关于工厂厂房中机器的十分重要的西格玛或“Cpk”等级的理论会令人困惑。一种统计过程控制（“SPC”）工具可计算答案，但如果机器始终低于制造商公布的数据，又该怎么办？甚至一些机器制造商也不一定同意机器在什么时候达到最佳水平：六西格玛的可重复性。大部分不确定因素集中在如何解释数据以及如何采用适当的变量上下限。正如这里所解释的，关键在于过程的标准偏差。

Demystifying Six Sigma

Bruce Brigham

The mythical gold standard for repeatability in reality depends on limits set for maximum acceptable variance from nominal.

Industrial processes have always demanded the utmost repeatability, to maximize yield within accepted quality limits. Take surface mount assembly: as packages such as 0201 passives and CSPs enter mainstream production, assembly processes must deliver that repeatability with significantly higher accuracy. As manufacturing success becomes more delicately poised, this issue will become relevant to a growing audience, including product designers, machine purchasers, quality managers and process engineers focused on continuous improvement.

This article explains and demystifies the secrets locked up in the charmingly simple – yet obstinately inscrutable – expression buried somewhere in a machine's specification sheet. You may have seen it written

Repeatability = six sigma @ ± 25 µm

This shows that the machine has an extremely high probability (six sigma) that, each time it repeats, it will be within 25 µm of the nominal ideal position.

A great deal of analysis, including the work of the Motorola Six Sigma quality program, among others, has led to Six Sigma becoming accepted throughout manufacturing as the gold standard for repeatability. A machine or process capable of achieving six sigma is surely beyond reproach. Not true: many do not understand how to correctly calculate the value for sigma based on the machine's performance. The selection of limits for the maximum acceptable variance from nominal is also critical. In practice, virtually any machine or process can achieve Six Sigma provided those limits are set wide enough.

This is an important subject to grasp. Understanding it will lead to meaningful comparisons between the claims of various equipment manufacturers when evaluating capital purchases, for example. You will also be able to set up lines and individual machines quickly and confidently, troubleshoot and address yield issues, and ensure continuous improvement. You will have a clearer view of the capabilities of a machine or process in action on the floor, and apply extra knowledge when analyzing the data you collect through SPC software in order to regularly reassess equipment and process performance.

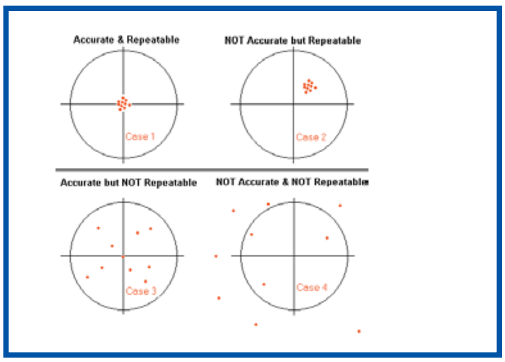

FIGURE 1: Small standard deviation does not guarantee accuracy. Case 1 shows a repeatable machine, Case 2 a repeatable machine that is not very accurate.

Instead of diving into a statistical treatise, let's take a graphical view of the proposition. All processes vary to one degree or another. A buyer needs to ask: Is the process or machine accurate and repeatable? And, How can I be sure? Accuracy is determined by comparing the machine's movements against a highly accurate gage standard traceable to a standards organization.

Consider the possibilities of accuracy versus repeatability. Suppose we measure the x and y offset error 10 times and plot the 10 points on a target chart (**Figure 1**). Case 1 in this diagram shows a highly repeatable machine as all measurements are tightly clustered and on target. The average variation between each point, known as the standard deviation (written as sigma, or the Greek symbol σ), is small.

However, a small standard deviation does not guarantee an accurate machine. Case 2 shows a very repeatable machine that is not very accurate. This case is usually correctable by adjusting the machine at installation. It is the combination of accuracy and repeatability we strive to perfect.

A simple way of determining both accuracy and precision is to repeatedly measure the same thing many times. With screen printers the critical measurement is x and y fiducial alignment. Theoretically, the x and y offset measurements should be identical, but we know that practically the machine cannot move to the exact location every time due to the inherent variation. The larger the variation, the larger the standard deviation.

After making repeated measurements, the laws of nature take over. Plotting all readings will result in what is known as the normal distribution curve (the bell curve of **Figure 2**, also called Gaussian). The normal distribution shows how the standard deviation relates to the machine's accuracy and repeatability. A consistent inaccuracy will displace the curve to the left or right of the nominal value, while a perfectly accurate machine will result in a curve centered on the nominal. Repeatability, on the other hand, is related to the gradient of the curve either side of the peak value; a steep, narrow curve implies high repeatability. If the machine were found to be repeatable but inaccurate, this would result in a narrow curve displaced to the left or right of the nominal. As a priority, machine users need to be sure of adequate repeatability. If this can be established, the cause of a consistent inaccuracy can be identified and remedied. The remainder of this section will describe how to gain an accurate understanding of repeatability by analyzing the normal distribution.

A number of laws apply to a normal distribution, including:

1. Of the measurements taken, 68.26% will lie within one standard deviation (or sigma) either side of average or mean.

2. Of the measurements taken, 99.73% will lie within three standard deviations either side of average.

3. Of the measurements taken, 99.9999998% will lie within six standard deviations either side of average.

Consider the bell curve shown in **Figure 2**. The process it depicts has three standard deviations between nominal and 25 µm. Therefore, we can describe the process as

Repeatability = three sigma at ±25 µm

Two important facts to note:

- Do not be confused by the fact that there are six standard deviation intervals between the upper and lower limits, -25 µm and +25 µm: this is not a six-sigma process. The laws governing the normal distribution say it is three sigma.
- The normal distribution curve continues to infinity, and therefore exists outside the ±25 µm limits. It continues to six-sigma, described by note 3 above, and even beyond. Simply by drawing extra sigma zones onto the graph, we can illustrate that the three-sigma process at ±25 µm achieves six-sigma repeatability at ±50 µm. It is the same process, with the same standard deviation, or variability.

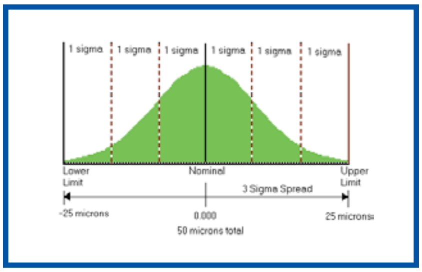

FIGURE 2: The narrowing of the bell curve relative to the specification limits is known as the spread. Here the bell curve shows three standard deviations between nominal and 25 µm …

Now consider what happens if we analyze a more repeatable process. Clearly, as the bulk of the measurements are clustered more closely around the target, the standard deviation becomes smaller and the bell curve will become narrower.

For example, let's discuss a situation where the machine has a repeatability of four sigma at ±25 µm, and is centered at a nominal of 0.000 (**Figure 3**). This bell curve shows an additional sigma zone between nominal and the 25 µm limit. Clearly, a higher percentage of the measurements lie within the specified upper and lower limits. The narrowing of the bell curve relative to the specification limits highlights what is referred to as the spread. Equipment builders attempt to design machines that produce the narrowest spread within the stated limits of the equipment, increasing the probability that the equipment will operate within those limits.

Lastly, we draw our bell curve with six-sigma zones to show what it means to state that a machine has ±25 µm accuracy and is repeatable to six sigma. You can see how the six-sigma machine has a very much smaller standard deviation compared to the three-sigma machine. In fact, the standard deviation is halved. This means the six-sigma machine has less variation and therefore is more repeatable. Consider the very narrow bell curve of **Figure 4** in relation to the laws governing the normal distribution, which state 99.9999998% of measurements will lie within six standard deviations of nominal.

Let's summarize the important points regarding the repeatability of a process:

- Any process can be called a six-sigma process, depending on the accepted upper and lower limits of variability.
- The term six sigma alone means very little. It must be accompanied by an indication of the limits within which the process will deliver six-sigma repeatability.
- To improve the repeatability of a process from, say, three sigma to six sigma without changing the limits, we must halve the standard deviation of the process.

Relationship to PPM

We can also now see why six sigma is so much better than three sigma in terms of the capability of a process. At three sigma, 99.73% of the measurements are within limits. Therefore, 0.27% lie outside; but this equates to 2700 parts per million (ppm). This is not very good in a modern industrial process such as screen printing, or any other SMT assembly activity for that matter. Six sigma, on the other hand, implies only 0.0000002% or 0.002 ppm (two parts per billion) outside limits. Readers familiar with the Motorola Six Sigma quality program will expect to see 3.4 ppm failures. This is because the methodology permits a 1.5 sigma "process drift" in mean not included in the classical statistical approach (which this article is following).

Whichever approach is taken, take care to evaluate companies' claims of six-sigma capability. For instance, if a machine vendor claims six sigma at ±12.5 µm, you must ask for the standard deviation of the machine. Then divide 12.5 µm by the figure provided to find the repeatability, in sigma, of the machine: if the result is six, the repeatability is six sigma and the vendor's claim for process capability is reliable. Depending on the intent of the vendor, you may find a different answer. For example, the machine may be only half the stated accuracy. This is because there is room for confusion over whether limits of ±12.5 µm would permit repeatability to be calculated by dividing the total spread, i.e., 25 µm, by the standard deviation. This is inconsistent with the laws governing the normal distribution, but it does provide scope to claim six-sigma performance for a process that is, in fact, only three sigma. Be careful.

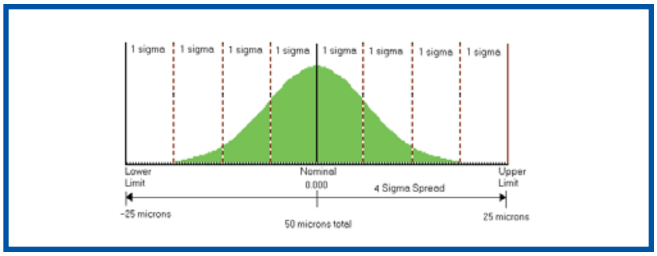

FIGURE 3: … And it narrows for four standard deviations …

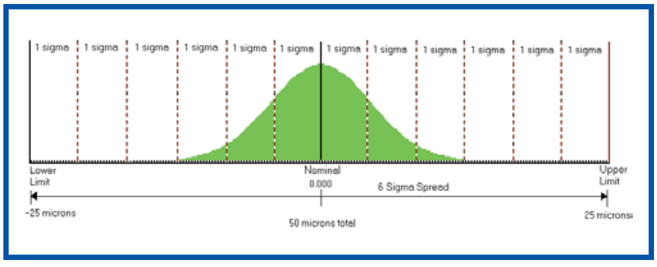

FIGURE 4: … And narrows further for six standard deviations, or six sigma.

When purchasing equipment, have the manufacturer provide proof. Request a report showing how the machine performed at the rated specification.

Most SMT equipment has built-in video cameras for self-alignment and, in some cases, inspecting the product it produces. Screen printers use cameras to align incoming boards and stencils. Even though the board-stencil alignment is relative to one another, an independent verification tool can be mounted in the printer to produce an unbiased measurement verifying the machine's stated accuracy and repeatability.

The SPC tools used by an equipment manufacturer to characterize its machines' ability to support particular processes will calculate the standard deviation, σ, from measurements taken directly from the machine.

Relationship to Cp and Cpk

The term Cp or Cpk describes the capability of a process. Cp is related to the standard deviation of the process by the following expression:

$$Cp = \frac{(USL - LSL)}{6\sigma}$$

where USL is Upper Specification Limit and LSL is Lower Specification Limit

But where the process capability is expressed in these terms, the majority of machine data sheets quote a figure for Cpk. Cpk includes a factor that takes process inaccuracy into account, as follows:

$$Cpk_{Upper} = \frac{(USL - \overline{X})}{3\sigma}$$

$$Cpk_{Lower} = \frac{(\overline{X} - LSL)}{3\sigma}$$

$$Cpk = Smaller\ of\ Cpk_{Upper}\ and\ Cpk_{Lower}$$

where $\overline{X}$ is the center point of the process.

You can see how Cpk varies with any offset in the bell curve caused by process inaccuracies. In the ideal situation, when $\overline{X}$ = 0, the process is perfectly centered and Cpk is equivalent to Cp.

Assuming the machine is set up by the manufacturer to be accurate, we can accept that $\overline{X}$ = 0 such that Cp = Cpk. In this case, we can see from the formula for Cp that six sigma corresponds to Cpk 2.0, four sigma corresponds to Cpk 1.33 and three sigma corresponds to Cpk 1.0. Note again, however, that the critical factors affecting Cpk are the limits and the standard deviation of the process.

It is also worth noting that Cp and Cpk refer to the capability of the entire process the machine is expected to perform. Consider the screen printer example. Repeatedly measuring the board-to-fiducial alignment alone will yield a set of data from which the capability of the machine could be assessed, expressed as Cm or Cmk. But several further operations, beyond initial alignment of the board and stencil, are required before a board is available for analysis. To extract a true figure for Cp or Cpk, then, we must be sure that we are not merely measuring the machine's capability to perform a subset of the target process.

Process Capability, or Alignment Capability?

After the alignment stage, several further elements of the machine's design, its build, or setup will influence the repeatability of the print process. For example, the lead screw for the table-raise mechanism could be warped or may have been cut inaccurately; on an older machine it could be worn or damaged, especially if the service history is not known. Other variables include the stencil retention or board clamping mechanisms; these may not be fully secure. Other machine components, such as the chassis, may lack rigidity. The act of moving a print head across the stencil, exerting a vertical force of some 5 kg while traveling at a typical excursion speed of 25 m/s, will almost certainly make the print performance less repeatable if the machine has weaknesses in these areas (**Figure 5**). To assess whether a machine will produce the print results required in a particular target process, the buyer needs to know that the capability figures refer to the machine's overall ability to output boards that are printed accurately to within the quoted limits.

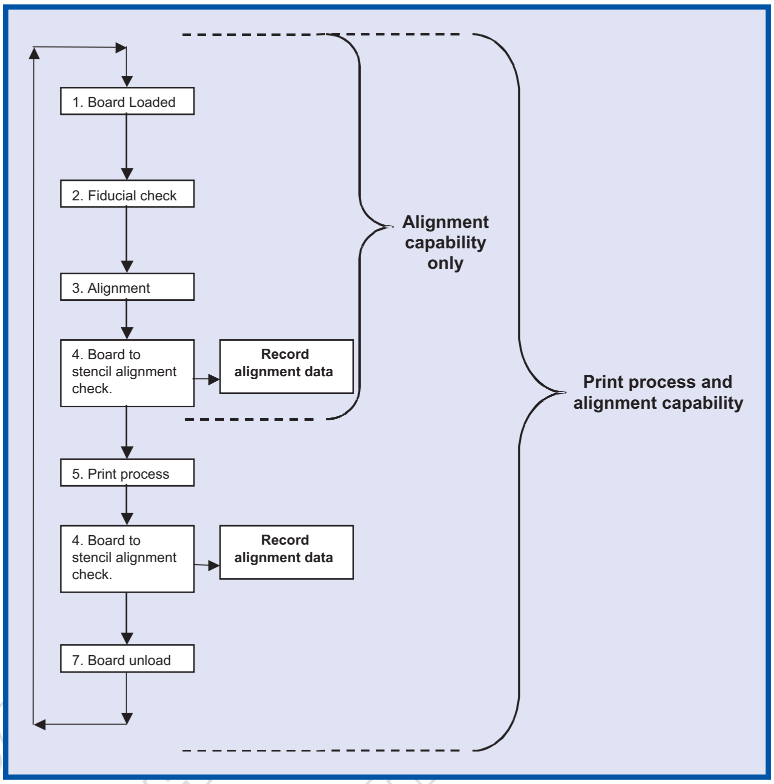

FIGURE 5: Alignment capability versus full process capability.

OK, so you have quizzed your machine supplier about its standard deviation, and the stated limits of repeatability. You have made sure the quoted performance figures relate to overall process capability, not to one aspect of its activities, such as alignment. You have verified the manufacturer's claims using your newfound familiarity with statistical analysis; and your new machine is up and running on your line. But it is not producing the repeatability you expected when running your target process. What do you do?

Depending on the type of machine, any number of factors could work alone or interdependently to cause a gradual or more abrupt deterioration in repeatability. In a screen printer, selection and setup of tooling, for example, is important. Inadequate underscreen cleaning may be causing blocked apertures over a longer time period. Or a change in solder paste supplier could introduce a step change in the results you are experiencing.

Some of these issues can be identified and resolved easily. Others may demand a more scientific approach. Using data collection and SPC can help machine owners analyze their machines' performance historically or in real-time, in the same way that the machine vendor may use such a tool to accurately characterize the machine before delivery. You can also perform trend analysis and have one or more actions, such as a point outside sigma limits, trigger automatically to help isolate causes of poor performance.

There is a difference between machine parameters and process parameters. The OEM provides machine parameters to work within while users set the machine with their own process parameters. Stay within this limit and good product will result.

1. Many people, including machine manufacturers, may be confused about how to calculate the capability of a process or machine.

2. Test the performance figures published by the machine vendor by asking for the machine's standard deviation. Divide the standard deviation into the upper or lower limit quoted by the manufacturer to find the machine's capability, in sigma.

3. Find out if the figure quoted applies to the entire process or only a certain part of it, such as dry fiducial alignment.

4. Depending on the above answer, this may change your opinion of the machine's capabilities.

5. The selection of other components, such as tooling, machine settings and process parameters, also influence repeatability on the factory floor.

6. Wear or damage to the machine may also impair repeatability.

7. Monitoring via a statistical process control permits an assessment of repeatability, can help identify trends and can aid troubleshooting and continuous process optimization. ■

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