CHAPTER 12

MACHINE TOOL ACCURACY

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12.1 Introduction

This review is organized into the following sections: 1) Measuring Tools, 2) Coordinate Measuring Machines, 3) Machine Tool Accuracy, 4) Workpiece Accuracy and Processing Considerations, 5) Temperature Considerations, 6) Accuracy Standards, 7) Statistical Process Control (SPC) and, 8) Summary. It is intended to be a brief overview of each area. Additional, independent study in each area is recommended to properly prepare for the certification exam.

Machine tools are purchased to produce workpieces at specified Engineering Document dimensions and tolerances. This means that the dimensions and geometry of the finished workpiece must be measured and verified after machining. In some cases the customer may require a sample part runoff prior to shipment in the machine tool builder's facility or in his own plant after installation. As a machine tool sales engineer, you need to understand the tools and methods of measurement in:
1. Selling the correct machine to produce the part (the machine must be more accurate than the workpiece specifications).
2. Verification of actual workpiece accuracy in a runoff.

Improved machine tool accuracy brings: 1) higher product quality and life, 2) reduced assembly costs, 3) lower inspection costs, 4) part interchangeability and, 5) reduced scrap. When machine performance exceeds Engineering Document tolerances, sell these benefits to the customer. When required to perform a part runoff, be sure to define the terms, equipment and procedures in advance. Let's define three important terms:

**Accuracy** is defined as the degree of conformity to, or deviation from a known standard. It is a comparison of the actual results with the desired results. In other words, how close did you come to the point aimed at? Standards are ultimately established by NIST (National Institute of Standards and Technology) in Washington, DC. However, in practical use the measuring tools found in the plant inspection area become the standard. These tools will include everything from hand-held micrometers; surface plates and height gauges to CMM’s.

**Precision (Repeatability)** is the degree of exactness with which a quantity is stated or the exactness of the measuring process and its repeatability. This term has to do with the closeness of the pattern or grouping formed by repeatedly aiming at a target position.

**Resolution** is defined as the least or minimum programmable increment capable of being recognized in the production system or measuring/inspection system used to define accuracy or repeatability. A rule of thumb is that the measuring system or inspection capability must be five to ten times more accurate than the desired tolerance in a manufacturing process. This is a good comparison to the accuracy, repeatability and resolution needed in a machine tool and the final workpiece inspection process, expected to produce highly precise components or output.

Many variables in the machining process affect the finished workpiece and fall into one of the above categories. No machining process is perfect and errors will be introduced that must be diagnosed - these can come from the:

3. Tooling and fixtureing.
4. Environment/Temperature.
5. Inspection process. Establishing the difference between accuracy and repeatability errors will help in the diagnostic procedure.
12.2 Glossary

Accuracy - The degree of conformity to an established standard.

Actual size - The measured or produced size of a part feature.

Ambient temperature - The average temperature of the surrounding workpiece or machine environment.

American National Standards Institute (ANSI) - A major standards development group in the USA. ANSI is a non-profit, non-governmental body supported by over 1000 trade organizations, professional societies and companies. It is the United States’ representative to the International Standards Organization (ISO).

Average - Average or "X bar" is the mean or average value in a group of SPC data.

Capability - When the process average +/- 3-sigma spread of the distribution of individuals is contained within the specification tolerance or when at least 99.73% of individuals are within specifications, a process is said to be capable.

CMM: Coordinate Measuring Machine. A device used to measure parts based on points (in coordinates) gathered on the workpiece.

Control limits - The limits within which the product of a process is expected to remain. If the process leaves the criteria, it is said to be out of “statistical control”, and a need for action is indicated.

CP Index (Process Capability) - An index, which reflects the maximum capability of the process, that is the potential of the process when the average is perfectly centered between the upper and lower specification limits.

CPk Index (Process Capability) - Similar to CP Index except it reflects the capability of the process under conditions present during production. It not only considers machine repeatability (like CP index), but it also considers machine targeting.

Characteristic - A distinguishing feature of a process or its output on which variables or attributes data can be collected.

Common cause - A source of variation that affects all the individual values of the process output being studied; in control chart analysis it appears as part of the random process variation.
Control chart - A chronological (hour by hour, day by day) graphical comparison of a current part characteristic with limits reflecting the capability of the process as shown by past experience.

Control limits - Reference points found on a control chart that are used to judge if a process is in or out of control. Normally, indicated as UCL (upper control limit) and LCL (lower control limit) values.

Dimension - The exact size or locational value specified on a shop Engineering Engineering Document.

Error of Bias - Error caused by either intentional or unintentional bias in measurement. An example would be to over-tighten a micrometer to obtain a desired reading.

GD&T: Geometric Dimensioning and Tolerancing. This is the American National Standard Institute’s (ANSI) standard for specifying manufacturing prints. This standard defines properties like Flatness, Roundness, Position, Runout, Parallism, etc.

GR&R: Gage Repeatability and Reproducibility. This is a test of a gage’s capability to evaluate a given dimension based upon its tolerance.

Gages - Tools used to check the conformity of a part feature to a standard of specific size or shape.

Graduations - The equally spaced lines on each edge of a rule, or the sleeve and thimble of a micrometer. These lines are used to denote units of measurement.

Individual - A single unit, or a single measurement of a characteristic.

Histogram - A picture of the process derived from "historical" data. A tally chart of measured dimensions that can tell about targeting, repeatability, distribution, process control, and data reliability.

Mean - The average of values in a group of measurements. See average.

Metrology - The science of measurement; the principles upon which precision machining, quality control and inspection are based.

NIST - National Institute of Standards and Technology (formerly the National Bureau of Standards)

Normal distribution - A predictable pattern of variation found in manufacturing processes that is the basis of SPC calculations and observations.

Plug gages – Go/no-go gages that are intended to check the diameter of a round hole.

Precision - The repeatability of a measuring process. This term has to do with the closeness of the pattern or grouping formed by repeatedly aiming at a target position.
**Process** - The combination of people, equipment, methods, and environment that produce output at a given rate for product or service. A process can involve any aspect of a company's business. A key tool for managing processes is Statistical Process Control (SPC).

**Randomness** - A condition in which individual values are not predictable, although they may come from a definable distribution.

**Range** - The difference between the highest and lowest values of a subgroup. The expected range increases both with sample size and with the standard deviation.

**Reliability** - The condition where the actual results are the same and/or better than the predicted or desired results.

**Repeatability** - See Precision.

**Sample** - A group of units taken from a population (sub-group).

**Sigma (σ)** - The Greek letter used to designate a standard deviation. Standard deviation is a simple way of measuring machine repeatability, or how one part varies from the next. It is the statistical measure of variance in a process.

**Standard** - An established known value used to measure an unknown quantity.

**Standard deviation** - Reference "sigma".

**Statistical Process Control (SPC)** - SPC is a process control method that allows measured data from the process to be plotted, statistically analyzed and projected in order to keep the process under control.

**Spread** - A general concept for the extent by which values in a distribution differ from one another; dispersion.

**Target** - The point aimed at. This would refer to the Engineering Document dimension that is the desired target on the workpiece.

**Tolerance** - The amount of permitted variation from the basic size dimension of a part feature. Ex: +/- 0.005”

**Variation** - The concept that no two parts (or anything else) are exactly alike.

**Vernier scales** - A system of measurement that uses sliding scales to make measurements.

**X bar** - X bar or Average is the mean value in a group of data.
12.3 Measuring Tools

The Machine Tool Sales Engineer should have a basic knowledge of the measuring tools used in the inspection of machines and workpieces. Keep in mind that proper technique must be used in obtaining good reading from ALL measurement devices. Also, the proper device must be chosen for a given dimension.

Choosing a measurement device depends on several factors. One very important consideration when selecting a measurement device is the gage’s stated accuracy as compared to the dimension to be measured. A commonly accepted rule for gage selection is an accuracy to tolerance ratio if 1:10. For example, if the tolerance to be inspected has a tolerance of 0.020”, the machine’s accuracy should be stated at better than 0.002”. Another important consideration is the measurement system’s resolution. It should have a minimum of 20 measurement increments within the product tolerance – for example, for a total tolerance of 0.020”, the resolution of the measuring device should be a MINIMUM of 0.001”.

“Common Instruments and Gages”

Here are a few of the more common instruments and gages and their uses:

- Touch Trigger or Manual CMMs for size and position characteristics
- Scanning CMMs for size, position, form, and orientation characteristics
- Rules and Tape Measures for size characteristics
- Indicators, Calipers, Micrometers (Vernier, Analog, Digital) for size characteristics
- Surface finish tracers for surface finish characteristics
- Optical Comparators for size characteristics (limited to “outside” dimensions)
- Height Gages (Vernier, Analog, Digital) for size characteristics
- Gage Blocks for size characteristics
- Form Instruments for characteristics like Roundness and Cylindricity
- Laser Interferometers for size characteristics
- Contour Profiler for size characteristics

In machine tool measuring probes are good for size and location as well as providing information for tool offsets and part location. In machine tool measuring is not recommended for final part inspection as parts may change dimension after removal from the machine tool. Many characteristics like form cannot be gaged properly with in-machine tool measuring probes.
Gage block sets are a common tool used to establish a known linear dimension in the shop. Sets are made up of different sizes that can be combined to establish a desired dimension. Four different accuracy grades apply to gage block sets -- the best grades (.05 or AAA) are manufactured to a tolerance of +/- 0.000001 in. (+/- 0.00003 mm.).

“Experienced inspectors and quality staff know how to apply the many measuring tools and instruments to measure surface finish, size, form, position and orientation.”

Surface Finish: Measure different characteristics of tool marks, texture, etc
Size: All characteristics like distance and diameters
Form: All characteristics like Roundness, Flatness, and Straightness
Position: All characteristics like True Position and Concentricity
Orientation: All characteristics like Perpendicularity and Parallelism

Quality must consider all of the above factors and the sales engineer who addresses these factors in meeting the customer's needs will have an obvious advantage. Become familiar with these terms as well as the correct application of instruments and gages. In addition, the sales engineer should know the technique and accepted standard practices associated with their use.

Here are a few of the more common instruments and gages.

- Steel rules & scales
- Vernier scales
- Micrometer instruments (Digital/Analog)
- Dial indicator instruments (Digital/Analog)
- Profilometer
- Comparator (Optical/Vision)
- Height gages
- Gage blocks
- Tallyround
- Laser beam

In addition, there are all types of specialty gages such as go/no-go, ring, plug, taper and snap gages. Some parts require custom gages to be manufactured.
12.4 Coordinate Measuring Machines (CMM)

Coordinate measuring machines can perform almost all the functions of manual inspection devices in either a manual, semi-automatic, or full CNC mode. CMM's are equipped with electronic probes mounted on precision slideways equipped with feedback devices. These probes collect digitized data through manipulation at each workpiece dimension and feature. The data is fed into its computer and displayed or printed for reference. The computer can also output statistical information useful for +/- 3-sigma and Statistical Process Control. Since CMM's are a measuring device, they must be calibrated and constantly verified to ensure measuring integrity. The ISO-10360 is the global CMM standard. Refer to current ISO-10360 standard.


It should be kept in mind that while coordinate measuring machines have dramatically improved the productivity of the inspection process they must be used within their design and environmental limitations. Here are some of the considerations:

1. CMM's are normally found in a temperature-controlled environment (68 degrees Fahrenheit), which is typically different than the shop temperature (Reference the discussion on Temperature Considerations). Today, many manufacturers are placing the Shop Hardened CMM in the shop environment. This helps reduce normalizing time for parts brought into a cooler inspection room.

2. The CMM is a machine and subject to similar measuring errors of the machine tool. This is true of feedback devices, deflection, alignment, temperature growth and tolerance buildup at joints. In a part runoff situation, ask for a volumetric calibration prior to workpiece inspection.

3. In some cases the workpiece should be brought to the CMM still mounted in the fixture, especially if the accuracy of the machine tool is being questioned. This will eliminate new errors introduced when the part is "sprung" from the fixture.

4. A good comparison check between the machine tool and the CMM is to equip the machine tool with measuring probes and probe the part while still on the machine - in the same environment - in the same fixture. Then verify the workpiece on the CMM.
12.5 Machine Tool Accuracy

Machine tool accuracy has improved significantly in the last 25 years and will continue improving in the future. The factors that affect the machine's accuracy are:

1. Rigidity of the structure.  
2. Slideway and spindle bearing design.  
3. Type of measuring/feedback system.  
4. Axis drive system.  
5. Foundation and environment.  
7. Control calibration techniques.  
8. Maintenance procedures.

These accuracies will be observed when we look at 1) spindle runout, 2) slide alignment (roll, pitch and yaw), 3) linear accuracy, 4) volumetric accuracy and 5) calibration techniques. Axis alignments can be verified with a laser or a cylinder square/dial indicator combination. Before a CNC machine tool is shipped it should be subjected to a computerized volumetric calibration. This process establishes a laser metrology frame covering the full range of machine travels (creating the machining volume). Readings are then taken with the laser in three dimensions and errors mapped for future reference. Some CNC systems can accept calibration compensation points to partially correct volumetric errors.

NOTES
12.6 Workpiece Accuracy & Processing Considerations

The machine tool accuracy is reflected in the workpiece, but is only one of several workpiece accuracy considerations. The list includes:

3. Fixtures & Number of setups. 7. Processing procedures.

Workpiece accuracy can be observed when we look at such things as: 1) hole locations, 2) surface to surface relationships, 3) surface to bore relationships, 4) roundness, taper and, 5) size relationships. Reference the discussion on Temperature Considerations.

The way that a workpiece is processed can have its effect on the final accuracy. For instance, heavy cuts and hot chip accumulation on the workpiece can introduce unwanted heat into the part (discussed later). Heavy cuts can also cause distortions, stress and warping on workpieces that are not sufficiently rigid. Also, fixture design and clamping pressures can distort the part during processing. Remember, the fewer the setups, the better. Each time the part is changed in the fixturing new errors can be introduced. Sometimes workpieces have not been stress relieved prior to machining. Residual stress (from casting, welding, etc.) can warp the part once metal is removed. Techniques such as vibration or heat treatment (sometimes called "shake and bake") should be employed to relieve these stresses prior to machining.

Statistical Process Control (SPC)
The work of Frederick Taylor in the 1920’s and Edward Deming in the 1950’s to 1980’s provided a major contribution to the quality of goods and services produced by worldwide manufacturing concerns. Deming, in particular, fostered the philosophy that management must give the proper tools to manufacturing workers to guarantee high quality production and quality end products. “SPC” or “Statistical Process Control” is a quality control plan based on the principles of statistics.

In simple terms, SPC involves:

- A careful study of all elements of a manufacturing process to determine suitability for production of a desired end result or degree of conformity to desired results.
- Establishment of tolerance limits to guarantee the desired end result of the process.
• Careful evaluation of measuring devices and the inspection procedure.
• Utilization of statistical methods to describe the output of the process (finding the process capability) and expressing the capability in statistical terms using process control charts.
• Trend the statistical data (control charts) in such a way as to predict process variation before exceeding tolerance limits.
• The end result of the application of SPC is to maintain all manufacturing processes under control to a desired standard.

It is the complete understanding of the “desired standard” that is essential to a machine tool sales engineer. The standard can be described in terms of “standard deviation” or “SIGMA” representing a numerical value. The practical result is that six sigma standards require production errors be less that six parts per million and achievement of this is far more difficult that a lower sigma rating. The SPC process is discussed in more detail in section 12.9.

NOTES
12.7 Temperature Considerations

The major environmental concern is always temperature. This can have a dramatic effect on machine and workpiece accuracy. Both the machine and the workpiece will experience dimensional changes with temperature change due to the coefficient of thermal expansion of the machine and/or workpiece material. Temperature changes can be caused by 1) ambient shop temperature, 2) cutting forces (friction) and hot chips and, 3) machine components (motors, bearings, etc.).

The workpiece can experience rapidly changing ambient temperature changes while being transported to and from the machine. Frequently, workpieces are taken to a temperature controlled inspection area and placed on a coordinate measuring machine. Most temperature-controlled areas are kept at around 68 degrees, which probably differs from the shop. This change can produce dimensional changes in the workpiece. The workpiece should be allowed to normalize to any new temperature environment before machining and prior to inspection. When trying to qualify a machine tool in a part runoff situation the part should be left in the fixture and checked in the same temperature environment as the machining process.

Machine tools are the victim of temperature changes as well. Cast iron has a coefficient of thermal expansion equal to 6 millionths of an inch per degree (Fahrenheit) temperature change. Considering a 10-degree increase of temperature over a 40” slide travel equals .0024” of growth! Be familiar with how to perform this type of calculation.

Thermal Expansion Formula

\[
\text{Growth} = \text{Length of Component} \times \text{Temperature Change} \times \text{Coefficient of Thermal Expansion}
\]

- **Growth:** Inches
- **Length of Component:** Inches
- **Temperature Change (Final minus Start):** Degrees F
- **Coefficient of Thermal Expansion:** Inches/Degrees (i.e. .000006 inches/degree)

In the above example:  \( \text{Growth} = 40” \times 10^0\text{F} \times .000006”/\text{F} = .0024” \)

Machines should be shielded from drafts and other rapid temperature variations. Heat producing components should be thermally isolated from the dimensional machine components.
12.8 Accuracy Standards

This section of the chapter is still under review and will be forwarded to you via e-mail by Clara Mora, Smartforce Development Administrator (703-827-5276), cmora@amtonline.org within the next few weeks.

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12.9 Statistical Process Control (SPC)

The desire to increase quality in the manufacturing process has led to the development of a statistical method to measure and track tolerance variations. These variations can be:

1) monitored on an ongoing "historical" basis,
2) compared to established limits and
3) corrections made when emerging patterns dictate.

SPC was designed to be a preventative method in keeping a process under control before it goes bad. Its ability to spot trends based on deviation changes can prompt action before scrap is produced. There are several factors that must be considered when trying to determine how a process is behaving when a batch of parts are produced.

Let's look at a similar situation. Assume you are at a shooting gallery and each time you step up to the counter you take 6 shots at the target. Obviously, you aim at the bull's-eye, but the 6 shots form a pattern to the upper right of the bull's-eye (Fig. 5). You are pleased with the close pattern, which indicates good consistency or **repeatability**. After making an adjustment to the sights you take another 6 shots. This time you discover that the pattern is similar, but the pattern has shifted to the upper left indicating that your **accuracy** has changed (Fig. 6). Next, you change your trigger technique and take another 6 shots only to discover that the pattern not only moved but spread out with respect to itself (Fig. 7).

This shooting gallery scenario has many similarities to machining a batch of parts. During the machining process both repeatability (variations with respect to the group) and accuracy (variations with respect to the absolute target) must be considered. To adequately measure and track both requires gathering and analyzing a lot of data. This is where the SPC process is of tremendous help.

![Fig. 5](image1.png)
![Fig. 6](image2.png)
![Fig. 7](image3.png)
When we apply the SPC process to machining a batch of workpieces there are basic steps to be followed:

1. Check & correct all gages or measuring instruments.
2. Take measurements from a sample lot or group of consecutive parts.
3. Define the target and control specification limits.
4. Plot dimension data and control specification limits.
5. Center the group's data by finding X bar.
6. Calculate +/- 3-sigma (6-sigma) deviation.
7. Calculate CP and CPk to determine if process is "in control".
8. Make corrections to process if needed.

Now, let's consider a machine tool example to better understand SPC. Let's assume we have machined 30 parts and then measured a critical dimension (4.2606") on all 30 parts. We have listed our findings of this dimension below:

1) 4.2605  
2) 4.2607  
3) 4.2609  
4) 4.2606  
5) 4.2606  
6) 4.2610  
7) 4.2604  
8) 4.2606  
9) 4.2602  
10) 4.2603  
11) 4.2606  
12) 4.2608  
13) 4.2608  
14) 4.2607  
15) 4.2606  
16) 4.2605  
17) 4.2606  
18) 4.2603  
19) 4.2609  
20) 4.2607  
21) 4.2607  
22) 4.2604  
23) 4.2605  
24) 4.2606  
25) 4.2608  
26) 4.2605  
27) 4.2604  
28) 4.2607  
29) 4.2608  
30) 4.2607
The measurements will vary slightly from part to part. Each part produced is unique, but the measurements for the batch will form a grouping or pattern. This pattern is similar to the pattern formed on the shooting gallery target. Since our goal is to keep the group as close to itself (tight) as possible, we must have a way to measure the pattern with respect to itself. This starts with finding two values – X-bar and Standard Deviation.

**Calculating \( \bar{X} \) (X-Bar) & Standard Variation (Sigma = \( \sigma \))**

**X-bar** - is another common term in SPC. Once we have a sample group of data recorded, the X-bar value is simply the mean or average value in that group. Finding this value allows us to center the deviations around a reference point. Add up all the values recorded and divide by the number of values.

**Standard Deviation (Sigma: \( \sigma \)).** The most common way to describe the range of variation is standard deviation (usually denoted by the Greek letter sigma: \( \sigma \)). The standard deviation is simply the square root of the variance, so let’s start by defining the variance.

To calculate the variance do the following:
1. Subtract the average (X-bar) from each data item (X) to get the individual deviations.
2. Square each deviation, and then find the average of the squared-deviations. In finding the average squared-deviation, divide by \( N-1 \) rather than \( N \). The result is the variance.

\[
\text{variance} = \sigma^2 = \frac{\sum (X - \bar{X})^2}{n-1}
\]

To calculate the **standard deviation** do the following:
1. Take the square root of the **variance**.

\[
\text{standard deviation} = \sigma = \sqrt{\frac{\sum (X - \bar{X})^2}{n-1}}
\]

The standard deviation is kind of the "mean of the mean," and often can tell the story behind the data. In simple terms, the standard deviation is the measure of variances in a process. The sigma is the average range that the dimensions or readings vary (deviation) in location when comparing part 1 to part 2, part 2 to part 3, part 3 to part 4, etc. The standard deviation is not concerned with how the dimensions vary from the desired Engineering Document position -- only from each other. Sigma is simply the average that the readings vary from themselves. It is the best way to track the patterns of repeatability for that process.
After all the measurements are taken we group the data with the same values together. In
the following sample chart each "1" represents one measurement that matches the dimen-
sion shown in the bottom row. This is called a frequency distribution chart. We can see
that of the 30 parts 4.2606 in. was the most frequently produced dimension. This type of
distribution is typical and forms a graphical representation called a bell curve.

![Frequency Distribution Chart](image)

Statistics show us that if we keep aiming at the desired dimensional target, and we have a
relativity good process, then chances are we will form a pattern with this bell-shaped
characteristic. The bulk of the dimensions will be grouped closer together with a
decreasing number scattered further out towards the edges. If we draw a line connecting
the tops of the data in our Frequency Distribution (Fig. 8) above we will form a bell
curve similar to Fig. 9 below.

![Bell Curve](image)

When trying to define how good is "good enough" for a process, we rely on statistics. All
of the area under the bell curve (Fig. 9) represents 100% of all the dimensions ever
recorded in a sample batch. We will want to disregard some of the dimensions that are on
the outer fringe or edge of the grouping. Standard Deviation (Sigma) is a value that can
help us quantify how much data to consider versus how much to disregard (data at the
outer edges). This is where statistics are applied. First, (using a good scientific calculator)
we calculate X-bar for our 30-part example above which yields the average value of
4.26061 inches (X-bar = 4.26061).

Next, we calculate standard deviation (using a good scientific calculator) or one standard
deviation, which yields .00010” (round off to .0002” for our example). Applying a +/-
range to sigma we will find that it will include the following range of dimensions in our example:

- **+/− 1 Standard Deviation (2 Sigma)** (+/− .0002") = all dimensions from 4.2605 to 4.2608" (21 values) or 68.26% of all parts above.
- **+/− 2 Standard Deviation (4 Sigma)** (+/− .0004") = all dimensions from 4.2603" to 4.2610" (29 values) or 95.44% of all parts
- **+/− 3 Standard Deviation (6 Sigma)** (+/− .0006") = all dimensions from 4.2600" to 4.2612". This will include 99.73% of all parts (while it appears that in this case it includes 100%, statistically there is the opportunity that .27% will be outside of 6-sigma). The +/- 3-sigma (6-sigma) is the most common standard deviation used, as it will include 99.73% of all parts machined based on a sample run of parts. While a good scientific calculator will quickly calculate X-bar and sigma, be familiar with the actual formulas by studying a good SPC text.

The larger the sigma value, the less data (or area under the curve) we can disregard as "fringe". Therefore, a +/- 4-sigma (8-sigma) is a much harder tolerance to hold than a +/- 3-sigma. Refer to Fig. 10 below.

Now that we have a way to measure deviations in small groups that represent 99.79% of all production, we can use this method to monitor a process by periodically sampling a
small group. If we want to successfully monitor a system we must set limits and watch how the deviations change within them. These established limits are called Upper Specification Limit (U.S.L.) and Lower Specification Limit (L.S.L.) as shown on Figure 11. These will be plotted on the same graph as the bell curve and the bell curve should be between these limits.

With each sampling observe if the 6-sigma bell curve is getting wider or narrower between the limits due to some changing process variable. Also, the shape of the curve (symmetrical, bi-modal, skewed right, skewed left, uniform, random or truncated) can yield valuable diagnostic information about the process.

**Control Charts**

The control chart is an essential tool in the SPC process. This time-based chart graphically depicts the status of the process variation. Each measured dimension is plotted sequentially on a time line. The Upper Control Limit (UCL) and Lower Control Limit (LCL) are indicated on the chart. Below are several typical control charts. They do **not** represent the example above.

![Fig. 11](image)

**A Process "In Control"**

The above control chart (Fig. 11) represents a system that is “in-control” with all data points well within the control limits.
The above control chart (Fig. 12) represents a system that is “out-of-control” with one data point outside the control limits. This indicates the presence of variation.

The above control chart (Fig. 13) represents a system that is “out-of-control” because a “trend” is present. A trend is a series of data points (usually six or more) that consistently increase or decrease. This may indicate a gradual degradation such as tool wear.

Control charts can easily demonstrate a number of problems with the measured data. Here are a few common conditions that will be revealed graphically on a control chart.

- Single data point outside of the control limits
- A “Run” which is a series of data points (usually 8 or more) that are consistently above or below the average or process centerline. This normally represents a shift in the process.
- A “Trend” is a series of data points (usually 6 or more) that consistently increase or decrease.
- “Cycles” are repeating patterns of data points.
- Other unusual patterns. This happens when more than 2/3 of the data points are in the center 1/3 of the chart or when more than 1/3 are near the control limits.

**Sample Frequency & Sample Size**

At an early point in the SPC process sample frequency and sample size must be determined. The size of the sample and the frequency of measurement must remain constant. They should be taken from the same “process stream.” For example, a process stream might be the same part run with a single tool.

Quality control or application engineers will use formulas to determine the size and frequency of sampling. A frequent error in SPC calculations is using a sample size that is too small.

**Process Capability (CP)**

The CP (Process Capability) Index shows the capability of the process when the average is perfectly centered between the upper and lower specification limits.

\[
CP = \frac{U.S.L. - L.S.L.}{6 \text{ sigma}}
\]

The result tells how many times the 6-sigma bell curve fits into the total tolerance band (reference figs. 14, 15 and 16). With a CP index of 1.00 the 6-sigma curve will fit once between the specification limits. The CP index should be at least 1.33 (many customers request 2.00).

**Capability Index (CPk)**

Another index, called the capability index (CPk), is similar to the CP index except it also factors in the machine targeting as well as the repeatability. It is a popular index because it shows how well the machine hits where it was aiming and how well it can do it over and over again.

\[
CPk = \frac{N.S.L. - X \text{ bar}}{3 \text{ sigma}}
\]

Where N.S.L. = Nearest specification limit

For a process to be considered under control the CPk index should be greater than 1.00. When the CPk index increases (ex. 1.5) it is an indication that the process repeatability grouping is tighter and the group is moving farther away from the Upper and Lower Specification Limits (U.S.L. or L.S.L.). Therefore, the system has a greater safety factor before being “out of control”. Thus a CPk of 1.5 is better than a CPk of 1.0.
Summary
To summarize the Statistical Process Control process we can say:
1. SPC is a method to improve quality by monitoring standard deviations.
2. Sigma improves as the machine's repeatability improves.
3. The smaller the sigma the narrower the bell curve.
4. The narrower the bell curve the more times it fits into the tolerance range.
5. The narrower the bell curve the higher the CP index.
6. The CP index only considers repeatability, not machine targeting. An increasing CP index indicates that the repeatability is getting better.
7. The CPk index considers both repeatability and machine targeting. An increasing CPk index indicates that system control is getting better.

This brief explanation of SPC is only a beginning. The machine tool sales engineer should study a text on Statistical Process Control, as these terms will appear on quotation requests and part runoff documents. Arbitration duties during part runoff may require mastery of these concepts.
12.10 Summary

Accuracy terminology and concepts are being widely used in the machine tool industry today. Some of the concepts are mastered by using common sense. However, others require more study. The sales engineer who can talk fluently in the language of accuracy, measurements and SPC will have a definite advantage over the competition. Take advantage of the knowledge base offered in your application-engineering department, local library and local vocational schools. Obtain several texts covering shop measurement techniques, manufacturing troubleshooting and statistical process control. Look for texts that explain these concepts in simple, practical terms rather than from the theoretical perspective. Refer to the "Reference Books & Suggested Reading" at the end of Volume II.

Remember to discuss the benefits of the machine's accuracy with the customer. Also, when required to perform a part runoff, be sure to define the terms, equipment and procedures in advance.

The accuracy and precision of today’s machine tools are greatly improved over those produced only ten years ago. This is due to rapid new developments in:

- Machine tool mechanical design improvements including basic machine structures, bearings, ball screws, slideway materials, computerized accuracy checks and basic construction/assembly procedures.
- Applications of computerized techniques in inspection of completed machine tools as well as component assembly.
- Rapid improvement in the quality and design of vendor supplied items such as power supplies, coolant systems, spindle/drive motors, clutch and brake devices and electrical components.
- An acceptance and understanding of SPC techniques by builders as well as machine tool component vendors.
- Improved employee communications and understanding of quality issues by all workers in machine tool factories.

Today’s machine tool industry is in the midst of rapid change. Machine tools become obsolete faster than ever before. The sales engineer must not only focus on their own products, but also constantly observe the product and process changes in industry. Attending trade shows, such as IMTS, is an excellent way to stay informed.

NOTES
12.11 Review Questions

These review questions are provided for study purposes only and are not on the CMTSE certification exam. Correctly answering these questions does not guarantee a passing exam grade.

1. Volumetric accuracy is a term normally associated with the accuracy of the:
   1. laser interferometer.
   2. Johannson blocks.
   3. coordinate measuring machine.
   4. granite master square.

2. The standard deviation of 6-sigma represents what percentage of a statistical sample?
   1. 100%
   2. 99.73%
   3. 95.44%
   4. 68.26%

3. To measure surface finish what instrument would you most likely use?
   1. Comparator
   2. Depth micrometers
   3. Profilometer
   4. Dial indicator

4. Which of the following is least likely to cause workpiece dimensional changes?
   1. Hot chips laying in the workpiece
   2. Rapid changes in the ambient temperature
   3. Light finish machining
   4. Heavy or roughing cuts

5. Which of the following tools is not a precision instrument?
   1. Micrometer
   2. Steel scale
   3. Vernier
   4. Dial indicator

6. Which of the following would normally be checked with a telescopic ballbar test?
   1. The accuracy of a machine tool describing a circular motion
   2. Compression of the guideways at maximum machine capacity
   3. The ability of the spindle to withstand lateral machining forces
   4. The impact of the environment on machine accuracy

7. A controlled environment usually maintains what temperature?
   1. 72°F
   2. 70°F +1°F
   3. 68°F +1°F
   4. 66°F +2°F
8. Which statistical process control value indicates the most desirable “under control” process?
   1. A sigma value of more than 2.0
   2. A sigma value of less than 2.0
   3. A CPK of 1.5
   4. A CPK of 1.33

9. The coefficient of thermal expansion is lowest in which of these materials?
   1. Bronze
   2. Nickel
   3. Aluminum
   4. Steel

10. A machine tool builder would use a laser interferometer to evaluate:
    1. surface finish of machine ways.
    2. accuracy and squareness of machine motions.
    3. X, Y dimensions of the bed.
    4. spindle vibration at maximum RPM.
ANSWERS TO REVIEW QUESTIONS

1. (3)
2. (2)
3. (3)
4. (3)
5. (2)
6. (1)
7. (3)
8. (3)
9. (4)
10. (2)