-0.36	-0.02	-0.21	-0.82	-0.92	0.14	-0.36
26	-0.92	-1.02	-0.99	-0.63	-1.17	-0.80	-0.91	0.12	-0.33	-0.31	0.00	0.29	0.02	-0.03
27	-0.76	-0.40	-0.48	-0.31	-0.62	-0.43	-0.49	-0.19	-0.06	-0.31	-0.25	0.45	0.39	0.01
28	-0.46	-0.71	-0.63	-0.63	-1.17	-0.54	-0.67	-0.15	0.43	-0.25	-0.01	-0.40	0.10	-0.05
29	-1.11	-1.17	-1.61	-1.20	-0.62	-0.65	-1.00	-0.54	0.05	-0.63	-0.09	-0.34	0.00	-0.26
30	-0.71	-1.14	-1.02	-1.11	-1.11	-0.53	-0.91	-0.24	0.20	-0.89	-0.65	-1.11	0.14	-0.43
31	-0.76	-0.67	-1.17	-0.69	-0.69	-0.69	-0.77	-0.39	-0.60	-0.22	0.30	-1.05	0.20	-0.29
32	-0.82	-1.24	-1.02	-1.02	-0.92	-0.37	-0.86	-0.53	-0.37	-0.48	-0.60	-1.11	0.04	-0.51
33	-0.82	-1.11	-0.65	-1.20	-1.20	-0.87	-0.95	-0.13	0.10	-0.63	0.06	-0.97	0.12	-0.24
34	-0.89	-0.87	-0.94	-1.24	-0.84	-0.82	-0.92	-0.17	-0.03	-0.65	-0.45	-0.89	-0.09	-0.38
35	-0.80	-1.31	-0.46	-0.60	-1.20	-0.65	-0.79	-0.82	0.29	-0.78	-0.25	-1.02	0.03	-0.43
36	-0.76	-1.14	-1.27	-1.05	-1.47	-0.82	-1.05	-0.33	-0.30	-0.65	-0.06	-0.76	0.30	-0.30
37	-1.05	-1.02	-1.05	-0.89	-1.08	-0.39	-0.88	-0.62	-0.09	-0.45	0.23	-0.69	-0.29	-0.32
38	-0.76	-0.56	-1.05	-0.99	-0.63	-0.20	-0.66	-0.39	0.17	0.23	0.31	0.41	0.44	0.20
39	-0.37	-0.71	-1.39	-0.78	-1.24	-0.80	-0.82	-0.29	-0.60	-0.73	-0.07	-1.05	0.02	-0.45
40	-0.82	-0.65	-1.47	-1.11	-0.60	-0.53	-0.81	-0.09	0.13	-0.04	-0.25	-0.94	0.18	-0.17
41	-0.40	-1.08	-0.62	-0.76	-0.92	-0.49	-0.68	-0.67	-0.07	-0.56	-0.34	-0.73	-0.06	-0.41

Statistical Analysis of Data

The first statistical analysis performed on data was to determine if resultant measured data found in Table 1 exhibited characteristics of a normal distribution. Figures 17 and 18 provide a visual representation of the frequency distribution of measured data. Histograms represent the averages of experimental reamers 50 through 55 and controlled reamers 56 through 61. In other words, in one part we have six follower bores that are reamed with experimental reamers, and six follower bores reamed with controlled reamers. The average measured results, per part, were calculated for both experimental and controlled finish reamers.

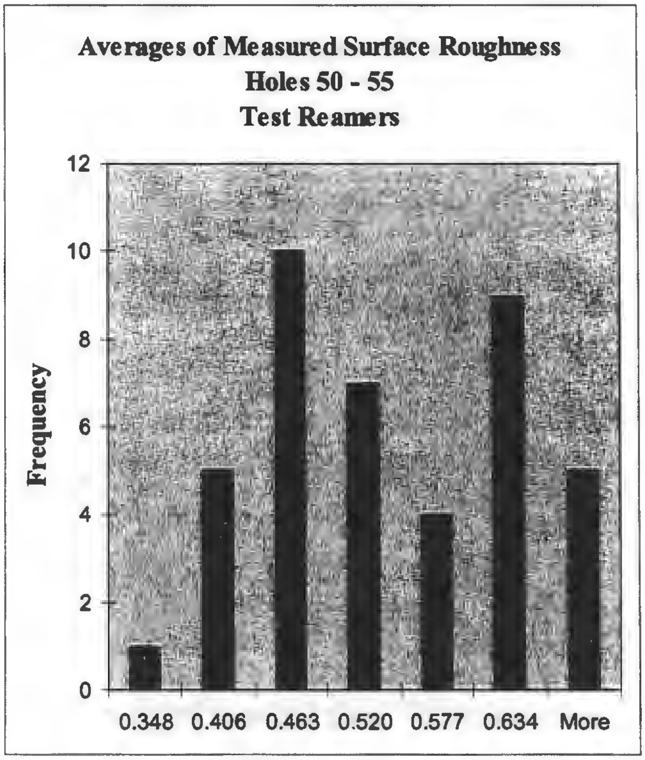


Figure 17. Averages of measured surface roughness holes 50-55 test reamers

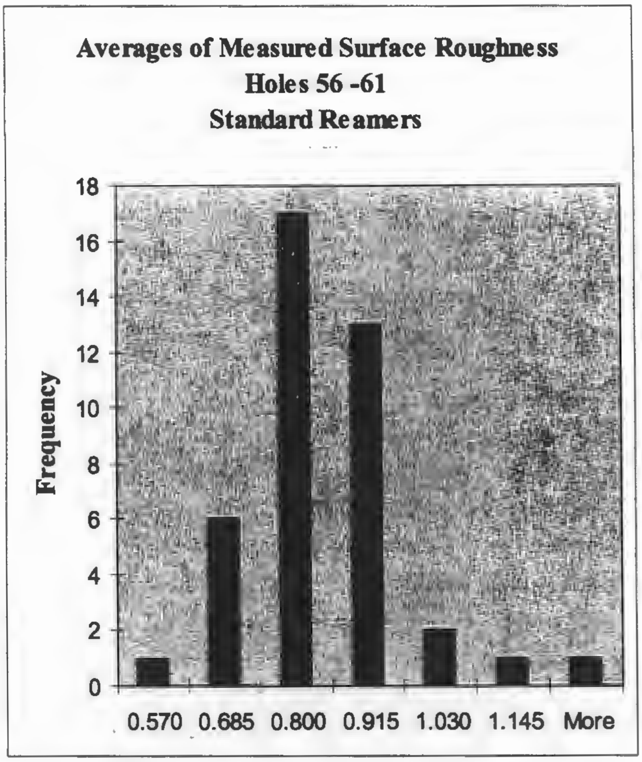


Figure 18. Averages of measured surface roughness holes 56-61 current reamers

Examining resultant histograms found in Figures 17 and 18, it is apparent resultant data did not follow a normal distribution. Since this was true, data was converted to log normal format. Doing this enabled standard normal distribution calculations be applied. Once calculations were completed, the 95% log normal value was converted back to 95% non log normal format. From this value the capability index of reaming process was calculated.

The second statistical evaluation performed on data consisted of performing basic statistical calculations on measured resultant data. The descriptive analysis module found in Microsoft Excel was used to perform calculations and results are listed in Table 3.

Table 3

Descriptive statistics results

	CSS Hole 50	CSS Hole 51	CSS Hole 52	CSS Hole 53	CSS Hole 54	CSS Hole 55	AVG Holes 50-55	STD Hole 56	STD Hole 57	STD Hole 58	STD Hole 59	STD Hole 60	STD Hole 61	AVG Holes 56-61
Mean	0.451	0.549	0.516	0.429	0.506	0.619	0.512	0.805	0.881	0.607	0.913	0.526	1.000	0.789
Std E	0.019	0.030	0.030	0.019	0.027	0.020	0.015	0.038	0.035	0.028	0.043	0.046	0.037	0.020
Median	0.440	0.510	0.500	0.390	0.500	0.610	0.512	0.790	0.880	0.550	0.910	0.430	1.020	0.785
Mode	0.470	0.850	0.850	0.360	0.550	0.500	0.403	0.540	0.960	0.640	1.060	0.350	1.130	0.790
Std Dev	0.120	0.193	0.195	0.122	0.173	0.131	0.093	0.246	0.222	0.178	0.274	0.296	0.234	0.129
Variance	0.014	0.037	0.038	0.015	0.030	0.017	0.009	0.061	0.049	0.032	0.075	0.088	0.055	0.017
Kurtosis	0.163	-1.005	-0.902	2.325	-0.172	-0.803	-1.169	1.493	0.887	3.103	-0.361	6.547	-0.216	3.578
Skewness	0.906	0.481	0.411	1.285	0.559	0.029	0.155	1.052	0.636	1.434	0.422	2.608	0.195	1.304
Range	0.47	0.64	0.68	0.60	0.74	0.52	0.34	1.10	1.08	0.88	1.15	1.30	0.97	0.69
Minimum	0.29	0.27	0.20	0.24	0.23	0.35	0.35	0.44	0.46	0.38	0.44	0.27	0.58	0.57
Maximum	0.76	0.91	0.88	0.84	0.97	0.87	0.69	1.54	1.54	1.26	1.59	1.57	1.55	1.26
Sum	18.50	22.51	21.14	17.57	20.73	25.39	20.97	33.02	36.11	24.89	37.44	21.57	41.02	32.34
Count	41	41	41	41	41	41	41	41	41	41	41	41	41	41

The next statistical analysis performed was to determine if sample data from the two different populations, experimental and controlled, have equal or unequal variances. Using the Excel F-test module, the calculated F value for the experimental reamer sample was found to be greater than F-critical. Since F-calculated is greater than F-critical, it can be stated there is a significant difference between the variance of each population. Since a significant difference exists between experimental and controlled reamer variances, the

Null Hypothesis can be rejected (Miller, Irwin, Freund & John, 1977). Note: Resultant averages per experimental and controlled tools were used in this calculation. See columns eight and fifteen found in Table 1, labeled AVG Holes 50-55, and AVG Holes 56-61.

Table 4

F-test results

F-Test Two-Sample for Variances		
	Std. Reamer	Test Reamer
Mean	0.78882114	0.51154472
Variance	0.01658378	0.00869908
Observations	41	41
df	40	40
F	1.90638322	
P(F<=f) one-tail	0.02218708	
F Critical one-tail	1.69279721	

The next analysis applied to resultant measured data was the T-test. The T-test analysis determined if a significant difference existed between experimental and controlled reamer population means (Miller et al., 1977).

Table 5

T-test results

t-Test: Two-Sample Assuming Unequal Variances		
	Std. Reamer	Test Reamer
Mean	0.78882114	0.51154472
Variance	0.01658378	0.00869908
Observations	41	41
Hypothesized Mean Difference	0	
df	73	
t Stat	11.1658482	
t Critical two-tail	1.9929971	

The results of the T-test verified that the value for t-stat was greater than t-critical two tail. This means a significant difference in means did in fact exist between experimental and controlled reamer populations. Therefore, the null hypothesis was rejected. The value of t-Stat could be compared to T-critical two tail in any T chart corresponding to the column headed by the 95% confidence level.

The next analysis completed on measured data focused on determining the capability index for both experimental and controlled reamers. Table 6 highlights statistical calculations performed on log normal data with a 95% confidence level, then converted back to normal 95%. The target capability index was 1.67. Based on output data, the upper spec limit (USL) was adjusted from 0.8μm.to1.55μm in order to satisfy index goal of 1.67. Figure 19 shows results of capability analysis in histogram form.

Table 6

Process capability index (Cpk) results

Reamer	Hole #	Max	Min	Range	Log Avg	Log Dev	95th Log	Median	95%tile	USL	Cpk
CSS	50	0.76	0.29	0.47	-0.828	0.253	-0.412	0.437	0.662	1.55	2.34
CSS	51	0.91	0.27	0.64	-0.660	0.353	-0.079	0.517	0.924	1.55	1.68
CSS	52	0.88	0.2	0.68	-0.735	0.394	-0.087	0.479	0.917	1.55	1.69
CSS	53	1.54	0.44	1.1	-0.883	0.263	-0.450	0.414	0.638	1.55	2.43
CSS	54	1.54	0.46	1.08	-0.740	0.347	-0.169	0.477	0.844	1.55	1.84
CSS	55	1.26	0.38	0.88	-0.502	0.219	-0.142	0.605	0.868	1.55	1.79
Std	56	0.84	0.24	0.6	-0.259	0.292	0.222	0.772	1.249	1.55	1.24
Std	57	1.59	0.44	1.15	-0.158	0.252	0.258	0.854	1.294	1.55	1.20
Std	58	1.57	0.27	1.3	-0.536	0.268	-0.095	0.585	0.909	1.55	1.70
Std	59	0.97	0.23	0.74	-0.136	0.307	0.370	0.873	1.447	1.55	1.07
Std	60	0.87	0.35	0.52	-0.739	0.401	-0.079	0.477	0.924	1.55	1.68
Std	61	1.55	0.58	0.97	-0.027	0.243	0.372	0.973	1.450	1.55	1.07

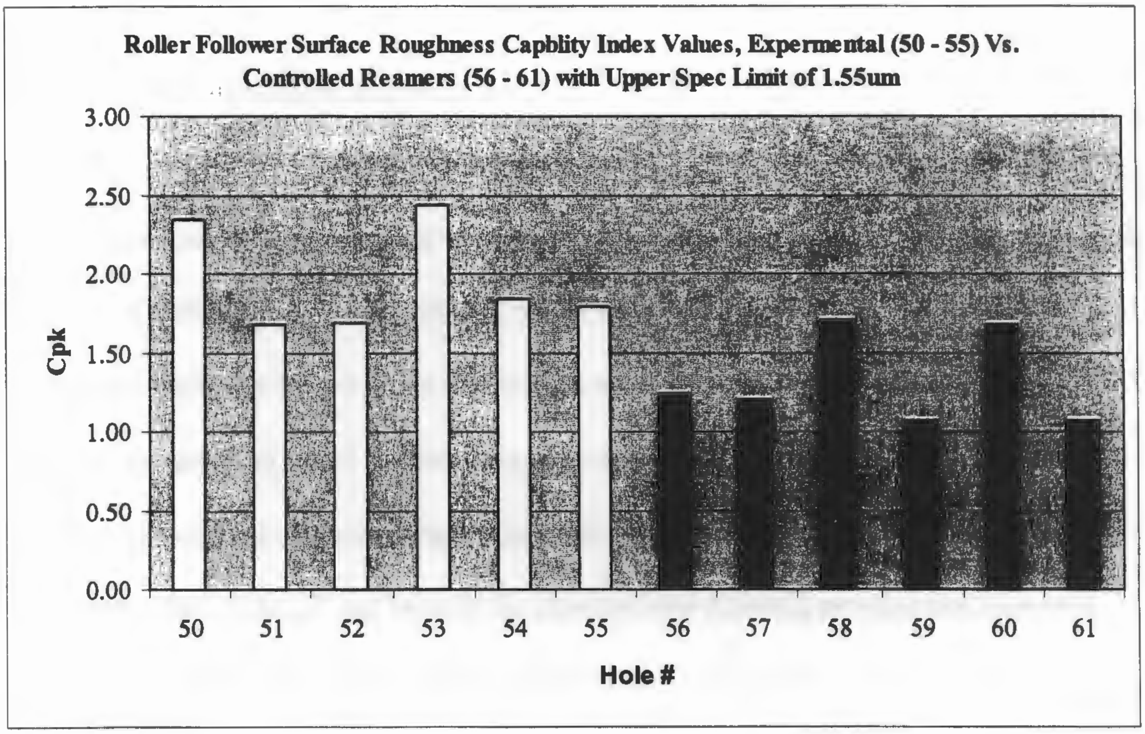


Figure 19. Process capability results highlighting test versus standard finish reamers.

Summarizing analysis performed on surface roughness resultant measured data. The F and T tests both rejected the Null Hypothesis. Regarding research question number two, process capability analysis results favored the experimental reamer over controlled finish reamer.

CHAPTER 5

DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

Discussions

This research proved to be valuable because patent pending newly designed finish reamer, (experimental), out-performed current production reamer, (controlled), by producing a follower bore with an improved surface roughness. Performance was validated by applying F and T tests along with calculating the process capability of both the experimental and controlled finish reamers. Because the experimental tool had a higher capability index, it can be said the experimental reaming process has improved stability and less variability over the controlled reaming process. However, the research did not satisfy all experimental expectations.

The capability calculation used an upper spec limit of 1.55μm not 0.8μm. From Table 3, surface roughness values varied from 0.20μm to 1.59μm, 1.54μm being the maximum value for experimental reamer. Unfortunately 1.54μm exceeded 0.80μm, thus promoting valuable discussions with product engineering which ultimately drove reassigning the upper spec limit to 1.55μm. Topics discussed with engineering included costs, changes to current process, gauging, plant layout, and product flow through manufacturing. It was noted that cost to implement a super abrasive process would range from one to three million dollars. Based on knowledge gained through discussions, better informed decisions focusing on return on investment were made. Changing upper spec limit to 1.55 meant manufacturing would not have to consider going to a super abrasive process, because targeted surface roughness values fall within standard reaming applications. See figure 3.

An additional topic brought to light through discussion was that lubrication influences life expectancy of roller follower bore, roller follower, and all components involved with valve train. If bearing surfaces are flooded with oil, the friction is almost independent of the nature of the material of the surfaces in contact. As lubrication is reduced, the coefficient of friction becomes more dependent upon the material of the surfaces (Oberg et al. 1982). This led the team to make product changes improving the flow of oil to roller follower, therefore improving life and running conditions between roller follower and follower bore. Though it is important to have a 0.8μm surface roughness in follower bore, the difference between 1.55μm and 0.8μm is less influential compared to not having sufficient lubrication. Not having sufficient lubrication greatly increases friction between follower and follower bore, ultimately decreasing life of components (*Lubrication Principles,* 1999).

The most challenging area of this research, besides project management, dealt with the science of measuring follower bores. It was found measuring surface roughness of a hole was not as easy as first expected. The special investigator had to locate the optimal stylist position when measuring, which at times took as long as ten minutes. An improved method of holding Profilometer stylus is being developed to save time and increase measuring efficiency.

Another key factor that influenced validity of measurement data was cleanliness of bores. Keeping follower bores as clean as possible was the goal of the special investigator. A clean rag was passed through each and every bore before measuring. This was the only way to rid each follower bore of fine debris.

Keeping track of tools, tool positions in spindles, and tool life was also key to the results of this study. Doing this enabled data to be examined from standpoint of trends and if any significant changes occurred from one sample to the next during production run. It was important to understand if experimental reamer performed better then controlled reamer with equal number of cutting cycles. During the machining of three thousand parts there were no noticeable trends between experimental and controlled reamers. Life of experimental reamers will continue to be monitored through future production runs so as to be able to benchmark tool change frequency. A positive statement at this point is that experimental reamers seem to have a similar life span as controlled reamers. Both experimental and controlled reamers are changed because size of follower bore goes small, not that surface roughness was degrading.

Finally, this manufacturing process involved a great deal of people and resources. Each person involved played an important roll towards achieving targeted goals. A process is only as strong as its weakest link. If any person fails with their part of the process, be it tool grinding, setting, loading, operator intervention and control, gauging, maintenance support, preventive maintenance, and many others, the process will not stand a chance and certain failure or less than desired results will occur. The supporting team of people involved in this research all performed to high standards.

Conclusions

Based on the null hypotheses H_{01}, there was in fact a difference between a process that demands a 0.8μm surface roughness verses 3.2μm. It was noted with a target of 0.8μm in order to perform at 1.67 Cpk at a 95% confidence level, the resultant surface roughness would have to run consistently at 0.47μm. A conventional finish reaming process would not have satisfied quality demands. A super abrasive process would have to be implemented. Between one to three million dollars would have to be invested in new machines and tools to be able to meet product design requirements.

Addressing research question one, it becomes obvious that a new process would be required. The process of super abrasive finishing would have to be implemented.

Addressing research question two was really the heart of study. Would experimental reamer perform better than controlled reamer? It was found through implementation of quantitative analysis the experimental reamer did in fact perform better than existing controlled reamer. Using Excel F-test module, I determined F value of the experimental reamer sample was greater then F critical. Since this was true, data from samples have unequal variances, and the Null Hypothesis was rejected. The results of the T-test verified value for T-stat was greater than T critical two tail. That meant a significant difference did in fact exist between experimental test reamer and controlled standard reamer, therefore the null hypothesis was rejected. Finally, a capability analysis was performed on resultant data and it was found the experimental reamer had a higher capability index value, thus proving that the experimental process had improved stability and less variability than controlled existing reamer. Actual average capability index values of experimental and controlled reamers were 1.95Cpk Verses 1.32Cpk respectively. It is true the test reamers did not perform to the standards originally targeted but through this investigative research, manufacturing and engineering both understood additional investments that would have to be implemented in order to achieve original target. It was through gained knowledge we were collectively able to make a decision to apply new upper spec limit of 1.54μm, thus eliminating the requirement of investing additional dollars into a super abrasive process. Further investigative research is continuing and that team will continue to strive to achieve original upper spec limit of 0.80μm.

Recommendations

It is highly recommended to complete the following additional research.

1. Replicate exact same research but use a larger sample of parts.
2. Replicate same research over a longer time frame.
3. Replicate same research and use a more sophisticated surface measuring instrument.
4. Replicate same research but instead of comparing six experimental tools in spindles 50 through 55 to six controlled standard finish reamers in spindles 56 through 61, machine 32 parts with experimental test tool in spindle 50. When complete, replace experimental reamer in spindle 50 with the controlled reamer and machine another 32 parts. Doing this removes variability between spindles and test is only focusing on one position not twelve.
5. Perform research examining the resultant size, taper, and run-out of roller follower bore. A comparison can be made between experimental and controlled reamers focusing on if any differences are evident.
6. Perform research focusing on life of experimental versus controlled reamers. Prove if there is an advantage going to a tool made from solid carbide verses carbide tipped.
7. Perform research examining economics between purchasing experimental versus controlled reamer.

8. Perform research focusing on if there is a difference between experimental versus controlled reamers in terms of power draw. If there was a significant difference then further analysis on tool geometry and cutting loads could be performed.
9. Repeat this research focusing on the frictional differences between 0.8μm and 1.55μm. Examine power draw and load differences between these extremes.

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