Applying Process Control to Gear Manufacturing

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Introduction:

A common goal of gear manufacturers is to produce gearing that is competitively priced, that meets all quality requirements with the minimum amount of cost in a timely manner, and that satisfies customers' expectations.

In order to optimize this goal, the gear manufacturer must thoroughly understand each manufacturing process specified, the performance capability of that process, and the effect of that particular process as it relates to the quality of the manufactured gear. If the wrong series of processes has been selected or a specific selected process is not capable of producing a quality part, manufacturing costs are greatly increased.

The manufacturing of a desired quality level of gearing is a function of many factors including, but certainly not limited to, the gear design, the manufacturing processes, the machine capability, the gear material, the machine operator, and the quality control methods employed. In this article we will make some basic assumptions about the gear design, engineering specifications, and the quality control methods employed, and concentrate mainly on the manufacturing processes, their control, and how they affect the gear quality produced.

Assumptions

In order to concentrate primarily on the gear manufacturing processes selected, their control, and how they affect gear quality, we have made several basic assumptions:

1. The gear designs are good, tooth contact analysis programs have been run, and motion curves and displacement values are within desired limits. Product testing and evaluation have been completed and found acceptable.

2. Engineering standards for accuracy and tooth contact location have been established according to design and testing requirements.

3. Acceptable quality control inspection methods are in place and GR&R studies (Gage Repeatability and Reproducibility) have been made, and the measured gage error has been deemed acceptable for all inspection measuring equipment and gages.

What Determines Gear Manufacturing Quality?

The quality level of a gear or gear set is determined during its manufacture by the specific sequence of production operations followed and the capability of each process. **The process sequence selected for the manufacture of a specific gear is determined by the final gear accuracies specified for that part.**

Two typical automotive/truck axle gear process flow diagrams are shown in this article. The target quality level of this type of gearing is generally set at AGMA 8. Example 1 (pg. 26) shows a general flow diagram of bevel gearing. Example 2 (pg. 27) is a general flow diagram of spur and helical gearing.

Note that it is possible, by the addition of a hard profile finishing operation after the heat treating operations, to increase the gear quality to AGMA 11 or 12. Along with this added operation, it may be necessary to tighten up some of the current manufacturing tolerances and to specify different workholding equipment. This would be primarily for bearing and bore diameters and could very easily affect the process capability of several different manufacturing operations.

What is Process Control?

Many gear manufacturers use process control techniques as a means of attaining the gear quality specified. AGMA defines process control as a method by which gear accuracy is achieved and maintained through control of manufacturing equipment, methods, and processes, without resorting to the inspection of individual elements of every gear produced.

Process control techniques analyze the manufacturing processes and quality control plans (METHODS), the gear steels used (MATERIAL), the machine capability (MACHINE), and the operator (MAN). When these techniques are properly applied to a specific process and that process is capable, then the gears manufactured will be of uniform quality.

How is the Process Monitored?

Data is collected on a specific characteristic for a specific process and then grouped in a histogram to get an idea of the distribution sample. With collected data, we can make some statistical calculations for the mean and the standard deviation. What we find is that the distributions will vary in shape, spread, and location relative to the tolerance, or any combination of the three.

The mean is defined as the sum of a group of numbers divided by the total number of elements within the group. The standard deviation is defined as the measure of dispersion (scatter or spread) of a set of data around its mean.

Statistical process control (SPC) techniques are excellent tools for evaluating a machine process. The results generated from an SPC evaluation give a "snapshot" picture of how the process is performing now and can be used to predict how it will perform in the future. These results can be used to compare the performance of other machines or processes and can be used to determine if a machine or process is capable of performing a specific task.

When is a Process "In Control"?

There are two causes of variation in any process. They are "common" and "assignable" causes. Common causes are random occurrences that are inherent to the process. They cannot be removed without changing the process. Generally, they are responsible for 85 to 90% of process variations. Assignable causes are non-random or patterned occurrences that can be identified and eliminated.

When conducting a capability study, material variations within one lot of material and variations caused by one operator may be significant; however, such variations are basic to the process and not easily eliminated. If there is no practical way of eliminating their influence on the process performance, these variations must be considered "common" variations.

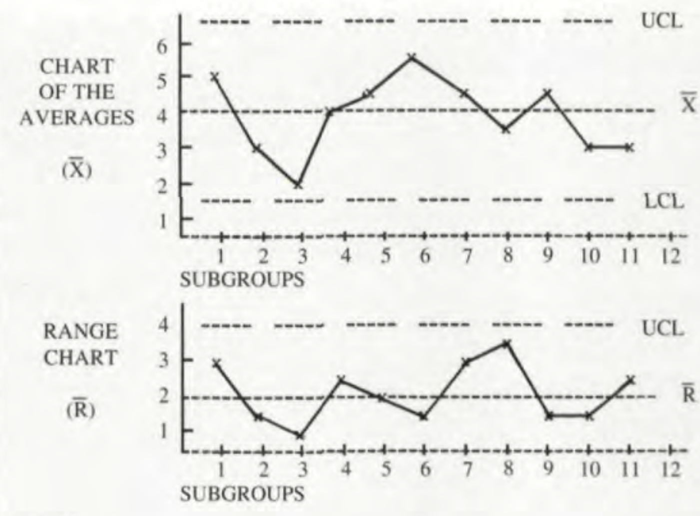

Fig. 1.

"Assignable" variations may come from many sources. A change in either operator from shift to shift or a material heat code lot change during the run are examples that can cause variation which is external to the basic process.

A process is said to be "in control" when the assignable causes have been eliminated. A process in statistical control will be evidenced on a control chart by the absence of points beyond the control limits and by the absence of non-random patterns or trends within the control limits (LCL, UCL). See Fig. 1.

What is Process Capability?

When the process is brought under control by eliminating the assignable causes, we can then assess its capability. It is important to note that a process "in control" may or may not be capable. Process capability is defined by two terms: Cp and Cpk.

Cp is the Process Capability Ratio. The Cp ratio is defined and calculated as follows:

Cp = Specification Tolerance Spread/(6 x Sigma), where Sigma is the standard deviation of the process being examined.

Basically, the Cp index is a comparison of the 6 Sigma spread of the distribution to the specification tolerance. Ideally, the 6 Sigma spread will fall within the specification toler-

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ance along with room to spare on each side of the specification limits. The Cp ratio does not account for centering the process relationship to the specification. See Fig. 2.

Cpk is the Capability Index. It gives an indication of the location of the distribution relative to the specification limits. Cpk accounts for the process centering.

For bilateral tolerances, when both upper and lower specification limits are given, Cpk is calculated by the following formula:

The <u>minimum</u> value of Cpk =
(USL - MEAN)/(3 X Sigma) or
(MEAN - LCL)/(3 X Sigma)

For unilateral tolerances, when only a minimum or maximum specification limit is given, Cpk is calculated by the following formula:

Cpk = (SL - MEAN)/3 Sigma

Where: USL = Upper Specification Limit
LSL = Lower Specification Limit
SL = Specification Limit
MEAN = Process Average
Sigma = Standard Deviation of Process

GIVEN PROCESS DATA:
MEAN = 17.5 SPECIFICATION TARGET = 16.5
STANDARD DEVIATION (SIGMA) = 1.3 TOLERANCE = +/- 5.5
Cp CALCULATIONS:
PROCESS SPREAD = 6 x SIGMA = 6 x 1.3 = 7.8
TOLERANCE SPECIFICATION SPREAD = UPPER SPEC. - LOWER SPEC.
= 22.0 - 11.0 = 11.0

$$Cp = \frac{\text{TOLERANCE SPECIFICATION SPREAD}}{\text{PROCESS SPREAD}} = \frac{11.0}{7.8} = 1.41$$

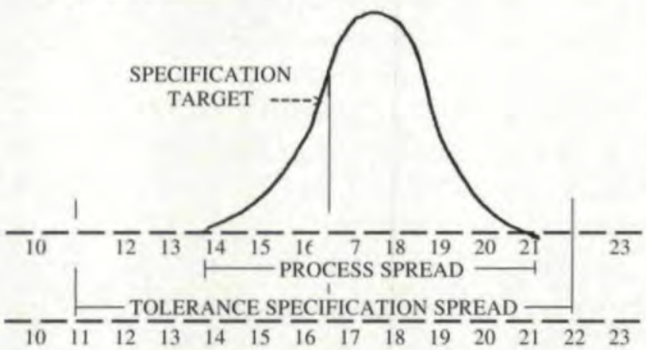

Fig. 2

Cpk calculation from data in Fig. 2:

$$Cpk = \frac{\text{UPPER SPECIFICATION LIMIT - MEAN}}{3 \times \text{SIGMA}}$$

$$= \frac{22.0 - 17.5}{3 \times 1.3} = 1.15$$

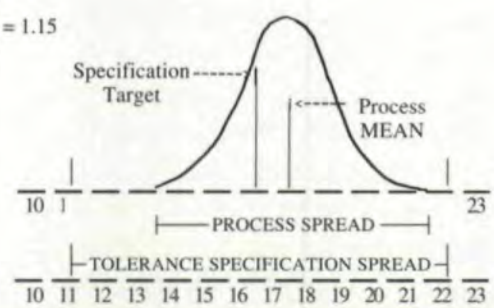

Fig. 3

Generally, the minimum accepted values for both Cp and Cpk are 1.33, which is equal to 75% of the tolerance for a 6 Sigma analysis. These indices give an indication of how well the process is making the product according to design or manufacturing specifications. Also, note that when the mean of the process is equal to the target value of the tolerance specification, then Cp = Cpk. The Cpk calculation from data in the previous example is shown in Fig.. 3.

It is also important to remember that the capability indices Cp and Cpk are based on two elements: the design tolerance and the standard deviation of the process. You can see, given the same data, we can change the tolerance to make the capability look better or worse for a given distribution. But the important element in the capability equation is the standard deviation (Sigma) of the measured distribution, and we cannot change that unless we change at least one of the process elements.

Applying Process Control - What Should Be Done?

In a word or two, **process control requires that the entire manufacturing process be examined from the forging coming in the door to the final shipment of the gear**. Where process capability studies are taken on each individual manufacturing operation to establish capability, control charts and plans must be maintained on a continuous basis to monitor performance capability. Also, do not forget the assumptions made in the beginning about the design, engineering specifications, and quality control methods employed.

Applying Process Control - Where Do We Start?

One of the most meaningful and eye-opening activities a gear manufacturer can pursue is the audit of several lots of finished gearing. Basically, it is a comprehensive self-assessment of your gear manufacturing capability. Select a variety of gearing based on pitch diameter, diametral pitch, and quality class required. Use lot sizes of at least twenty-five pieces and inspect all critical gear-related characteristics. Analyze the results using statistical methods. Now answer the following questions:

1. Are all the characteristics inspected within print specification?

2. After statistically analyzing the data, are the 6 Sigma values calculated less than the tolerance specification for that characteristic?

3. Are the data distributions centered with respect to the specification limits? Remember, Cp and Cpk values of 1.33 are generally the minimum accepted numerical value.

If the answers to Questions 1, 2, and 3 are "yes," and the calculated Cp and Cpk values are greater than 1.33, one should feel very confident about the quality of the overall gear manufacturing operation. Probably SPC techniques to monitor all manufacturing operations are already in use and the exact performance capability of each and every process in the plant is known.

If the answer to any one of the questions above is "no," there is work to be done. If the discrepancies are few and the manufacturing operation has a formal process control system in place, corrective action may not be much more than trouble-shooting a specific process operation. If the discrepancies are many, are critical characteristics, and the manufacturing operations are weak in the areas of SPC and process controls, a great deal of work will need to be done.

Applying Process Control - Perform Capability Studies

Knowledge of the performance capability of a process is essential to the overall concept of producing a quality gear. If the equipment selected and used is sufficiently accurate to meet quality requirements, an acceptable gear can be expected. When the quality is marginal or unsatisfactory, or when the processing equipment cannot meet the quality requirements, then the additional costs of scrap, rework, decreased productivity, and warranty result.

A process capability study is a technique for measuring that which a process is capable of producing under normal, in-control conditions. In a capability study, measurements of gears produced in a run are analyzed to determine whether or not the process is capable of producing, to specifications, a given characteristic on successive parts under production conditions. Process capability is a measurement of the inherent precision of a manufacturing process.

Applying Process Control - Identifying the Process Elements of a Capability Study

There are numerous combinations of manufacturing processes that can be used to produce an acceptable gear. Manufacturing engineering has the latitude to select the process to be used, depending on the capability of the equipment available and the available open capacity.

The results of capability studies show what is causing the "assignable" variation and what must be done to get it out of the process. Once this variation is eliminated, true process capability results.

In most processes, a capability study will show a large amount of initial variation. If capability studies have not been made on the process previously, the "assignable" variation is likely to be the greater part of the total variation. It is most likely the variation that gets the shop into the most trouble. The process capability study will work to detect and reduce or eliminate the "assignable" variation.

Table 1

1. MAN
   . Training on equipment and procedures
   . Work day fatigue/awareness
   . Setup skill & operating skill
   . Operator and operator changes
2. MACHINE
   . Quality capable
   . Machine alignment
   . Spindles
   . Draw
   . Speeds, feeds, and thermal growth
   . Rigidity
   . Balance
   . Machine maintenance & lubrication
3. MATERIAL
   . Material hardenability
   . Material chemistry
   . Microstructure
   . Hardness
   . Machinability
   . Material cleanliness
   . Dimensional characteristic
   (diameters, lengths, parallelism, runout)
   . Geometrical considerations
   (rims, webs, thickness, position)
4. METHODS
   . Workholding equipment type & condition
   . Workholding rigidity
   . Coolant type and volume
   . Cutting tool quality, new & resharpened
   . Cutting method
   (hob, shape, shear speed, mill, broach)
   . Material handling system

EXAMPLE 1
HYPOID/SPIRAL BEVEL GEAR AND PINION SET PROCESSING

GEAR

FORGING

PRE-TREATMENT NORMALIZE

BLANKING - PROFILE TURNING
- BROACHING
- *HOLE DRILLING*
- IDENTIFICATION

TOOTH CUTTING - MACHINE SETUP

GREEN TEST - CUTTING SETUP APPROVAL
- SIZE AND CONTACT COMPARISON TO PRODUCTION "REF".
- INSPECTION

BURRING, CHAMFERING

HEAT TREAT - CARBURIZE AND QUENCH
- BORE SIZE
- GEAR GEOMETRY

HARD GRIND - BORE I.D.

PINION

FORGING

PRE-TREATMENT NORMALIZE

BLANKING - PROFILE TURNING
- SPLINING
- GREEN GRINDING
- THREADING
- IDENTIFICATION

TOOTH CUTTING - MACHINE SETUP

GREEN TEST - CUTTING SETUP APPROVAL
- SIZE AND CONTACT COMPARISON TO PRODUCTION "REF"
- INSPECTION

BURRING, CHAMFERING

HEAT TREAT - CARBURIZE AND QUENCH
- INDUCTION ANNEAL
- STRAIGHTENING

HARD GRIND - BEARING JOURNALS

MATCH AND LAP OR HARD FINISH - REFINE TOOTH SURFACES FOR ACCEPTABLE TOOTH CONTACTS AND NOISE LEVEL

HARD TEST - MONITOR FINISHING OPERATION

PROTECT - PHOSPHATE COATING FOR BREAK IN, RUST PROOFING, AND IDENTIFICATION

SHIP - ASSEMBLY LINE OR CUSTOMER

To help identify "common" and "assignable" variations within a process, we would suggest that every process or operation that is analyzed be divided into four distinct categories, as shown in Table 1, and each category evaluated through the analysis of process elements. The four categories are 1) Man, 2) Machine, 3) Material, and 4) Methods.

Can We Sum This Up?

The gear quality level specified by the design dictates the processes used in your gear manufacturing to achieve that specified gear quality. Each process selected must be performance-capable over the long term to assure that the quality is maintained from one operation to the next. Audits of finished product must be conducted on a regular basis.

If quality defects occur, use process capability techniques to identify and fully understand the root causes of the problems and the paybacks associated with fixing them. After identifying the problems, use the Pareto principle to determine the areas of the highest payback. Develop a gear quality group, a game plan, and start small. After several successes are achieved, the quality group can grow aggressively and take on more quality problems.

Once process control techniques are employed, a gear manufacturer generally realizes tremendous benefits. One of the spin-offs of this type of analysis is that it will not take long before most gear manufacturers will want to make some fundamental changes in the manufacturing process to improve quality, improve productivity, or to implement some cost reduction projects. This comes from the thorough understanding of the process and its present capability.

There are many days we all struggle with gear quality issues. They consume a great deal of our time and effort. There can be a great deal of frustration; but in today's competitive environment, a formal process control system in place is essential no matter what product is manufactured. ■

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EXAMPLE 2
SPUR/HELICAL GEAR AND PINION PROCESSING

GEAR OR PINION

FORGING

PRE-TREATMENT NORMALIZE

BLANKING
- PROFILE TURNING
- HOLE DRILLING, BROACHING, SPLINING
- KEYWAY, THREADING
- IDENTIFICATION
- "GREEN" GRINDING

TOOTH CUTTING
- HOBBING, SHAPER CUTTING, SHEAR SPEED, MILLING, ROLLING
- SHAVING

GEAR INSPECTION
- CUTTING SETUP APPROVAL
- PIN DIMENSION
- LEAD, CROWN, AND INVOLUTE FORM
- PRECISION INDEX

CHAMFERING, BURRING, ETC.

HEAT TREATMENT
- CARBURIZE & QUENCH, NITRIDE, INDUCTION HARDENING, ETC.
- INDUCTION ANNEAL
- BORE SIZE, SPLINE SIZE, ETC.
- TOOTH SIZE AND TAPER
- RUNOUT, STRAIGHTENING, ETC.

HARD GRINDING
- BORE AND FACE LOCATIONS
- BEARING DIAMETER, JOURNALS, ETC.

SPEED OR HONE
- MONITOR MANUFACTURE
- NICK AND KNOT REMOVAL

HARD PROFILE FINISHING

CUSTOMER
- ASSEMBLY
- OUTSIDE CUSTOMER