The Value of a Measurement is in the Application of its Result

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Manufacturing professionals rely on metrology equipment as an essential "tool" in the development and control of processes. However, it is very difficult to find formal training in the field of metrology – and even more difficult to find training in the application of metrology.

This presentation provides an introduction to *applied metrology* in the context of honing. The basic elements of the measurement will be considered with special emphasis placed on the estimation of uncertainty.

Metrology in Manufacturing

Measurements are essential in any development, improvement or process control activity. However, the user often treats the results of the measurement as a "black and white" answer – without considering the science behind the measurement. To a manufacturing engineer working on a honing process, the bore that is produced is often subjected to great scrutiny – considering both the process and the ultimate quality of the workpiece. Similarly, to a metrologist, a measurement is subjected to great scrutiny – considering the measurement process and the ultimate "quality" of the result.

In order to effectively apply metrology in the manufacturing context, some of this "metrology thinking" needs to be present. This does not require that all of those involved become metrologists. It is simply a matter of having the necessary knowledge to effectively use and understand the tools of measurement.

Question Everything (and be specific)

The effective use of measurement involves the collection of data for the purposes of answering questions. Example questions may be:

Does my crosshatch angle meet specification?
Should I adjust my pressure?
Is my size within tolerance?
Is my stroke in the right position?
Is it time for lunch? (For this you need a metrology instrument known as a "watch" or "clock".)

If the "question" can be formulated more specifically, the measurement can often be tailored to provide a more specific answer.

For example, one may be interested in adjusting the stroke length and position in a honing process. The question would be:

Should I adjust my stroke length and position?

The formulation of the question helps to define the *measurand*. The measurand is the item that is to be produced by the measurement and it is often a number but it can be in the form of many other things such as plots, sounds, colors, etc. In the case of honing stroke adjustment, we could consider the errors that we are trying to control (see Figure 1) and devise a measurand accordingly.

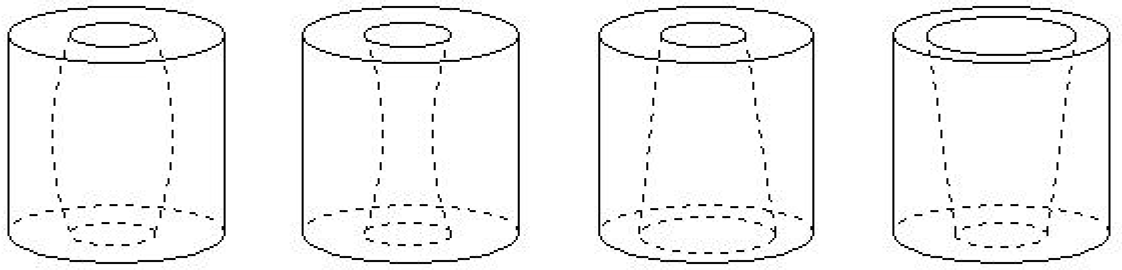

Figure 1. Errors in geometry related to honing stroke.

At first glance, the shapes in Figure 1 tend to lead to the selection of “cylindricity” as the measurand. However, while cylindricity does provide a measure of these shapes, it also includes others aspects of the bore that may not be related to the adjustment of the stroke.

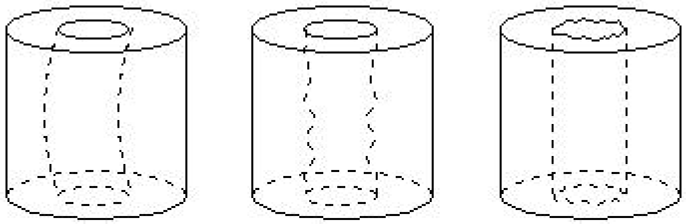

Figure 2. Cylindricity conditions that are not necessarily related to stroke length and position.

In the case of stroke adjustment a better measurand would be the conical *taper* and the parabolic *barrel/hourglass* of the bore. These could be separated as two measurands – the conical (linear) taper relating to stroke position and the parabolic shape relating to the stroke length. A corresponding positive/negative convention could be defined as shown in Figure 3.

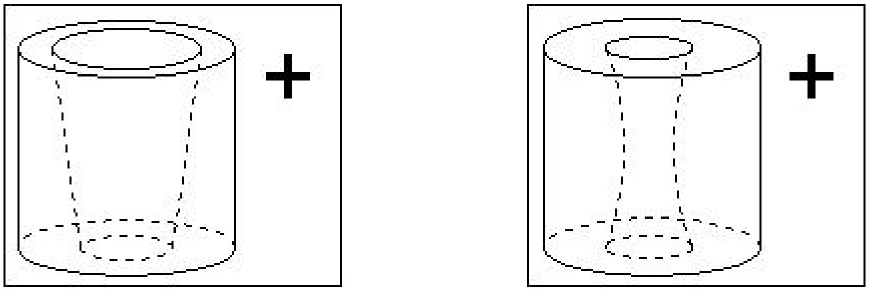

Figure 3. Positive direction convention for linear and parabolic errors due to stroke position and length.

The Investigation (collecting data to answer the question)

With the measurand adequately defined, the next step is to establish the *measurement system*. Note, this is not a matter of simply selecting a “gage”. Measurement results are produced by this *system* including attributes such as:

- The Gage (and the condition thereof)
    Tip radius, data points, mechanical & electronic attributes, math, etc.
- Calibration/Traceability (or the lack thereof)
- Operator (and the skill level thereof)
- Procedures (and the following thereof)
- The Environment
    Temperature, cleanliness, vibration, etc.
- Workpiece condition

Upon utilizing a measurement system to obtain some result, the appropriate supporting information should be immediately attached to the result. This supporting information includes, measurement units, operator, date/time, etc.

The Implications (what to do based on the result)

The actions taken as a result of the measurement should be based on the result of the measurement coupled with the knowledge of the *uncertainty of the measurement*. Historically, emphasis was placed on the accuracy and repeatability of a measurement. In most practical applications, the repeatability and reproducibility (R&R) were the main concern – accuracy often held a distant second place.

In more recent years, an increased emphasis is being placed on the understanding of the overall measurement uncertainty. Measurement uncertainty, quite simply addresses the question:

How far away from my result could the true value of the measurand lie?

This is depicted graphically in Figure 4. In this example, a measurement produced a value of 2.12 µm, however there was an estimated uncertainty of 1.3 µm. Thus the “true value” may lie anywhere between 0.82 µm and 3.42.

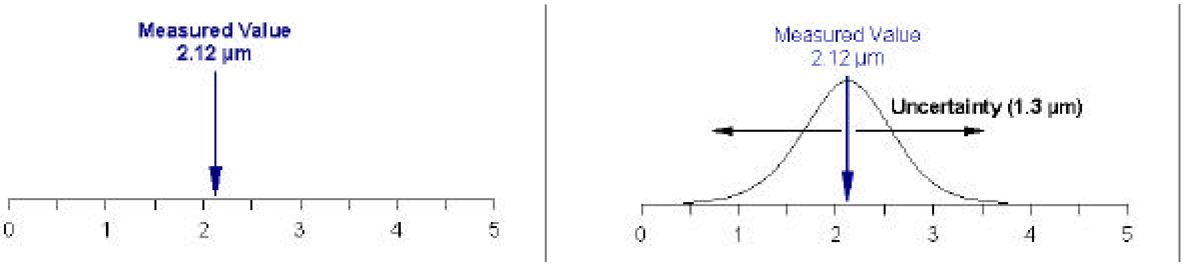

Figure 4. A measurement and the associated uncertainty. The "true value" of the measurand should lie between 0.82 µm and 3.42 µm (95% confidence).

The estimation of measurement uncertainty is often perceived as difficult or highly theoretical. This is not necessarily the case. In fact, very good estimates of uncertainty can be developed quite easily – the only specialized knowledge that is needed relates to understanding the components of the measurement system that may cause errors. In many regards, this is very similar to the kind of thinking that is required in performing a Failure Mode and Effects Analysis (FMEA).

This process of estimating uncertainty will be illustrated through the use of an example of measuring crosshatch angle (Figure 5):

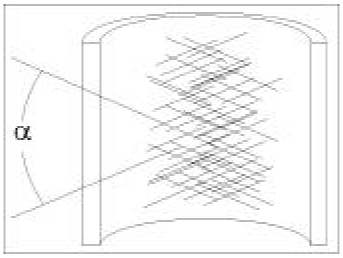

Figure 5. Crosshatch angle assessment.

Question: Should my crosshatch angle be adjusted? The tolerance is 45° +/- 5°.

Measurand: Crosshatch angle.

Measurement: Mylar template (flexible protractor) with angular indications every 1 degree.

Result: 47.5°

The measured angle shows we may have used on half of the tolerance (on the positive side). However, without an understanding of the uncertainty, we don't know where the true value of our crosshatch angle lies.

Step 1: Determine the uncertainty contributors.

This is the fun part! List all of the possible errors in the measurement system.

In the case of crosshatch angle assessment with the Mylar template we may have:

- Dirt on the surface
- Visual resolution of the operator/lighting etc.
- Printing errors on the template
- Temperature
- Humidity
- Vibration
- Miscellaneous errors from unknown sources.

Step 2: Determine the amount that each of these contributes to the uncertainty.

Consider each effect as if it were the only problem in the measurement and then determine a distribution for the errors. During this step you may find that some of the contributors are relatively small and can therefore be ignored. It is often useful, at this stage, to perform some small studies targeting specific contributors and determining their impact on the results. (These contributors, with experimental data supporting them, are classified as Type "A" contributors). In other cases, the contributions can be estimated based on "engineering judgment". (These contributors are classified as Type "B" contributors.)

Distributions are now determined for each of the contributors. Consider the influence of each as if there were no other contributors. (The assessment of *interactions* is a bit messy and doesn't necessarily provide that much extra information.)

- Visual resolution of the operator/lighting

  In this example, a small study was performed to determine that the operator could resolve angles to within 0.5°. Thus, for a given angle, the operator had an equal chance of reporting any angle within +/- 0.5° of the actual angle. This results in a uniform distribution of errors as shown in Figure 6.

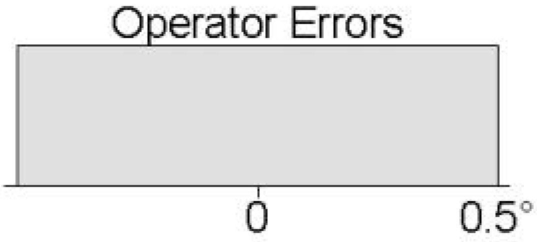

Figure 6. The distribution of errors associated with the operator and lighting.

- Printing errors on the template

  In this example, additional templates were printed and were each assessed under high magnifications. The results showed that the errors were generally small and never exceeded 0.1°. This was approximated as a triangular distribution of errors as shown in Figure 7.

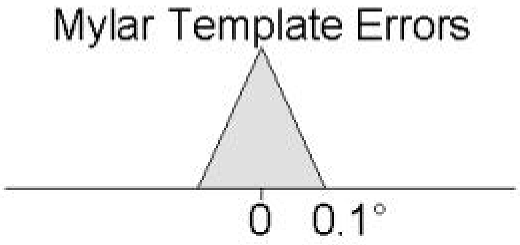

Figure 7. The distribution of errors associated with the printing of the template.

In the crosshatch example, the following effects will be ignored:

- Dirt on the surface
    - The operator will look for "lines" during assessment, not "particles".
- Temperature
    - Uniform thermal expansion does not change angles.
- Humidity
    - Uniform humidity effects do not change angles.
- Vibration
    - This is insensitive to vibration
- Miscellaneous errors from unknown sources.
    - It was felt that these are relatively small compared to the above two contributors.

Step 3: Combine the uncertainty contributors.

The next step in uncertainty estimation is to combine the effects of each of the uncertainty contributors. Since we are dealing with independent contributors, this is simply a matter of determining equivalent, normal distributions and then pooling these normal distributions. (Tables exist for converting various distributions into equivalent normal distributions.)

The equivalent normal distributions for the crosshatch uncertainty contributors are shown in Figure 8.

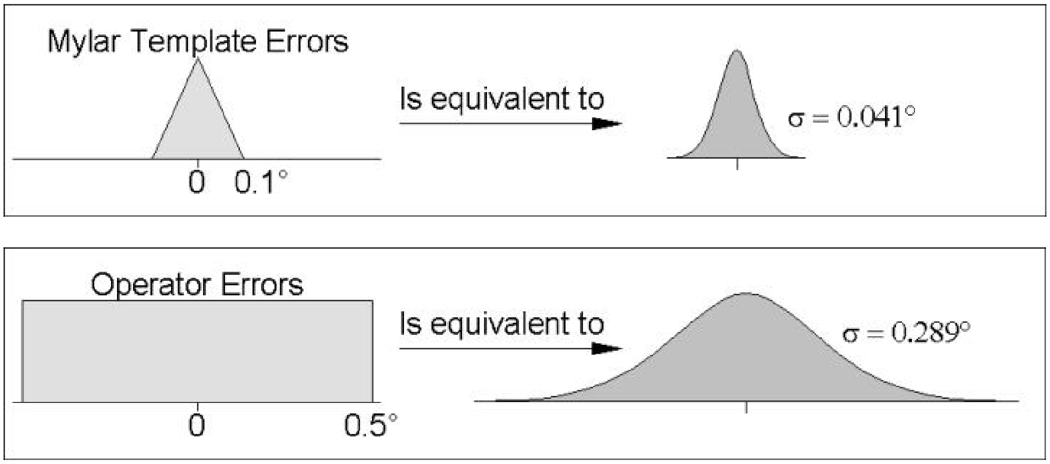

Figure 8. Uncertainty contributions for crosshatch angle assessment.

These normal distributions are characterized by a standard deviation value and a mean value (the mean is zero). Therefore, the distributions can be combined by “pooling” the standard deviations whereby the resulting (pooled) standard deviation is the square root of the sum of the squares of the individual standard deviations.

$$s_{combined} = \sqrt{s_1^2 + s_2^2 + s_3^2 + \ldots + s_n^2}$$

In our example of crosshatch angle assessment we have:

$$s_{combined} = \sqrt{s_{mylar}^2 + s_{operator}^2}$$

$$s_{combined} = \sqrt{0.041^2 + 0.289^2} = 0.292°$$

Step 4: Expand the uncertainty.

At this point we have the standard deviation value for the distribution in which the “true value” should lie. (See Figure 4.) However, uncertainty is typically reported based on a 95% probability or 2-sigma range. The “2” is the coverage factor and is commonly referred to as the constant “k”.

Thus, the uncertainty is reported as follows:

$$U_{95} = k \cdot s_{combined} = 2 \cdot 0.292 = 0.584° \approx 0.6°$$

Finally, the measured value was 47.5°, however, given our uncertainty of 0.6°, we know that the true value of the crosshatch angle should lie between 46.9° and 48.1° (which is within the tolerance of 45° +/- 5°).

Summary

This paper presented some of the basic concepts surrounding metrology and the interpretation of measurement results in the context of honing. Metrology, like any other tool, can be more useful when the operator is more skilled in its use. This process of determining the “Question” and “Measurand” followed by the “Measurement” and “Interpretation” provides a useful recipe for improving the understanding and ultimate usefulness of measurement in the context of honing.