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University Park, Pennsylvania  
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Ames, Iowa

ABSTRACT

The dimensional capabilities of production aluminum castings are described. More than 480 production casting features have been evaluated for jobbing shop aluminum castings made in green sand and permanent-mold castings. A comprehensive database of casting, feature and process descriptors has also been developed, so that the influence of these factors on casting dimensional variability can be evaluated.

Measurement system analysis techniques have been used to ensure that the dimensional variability measured was not influenced by excessive measurement system errors. The dimensional variability of both green sand and permanent-mold castings is less than is suggested by International Standards Organization (ISO) casting dimensional tolerance specifications.

Both feature length and casting weight significantly influenced the dimensional variability of aluminum castings produced in permanent molds. The dimensional repeatability of aluminum castings is also compared to the dimensional repeatability of iron and steel castings from similar studies.

INTRODUCTION

In order to survive in an increasingly competitive market, foundries must produce products that satisfy customer expectations, in a timely and cost-effective manner. Casting dimensional integrity is a key component of customer satisfaction. All foundry process steps, including molding, pattern removal, core making, core assembly, pouring, heat treating and grinding, contribute to casting dimensional variability. In order to remain competitive with other aluminum processing methods, the factors that influence casting dimensional integrity must be determined, quantified and controlled. Even though many critical casting features are subsequently machined, a tight control of as-cast dimensions is often necessary to ensure consistent setup of castings in machining fixtures.

A key component of overall casting dimensional integrity is casting dimensional variability. United States and international standards and guidelines describing the expected dimensional capabilities of both sand and permanent-mold castings have been published.1,2,3 This includes International Standard Organization specification ISO 8062-94 (specifications for all castings including aluminum castings),1 the AFS Aluminum Division tolerance guidelines for aluminum green sand and permanent-mold castings,2 and the dimensional standards for aluminum sand and permanent-mold castings published by the Aluminum Association.3 Appendices A–C contain summaries of these current standards and guidelines.

However, these current dimensional tolerance specifications and guidelines may not adequately reflect the true dimensional capabilities of aluminum castings. Recent studies have suggested that existing casting dimensional tolerance specifications are likely confounded with measurement errors that overestimate casting dimensional variability.4 Unnecessarily wide dimensional tolerance specifications for castings can indicate to potential customers that casting processes are not capable of producing close-tolerance parts. Because of this, potential casting customers may not choose castings, due to the perception that foundries cannot adequately control casting dimensions.

A foundry must also be aware of its own dimensional capabilities so that it can quote accurate dimensional tolerances to potential customers. This knowledge reduces the lead time and cost associated with ill-conceived attempts to meet excessively tight customer dimensional tolerance specifications. Accurate knowledge of the ability of casting processes to control feature dimensions must be developed from comprehensive studies of production castings. Not only can this lead to accurate industry guidelines of casting dimensional capabilities, but individual foundries can benchmark the dimensional capabilities of their own processes.

In this study, the dimensional capabilities of aluminum castings produced by typical jobbing foundries using green sand molding and permanent-mold casting methods have been established. Dimensional capabilities are compared to iron and steel castings.

PROCEDURES

In order to assess the dimensional capabilities of the participating foundries involved and of the industry, in general, feature dimensional variability data was collected from typical production castings. The data used in this study was collected on-site at the participating foundries. In addition to the collection of feature dimensional data, more than 70 casting-specific and process-specific variables were collected for each feature measured.

This database of process and feature information simplified the evaluation of the influence of specific variables on the dimensional variability of casting features. Dimensional data was collected from 52 casting types at three aluminum green sand foundries and from 14 casting types from one aluminum permanent-mold foundry. The dimensional capabilities of green sand molding processes were characterized for both jolt squeeze and high-pressure automatic molding systems.

Overall, 399 green sand casting features from 66 production castings were evaluated. Green sand castings ranged in weight from 0.2–24 lb (0.1–11 kg). Permanent-mold castings ranged in weight from 0.4–51 lb (0.2–23 kg).

In most cases, 30 measurements of each casting feature were measured from at least two different production runs over a two-month period. In some cases, only 20 replicated castings were evaluated. Only feature measurements, such as length, outside diameter, inside diameter, etc., were measured. The variability of geometric characteristics, such as flatness and perpendicularity, were not evaluated in this study.

Throughout the data collection phase of this study, data integrity was of paramount concern. Excessive measurement errors can be mistakenly reported as a component of casting dimensional variability, if adequate measurement systems are not used. Measurement systems analysis procedures developed by the Automotive Industry Action Group5 were used throughout this study, to insure that
measurement system errors were acceptably small for all casting feature measurements.

For each of the casting feature measurements taken in this study, the repeatability and reproducibility (R&R) of the specific measurement system used to collect the data was evaluated, to ensure that it was capable of adequately measuring the feature. If the %R&R of the measurement system was greater than 30% of the total feature dimensional variability, then the measurement system was deemed inadequate and was improved until it was capable of measuring the feature. If changes in the measurement system did not produce satisfactory results, then the dimensional data was not included in the study.

Most of the dimensional studies were done using hand-held instruments such as calipers and micrometers. Other variability data was collected using coordinate measurement machines (CMMs). In all cases, a measurement system was considered to be acceptable if the overall measurement system repeatability and reproducibility (%R&R) was less than 30% of the total feature variability.

MEASUREMENT SYSTEM EVALUATION

Study of aluminum casting dimensional variability and ongoing study of the dimensional variability of other casting processes has indicated the general acceptability of common foundry measurement systems used for casting inspection. Table 1 shows the repeatability and reproducibility of common foundry measurement systems used for casting inspection. Hand-held instruments can be successfully used to measure both aluminum sand casting and permanent-mold casting features.

However, the acceptability of these measurement systems cannot be assumed, it must be verified. In many cases, acceptable %R&R could not be achieved for small features on permanent-mold castings when hand-held instruments were used. The small variability observed for these features could only be reliably measured using a CMM. In general, the R&R for a CMM is adequate for measuring casting variability.

The measurement system acceptability criteria of <30% R&R is dependent on the tolerance limits or variability to be measured. Because diecasting and investment casting processes generally produce less casting feature variability, the acceptable measurement system R&R is also small.

A survey of the green sand and permanent-mold dimensional features measured at participating foundries is shown in Table 2. Figure 1 shows the feature size and cast weight distribution of the castings evaluated. For each one of the “data points” on this and subsequent figures, 30 casting feature measurements were made to estimate feature dimensional variability. In addition, comprehensive process and geometry descriptors were collected for each casting feature.

The dimensional data and all descriptors were evaluated using a relational database program. Included with the measured casting feature dimensions were over 70 casting-specific and feature-specific variables. The purpose of this exhaustive data collection was to assist in the evaluation of factors that contributed to feature variability through statistical methods. A list of the comprehensive casting process and feature descriptors contained in the database is contained in Appendix D.

Analyses were performed to isolate the variables that most influenced the dimensional variability of castings. Casting feature variability was also compared to published dimensional tolerance standards. Initial database queries were used to determine which of the process and geometric variables influenced casting feature di-
RESULTS

Casting dimensional variability measured in the study was influenced by casting-specific, feature-specific and foundry-specific factors. Some of the more significant factors include the molding process used, feature length, casting weight and presence of the mold parting line through the casting feature. The overall influence of individual factors on dimensional variability will first be presented, followed by a more detailed discussion of the interactions between geometric and process variables.

Figure 2 shows casting feature dimensional variability as a function of feature length and parting line for castings produced in green sand and permanent molds. In this figure, and in all subsequent figures, the dimensional variability is expressed in terms of the "total-tolerance" or six standard deviations (6σ) about the mean. Each data point shown on this and subsequent figures is the calculated total variability (6σ) determined from dimensional measurements of the same casting feature on typically 30 castings.

Casting dimensional variability can be observed to increase slightly as feature length increases, particularly for green sand castings. Figure 2 also indicates that no significant additional dimensional variability is observed for features that cross the mold parting line.

Figure 3 shows casting dimensional variability as a function of casting weight and parting line for castings produced in green sand molds and permanent molds. The overall casting weight has little influence on casting feature variability. The presence of the parting line slightly increases the amount of dimensional variability observed for features on the same castings (same weight) produced in green sand molds. It should be noted that the weight range for the aluminum green sand castings measured was small; therefore, a strong influence of casting weight on feature variability is not expected.

Table 3 summarizes the overall influences of many different process and geometric factors on dimensional variability for green sand castings. The various "mold relationships" listed in this table are...
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Table 1.
Acceptability of Foundry Measurement System for Casting Dimensional Variability Assessment

<table>
<thead>
<tr>
<th>Measurement System</th>
<th>Sand Castings</th>
<th>PM Casting</th>
<th>Investment Casting</th>
<th>Die Casting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micrometer</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>N</td>
</tr>
<tr>
<td>Calipers</td>
<td>S</td>
<td>S</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Layout Machine</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>N</td>
</tr>
<tr>
<td>CMM</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

N = %R&R typically not acceptable; Y = %R&R typically is acceptable; S = %R&R marginally acceptable and sometimes not acceptable.

Table 2.
Summary of Aluminum Casting Dimensional Variability Data

<table>
<thead>
<tr>
<th>Molding Process</th>
<th>Number of Molding Lines Studied</th>
<th>Number of Casting Features Measured</th>
<th>Feature Length Range</th>
<th>Casting Weight Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jolt squeeze</td>
<td>3</td>
<td>135</td>
<td>2–200 mm</td>
<td>0.1–11 kg</td>
</tr>
<tr>
<td>High-pressure squeeze</td>
<td>3</td>
<td>264</td>
<td>5–190 mm</td>
<td>0.3–3 kg</td>
</tr>
<tr>
<td>Permanent mold</td>
<td>1</td>
<td>84</td>
<td>5–1000 mm</td>
<td>0.2–23 kg</td>
</tr>
</tbody>
</table>

Fig. 1. Distribution of feature lengths and casting weights for castings measured.

(1a) green sand castings

(1b) permanent-mold castings
The strong influence of casting weight on feature variability is not expected. Significant differences in feature variability are observed for features that cross the mold parting line. In many cases, the presence of the mold parting line through the casting feature has little influence on the feature variability. The overall influence of the parting line will first be presented, followed by a more detailed discussion of the interactions between geometric and process variables.

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Table 3 summarizes the overall influences of many different process and geometric factors on dimensional variability for green sand castings. The various "mold relationships" listed in this table are expected.
described in Fig. 4. Because feature length is a confounding factor that influences dimensional variability, the average feature length for each variability category is also listed in Table 3. For example, additional variability (1.06 mm vs. 0.76 mm) was observed for features crossing the parting line, compared to dimensions contained within the cope or drag portions of the mold. However, because the average feature length for dimensions crossing the parting was also greater, some of the additional parting line variability can be attributed to differences in the average feature length. Molding method was also observed to have a significant effect on dimensional variability. Greater dimensional control was observed for automated high-pressure molding than for manual jolt-squeeze molding.

Mold relationship, as defined in Fig. 4, can be expected to have an influence on casting variability. For example, a type E dimension or wall-thickness feature may have more dimensional variability than a feature completely by cope or drag tooling, because of additional variations in core placement. A type F dimension, across a core, is only influenced by coremaking variations. However, closer examination of the effect of feature type on dimensional variability indicates that these results are confounded due to variations in average feature length for the different feature types.

Figure 5 shows variability as a function of feature length for each of the three green sand foundries. No significant differences in foundry-to-foundry dimensional variability can be observed. All three foundries produced castings of similar dimensions, and each had similar dimensional capabilities. Figure 6 shows variability as a function of casting weight for the green sand foundries. Again, total tolerance was not significantly affected by the weight of the castings, and all of the foundries exhibited similar dimensional variability. However, differences in foundry-to-foundry capabilities can be seen upon further analyses of the data.

The dimensional capabilities of the three green sand foundries were further compared to each other in Table 4. The additional variability across the mold parting line for each foundry was greater than 0.010 inch. The average dimensional variability for jolt-squeeze molding for Foundry B and C was about twice as much as their average dimensional variability for their high-pressure squeeze molding lines.

The influence of other process and geometric factors on the dimensional capabilities of the individual green sand foundries is also summarized in Table 4. In general, the trends in the data and the dimensional capabilities of the foundries were similar. All foundries exhibited additional dimensional variability for features crossing the mold parting line of more than 0.01 in (0.25 mm). Automated high-pressure squeeze molding resulted in reductions in dimensional variability from 35–50%, compared to manual jolt-squeeze molding. The exception was Foundry A. However, the average feature size for jolt-squeeze molding for Foundry A was very small compared to the average feature size for the other molding lines evaluated. This

Table 3.

Summary of Influence of Process and Geometric Variables on Dimensional Variability of Green Sand Casting Features

<table>
<thead>
<tr>
<th>Factor</th>
<th>Total Tolerance - 6σ (in)</th>
<th>Average Feature Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension</td>
<td>Overall</td>
<td>Overall</td>
</tr>
<tr>
<td>Cope</td>
<td>0.029</td>
<td>0.76</td>
</tr>
<tr>
<td>Drag</td>
<td>0.029</td>
<td>0.76</td>
</tr>
<tr>
<td>Across PL</td>
<td>0.041</td>
<td>1.06</td>
</tr>
<tr>
<td>Mold</td>
<td>A</td>
<td>0.033</td>
</tr>
<tr>
<td>Relationship</td>
<td>B</td>
<td>0.031</td>
</tr>
<tr>
<td>(see Fig. 4)</td>
<td>D</td>
<td>0.026</td>
</tr>
<tr>
<td>E</td>
<td>0.028</td>
<td>0.71</td>
</tr>
<tr>
<td>F</td>
<td>0.041</td>
<td>1.05</td>
</tr>
<tr>
<td>H</td>
<td>0.051</td>
<td>1.31</td>
</tr>
<tr>
<td>Molding Method</td>
<td>Jolt Squeeze</td>
<td>0.039</td>
</tr>
<tr>
<td></td>
<td>High-Pressure Squeeze</td>
<td>0.033</td>
</tr>
</tbody>
</table>

Fig. 4. Schematic of mold relationships for green sand castings. Feature type: A, mold to mold across casting; B, mold to mold across mold; C, mold to mold across mold and casting; D, mold to mold across casting/mold/casting; E, mold to sand core across casting; F, sand core to sand core across sand core; G, mold to sand core across casting and sand core; H, mold to mold across casting/sand core/casting.

Fig. 5. Influence of feature length on dimensional variability for each green sand foundry.

Fig. 6. Influence of casting weight on dimensional variability for each green sand foundry.
artificially reduced the average dimensional variability that could be expected for Foundry A jolt-squeeze molding.

The variability associated with each of the molding processes was modeled using regression analyses. Initial multiple linear regression analysis began with many of the processing and casting variables that were collected as part of this study. This included casting weight, feature length, molding method, parting line, dimension type, projected area of the casting, and the bounding box of the casting. Stepwise elimination methods were used to remove insignificant terms from the resultant regression equations and develop tolerance prediction models with the highest correlation coefficients.

The following regression equations were developed:

**Green Sand Molding:**

\[
6\sigma \text{ (in.)} = 0.00203 \times \text{feature length}^{1.5} \text{ (in.)} \\
+ 0.00837 \times \text{molding method (0 if jolt squeeze, 1 if automatic)} \\
+ 0.00482 \times \text{parting line (1 if feature crosses parting line, 0 if not)} \\
+ 0.0318
\]

or

\[
6\sigma \text{ (mm)} = + 0.0516 \times \text{feature length}^{1.5} \text{ (mm)} \\
+ 0.2126 \times \text{molding method (0 if jolt squeeze, 1 if automatic)} \\
+ 0.1224 \times \text{parting line (1 if feature crosses parting line, 0 if not)} \\
+ 0.8077
\]

Feature length, casting weight and parting line influences all significantly influenced dimensional variability for green sand molding. Even after removing all of the insignificant variables from the model \((\alpha = 0.05)\), a regression equation coefficient of determination of only 0.192 was achieved. This indicates a poor correlation between predicted variables and dimensional variability.

Analysis of residuals indicates that the low coefficient of determination was due to "random variability" in the model, rather than to model lack of fit. This equation accounted for approximately 20% of the total dimensional variability as indicated in the regression analysis. The length term was the most significant of the terms in this model, accounting for approximately 70% of the regression sum of squares. Molding method accounted for approximately 24% of the regression sum of squares, and parting line accounted for the remaining 6%.

Similar regression analyses were also performed for the permanent-mold casting data. The following regression equations were developed:

**Permanent-Mold Casting:**

\[
6\sigma \text{ (in.)} = 0.000407 \times \text{feature length (in.)}^{1.125} \\
+ 0.00608 \times \text{casting weight (lb)}^{0.75} \\
+ 0.00502
\]

or

\[
6\sigma \text{ (mm)} = 0.0103 \times \text{feature length (mm)}^{1.125} \\
+ 0.1544 \times \text{casting weight (kg)}^{0.75} \\
+ 0.1275
\]

The coefficient of determination for this equation was 0.363. This also indicates a relatively poor fit of the model. Feature length and casting weight were observed to have a significant effect on dimensional variability. However, the effects of parting line and other variables were insignificant. A graphical representation of the effects of feature length and casting weight on the dimensional variability of permanent-mold casting, plotted from Equation 3, is shown in Fig. 7.

![Fig. 7. Influence of feature length and casting weight on total tolerance for permanent-mold castings.](image-url)
Additional regression analysis was performed to determine if dimension type had a significant influence on dimensional variability when adjusted for casting weight and feature length. Figures 4 and 8 schematically show the mold relationship categories used in this analysis, for both green sand molding and permanent-mold casting.

Regression equations with dimension type terms were “force fit” to the regression equations developed previously, using step-wise elimination methods. By comparing the “\( \beta_0 \) values” for the new regression models with dimension type terms, the influence of dimension type can be evaluated independent of casting weight and feature length differences. Tables 5 and 6 show the influence of dimension type on variability, as expressed as “average \( \beta_0 \) difference” from the overall regression fit equations.

![Fig. 8. Schematic diagram of mold relationships for permanent-mold castings. Feature type: \( J \), mold to permanent core across casting; \( K \), permanent core to permanent core across permanent core; \( L \), mold to permanent core across casting and permanent core; \( M \), mold to mold across casting/permanent core/casting.](image)

### Table 5

**Comparison of Average Dimensional Variability for Each Mold Relationship for Green Sand Castings**

<table>
<thead>
<tr>
<th>Mold Relationship</th>
<th>Average Total Tolerance (6σ) (in.)</th>
<th>Average ( \beta_0 ) Difference (in.)</th>
<th>Number of Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.033</td>
<td>-0.0089</td>
<td>77</td>
</tr>
<tr>
<td>B</td>
<td>0.034</td>
<td>-0.0061</td>
<td>36</td>
</tr>
<tr>
<td>D</td>
<td>0.026</td>
<td>-0.0202</td>
<td>29</td>
</tr>
<tr>
<td>E</td>
<td>0.031</td>
<td>-0.0077</td>
<td>77</td>
</tr>
<tr>
<td>F</td>
<td>0.058</td>
<td>0.0110</td>
<td>107</td>
</tr>
<tr>
<td>H</td>
<td>0.064</td>
<td>0.0106</td>
<td>71</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.041</strong></td>
<td></td>
<td><strong>397</strong></td>
</tr>
</tbody>
</table>

### Table 6

**Comparison of Average Dimensional Variability for Each Mold Relationship for Permanent-Mold Castings**

<table>
<thead>
<tr>
<th>Mold Relationship</th>
<th>Average Total Tolerance (6σ) (in.)</th>
<th>Average ( \beta_0 ) Difference (in.)</th>
<th>Number of Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.013</td>
<td>-0.0022</td>
<td>41</td>
</tr>
<tr>
<td>B</td>
<td>0.052</td>
<td>0.0166</td>
<td>10</td>
</tr>
<tr>
<td>D</td>
<td>0.030</td>
<td>0.0112</td>
<td>8</td>
</tr>
<tr>
<td>M</td>
<td>0.008</td>
<td>-0.0056</td>
<td>8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.020</strong></td>
<td></td>
<td><strong>67</strong></td>
</tr>
</tbody>
</table>

In these tables, the number of observations for each dimension type is also included. As the number of observations decrease, the uncertainty in the average \( \beta_0 \) difference increases.

For green sand aluminum castings (Table 5), mold relationships A, B, D and E have less average variability than the fitted overall regression model. Similarly, mold relationships F and H exhibit more dimensional variability than the other mold relationships and the overall regression equation. For permanent-mold castings (Table 6), mold relationships A and M exhibited lower dimensional variability than the overall regression model, while mold relationships B and D exhibited higher dimensional variability than the overall regression model.

### COMPARISONS TO PUBLISHED TOLERANCE SPECIFICATIONS

A number of organizations have published dimensional tolerance standards or guidelines for aluminum castings.\(^{1,2,3}\) Summaries of the Aluminum Association dimensional tolerance guidelines and the AFS Aluminum Division tolerance guidelines are shown in Appendices B and C, respectively, for reference. The dimensional variability observed for green sand and permanent-mold castings measured in this study were compared to casting dimensional tolerance standards published by the International Standards Organization (ISO 8062-94).\(^{1}\)

Key Components of the ISO 8062 tolerance specification are summarized in Appendix A. Comparisons between ISO 8062 tolerance guidelines and the dimensional variability measured in this study indicate that the actual dimensional variability of aluminum castings is significantly better than these published tolerance specifications would indicate.

Table 7 shows the dimensional variability of green sand casting features for each foundry and each molding method, compared to the applicable ISO tolerance specifications. Foundry capabilities in Table 7 are expressed as a percent of casting feature that had variability less than the ISO tolerance limits. This table also separates that data by molding method. For each of the foundries, the automatic high-pressure molding produced a higher percentage of features conforming to ISO tolerance.

Table 8 similarly shows a comparison between the dimensional variability of permanent-mold castings and the applicable ISO tolerance specifications. Although the variability of most of the permanent-mold casting was less than indicated in ISO 8062, 6% of the castings had variability greater than the loosest tolerance grade (CT 8) and 28% had variability greater than the tightest tolerance grade (CT 6).

Figure 9 shows how the 10% and 90% variability confidence levels, developed from the regression equations, compare to the ISO 8062 tolerance specifications for sand castings. Figure 10 shows a similar comparison for permanent-mold castings. Ninety percent of the casting features exhibited variability less than the 90% confidence limit line, while 10% of the variability values fell below the 10% confidence limit line.

Comparisons were also made between the variability measured in this study and American Foundrymen’s Society (AFS) and Aluminum Association (AA) guidelines. One hundred percent of the permanent-mold features exhibited variability less than the AFS
guidelines for features that cross a parting line, and 80% conformance to the AFS guidelines for features that do not cross a parting line.

Comparisons between Aluminum Association standards and the variability data collected as part of this study are more difficult to make. However, in general, the dimension tolerances indicated in the Aluminum Association guidelines are quite broad, compared to the variability observed in this study.

All of these comparisons between published dimensional specifications and castings measured in this study are valid only for the size castings measured in this study—up to 24 lb for green sand castings, and up to 51 lb for permanent-mold castings. The dimensional variability of significantly larger castings is the subject of future study.

Foundries, in some cases, “upgrade” castings dimensionally by pressing, straightening, or premaching. Dimensional repeatability after upgrading was not evaluated in this study.

It should be stressed that, in the above comparisons, only the variability of casting features was compared to existing standards. This analysis does not include deviations from desired or nominal dimension. Mold or tooling dimensional errors can further reduce casting feature conformance to customer specifications. A feature could be less variable than the existing standard, but still not satisfy the customer’s requirement because of a dimensionally incorrect pattern or mold.

### Table 7.
<table>
<thead>
<tr>
<th>ISO 8062 TOLERANCE GRADE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molding Foundry Method</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>A Jolt Squeeze 57% 77% 98% 100% 100% 100%</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>B Jolt Squeeze 35% 65% 82% 100% 100% 100%</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>C Jolt Squeeze 57% 74% 89% 94% 100% 100%</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Note: CT 7–CT 9 casting tolerance grades are recommended for long-series production aluminum castings produced using sand cast, machine molding and shell molding processes. CT 9–CT 12 are recommended for aluminum castings produced using sand cast hand molding processes.</td>
</tr>
</tbody>
</table>

**CAPABILITY COMPARISONS WITH OTHER CAST METALS**

Figure 11 compares the dimensional variability of aluminum sand castings to the variability of iron and steel sand castings also measured as part of ongoing Penn State University research. It should be noted that the iron and steel tolerance confidence levels were developed from much more data than has been collected, to date, for aluminum castings. Studies of dimensional variability for iron and steel castings included castings from a much broader weight and size range than the aluminum castings measured.

Although aluminum castings appear to be more dimensionally capable at large feature lengths, the dimensional capabilities for small aluminum casting features are similar to the capabilities for iron and steel sand castings. As discussed previously, casting weight was not a significant factor in the regression model for the small aluminum green sand castings. Casting weight is, however, a significant factor in the equations for iron and steel, which have a higher density than aluminum and can exert more metal state pressure on the mold. For heavier aluminum castings, weight may influence variability. Also, for large aluminum castings with greater feature lengths, a correlation between feature length and variability may become apparent.

Finally, the dimensional variability of aluminum green sand castings is compared to steel shell castings (Fig. 12). Steel shell molded castings typically exhibited the lowest sand casting dimensional variability. Figure 12 also shows the 10% and 90% confidence levels for steel shell castings and for aluminum green sand castings. The process capabilities are similar for these two processes.

### Table 8.
<table>
<thead>
<tr>
<th>Percentage of Permanent-Mold Casting Features Variability Measurements That Conform to ISO 8062 Dimensional Tolerance Standards.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT 6 CT 7 CT 8</td>
</tr>
<tr>
<td>Conformance 72% 88% 94%</td>
</tr>
<tr>
<td>Note: CT 6–CT 8 casting tolerance grades are recommended for gravity and low-pressure permanent-mold castings.</td>
</tr>
</tbody>
</table>

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Fig. 9. Ten % and 90% variability confidence levels compared to ISO 8062 specifications for green sand castings.

Fig. 10. Ten % and 90% variability mold confidence levels compared to ISO 8062 tolerance specifications for permanent-mold castings.
Figure 13 compares the capabilities of aluminum sand and permanent-mold castings. Permanent-mold castings are more dimensionally capable than aluminum green sand castings for the range of feature lengths measured in this study. This comparison cannot be extended beyond 200 mm feature lengths, since larger sand castings have not yet been evaluated.

SUMMARY

The dimensional variability of aluminum green sand and permanent-mold castings has been characterized and compared to the capabilities of other casting processes and to current casting dimensional tolerance standards. This provides general comparisons that can be used by other aluminum foundries to benchmark their own dimensional capabilities. The role of both process and geometry characteristics on dimensional variability has been evaluated. More work is needed to fully establish the specific role of process parameters and geometric parameters on the dimensional variability that can be expected for aluminum sand and permanent-mold castings.

Although a considerable amount of dimensional data were collected in this study, much more additional data needs to be collected to develop robust strategies for dimensional variability reduction at foundries. Tooling allowance issues that affect “cyntering” must also be addressed. Foundry-to-foundry dimensional variability differences were observed in this study. This indicates that molding system and sand system control parameters, as well as system and tooling maintenance factors, can be expected to influence dimensional capabilities. The challenge before us is to identify these important dimensional control factors, to reliably satisfy customer dimensional requirements.

REFERENCES


APPENDIX A

ISO 8062 Tolerance Guidelines for Castings

The basic format of the ISO 8062 dimensional tolerance standard is shown below. Refer to the standard document itself for detailed footnotes and exceptions to the tolerance limits indicated in Tables A1 and A2.

APPENDIX B

Summary of Aluminum Association Dimensional Tolerance Guidelines

In 1988, the Aluminum Association published dimensional tolerance specifications for aluminum castings produced in green sand and permanent molds. The tolerances stated are intended for castings produced at the “most economical level.” “Greater accuracy that could be achieved through extra close work or care in production should be specified only when and if necessary, since additional cost may be involved.”

The Aluminum Association guidelines have been developed for features on one side of the parting line, those across the parting line and those influenced by cores or slides. The basic tolerance for a
Table A1.  
Total Casting Tolerance

<table>
<thead>
<tr>
<th>Raw casting basic dimension</th>
<th>(all numbers in mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>over up to including</td>
<td>3</td>
</tr>
<tr>
<td>—</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>16</td>
</tr>
<tr>
<td>16</td>
<td>25</td>
</tr>
<tr>
<td>25</td>
<td>40</td>
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<tr>
<td>40</td>
<td>63</td>
</tr>
<tr>
<td>63</td>
<td>100</td>
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<tr>
<td>100</td>
<td>160</td>
</tr>
<tr>
<td>160</td>
<td>250</td>
</tr>
<tr>
<td>250</td>
<td>400</td>
</tr>
<tr>
<td>400</td>
<td>630</td>
</tr>
<tr>
<td>630</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table A2. 
Tolerance Guides

| Tolerance grades recommended for short-series for single-production raw castings: |
|-----------------------------|---------------------|
| Method | Molding material | Tolerance grade CT Casting material Light-metal materials |
| Sand cast, Clay-bonded | 11 to 13 |
| Hand-molded, Chemically bonded | 10 to 12 |

Tolerance grades for long-series production raw castings:

| Method | Tolerance grade CT Casting material Light-metal materials |
| Sand cast, hand-molded | 9 to 12 |
| Sand cast, machine-molded and shell molding | 7 to 9 |
| Metallic permanent-mold (gravity and low-pressure) | 6 to 8 |

Dimension on a green sand aluminum casting on one side of the parting line is ±0.030 in. up through 6 in., and an additional tolerance of ±0.003 in. for each inch over 6 inches. It should be noted that these Aluminum Association guidelines are expressed in terms of the half tolerance (±0.25) rather than the total tolerance (±0.50) used in ISO 8062. The basic tolerance for a dimension on a permanent-mold aluminum casting on one side of the parting line is ±0.015 in. up through 1 in. for fully machined mold cavities, and ±0.030 in. up through 1 in. for cast-to-size molds. A fully machined mold cavity casting is given an additional ±0.002 in. tolerance for each inch over 1 inch. A casting produced in a cast-to-size mold receives an additional ±0.003 in. tolerance for each inch over 1 inch.

Tables B1 and B2 show the additional tolerances allowed for features that cross the parting line, and those that are affected by a core or slide. All of these features are in addition to the basic tolerances described previously. The additional tolerance is based on projected area.

APPENDIX C

Summary of AFS Aluminum Division Dimensional Tolerance Guidelines

A widely used handbook published by the Aluminum Division of the American Foundrymen’s Society suggests molding process capabilities for all common aluminum casting processes. It describes basic design considerations for each molding method. These tolerance guidelines are intended for simple shapes that are produced using traditional molding methods.

A nominal dimensional variability is recommended for Al sand casting features between two points in the same half of the mold that are not affected by the parting line or a core. Additional variability is allowed for four additional conditions: features that cross the mold parting line, features affected by a core, features affected by draft and features that are affected by finishing operations. Tolerances for permanent-mold castings are similarly described.
A nominal dimensional variability tolerance can be increased for features crossing a mold parting line, features affected by moving parts, features affected by draft, features requiring finishing and surfaces that are subjected to a flatness tolerance.

APPENDIX D
Casting and Feature Characteristics
Included in Database

A comprehensive database of process variables and casting geometry descriptors were collected, along with the dimensional variability data. These variables and descriptors are listed. Database searching permits the influence of these factors on casting dimensional variability to be readily determined.

- **Casting Variables**
  - Castings produced per year
  - Castings produced per lot
  - Castings per mold
  - Minimum space between castings
  - Type of flask
  - Dimensions of the mold
  - Area of the parting line
  - Height of the cope
  - Height of the drag
  - Are jackets used during pouring?
  - Metal and/or alloy type
  - Pouring temperature control limits
  - Are molds weighted during pouring?
  - Heat treatment
  - Total pouring weight
  - Finished weight
  - Largest dimension of the casting
  - Pouring time
  - Maximum wall thickness
  - Minimum wall thickness
  - Projected area of entire casting
  - Volume of the casting bounding box
  - Number of cores per castings
  - Volume of all internal cores
  - Pattern material(s)
  - Condition of the pattern
  - Pattern equipment age
  - Pattern mounting
  - Type of molding sand
  - Is facing sand used?
  - How often is pin alignment checked?
  - Compaction method
  - Are chills used?

- **Sand System Variables**
  - Type of molding sand
  - General type of binder
  - Type of molding equipment

- **Feature Variables**
  - Age molding equipment
  - Type of muller
  - Is a sand cooler used?
  - Is a sand heater used?
  - Type of mold wash
  - Mold wash application method
  - Mold wash drying method
  - Type of sand
  - AFS gfn
  - Permeability control limits
  - Compress strength control limits
  - Shear strength control limits
  - Moisture control limits
  - Compactibility control limits
  - Clay control limits
  - Mold hardness control limits
  - New sand percentages
  - Tensile strength control limits
  - Sand temperature control limits

- **Core System Variables**
  - Type of core binder
  - Core sand mixing equipment
  - Type of core wash
  - Core wash application method
  - Core wash curing method
  - Type of sand
  - AFS gfn
  - Permeability control limits
  - Binder percentage control limits
  - Hardness limits
  - New sand percentage
  - Tensile strength control limits

- Feature location (cope, drag, PL)
  - Direction, with respect to parting line
  - Is this feature drafted?
  - Affected by grinding?
  - Does mold wash affect feature?
  - Affected by straightening?
  - Nominal dimension of feature
  - Mold relationship type
  - Crosses mold parting line?
  - Does core wash affect this feature?
  - How are cores set?
  - Are core assemblies used?
  - Fixtures used to assemble cores?
  - Cross a core assembly joint?
  - Corebox material(s) used
  - Condition of corebox(es) used
  - Measurement instrument used
  - Corresponding pattern dimension