DECEMBER 2000 / VOLUME 52 / NUMBER 12

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Know Your Capabilities

How to develop a process capability study.

Generally, machinists produce parts and inspectors verify the quality of those parts as the last step before shipping them to customers. Inspection is performed because there is variability in all parts.

But how can a shop convince a prospect that its machining processes can actually produce the needed parts? The answer is by conducting a process capability study.

Ask any reputable machine tool builder or distributor about a machine's capability and he'll probably describe the machine's accuracy or repeatability. While those numbers are meaningful when comparing equipment, they don't indicate true capability. If the numbers did, a shop would make every part to a print specification that falls within the machine tool builder's parameters.

But a machining process involves many variables besides the machine. Among them are tooling, workpiece material, CNC program (method), the person setting up the machine or running the parts, physical environment, coolant, age and condition of the machine, and the gages that measure part features.

So, what is this thing called capability? It defines how well the process produces parts to a given specification. It includes all the variables previously mentioned and predicts the distribution of the expected outcome.

Take Your Measure

Three measures of capability are important to a machinist: gage, machine and process.

Gage capability is a quantification that helps determine how much variation can be expected from measuring instruments. If, for example, the bore diameters in 10 parts vary by 0.002", it is important to determine whether that variation is really a size difference or just variation caused by an incapable gage. It's standard practice to designate a gage as being capable if it returns a value of 0.10. This value refers to the 10-to-1 rule, which states that if the tolerance being measured is 0.001", the gage should be capable of measuring to 0.0001".

The mechanics of performing a gage capability study are beyond this paper's scope. The point here is that to determine a process' capability, it's necessary to first determine the capability of the gages used.

Before beginning a discussion of machine and process capability studies, let's quickly review some measures of variation. The simplest is the range. For a set of data points or measurements, the range is simply the difference between the largest and the smallest value in the set. If the number of data points is small, the range is a meaningful measure. But as the number of data points increases, a better method of measuring variation is needed.

The term "standard deviation" tends to strike fear in engineers and machinists alike, because it can be difficult to understand and calculate. But, fundamentally, the standard deviation is merely the average distance, or deviation, that each data point varies from the arithmetic mean, or midpoint value.

For example, consider a series of 20 data points that have a mean average of 21. The smallest point is 16 and the largest is 26. Therefore, the range is 10, but it doesn't indicate how many data

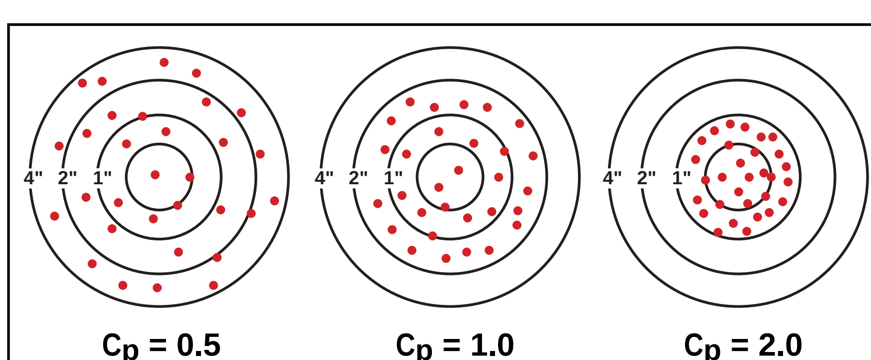

Figure 1: An archer's process capability (C_p) measures how close his arrows can hit a given tolerance range, as illustrated by the distance from the bull's-eye.

points vary from the mean or how far each of those points varies from the mean—only the two extremes. It could be that 18 of the 20 points are exactly 21, with one being 16 and another being 26. However, based on the actual data, the standard deviation may be less than three, giving a more accurate indication of the data points' actual spread.

Another important term is "normal distribution," otherwise known as the bell curve. For now, just remember that there are 3 standard deviations from the center of the bell curve to each tail.

Machine, Process Capabilities

The potential capability index (C_p) is used to measure how capable a machine or process is at meeting a given tolerance. Finding the C_p is normally a short-term study in which the location of specification limits is ignored.

An example would be setting up a lathe to turn 40 pieces without making adjustments. The result is the capability of that machine to turn a specific diameter. It doesn't matter where the specification limits are, because the operator can adjust for that. The result will be an indication of the machine's ability to turn a diameter to some tolerance.

C_p can be described as the allowable spread divided by the actual spread. The allowable spread is the difference between the upper and lower specification limits, or the total tolerance. The actual spread is found in the raw data that's measured and collected during the study. The actual spread is further defined as six times the standard deviation (S) of the actual data, meaning 99.73 percent of the potential data points can be accounted for under the bell curve.

The formula then becomes:

$$C_p = \frac{\text{Tolerance}}{6S}$$

If the C_p is 1.0, then the tolerance (the allowable spread) equals the actual spread. While that may appear to be the desired result, remember the discussion about gage capability. There needs to be some room left for gage-measurement error as well as for the tails of the normal distribution curve, since only 99.73 percent of the data will be within the curve.

Therefore, the rule of thumb for determining capability states that a process is considered potentially capable when the value generated from this C_p formula is 1.33 or greater.

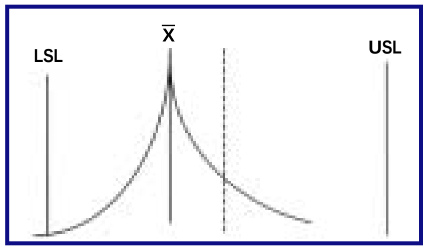

Figure 2: This process has shifted left of the true center (dashed line) of the specification limits.

To help illustrate the point, consider an archer shooting at a 2"-dia. bull's-eye. The bull's-eye is the specific tolerance and the center of the bull's-eye is the midpoint of that tolerance. The archer shoots 40 arrows without making any adjustments and all of the arrows hit within the 2" diameter, although off-center by half of the target or less. The C_p would be 1.0 if the arrows hit within the 2"-dia. zone, 2.0 if they hit within a 1"-dia. zone, 0.5 if they hit within a 4"-dia. zone, and so forth (Figure 1).

Since C_p only measures the potential for capability, you might wonder what value it has for machinists and shop owners. It has value for companies that, when purchasing a machine tool, specify in the purchase agreement that the machine must be capable of maintaining a certain C_p. When some companies buy a machine tool, they specify that it must be capable of maintaining a 1.33 C_p, based on a specific tolerance, such as 0.001" or 0.0005". Doing that ensures that the machine is at least capable of producing parts to tolerances normally seen in the shop.

C_{pk} Index

Unlike C_p, the process capability index (C_{pk}) goes a step further by taking into account the actual specification limits. Therefore, it's a better indication of capability.

The calculation for C_{pk} is similar to the one for C_p. But with C_{pk} we will now measure how far away we are (the average, or $\overline{X}$) from the nearest specification limit and divide that number by 3 standard deviations (3S). Since we are estimating how far away our actual results deviate from the nearest limit, this calculation represents the worst-case scenario. The formula is:

$$C_{pk} = \text{The lesser of: } \frac{\overline{X} - LSL}{3S} \text{ or } \frac{USL - \overline{X}}{3S}$$

where LSL = lower specification limit and USL = upper specification limit.

As with C_p, a value of 1.33 for C_{pk} is considered the minimum to assure a capable process.

Figure 2 shows the process shifted to the left of the true center (dashed line) of the specification limits. Don't be concerned about parts being generated beyond the USL because there's little probability of that occurring.

But there may be some concern about parts being made that exceed the LSL, because the tail of the actual distribution of measurements is close to the limit. If the process were perfectly centered, using only one-half of the tolerance, the C_{pk} value would be 2.0.

So, what's the significance of C_{pk}? Aside from being required by some customers, C_{pk} can accurately predict the probability of producing parts outside the specification limits, as shown in Table 1.

C_{pk}	±Standard Deviations	Out-of-Spec Parts
1.00	3	2,700 parts per million
1.33	4	63 parts per million
2.00	6	2 parts per billion

Table 1: C_{pk} can accurately predict the probability of producing parts outside the specification limits.

Technology Works

Today's computers and spreadsheet software packages make it a snap to conduct a capability study. For one study, I conducted 42 consecutive measurements of a process without making any adjustments (Table 2). The data was entered into the spreadsheet and calculated for both C_p and C_{pk}, and the results showed whether the process was capable or not.

0.0189	0.0191	0.0192	0.0198	0.0194	0.0199	0.0196	0.0198	0.0180	0.0197	0.0191	0.0195	0.0198	0.0193
0.0202	0.0188	0.0198	0.0174	0.0183	0.0198	0.0192	0.0202	0.0199	0.0191	0.0199	0.0186	0.0196	0.0186
0.0200	0.0200	0.0190	0.0197	0.0194	0.0194	0.0198	0.0193	0.0194	0.0192	0.0201	0.0191	0.0195	0.0194

Table 2: The author conducted 42 consecutive measurements of a process without making any adjustments.

The mean in Table 2 is 0.01938", with a standard deviation of 0.00059". Based on a 0.001", or ±0.0005”, tolerance, the C_p is 0.28. The total tolerance would need to be 0.005" to yield a capable result [C_p = 0.005/(6 × 0.00059) = 1.41].

The specification limits in this case were 0.017" to 0.023", or a total tolerance of 0.006", so this process was capable of producing parts within the specification limits.

Now, let’s do the math for C_{pk}. The mean of the specification limits is 0.020". Since the actual mean of the output is 0.01938", the actual mean is closer to the lower limit than to the upper limit. Therefore, taking the average minus the LSL and then dividing by 3 standard deviations, we get 0.01938 - 0.017 = .00238 / (3 × 0.00059) = 1.34 C_{pk} = a capable process.

Why calculate both C_p and C_{pk}? Because the actual process is rarely centered on the specification’s midpoint. In this example, the midpoint is 0.020". If the measured data averaged exactly 0.020", the C_p and C_{pk} would be, in this case, exactly the same—1.70. In practice, the C_{pk} can only be equal to or less than the C_p, given the same tolerance.

It should be noted that for a short-term machine capability study, C_p is frequently calculated with ±4S (4 standard deviations) to help ensure long-term capability. In this case, divide by 8S to obtain the C_p. (I used 6S in Table 1 because most of the processes I see are relatively short in duration.) Adjust the formulas to fit the specific situation.

Prove It

There is a great difference between machine accuracy and process capability. The ability to predict whether or not a process is capable of meeting customer expectations is necessary to survive in today’s competitive machining industry. C_p and C_{pk} allow shops to understand their true capability and make improvements that will benefit them and their customers.

As industry moves toward Six Sigma, it’s imperative that shops know their true capability and use that information to their competitive advantage.

About the Author

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