How to Determine Measurement Variability in the Pattern Shop

This article presents methods to ensure accurate and repeatable pattern and tooling measurements for more precise castings.

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Today’s casting customers are demanding castings with tighter dimensional tolerances, thus placing additional demands on the patternmaker. As casting tolerances become tighter, patterns themselves must be more accurate. Therefore, the measurement equipment used to measure the patterns (and final castings) must also be more accurate.

To ensure accurate and repeatable measurements, pattern shop and tooling department measurement equipment must be evaluated. This article describes such an evaluation based on the casting dimensional tolerances, specified by the casting customer.

Cast Dimensional Variability

The total dimensional error seen by the casting customer is a combination of the dimensional variability from the casting process and pattern errors. Pattern errors are caused by incorporating an incorrect shrinkage allowance as well as producing the pattern to the wrong size. For a casting feature to satisfy the customer tolerance, one-half of the dimensional variability, plus the pattern error, must be less than one-half of the specified tolerance, as shown in Fig. 1.

Clearly, the foundry and the pattern shop must “share” the total tolerance specified by the customer. As the customer-specified total tolerance decreases, it becomes important to control all sources of dimensional variability both in the foundry and pattern shop.

One important source of pattern error that should be regularly monitored and controlled by the pattern shop (and the foundry) is measurement error. This isn’t simply a matter of ensuring that measurement instruments are correctly calibrated—they must also be appropriately and consistently used.

In many cases, a pattern feature is measured only once and the measurement is assumed to be perfect. However, a range of dimensional values is likely if the same pattern feature measurement is repeated by a single inspector, or by different inspectors. These typically small errors may not be significant for castings produced to wide customer dimensional tolerances. But, as will be shown, they can be unacceptable in patterns for close tolerance castings.

Measurement system analysis, commonly known as gage repeatability and reproducibility (gage R&R), should be conducted, regularly to check the acceptability of all pattern shop inspection processes. Figure 2 outlines the steps in determining if a measurement method is acceptable.

Measurement Error

One source of measurement error is gage accuracy. To eliminate this source, all measurement equipment should be calibrated regularly. Ensuring the accuracy of measurement equipment by frequent calibration, however, isn’t sufficient. Measurement variability must also be considered.

Before determining measurement variability, a quick check is necessary to assure the measurement instrument has adequate resolution. As a general rule, the resolution on the measurement instrument must be at least one-tenth of the tolerance you’re trying to measure. A measurement instrument with acceptable resolution is a requirement for acceptable repeatability, but it is not a guarantee.

Measurement error in the pattern shop must be compared with the tolerance allowed for the pattern feature. A feature with a small dimensional tolerance can’t afford to allow as much variability in the pattern shop measurement method as a feature with a larger dimensional tolerance. Measurement error can be defined as:

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\text{Measurement Error} = \frac{\text{(Measurement Variability/Pt Tolerance)}}{100}
\]

To test the random variation for Gage R&R, you require at least two patterns or parts and at least two inspectors or inspectors’ “readings” on the same part.

A test for gage linearity requires a test for gage bias.

According to an Automotive Industry Action Group manual, the ability of a measurement method to produce acceptable measurements is evaluated using the following criteria:

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Acceptability</th>
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</thead>
<tbody>
<tr>
<td>Under 10%</td>
<td>Acceptable</td>
</tr>
<tr>
<td>10-30%</td>
<td>Marginally acceptable</td>
</tr>
<tr>
<td>Over 30%</td>
<td>Needs improvement</td>
</tr>
</tbody>
</table>

Measurement variability can be divided into variability (equipment and operator) and variability (operator) errors. Repeatability error is the variation of repeated measurements taken by one inspector using a single gage. Repeatability error will be large if

Fig. 1. As shown in this drawing, one-half of the dimensional variability plus the pattern error must be less than half of the dimensional tolerance to satisfy the customer-specified tolerances.
the measurement increments are large compared to the part tolerance. Other causes of repeatability errors include inconsistent use of a measurement instrument by a single inspector and inadequate fixturing to locate the measurement.

Reproducibility error is the variation caused by different inspectors measuring the same parts using the same measurement equipment. This is primarily caused by the different inspectors using the gage inconsistently, and can be minimized with proper training.

**Gage R&R Test Procedures**

Gage R&R tests measure the amount of variability contributed by the lack of both repeatability and reproducibility.

A simple method of determining the measurement variability is to have two or more patternmakers measuring the same pattern dimension several times. The variability of the measurements could be calculated directly. Testing bias is likely, however, because inspectors "remember" previous results.

Therefore, the preferred gage R&R test involves at least two workers taking at least two measurements on several parts or patterns. In order to separate actual part variability from the measurement variability, the exact measurement locations must be identified on each part or pattern so that each subsequent measurement is taken at the same location.

To minimize the chance of a biased test, the parts must be measured in a random order. An additional person is required to record the measurements to further eliminate bias. When using a coordinate measuring machine (CMM) or similar machine, the fixturing and setting up of the pattern is part of the measurement procedure and must be repeated with each measurement.

An example of a completed gage R&R test is displayed in Fig. 3. In this example, two inspectors measured a specific feature on 10 identical patterns. The difference in each pair of measurements is a single feature on an inspector is used to calculate the repeatability component of measurement error. The reproducibility component is calculated from the difference between the average value of all measurements taken by each inspector.

The values calculated in the worksheet are good estimates for repeatability, reproducibility, and total gage R&R (5.15 standard deviations). Statistically, these values account for 90% of the measurement variability. If the total gage R&R (measurement error) is less than 30% of the pattern tolerance, then the measurement method is adequate to measure this particular pattern feature.

**Modified Gage R&R**

Because 10 identical patterns aren't typically available, the standard gage R&R procedures must be modified for use in the pattern shop. Figure 4 is a guide to select the appropriate modified gage R&R test for these situations.

Option 1 is used when two identical patterns are available. Measurements at five different locations of a flange thickness are taken from each pattern. Again, the measurement locations should be marked and the order of the measurements should be random.

Option 2 uses measurement at 10 different locations on the same pattern.

Option 3 is a less desirable but adequate way to measure gage R&R when there are limited places to take measurements. When using Option 3, be sure that the inspectors don't "remember" previous measurements and bias the test.

Measurement system analysis must be done for each operator, measurement instrument and measurement technique. For example, there's a greater chance of measurement variability using a caliper on an inside diameter than an outside measurement of a square feature. The gage R&R tests should be repeated at least annually to ensure no changes have occurred in the measurement methods.

**Acceptable Pattern Shop Measurement Errors**

Gage R&R measurement error must be interpreted with respect to the ac-
acceptable pattern tolerance. The foundry and pattern shop must share the total casting feature tolerance called out on the casting drawing. When measuring castings, the total measurement variability is compared to the tolerance specified on the print by the customer.

The tolerance on the pattern features, however, can only be a fraction of the tolerance specified for the casting features. The amount of variability within which the foundry expects the patternmaker to work should be agreed upon by both parties at the time of the pattern order. A percentage of the casting tolerance (10–30%) may be an appropriate method for establishing the patternmaker’s portion of the tolerance.

An example of comparing the pattern measurement variability with the pattern tolerance follows. According to ISO CT6 casting tolerance standard, the total casting feature tolerance for a 1 in. (25.4 mm) feature on an iron casting is 0.051 in. (1.30 mm). If the pattern will be made with a dimensional tolerance equal to 20% of this casting tolerance, the total allowable pattern tolerance is 0.010 in. (0.26 mm). An acceptable method of measuring this pattern can consume only 30% of this pattern tolerance, or 0.0030 in. (0.078 mm). In this example, the upper limit of the measurement error acceptability, 30% of the tolerance, was used.) As a result, the allowable measurement error for the pattern shop inspection is ultimately only 6% of the casting feature tolerance.

To provide a comparison, the following measurement equipment repeatability values were obtained when measuring machined surfaces.

| CMM | 0.00012 in. (0.0030 mm) |
| Digital micrometer | 0.0011 in. (0.029 mm) |
| Digital calipers | 0.0044 in. (0.112 mm) |

Scale—0.054 in. (1.37 mm)

In this example, only the CMM and micrometer have a repeatability error less than the 0.0030 in. (0.078 mm) measurement variability limit. The caliper and scale aren’t appropriate measurement instruments for this pattern feature. In an actual situation, the repeatability error (due to the operator) must also be included with the repeatability to determine acceptability.

The repeatability listed above for the scale is 0.054 in. (1.37 mm). Calculations similar to those above indicate that a scale or shrink rule can only be used to measure patterns in which the casting feature tolerance is at least 0.90 in. (22.86 mm).

The choice of equipment for measuring pattern dimensions should be decided upon when planning a new pattern’s production. To determine the acceptability of a measurement method, gage R&R can be performed on similar features of an existing pattern. This assures that the measurement variability will be the same when measuring similar features on other patterns.

Gage R&R tests should be performed on all pattern shop measurement equipment and inspection personnel on a regular basis. These simple tests are necessary to ensure that the pattern shop measurement equipment and techniques are adequate. Since measurement variability is compared to the allowed tolerance, clearly the requirements on the inspection technique are more severe when producing pattern equipment for castings with tight tolerances.