INCORPORATING GD&T REQUIREMENTS IN SPINDLE HOUSING OF CNC LATHE TO IMPROVE THE DESIGN AND MANUFACTURING PROCESS

Process capability optimization

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Abstract: The most important part for machine tool system is *spindle housing system*. The spindle housing system of precision lathe is one of the main parts of CNC lathe, and also a executive part of the main motion of the machine tool, it directly clamping the work piece and drive it to rotate. the running accuracy directly relate to assembly accuracy. The machine tool accuracy directly affects the dimensional accuracy of the machined products. This study has been undertaken to incorporate GD&T requirements in spindle housing of CNC lathe using Process Capability Analysis(PCA) and Root Cause Analysis(RCA) to ensure the assembly accuracy of the spindle housing system, improve the assembly quality and shorten the assembly cycle. The geometrical requirements to be met by the spindle housing apart from dimensional requirements are: Circularity, Cylindricity, Straightness, Concentricity, Flatness, Total Runout etc. This work depicts the application of GD&T rules and standards to modify the Conventional drawing by incorporating the GD&T characteristics, viz., cylindricity, concentricity, flatness to increase the assembly accuracy and get interchangability. Incorporate geometric requirements in this project work are: Concentricity, cylindricity, flatness. Since they have direct influence on the functioning of the components. In spindle housing, it was found that concentricity of bore plays a major role on the assembly as well as function of the spindle housing system, here, attempts based on the carefully planned and conducted experiments, process capability can be measured. Process capability analysis along with root cause analysis are carried out to eliminate or control the causes of variation in process parameters to improve the manufacturing process capability. Tapered in bore and failure of hydraulic system in honing process was controlled by 5-why analysis and FMEA to improve Cpk value from 0.74 to 1.34 which were contributing for poor process capability. From coordinate measuring machine, the concentricity of 0.05 mm for spindle housing and cylindricity of 0.02 for spindle are found.

***Index Terms* – GD&T, Spindle Housing, Process capability, assembly, concentricity, cylindricity.**

I. INTRODUCTION

Geometric Dimensioning and Tolerancing (GD&T) is an engineering product definition standard that geometrically describes design intent. It also provides the documentation base for the design of quality and production systems. Used for communication between product engineers and manufacturing engineers, it promotes a uniform interpretation of a component's production requirements. Using GD&T, the allowable limits of variation during the design, fabrication, and evaluation processes are specified using a standard syntax for describing the proper positioning sequence for accepting the component. Used properly, GD&T coordinates these activities effectively and reduces the influence of variation on final assembly. Ignoring GD&T creates inaccuracies in the inspection process, which can generate a misleading impression of the process capability of a fabrication activity. GD&T symbols are used in an engineering drawing to communicate the required functionality of the component by design. These symbols are also used by the inspection department to describe how to position the component during inspection and the allowable dimensional variation for individual features. The combination of GD&T symbols applied to a component is referred to as its GD&T specification. The GD&T specifications of a design are directly associated with its performance and functional requirements. They also govern the manufacturing and quality control processes needed to achieve those requirements.

Geometric dimensioning & tolerancing (GD&T) and process capability indices (PCIs) play critical roles in quality assurance. Conventional PCIs, when used together with GD&T, strongly rely on certain assumptions (e.g. normality and regularity of specification region). GD&T requirements often involve interrelated tolerances, creating irregular tolerance regions. Geometric Dimensioning and Tolerancing (GD&T) has gained popularity in design and manufacturing to ensure quality, functionality, and manufacturability. Process capability indices (PCIs) are a widely used evaluation tool for quality assurance and decision making in manufacturing. However, the popular PCIs (e.g. Cp, Cpk, etc) rely mainly on normality, univariate, and regularity (specification spaces in multivariate cases) assumptions. They fail to accommodate the complex evaluation problems of manufacturing processes with GD&T design requirements. Process Capability Study (PCS) refers to the evaluation of how well a process meet specifications or the ability of the process to produce parts within engineering specifications. Process capability is a measurable and statistical property of a process which generally determines if the process is meeting its desired specification or not. The two main functions of process capabilities are: Measure the variability of the output of a process, and compare that variability with product tolerance. The output of this measurement is represented by a histogram and predicts how many parts will be produced out of specification and is expressed as a process capability index. Statistical process control studies form the basic tool for obtaining the required process capability confidence levels. The various process capability indices are defined as follows:

$$C_P = \frac{\text{USL}-\text{LSL}}{6\sigma} \quad (1)$$

$$C_{PKU} = \frac{\text{USL}-\mu}{3\sigma} \quad (2)$$

$$C_{PKL} = \frac{\mu-\text{LSL}}{3\sigma} \quad (3)$$

$$C_{PK} = \min\left\{\frac{USL-\mu}{3\sigma}, \frac{\mu-LSL}{3\sigma}\right\} \quad (4)$$

Cp is the capability the process could achieve if the process was perfectly centered between the specification limits. On the other hand, Cpk is the capability the process is achieving whether or not the mean is centered between the specification limits. The problem with defining process capability for unilateral tolerance will lead to process distribution is non normal and usually skewed to the right. Since process capability indices implicitly assume a normally distributed process, calculation of the process capability indices when normality is clearly not present can lead to misleading and incomplete result. Currently for unilateral tolerance, Cp does not exist since the process mean cannot be centered at the target. This is due to the fact that if the mean of a normal distribution were centered at the target value of zero, some process characteristics would have negative values. Since this is physically impossible Cp is not reported. Therefore, Cpk is the only index that is reported in this situation and it is defined identically to the CpU index for the bilateral specification case with the target value centered between the specification limits. Montgomery and Douglas in their book, *Introduction to Statistical Quality Control*, recommend the following minimum values for *Cpk*.

Sl. No.	Situation	Minimum C_{pk} for Two-Sided Specifications	Minimum C_{pk} for One-Sided Specifications
1	Existing process	1.33	1.25
2	New process	1.50	1.45
3	Safety or critical parameter for existing process	1.50	1.45
4	Safety or critical parameter for new process	1.67	1.60
5	Six Sigma quality process	2.00	2.00

Figure-1 Recommended value for Cpk

Root Cause is the fundamental breakdown of a process which and when resolved, prevents a recurrence of the problem. Root cause analysis is a problem solving technique for experimenting an investigation into an identified incident, causes, problem, concern or non-conformity. Root cause analysis requires the investigator to look beyond the solution to the immediate problem and understand the fundamental or underlying causes of the situation and put them right, thereby preventing re-occurrence of the same problem. This may involve the identification and management of processes, procedures, activities, inactivity, behaviors or conditions, operations and their parameters. RCA Tools are: Cause and Effect Diagram (Fishbone diagram), Five-Why Analysis, Failure Mode and Effective Analysis (FMEA), Histogram etc.

The benefits of comprehensive root cause analysis include:

- Identification of permanent solutions to eliminate or control error
- Prevention of recurring problem or error
- Introduction of a logical problem solving process applicable to errors and non-conformities of all sizes

Process improvement is the crux of all things Six Sigma. For us, we find that reducing variation is imperative to successful process improvement. The five ways for improvement of process.

1. Eliminate Non-value adding process

Firstly, to remove your non value adding steps, you need to have a concrete understanding of how processes work. Also, ask yourself: What happens in a process? What does it do? Once you know the process steps and involved, you can zero in on unnecessary steps, and eliminate them accordingly.

2. Improve Your Measurement System

It's important to understand how data work and relates to Six Sigma. When you collect data, you can understand very well that how variation or problem arises. Variation accumulates in both the process and your measurement (inspection) system. As such, measurement variation depends on how clearly you define your operations for each measure.

3**.** Minimize Common Causes Variation

Experts break down variation into two categories: common and special causes. The two categories are separated by how frequently they appear in the processes. Common cause variation appears regularly and should be labeled using a CED. Reducing common cause variation relies on how you stratify your data. Consider your process location, how early or late it appears, and timing. Significant differences in your process will help you to recognize issues. Design of Experiments (DOE) is another great method of gathering information as it requires active engagement in process variations and changes.

4. Minimize Special Cause Variation

Special cause variation factors into when and where process change appears. Change can have a positive or negative impact in your system. Being able to identify the when, where and why will help you understand and identify the root cause. Special cause variation consists of three different steps to control:

- A unique change outside control limits, like a traffic collision during a blizzard.

- A process shift to a lower performance level, i.e. a sudden change in the number of packages delivered by a new.
- A gradual process change over time, resulting in a trend such as the steady increase of someone's hair length.

5. Change Your Process Mean to Improve Process Capability

If you have to understand how to improve your process capability, you should know how your process mean affects it. Your process capability (Cp and Cpk) describes your ability to deliver outputs within your specifications. If the variation is high, then your mean will be centered between two specifications. This means more rework will be required since more values will fall on one side than the other. Moving the process mean to an equal location will reduce the level of rework required. This streamlines your process capability and improving your results.

II. LITERATURE SURVEY

Lowell W. Foster presented application and interpretation of geometric characteristics (emphasizing symbology), fundamentals, rules, etc. Basis for the content of this paper is USASI Y14.5-1966 "Dimensioning and Tolerancing for Engineering Drawings. This paper describes the implementation and practice to accomplish these through illustrating methods to state design requirements specifically and clearly and to provide for maximum productivity, uniformity of interpretation, etc. **A Krulikowski** described a common myths about geometric dimensioning and tolerancing (GD&T) in the world because half of world is used this concept in their organization. In this Paper, author tells about the people's misconception about GD&T and gives the practical response on each to increase the scope of geometric dimensioning and tolerancing in the design & manufacturing requirements. **Saurin Sheth et al** demonstrates how GD&T can improve the quality of product and reduce the cost of manufacturing by reducing the rework. Here an attempt is made to use the concepts of DFMA and GD&T on dual plate check valve. Applying proper tolerance to the mating parts plays a vital role in inspection and assembly of the product. So by using GD&T standards, one can apply zero tolerancing and maximum material virtual conditions (VC) which will lead to proper assembly of the part. The conventional drawing should be revised to GD&T drawing, so that the rework in assembly of the valve can be eliminated or minimized. The geometrical characteristic "cylindricity" is explained and measurement technique is described by **Dean J.W. Dawson**. For cylindricity measurement to develop adequately for high precision components, firstly improvements in instrument accuracy need to be made and secondly, parameters need to be developed that will enable the detection and measurement of 3-D forms. **Saurin Sheth et al** described a methodology can be used to convert the conventional drawing into a GD&T drawing is : A. Study the conventional drawing. B. Study the machine capability. C. Convert the linear tolerances in to the Geometrical tolerances D. Manufacturing and assembly of the valve according to new revised GD&T drawing. According to **A. Saravanan et al**, Engineering design is done in two stages: assembly design and detail design. In the first stage, an assembly is designed considering certain system level functions and in secondary detail design stage; decomposition of the assembly is done and process tolerancing is employed for the parts. Hence, assembly and detail design are done in different phases with dissimilar perspectives. As a result, geometric tolerance design often lands in conflict, redesign, and in the case of concurrent engineering, costly reiterations are performed. This paper offers a framework for a design engineer to bridge the gap and to establish the relation between these stages. **S.M. Kim et al** describe, how to find critical design parameters in spindle housing and determining the significant factors affect on it. **Z.X. Wang et al** presents the importance of *Spindle Housing System* in CNC lathe in the context of design parameters, assembly process, running accuracy. The spindle system of precision lathe is one of the main parts of CNC lathe, and also a executive part of the main motion of the machine tool, it directly clamping the work piece and drive it to rotate. And the running accuracy directly relate to assembly accuracy. Through the corresponding assembly process experiment, the assembly process of precision spindle system is established, which ensures the assembly accuracy of the spindle system, improves the assembly quality and shortens the assembly cycle. **Joymalya Bhattacharya** presents a Importance of RCA in manufacturing industry to eliminate failure management in the product design as well as in production process in order to improve the process and machine capability. Root cause analysis is one cause of the best processes to eliminate failure management in industry. This paper highlights about the tools which are use in root cause analysis and the methodology of root cause analysis. The procedural approach is one of the most important thinking for root analysis, because without selecting perfect tools it is not possible to analysis the perfect root cause. Mohammad Javad Ershadi et al presents Root Cause Analysis (RCA) tools viz., Fishbone Diagram, FMEA, 5-Why Analysis, Histogram are used for determining the root causes and variation of causes of quality problems. Possible actions and solutions can be taken from these tools are become very easy. **Aysun Sagbas** used to present Process Capability Analysis (PCS) technique which can be used in product design to determine the ability to manufacture parts within the tolerance limits and engineering values. The process-capability analysis, which is a SPC technique, helps to determine the ability for manufacturing between tolerance limits and engineering specifications. The capability analysis gives information about the changes and tendencies of the systems during production. Process-capability analysis is a technique applied in many stages of the product cycle, including process, product design, manufacturing and manufacturing planning. **M. Joseph Gordon Jr.** gives the information about process capability index (Cpk) which can be used and applicable to calculate for unilateral tolerance limits which is given in the engineering values instead of Cp index. The value of Cpk should be atleast 1.33 for unilateral tolerance limits. Cp is the capability the process could achieve if the process was perfectly centered between the specification limits. On the other hand, Cpk is the capability the process is achieving whether or not the mean is centered between the specification limits. The difference between your company's quality processing goal of a CpK of 1.33 or a CpK of 1.5 (Six Sigma) is only an additional 60 defects. If your production run is large, more than 20,000 parts, you can anticipate random defects for a process of CpK just meeting 1.33. **P.Satheesh et al** gives details about honing process parameters and eliminating quality problems by reducing cycle time. In a honing machine, boring tool or honing stick is used to bore an internal bore in the material. It is timed operation and also rate of production is very less. Timing of honing is defined by quick cutting of the peaks of the pre-machined bore surface. They introducing buffing tool in honing machine. It have multiple point cutting edges and it boring a material in a stock. Here machining time is considerably less when compare with other operation. The cost of an operation also reduced. Strength of the material may be increased. This rapidly achieves a smoothing of surface in material. **Javad Akbari** perfomed details study on the effect of honing tool on part features in the context of shape accuracy (geometric quality of bore) and surface finish. While horizontal honing is widely used in industry, most of research works have been performed on vertical honing machines. On the other hand, using honing fluid in a horizontal bore causes a different lubrication condition in this process, which has effect on the results. This study investigates the effect of tool over-run from two ends of the bore during horizontal honing. Experiments indicate that the amount of over-run has influence on shape accuracy and surface finish. Furthermore, unequal over-run causes a better condition for uniform lubrication, which increases the process quality.

III. PROCESS SEQUENCE

In recent years, the importance of looking at the complete manufacturing chain instead of isolated single process steps in order to reduce scrap and rework and thus, increase quality was slowly recognized by industry and academia.

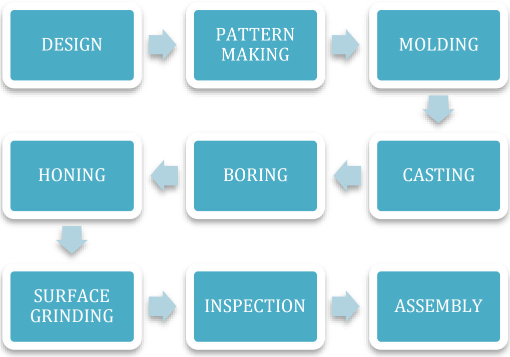

Figure 2 process sequence

Primary stage: Design phase

As per the customer requirement, drawing of the spindle housing could be prepared by the design engineer in which, he prepared the design according to the required dimensions and tolerances. Design should be prepared to fulfill the requirement of manufacturing, assembly and the customer needs. Design should be prepared in such way that design intent would be clear to the manufacturing as well as assembly fellow.

Secondary stage: Manufacturing phase

Manufacturing phase in which casting boring and honing would be come about according to the drawing. As per the design intent, pattern making process would be done. If the pattern of the spindle housing is prepared, mould making process would becometh. Casting will be prepared after the completion of pattern and mould making. Casting product will transfer to the boring purpose in which main bore and bolt holes would be drilled according to dimensions and related tolerances. Bore of the housing would be grind in honing machine to create accurate inner bore surface as far as the accuracy and assembly would concern. Surface grinding would becometh in order to obtained the precision and surface finish product.

Tertiary phase: assembly phase

Assembly of the spindle housing with the main spindle is done in this phase which very most critical phase because assembly accuracy will directly affect to the running accuracy of the system and it will affect on the job.

3.1 Boring operation: Horizontal boring machine

Horizontal boring machine is used to enlarge the existing hole of spindle housing which is come from the casting to achieve greater accuracy of the bore diameter of 170.02 to 170.05. In casting product, there is a tapered hole in in the bore on which boring can be done through hole. A single point cutting tool is used to cut the material horizontally in the bore of spindle housing. Cutting tool which is mounted on a boring bar. Boring bar of diameter D1= 55 mm and D2=67 mm having length of 300 mm. overhanging length of boring bar is 100 mm. Tool holder of 12*12 mm is mounted on boring bar which clamp and locate the insert(strip) by screw clamping. Insert of having YG6 grade carbide tip and size of R245 is used.

Figure 3 horizontal boring machine

3.2 Operation cycle

a. Mount and fixture the job on table to qualify the bottom surface of the spindle housing to achieve the surface roughness of 0.2 to 0.8 micron.

b. Mount and fixture the job to facing other surfaces.

c. Mount and fixture the job for centering and positioning with the tool. Edge and centre finder of groz ef 12 is used to positioning tool, accurately locating work edges, center point on the bore face of the job.

d. To take all the dimensions with reference to the qualified bottom surface.

e. Boring can be done.

3.3 Manufacturing Data

Manufacturing data of boring operation of spindle housing is shown table 1.

Table 1 Manufacturing data for boring operation

Cutting tool	Single point cutting tool
Chuck RPM	112 RPM
Cutting feed	0.19 m/min
Multi stroke boring operation	Roughing1 : 3 mm both side
	Roughing2 : 1.5 mm both side
	Final cut: 0.5 mm both side
Depth of cut	5 mm
Tool material	carbide
Material Grade	YG 6 Carbide tips
Tool brand	YG 6
Tool holder size	12*12 mm
Length	100 mm

3.4 Boring Machine Specification

Horizontal boring machine specifications are shown in table 2

Table 2 Boring machine specification

Type	Table type Horizontal Boring Machine
Model	TOS W100
Surface roughness	30 Microns
Spindle Speed	45-1120 RPM
Spindle Diameter	100 mm
Spindle Taper	Mt-6
Max. Loading Weight	2800 Kg
Travel Length	X: 1600 mm
	Y: 1250 mm
	Z: 2000 mm
Spindle Travel	1200 mm
Table Size	1250*1250 mm
Total Power	15 KW
Weight	14 Ton
DRO Type	3 Axis DRO
Facing Chuck Diameter	600 mm

Max. Facing Diameter	900 mm

3.5 Honing operation: Vertical Honing Machine

Hydraulically operated honing machine is used to reduces the defects related honing operation which is listed below,

- To avoid deep line marks on the internal surface of the spindle housing
- Avoiding indentation marks on the surface
- Avoid tapered of bore of spindle housing within suitable limit.

In honing process of spindle housing, four step of operation with different grades of abrasive stone is required. Abrasive stones and paper of aluminum oxide is used to remove the tool marks and achieve finishing. But for Cast Iron work, abrasive paper of Silicone carbide is preferable according to standard. Honing process is done in 4 steps with different grades are used like 36, 80, 100, 220, 320. 80, to remove the machining lines and polishing up to 8 micron whereas 220 and 320 is used for finishing up to 1micron. Load capacity of honing machine is 1 to 1.5 ton. Machine capacity is DIA 40-310*22OO. The honing tool of 170 mm is used. Honing machine and honing tools are shown fig 4.

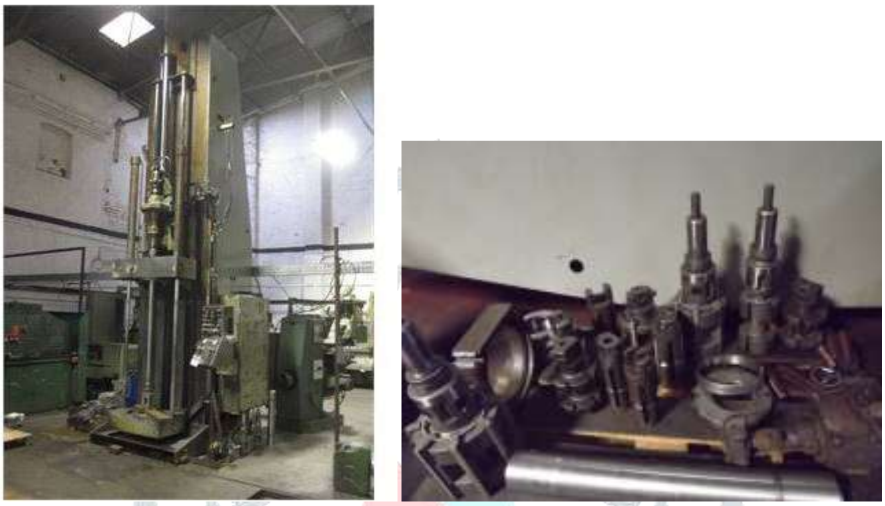

Figure 4 vertical honing machine and honing tool

3.5.1 Operation Cycle

1. Mount the housing to hone on the table.
2. Fixture the housing on the table.
3. Adjust the tool holder such that it easily passes through the job.
4. Start the motor to take light cut.
5. Operate the reciprocating arrangement using feed handle.
6. On finishing release the tool holder & remove from job.

3.5.2 Cycle time of honing operation

Cycle time is the actual time spent working on producing a part or providing a service, measured from the start of the first task to end of the last task. Cycle time having different steps of machining with different grades of abrasive paper, surface finish and size of the part are measured.

Normal operating cycle time:

Component Details: Spindle housing bore diameter = 170(0.02 to 0.05) mm

Surface Finish= 0.2 RA

Total Length = 300 mm

Honing Procedure for Roughing: Honing sticks width= 6mm Thickness= 6mm

Length = 75mm

No of sticks = 6 nos

Using Stick Grid D36

Machining Size = 169.5mm

Honing Cycle Time = 30.00mins

Honing Size = 169.80 mm

Surface Value= 2.2RA

Honing Finishing:

Honing stick width = 6mm

Thickness = 6mm

Length= 75mm

No of Sticks = 4nos

Honing size = 170.02mm

Using Stick Grid D80

Cycle time = 03.00mins

Diameter = 169.92 mm

Surface Value = 1.8RA

Honing Fine Finishing:

Honing sticks width= 6mm Thickness = 6mm

Length = 75mm

No of sticks = 4 nos

Using Sticks Grid D100

Cycle time = 05mins

Machining size = 169.92 mm

Surface Finish Value = 0.8RA

Honing size = 170 mm

Using Sticks Grid D220/D320

Cycle time = 05mins

Machining size = 170 mm

Surface Finish Value = 0.2RA

Honing size = 170.02 mm

Finally:

Component size = 170.02mm

Total Cycle Time= 43.00mins (both value added time and non value added time)

Abrasive material: Aluminum oxide

Total cycle time should be 43 minutes for machining a single piece of part. But if talk about the real situation, it is more than that because of more time consumed in setup. So setup time is minimum such a way that cycle time of honing operation of 43 minutes or less than that would be achieved. Regularly monitoring a cycle time will allow you to identify unexpected cycle time increased due to unpredicted changes. It is key to monitor cycle times to verify that customer demand will be met, as well as to identify possible cost saving initiatives.

IV. ROOT CAUSE ANALYSIS

Root Cause is the fundamental breakdown of a process which and when resolved, prevents a recurrence of the problem. Root cause analysis is a problem solving technique for experimenting an investigation into an identified incident, causes, problem, concern or non-conformity. Root cause analysis requires the investigator to look beyond the solution to the immediate problem and understand the fundamental or underlying causes of the situation and put them right, thereby preventing re-occurrence of the same problem. We are trying to identified root causes and their effect on the performance of the machine as well as on the product and rectify or eliminate by the study the effect of process parameter on spindle housing and by the study of system of machine. WHY-WHY Analysis can be carried out to find out the possible root causes and to take appropriate actions to control them. Failure mode and effective analysis (FMEA) can also be carried out against the common root causes. Root cause analysis tools are listed below:

4.1 Causes and Effect Diagram(Fishbone diagram)

Six main causes (men, material, method, environment, cutting phenomena and tooling parameter) and 13 secondary causes which affect on the fit and function of the spindle housing by affecting the process capability.

In this diagram, we are trying to find out the root causes which will affect on our process and precision of machine and control or eliminate them by the study on process parameters and machine and that effect on product parameter.

Some possible special and system causes are described in the fishbone diagram as shown in figure.

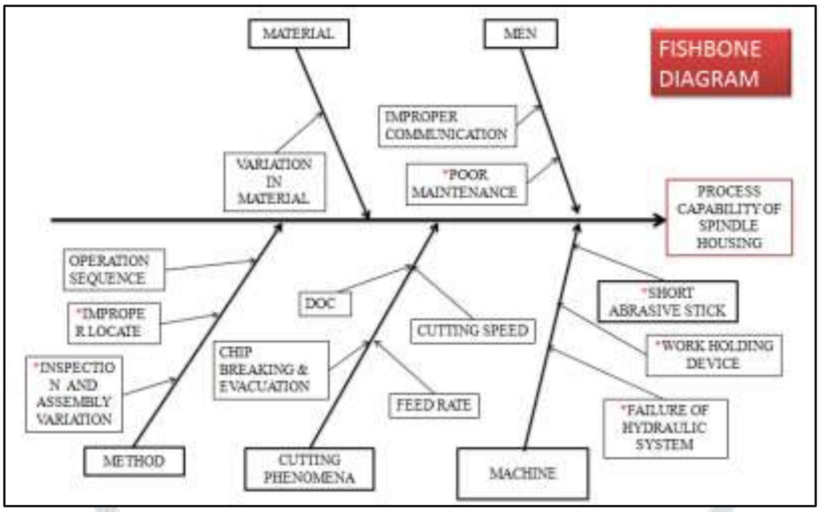

Figure 5 fishbone diagram

4.2 WHY-WHY Analysis (RCA)

Why-Why analysis can be carried out to find out the root cause of tapered bore and possible solution. You have a taper problem when your bore is not as straight as it needs to be. The bore diameter becomes progressively larger or smaller towards one or both ends. In some cases the taper occurs at both ends resulting in an “hourglass” or “barrel” shaped longitudinal profile will lead to create problem in assembly with the spindle that will require to rework the spindle housing to eliminate the tapered will take more time and increase the cost.

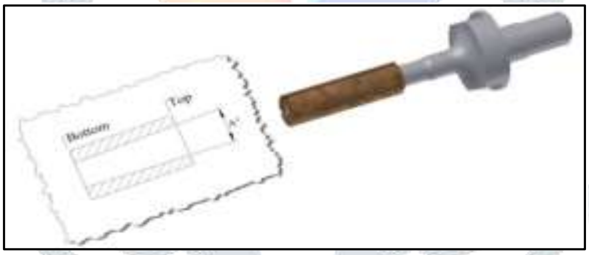

Figure 6 Tapered bore in spindle housing

The solution may be as simple as used longer abrasive stone so that it extends further into, or just beyond, one or both ends of the bore. This insures that every area of the bore gets an equal amount of time exposure to the grinding wheel. If the bore is relatively shallow and the honing wheel covers its full length, but you are still getting taper, You would think that every area of the bore would be getting equal exposure to the wheel’s surface. Unfortunately, this is where the reality of “deflection” comes into play. The pressure of the wheel on the part tends to deflect the honing wheel away from the surface of the bore. So the surface of the wheel is never entirely parallel to the surface it is grinding. This slight deviation from parallel may cause unacceptable taper in the bore where the honing wheel is bent slightly away from it. An easy way to make this problem disappear is to reverse dress a compensating taper into the wheel. The wheel will then have a shape that is the opposite of the tapered bore. This may be all you need to do. If we used to eliminate tapered bore in spindle housing, part must be check prior to honing weather it is axially straight, part is accurately locate on the fixture and use longer abrasive stone in honing wheel. Green silicon carbide of abrasive stick (stoke) used as an abrasive material instead of aluminum oxide based on type of material to be honed, material specification, geometric tolerance involved, existing abrasive problem and bore condition prior to honing. 5-Why analysis would be carried out for “tapered bore” error in spindle housing as shown in table 3.

Table 3 Five-analysis

CAUSE	WHY-1	WHY-2	WHY-3	WHY-4	WHY-5
FUNCTION AND FIT	Tapered in bore	Part not axially straight	Fixture is distorting the part	Check part accuracy prior to honing	Use Longer Abrasive

4.3 Failure Mode & Effective Analysis of Major Components of Hydraulic System in Honing Machine

The failure of major components in honing machine will directly affect on the product parameters and geometric feature of spindle housing. Failure mode and their potential effect on machine as well as the possible causes and taking suitable action to control these potential causes as shown in table 4.10. The major components of hydraulic system are Cylinder, DCV and Pump. Parameters of these components will affect the design parameters of spindle housing. Hydraulic circuit of balancing system is shown in figure 7.

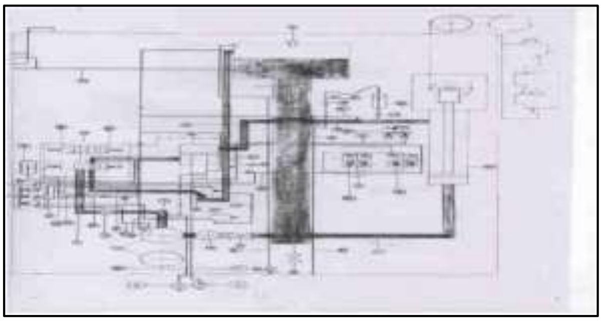

Figure 7 hydraulic circuit

The source of power for hydraulic system is an electric motor. The input component of the system is positive displacement gear pump. Coupling is provided between the pump and electric motor. Hydraulically operated 4/3 direction control valve and 4/2 directional control valve is connected between pump and hydraulic cylinder. The pressure relief valve is set between the pressure line (pump outlet) and the reservoir. Flow control valve is set between the directional control valve and cylinder which control the speed of cylinder. The filter is placed in return line of system. Function of 4/3 direction control valve is to control slow movement of turret mechanism while inserting the taps into the tray. Function of 4/3 direction control valve is to achieve faster movement of turret mechanism from the point of tap loading to surface of abrasive particles in the tray. The failure modes and effects analysis (FMEA) is one of the most efficient low-risk tools for prevention of these factors can be obtained from the detailed study of the system which is further used for evaluating the maintenance strategy to be adopted. The result of the FMEA analysis was identification of three failure mode that should be prioritized in the maintenance plan. The frequency of the high priority maintenance activities should be increased or new maintenance activities should be implemented. FMEA analysis in this thesis ranks the DCV as the highest priority. While the pump has the second highest priority and cylinder is the last highest risk priority number. The valve, pump and cylinder should be prioritized in the maintenance plan. These hydraulic components and their factors are affecting on the performance of process parameter and that will effect on the quality of operation, product parameter (surface finish etc.), function and reliability of the spindle housing. Those factors will lead to poor process capability.

Table 4 FMEA

NO	FUNCTION	FAILURE MODE	POTENTIAL EFFECT	POTENTIAL CAUSES	CURRENT CONTROL
1	Cylinder	1.Rod Failure 2.Oil Leakage 3.Cylinder Noise 4.Rod Vibration	1.Machine stops 2.System Pressure lowers 3.unpleasant working condition 4. Noise	1. High operating temperature ,over load 2.Erosion 3. High speed ,excessive Friction 4. high speed,	1.Working under prescribed limit 2.Painting the surface 3.Improper lubrication 4.Proper alignment of components
2	DCV	1. Failure of valve port 2.failure of spool 3.defective spring 4.valve leakage	1.Flow stops 2. Improper oil flow 3.Improper shifting 4.Pressure lowers	1.High fluctuation pressure 2. High wear , improper spool adjustment 3 High fluctuation load, over load 4. High fluid temperature , erosion	1.Cleaning, Fitting and Tightening 2. Cleaning and fitting 3. Work under permissible

3	Pump	1. Leakage of pump 2. Leakage in suction Pipe 3. Pump shaft broken 4 blockage in suction	1.System pressure lower 2. System pressure lower 3. System stops 4 Flow of oil stops	1.Contaminated high pressure of fluid 2. Erosion 3.Excessive loading 4.Contamination of oils	1.Proper fitting 2.Check hydraulic hoses and fitting 3. Check flow rate ,visual inspection

V. EXPERIMENTATION AND RESULTS

.1 Process Capability of Spindle Housing

Process capability is the repeatability and consistency of a manufacturing process relative to the customer requirements in terms of specification limits of a product parameter. This measure is used to objectively measure the degree to which your process is or is not meeting the requirements. Process capability data for bore diameter of spindle housing can be measured with 50 sample size in 5 sample subgroups as shown from table 5. Average, Range and Standard deviation can be calculated from equations shown in table 7.

Table 5 Process capability data for spindle housing bore

PART NAME:		HEADSTOCK HOUSING			SPECIFICATION:		170.02 to 170.05(UT spec) LSL= 0, USL= 170.05			
DIMESNSIONS:		BORE DIAMETER IN mm			OPERATION:		BORING AND HONING			
SAMPLE SIZE:		50 NOS			NO OF DECIMAL:		2			
SR NO.	1	2	3	4	5	6	7	8	9	10
1	170.03	170.02	170.03	170.04	170.02	170.03	170.02	170.04	170.03	170.02
2	170.04	170.05	170.02	170.03	170.02	170.04	170.02	170.03	170.03	170.02
3	170.02	170.04	170.03	170.02	170.02	170.02	170.03	170.02	170.03	170.04
4	170.03	170.03	170.02	170.04	170.03	170.03	170.02	170.05	170.04	170.02
5	170.05	170.02	170.04	170.02	170.03	170.03	170.04	170.05	170.03	170.02
AVG	170.034	170.032	170.028	170.03	170.024	170.03	170.026	170.038	170.032	170.024
RANG	0.03	0.03	0.02	0.02	0.01	0.02	0.02	0.03	0.01	0.02

Table 7 Sigma calculation

Xd BAR	170.0298	
R BAR	0.021	
SIGMA(S)	R BAR/D2	0.009028
6S	**0.0542**	
3S	**0.0271**	

Table 6 constants

SAMPLE	D2	A2	D4	D3
2	1.128	1.88	3.267	0
3	1.693	1.023	2.574	0
4	2.059	0.729	2.282	0
5	2.326	0.577	2.114	0

Process capability index (Cpk) can be calculated from the constants of A2, D2, D4 are shown in table 6.

Histogram graph for 50 sample size is prepared in table 4.4 which shows that variation from value of bore diameter of 170.02 to 170.05 that is higher which lead to poor process capability. Frequency versus interval is plot to find out the variation of the sample size.

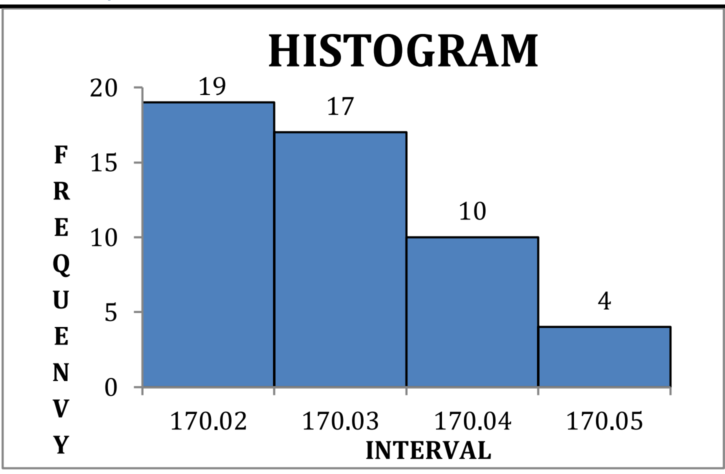

Figure 8 Histogram

4.2 Estimation of Process Capability Indices

Process Capability Index (Cpk):

$C_P = \frac{\text{USL}-\text{LSL}}{6\sigma}$ = not applicable (unilateral tolerance)

$C_{PKU} = \frac{\text{USL}-\mu}{3\sigma}$ = 0.74

$C_{PKL} = \frac{\mu-\text{LSL}}{3\sigma}$ = LSL is not given because of unilateral tolerance used

The problem with defining process capability for unilateral tolerance will lead to process distribution is non normal and usually skewed to the right. Currently for unilateral tolerance, Cp does not exist since the process mean cannot be centered at the target. This is due to the fact that if the mean of a normal distribution were centered at the target value of zero, some process characteristics would have negative values. Since this is physically impossible Cp is not reported. Therefore, Cpk is the only index that is reported in this situation and it is defined identically to the CpU index for the bilateral specification case with the target value centered between the specification limits. Cpk value of 0.74 is evaluated from the process capability data which is lead to poor process capability. So, we have to improve process capability by identify and rectify the poor process parameter.

4.3 Process Capability of Spindle

Sampling data of spindle shaft diameter in sample size of 50 (minimum of 50 sample size according to AIAG SPC) was taken from table 8. Process capability index (Cpk) is responsible for poor process capability. Cp and Cpk can be calculated from the Average (μ), Range (R bar) and Standard deviation (σ) from table 8 and 9.

Process Capability Index (Cpk):

$C_P = \frac{\text{USL}-\text{LSL}}{6\sigma}$ = not applicable (unilateral tolerance)

$C_{PKU} = \frac{\text{USL}-\mu}{3\sigma}$ = 1.45*

$C_{PKL} = \frac{\mu-\text{LSL}}{3\sigma}$ = LSL is not given because of unilateral tolerances limit used

Where, $\mu = 169.9872$

USL = 169.99

LSL = Not given because of unilateral tolerance

$\sigma = 0.000645$

Table 8 Process Capability Data for Spindle

PART NAME:	SPINDLE			SPECIFICATION:		170(-0.010 to -0.015)				
PART NO:	A2-5			MATERIAL:		AM41B				
SAMPLE SIZE:	50 NOS			NO OF DECIMAL:		3				
SR NO.	1	2	3	4	5	6	7	8	9	10
1	169.987	169.987	169.985	169.989	169.985	169.987	169.987	169.988	169.987	169.99
2	169.987	169.988	169.985	169.989	169.985	169.987	169.987	169.988	169.988	169.99
3	169.988	169.986	169.985	169.988	169.986	169.988	169.987	169.986	169.988	169.988
4	169.988	169.986	169.986	169.987	169.986	169.988	169.988	169.988	169.986	169.99
5	169.988	169.986	169.986	169.987	169.986	169.987	169.987	169.988	169.986	169.99
AVG	169.9876	169.9866	169.9854	169.988	169.9856	169.9874	169.9872	169.9876	169.987	169.9896
RANG	0.001	0.002	0.001	0.002	0.001	0.001	0.001	0.002	0.002	0.002

Table 9 Sigma Calculation

Xd BAR	169.9872	
R BAR	0.0015	
SIGMA(S)	R BAR/D2	0.000645
6S	**0.0039**	
3S	**0.0019**	

SAMPLE	D2	A2	D4	D3
2	1.128	1.88	3.267	0
3	1.693	1.023	2.574	0
4	2.059	0.729	2.282	0
5	2.326	0.577	2.114	0

4.6 Improved Process Capability of Spindle Housing

Sampling data of spindle housing bore diameter in sample size of 50(minimum of 50 sample size according to six sigma) was taken after controlling the possible causes which will affect on design parameters. Process capability index (Cpk) is responsible for poor process capability. Improved Cpk value can be calculated from the value of standard deviation which is calculated in below table 1o to 12.

Table 10 Process capability data for spindle housing

PART NAME:	HOUSING			SPECIFICATION:		170.02+0.03				
PART NO:				OPERATION:						
SAMPLE SIZE:	50 NOS			NO OF DECIMAL:		2				
SR NO.	1	2	3	4	5	6	7	8	9	10
1	170.03	170.04	170.03	170.03	170.04	170.03	170.04	170.04	170.03	170.03
2	170.03	170.05	170.03	170.03	170.04	170.04	170.03	170.03	170.03	170.04
3	170.03	170.05	170.03	170.02	170.05	170.04	170.03	170.04	170.04	170.04
4	170.02	170.04	170.03	170.02	170.05	170.03	170.04	170.03	170.04	170.03
5	170.02	170.04	170.04	170.02	170.05	170.03	170.04	170.03	170.03	170.03
AVG	170.026	170.044	170.032	170.024	170.046	170.034	170.036	170.034	170.034	170.034
RANG	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Table 11 Sigma Calculation

SAMPLE	D2	A2	D4	D3
2	1.128	1.88	3.267	0
3	1.693	1.023	2.574	0
4	2.059	0.729	2.282	0
5	2.326	0.577	2.114	0

$Mean(\mu)$	170.0344
R BAR	0.01
SIGMA(σ)	R BAR/D2
6 σ	**0.0258**
3 σ	**0.0129**

Table 12 Cpk calculation

PROCESS CAPABILITY (Cp)	USL-LSL/6S	1.163	
PROCESS CAPABILITY INDEX (Cpk)	Cpk U	(U.S.L-XdBAR)/3S	1.20952
	Cpk L	(XdBAR-L.S.L)/3S	1.11648

Histogram graph for 50 sample size is prepared in table 4.15. It shows that variation from value of bore diameter of 170.02 to 170.05 is larger which is responsible for poor process capability.

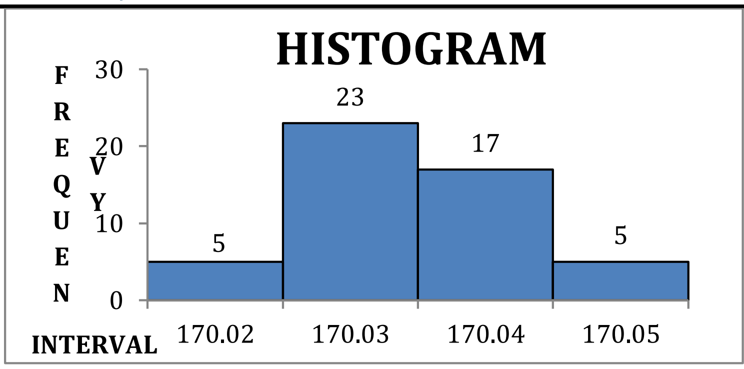

Figure 9 Histogram

From the improved process capability data of spindle housing, the Cpk value is 1.21 which is indicate the process is adequate but still it is not satisfactory because of taking CMM data for concentricity, some rework is predominant. That is why we are find out the possible reason behind the low process capability index and rectify it with taking possible action. To eliminate error coming from the fixture design, why-why analysis can be carried out to found the root cause and control it. Taking consecutive data for process capability after controlling the possible cause (tapered in bore) of housing and calculation as shown in below.

Capability index	Estimation of the process
$C_{pk} = C_p$	Process is placed exactly at the centre of the specification limits
$C_p < 1$	Process is not adequate
$1 \leq C_{pk} < 1.33$	Process is adequate
$C_p \geq 1.33$	Process is satisfactory enough
$C_p \geq 1.66$	Process is very satisfactory
$C_{pk} \neq C_{pk}$	Process is inadequate, new process parameters must be chosen

Figure 10 Estimation of process

Process capability index can be improved by eliminating or controlling the causes which are found out from the root cause analysis (fishbone diagram, 5-why, FMEA etc). The major causes of variation are coming from work-holding fixture and hydraulic system in vertical honing machine. These factors are controlled to improve process capability. Calculation of process capability index (Cpk) as shown in table 15

Table 13 Process Capability data for Spindle housing

PART NAME:	HEADSTOCK HOUSING		SPECIFICATION:	170.02 to 170.05					
CRITICAL FEATURE:	BORE DIA(in mm)		OPERATION:	HONING					
SAMPLE SIZE:	50 NOS		NO OF DECIMAL:	2					

SR NO.	1	2	3	4	5	6	7	8	9	10
1	170.03	170.04	170.03	170.03	170.04	170.03	170.03	170.03	170.03	170.03
2	170.03	170.03	170.04	170.03	170.04	170.04	170.03	170.03	170.03	170.04
3	170.03	170.03	170.03	170.02	170.03	170.04	170.03	170.04	170.03	170.03
4	170.03	170.04	170.03	170.04	170.03	170.03	170.04	170.03	170.03	170.03
5	170.04	170.04	170.04	170.03	170.03	170.03	170.03	170.03	170.03	170.03
AVG	170.032	170.036	170.034	170.03	170.034	170.034	170.032	170.032	170.03	170.032
RANG	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0	0.01

Table 14 Sigma Calculation

Xd BAR	170.0326	
R BAR	0.01	
SIGMA(S)	R BAR/D2	0.004299
6S	**0.0258**	

Table 15 Cpk calculation

PROCESS CAPABILITY (Cp)	USL-LSL/6S		
PROCESS CAPABILITY INDEX (Cpk)	Cpk U	(U.S.L-XdBAR)/3S	1.34908
	Cpk L	(XdBAR-L.S.L)/3S	0.97692

Histogram graph for 50 sample size is prepared in figure 11 which shows that variation from value of bore diameter of 170.02 to 170.04 is lower than above data which is lead to increase the value of Cpk and improve the process capability. Frequency table according to sampling data is shown in table 16

Table 16 frequency

INTERVAL		FREQUENCY
170.02		1
170.03		35
170.04		14
170.05		0

Histogram graph for 50 sample size is taken as shown in figure 11 which shows that variation from value of bore diameter of 170.02 to 170.05 is lower than above data which is lead to increase the value of Cpk. Thus improve the process capability.

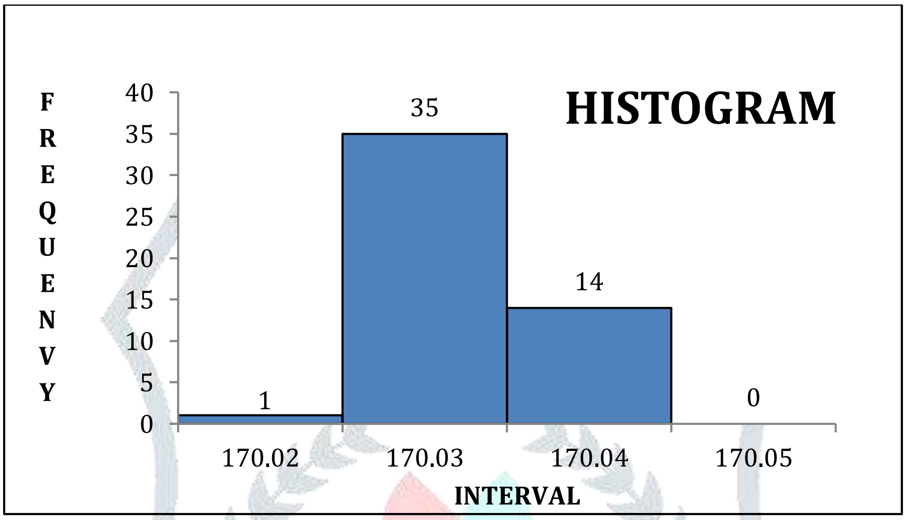

Figure 11 Histogram

VI. METROLOGY AND INSPECTION

Inspection procedure of Spindle and spindle housing

Inspection of concentricity (Spindle housing)

- Start the Coordinate measuring machine.
- Run MICAT Mitutoyo geopack Lear mode.
- Calibration of machine by standard specimen.
- Select Z plane which is reference plane for the spindle housing.
- For the spindle housing, first take 24 point measurement on the primary datum. Here it takes three datum circles from the reference plane.
- Now probe will move in bore to take 24 point measurement.
- After measuring section for determining concentricity software would measure the centre distance of primary and secondary datum circles.
- Now repeat the procedure for the remaining samples.

Table 17 Concentricity of bore

NO.	CONCENTRICITY (mm)	NO.	CONCENTRICITY (mm)	NO.	CONCENTRICITY (mm)
1	0.040	10	0.035	19	0.034
2	0.034	11	0.037	20	0.046
3	0.035	12	0.054	21	0.036
4	0.033	13	0.032	22	**0.050***
5	0.036	14	0.028	23	0.042
6	0.032	15	0.038	24	0.038
7	0.060	16	0.033	25	0.044
8	0.032	17	0.039		

The concnetricity requirement of bore is 50 to 70 micron. Now from the above sampling data of concentricity of bore, we can say that, limit of concentricity value is 0.05 mm. if the value of concentricity of bore is more than 50 micron will be required to rework. The value of concentricity of bore of 0.054 and 0.06 mm, part will NG as shown in table 17. We should have required to improve process capability index from 1.20 to 1.33. The main reason behind the low capability index is work holding fixture system in honing machine because that will give tapered in bore. If the accuracy of the fixture is not good, part will not axially straight so that part will distorted. Checking the fixture accuracy prior to honing will minimize the error and taking data of concentricity of bore as shown in table 18.

Table 18 Concentricity of bore

NO.	CONCENTRICITY (mm)	NO.	CONCENTRICITY (mm)	NO.	CONCENTRICITY (mm)
1	0.046	10	0.039	19	0.045
2	0.040	11	0.041	20	0.042
3	0.048	12	0.043	21	0.035
4	0.043	13	0.038	22	0.046
5	0.045	14	0.043	23	0.039
6	0.046	15	0.036	24	0.042
7	**0.050***	16	0.045	25	0.046
8	0.044	17	0.044		
9	0.040	18	0.040		

Data of concentricity measurement for housing bore and spindle shaft in sample size of 25 was taken from the CMM inspection. According to design criteria, concentricity of bore should be 0.05 mm or less than that would be acceptable for our design. In bore of spindle housing, 0.05 mm concentricity should be described in feature control frame in drawing with reference to datum A.

Inspection of Cylindricity (Spindle)

- Start the Coordinate Measuring Machine.
- Calibration of machine by standard specimen.
- Select Z plane which is reference plane for the spindle shaft.
- To prepare primary datum control of cylindricity will necessary.
- For the spindle shaft to measure cylindricity first take 24 point measurement on the primary datum. Here it takes three datum circles from the reference plane on outer periphery of spindle shaft to measure the cylindricity.

The cylindricity requirement of the spindle shaft is 10 to 30 micron. Cylindricity can be measured by different method like V-block method, by CMM inspection. Cylindricity of spindle shaft would be measured from CMM inspection. We take 25 consecutive reading of concentricity and average it. Check weather is acceptable or not. If there is no problem during function and assembly, it would be acceptable otherwise revise it.

Table 19 Cylindricity of Spindle shaft

No.	Cylindricity (mm)	No.	Cylindricity (mm)	No.	Cylindricity (mm)
1	0.02	11	0.02	21	0.03
2	0.02	12	0.03	22	0.02
3	0.03	13	0.02	23	0.02
4	0.02	14	0.01	24	0.03
5	0.03	15	0.03	25	0.02
6	0.01	16	0.02		
7	0.02	17	0.02		
8	0.03	18	0.02		
9	0.02	19	0.02		
10	0.02	20	0.02		

The value of cylindricity for spindle shaft is achieved 0.02(20 micron) from the measurement in CMM machine which would acceptable for all the A-25 spindle. As shown in table 19, 25 consecutive data can be taken to verify the cylindricity error in CMM machine.

VII. ENGINEERING DRAWING

7.1 Conventional Drawing of Spindle Housing

Coordinate dimensioning and tolerancing is used in conventional drawing of spindle housing as shown in figure 12. Conventional drawing does not give information clearly regarding manufacturing setup, inspection setup and design intent. It is only indicate the dimensions and linear tolerances which lead to improper communications between customers and suppliers. So there is not follow the proper sequence and, method and design function integrity will increase the time, cost, error, rework and rejections.

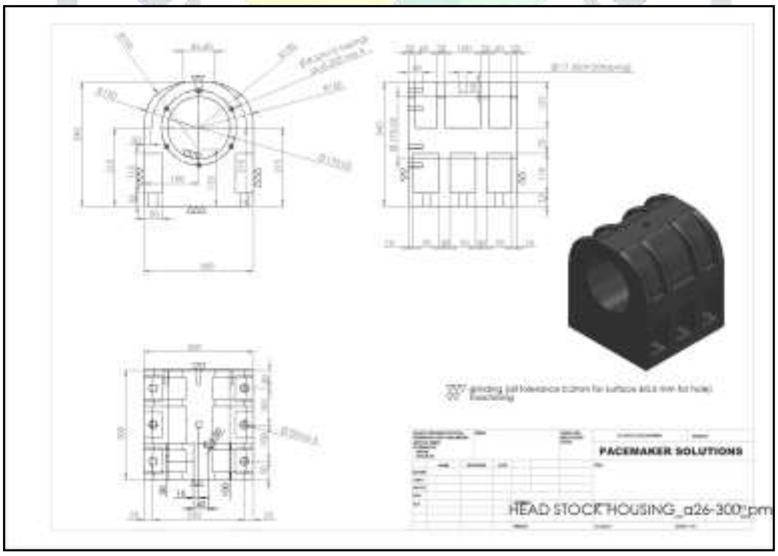

Figure 12 Conventional drawing of spindle housing

A drawing with missing dimensions and insufficiently defined tolerances may produce artificially low cost estimates that can cause manufacturing to produce nonfunctional parts. No tolerance limit and tolerance range of bore diameter is described in conventional drawing of spindle housing will lead to allow guesswork and assumptions throughout the manufacturing and inspection process. There is absence of clarity and precision of conventional drawing may require less time initially, but time is required more later.

7.2 Cad Model of Spindle Housing

3D Computer aided design (CAD) model was prepared in CREO Parametric 6.0.0 as shown in figure 13, in order to better visualization, future forecasting and Enhances designer output.

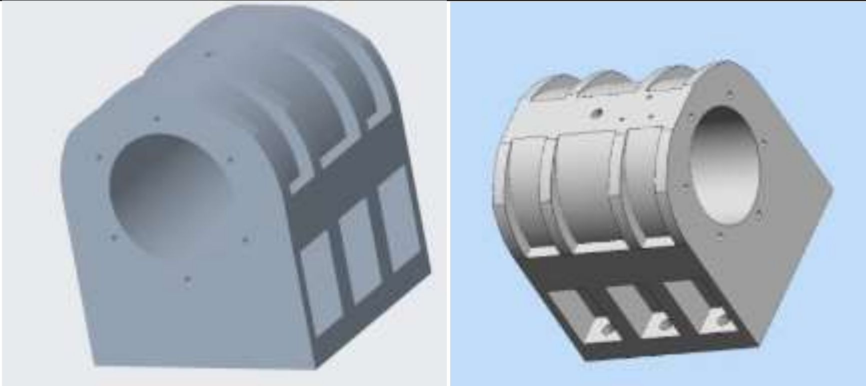

Figure 13 CAD Model for spindle housing

7.3 Conventional Drawing of Spindle

Conventional drawing of spindle assembly is shown in figure 14.

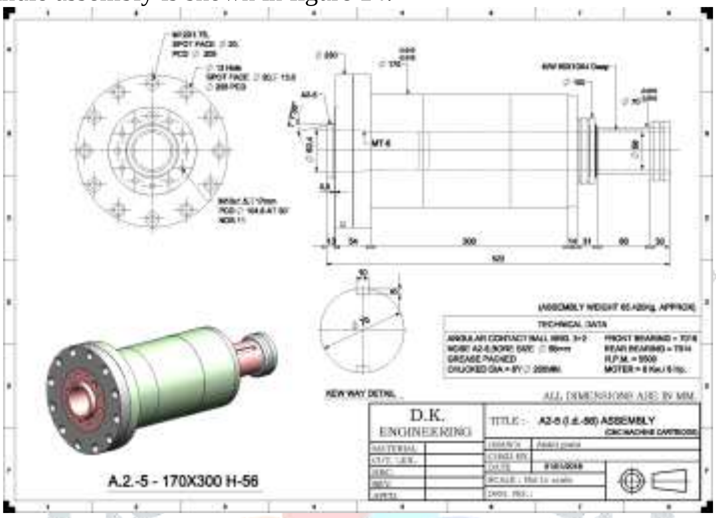

Figure 14 Conventional drawing of spindle assembly

7.4 CAD Model of Spindle Assembly

3D Computer Aided Design (CAD) model was prepared for spindle assembly is shown in figure 15.

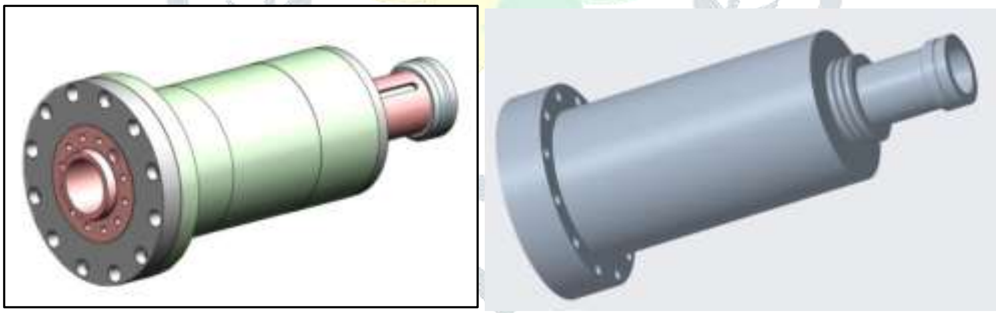

Figure 15 CAD Model for Spindle

7.5 GD&T drawing of spindle and spindle housing

Incorporate geometric dimensioning and tolerancing (GD&T) requirements in spindle and spindle housing to improve product reliability, ease of assembly, and eliminate errors, rework, rejections and scrap. GD&T Drawing will allow communication among all levels and functions within company, as well as with their customers and suppliers. The clarity and precisions of GD&T may require more time initially, but time is saved later. GD&T, meets today's demands and performs even better when designers use it to thoroughly think through part function. GD&T's philosophy and rules are applied to all part features, treating all of them as critical and to the entire process of creating drawings, the benefit of GD&T increases exponentially. Engineering drawing of spindle housing with GD&T requirements are shown in figure 16. Datum reference frame (DRF), Concentricity characteristic, Flatness control and Feature Control Frame (FCF) are described in the engineering drawing. Concentricity tolerance of 0.05 mm is shown in feature control frame with respect to datum A.

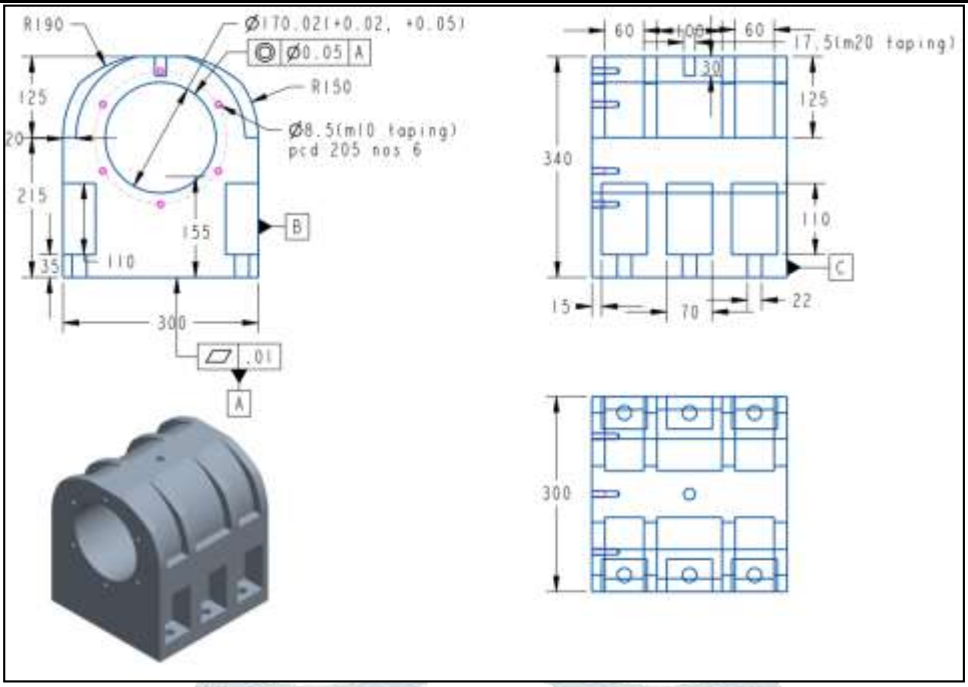

Figure 16 GD&T Drawing for Spindle housing

GD&T drawing for spindle assembly is shown in figure 17. Cylindricity characteristic and feature control frame are described in the engineering drawing. Cylindricity of 0.02 mm is described in feature control frame. The requirement of Cylindricity tolerance in spindle shaft is to get proper seating or mating with inner surface of the spindle housing and that will give ease of assembly, less time consuming and eliminate rework and rejections. Assembly drawing of spindle and spindle housing will give proper understanding and better visualization of geometrical characteristics of features. Critical features can be evaluate from this assembly drawing which is shown in figure 18

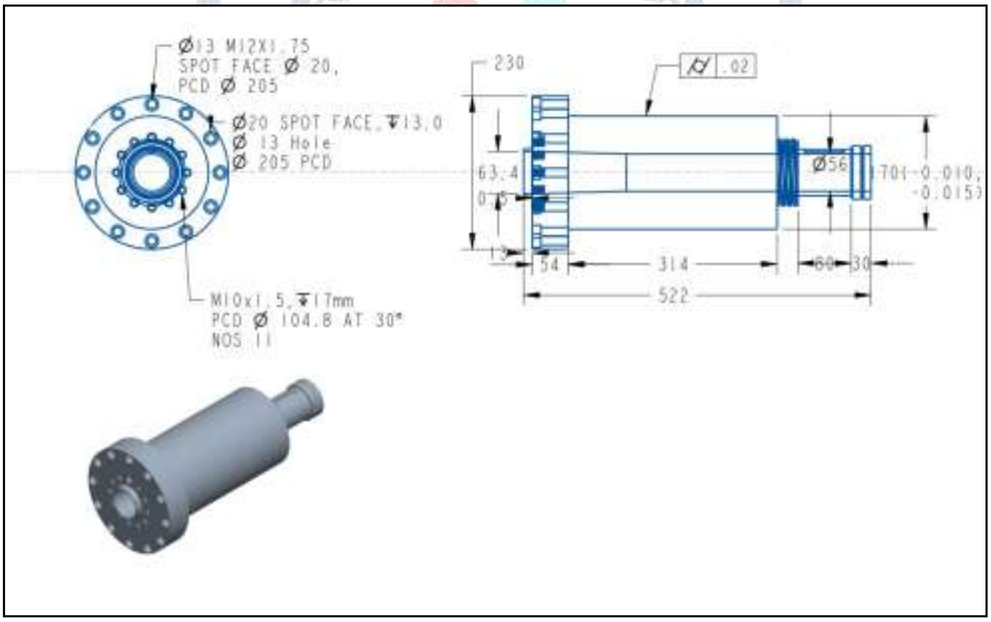

Figure 17 GD&T Drawing for Spindle assembly

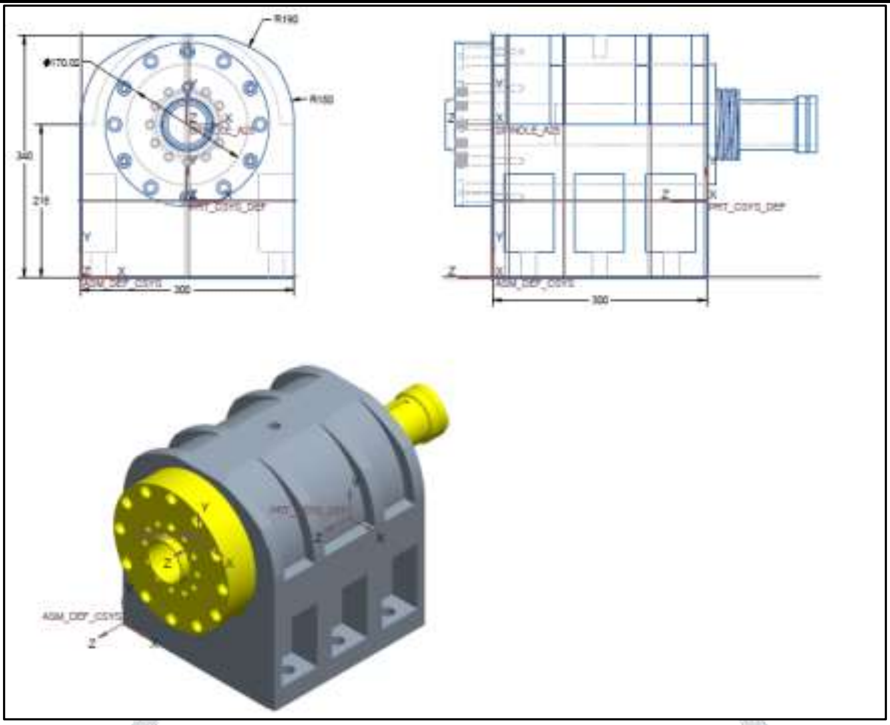

Figure 18 2D Drawing for Spindle housing system

3D CAD Model for assembly of spindle and spindle housing was prepared in CREO Parametric 6.0.0 software which is shown in figure 19.

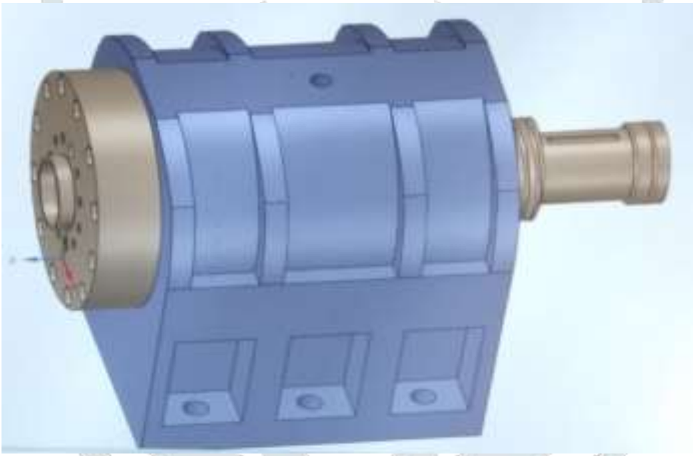

Figure 19 CAD Model for spindle housing system

VIII. CONCLUSION AND FUTURE SCOPE

8.1 CONCLUSION

In this present work, experimental work has been performed to improve the process capability and incorporate GD&T requirements in spindle as well as spindle housing to optimize and modify the engineering design, improve the running accuracy, assembly quality, shorten the assembly cycle, avoiding design iteration, product delays and low product yields. In this study the Process-Capability Analysis (PCA) was carried out for the elimination of the quality problems during honing operations. The number of non-conforming parts was determined in observed values, in short and long periods of time. For the elimination of the observed quality problems, some suggestions were proposed. Faults regarding manufacturing out-of-tolerance limits were eliminated, the variability in the process and the cost due to low-quality production were reduced in the particular company. Root Cause Analysis (RCA) has been carried out to find root causes for poor process capability and eliminate or control it to incorporate GD&T requirements (Concentricity, Cylindricity, Flatness and Datums) in spindle design. Datum reference frame has been incorporated into the manufacturing as well as inspection of spindle housing to clearly define the part design intent and manufacturing setup. Concentricity tolerance has been incorporate in spindle housing to eliminate the “tapered bore”. In spindle shaft, cylindricity tolerance has been incorporate to achieve mating surface and ease of assembly with the spindle housing.

The following results were obtained from the experimental work:

- From Cause & Effect Diagram in Root Cause Analysis (RCA), the main causes of variation for poor process capability are Work Holding Device, Failure of hydraulic system in honing machine, Inspection and Assembly variation, Poor maintenance.

- From 5-WHY Analysis, Use longer abrasive stone and check accuracy of part setup prior to honing are the possible solutions to eliminate tapered bore in spindle housing.
- From Failure Mode and Effective Analysis (FMEA), Hydraulic system in honing machine has been analyzed. A different failure in DCV, Pump, and Cylinder and their possible causes and effects has been troubleshooted.
- From Process Capability Analysis (PCA), Practical data of inner bore diameter of spindle housing in the sample size of 50 was taken. Because of unilateral tolerances used, the process capability index (Cpk) is considered, and calculate the value of Cpk is 0.74 which leads to poor process capability. Processes have been improved to 1.34 by eliminating and control the common causes of variation evaluated from the Root Cause Analysis (RCA).
- Process capability index (Cpk) for spindle was calculated to 1.45 which indicates the good process capability. The requirement of Cylindricity tolerance in spindle shaft is to get proper seating or mating with inner surface of the spindle housing.
- From the Coordinate measuring machine (CMM), concentricity of bore and cylindricity of spindle shaft has been measured. The concentricity for bore of 0.05 mm and the cylindricity for the spindle shaft of 0.02 mm are measured and incorporate in the engineering drawing.

8.2 FUTURE SCOPE

- Concentricity value in spindle housing will improved by controlling the factors of turning.
- Incorporate GD&T requirements of Maximum Material Condition (MMC), Least Material Condition (LMC), Perpendicularity, and Straightness in spindle and spindle housing to optimize the process as well as product parameters.
- Total Runout is also may incorporate to control the cylindricity and coaxiality of the spindle to a datum axis. If it is used on a surface that is 90° to the datum axis, it is capable of controlling the flatness and perpendicularity of the surface to the datum axis.

IX. ACKNOWLEDGEMENT

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