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Application of Statistical Methods for Analyzing the Relationship Between Casting Distortion, Mold Filling, and Interfacial Heat Transfer in Sand Molds

Final Report

Y. A. Owusu

March 1999

Work Performed Under Contract No. DE-FC07-95ID13363

For
U.S. Department of Energy
Assistant Secretary for
Energy Efficiency and Renewable Energy
Washington, DC

By
Florida A & M University
Tallahassee, FL

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EXECUTIVE SUMMARY

This report presents a statistical method of evaluating geometric tolerances of casting products using point cloud data generated by coordinate measuring machine (CMM) process. The focus of this report is to present a statistical-based approach to evaluate the differences in dimensional and form variations or tolerances of casting products as affected by casting gating system, molding material, casting thickness, and casting orientation at the mold-metal interface. Form parameters such as flatness, parallelism, and other geometric profiles such as angularity, casting length, and height of casting products were obtained and analyzed from CMM point cloud data.

In order to relate the dimensional and form errors to the factors under consideration such as flatness and parallelism, a factorial analysis of variance and statistical test means methods were performed to identify the factors that contributed to the casting distortion at the mold-metal interface. The results of some of the statistical analyses have been provided, for three casting thicknesses: ¼ in., ½ in., and ¾ in. Three sand molding materials for the research included: resin-bonded sand, lost foam silica sand, and lost foam (carbon) low expansion sand.

US Department of Energy (DOE) and American Foundrymen's Society funded this research work. The research was carried out jointly by University of Alabama in Tuscaloosa, Florida A & M University in Tallahassee, General Motors Company, Mercury Marine Company, Willard Industries, and CMI Test Center.

The summary of the research is as follows:

1. CMM point cloud data have been statistically analyzed successfully to evaluate casting distortion.
2. This research has established that casting distortion (or casting quality) is influenced by the following parameters: casting thickness, orientation, gating system, and type of molding material of different degrees.
3. The quality parameters monitored for the distortion include: casting length, height, thickness, parallelism, flatness, and casting angularity (angle).
4. From the analyses, it was found that resin bonded sand, top gating, and orientation down contributed most to the casting distortion

CHAPTER 1

INTRODUCTION

Metal cast products have improved greatly in the last two decades due to the use of statistical process control techniques. However, thin sand castings still lack the dimensional accuracy needed for certain applications. Controlling the dimensions of thin sand castings is a priority. The focus of this research work was to present a statistical approach to evaluate the dimensional and form variations that exist as gating system, molding material, casting thickness, and orientation of the casting are varied.

The objective of manufacturing is to produce products of specific shapes, sizes, finishes, and complexity. The quality of the manufactured part is the measure of the extent to which a part conforms to the needs or desires of the customer or user. Quality assurance is the mechanism that is responsible for maintaining consistent product quality. Under the umbrella of quality assurance is quality control. Statistical quality control techniques have allowed castings to greatly improve over the past twenty years, yet controlling casting dimensions is a challenge that foundries must tackle. Alleviating this problem will allow foundries to remain competitive and to maximize the production of dimensionally optimal products.

1.1.1 Description of Problem

In the foundry industry, challenges often come about in maintaining the dimensional and form integrity of thin metal casting products because they are generally nonlinear in nature. Casting distortion is caused by air gap formation at the mold-metal interface. This phenomenon

has not been successfully modeled; thus, air gap formation is not fully understood [Piwonka *et al.*, 1995]. Figure 1.1 illustrates the process of air gap formation. Figure 1.1(a) indicates the temperature profile immediately after the molten metal is poured which is before air gap has formed. As the metal begins to solidify, it contracts, while the sand mold expands. The expansion of the mold does not compensate for the contraction of the metal; thus, an air gap forms. Figure 1.1(b) indicates the temperature profile after formation of the air gap. This occurrence is the function of three mechanisms [Ho and Pehlke, 1984]. They are surface interaction of the metal and mold, the transformation of metal and mold materials, the effects of geometry. The air gap that is formed at the mold-metal interface decreases the heat transfer rate.

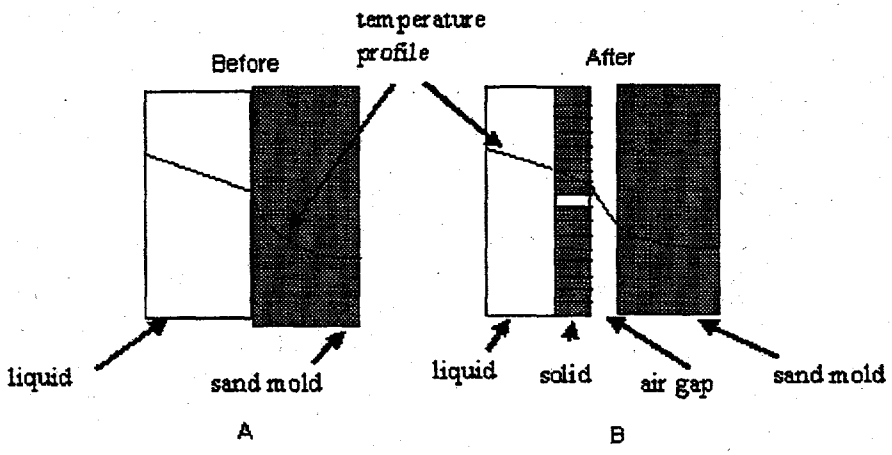


Figure 1.1 Heat transfer at mold-metal interface.

Thus, the solidification process of the casting retards. This air gap may cause serious dimensional problems, such as warping or casting distortion. The focus of this work was to present a statistical approach for evaluating the effect of gating system, molding material, casting thickness, and orientation on casting dimensional and form variations.

CHAPTER 2

LITERATURE SURVEY

This chapter provides a survey of the factors affecting casting accuracy, sand casting processes, tolerance evaluation and statistical analysis.

2.1 Factors Affecting Casting Accuracy

There has been some study of the heat transfer at the mold-metal interface. Nishida and other scientists studied the process of the air gap formation at the casting mold interface for pure aluminum, an aluminum alloy (Al-13.2 pct Si) and cast iron [Nishida *et. al.*, 1986]. The results showed that in a thin air gap, the heat through the air gap was transferred mainly by heat conduction. In addition, they found that the shape of the casting induced different movements on the mold wall. In cylindrical castings, the mold wall moved outward immediately after pouring and remained in that position until the solidification had greatly advanced, while flat surfaces pressed in on the casting after pouring and then it moved outward with the casting.

Ho and Pehlke [1984] characterized the physical mechanisms of heat transfer at the metal-mold interface by proposing that the cause of air gap formation was due to the friction between the casting and the sidewall. They also indicated that the shrinkage experienced by sidewalls due to the evaporation of their volatile components. They also found that the heat transfer coefficient may remain relatively low if non-conforming contacts (i.e. oxide films and mold coatings) were present even when no air gap is formed. The thermal resistance due to the air gap

has been studied by Ross and Stoute [1962]. Their study showed that the thermal resistance due to air gap formation has a direct effect on cooling and casting solidification. Sugiyama [1975], Sun [1970], and Prates [1972] have obtained some reliable data experimentally for the heat transfer coefficient. They measured the heat transfer coefficient by a one-dimensional solidification, immersion method, and fluidity test in a mold. However, the relationship between casting shape, thickness, orientation, mold material, and gating system has not yet been fully determined. Furthermore, it is unknown as to what extent these factors influence air gap formation.

2.1.1 Effect of Air Gap Formation on Casting Distortion

Initially, the effect of the mold-metal air gap formation was found in continuous cast steel slabs [Tien *et al.*, 1982] and [Richmond, 1990]. They formed models that showed that air gap formation reduces metal resistance to deformation. The air gap slows down the cooling process. Thus, an uneven cooling and uneven shrinking is introduced in the metal. As this occurs, the solidified metal begins to pull the parts of the casting that have higher temperature and least resistance into deformation. Figure 2.1 illustrates the effect of air gap formation on casting distortion. This same argument is valid in sand molds. There is greater dimensional accuracy in sand castings with no air gap formation [Woodbury, 1995]. The lost foam process is proof of this argument. Lost foam processes produce dimensionally superior castings in comparison with green sand castings because, the sand collapses around the pattern and when the foam pattern is burned away, the air gap is entirely eliminated.

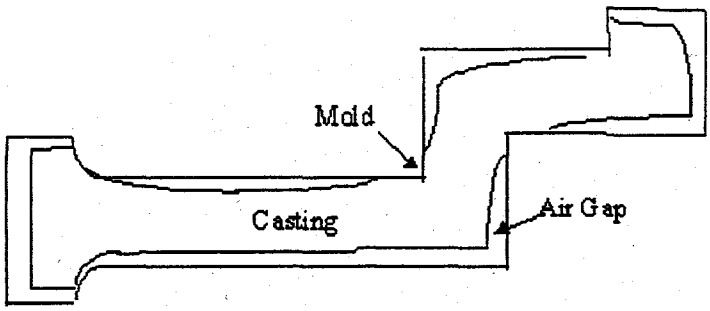


Figure 2.1 Casting Distortion Resulting from Air Gap Formation

2.1.2 Effect of Casting Thickness and Orientation on Casting Distortion

Piwonka and Berry studied the importance of interfacial heat transfer in 1993 [Piwonka and Berry, 1993]. They found that when the actual heat transfer coefficient is higher than the value used in the simulated theoretical model, very little error is introduced at solidification time. However, when the actual heat transfer coefficient is lower than the one used in the model (meaning an air gap has formed), a substantial error is introduced. In addition, this error increased when the casting thickness decreased. Therefore, casting thickness is an important factor in casting distortion. Orientation also affects the way casting solidifies. Since gravity pulls the metal inside the mold, the parts at the bottom have the tendency to stay in contact with the mold wall. This eliminates the air gap formation in these areas. Woodbury and others found that in some cases changing the casting orientation eliminates casting problems.

2.2 Sand Casting Process

The casting process is a method by which an object is formed by pouring liquid metal into a mold, allowing it to solidify, breaking the mold, and machining the final casting product. There is no limitation in the size of the object that can be made. The process is very flexible.

Objects can be made with high tolerance and good surface roughness (texture). There are a variety of materials that may be used for casting. The different types of casting processes include: sand, precision investment, shell-mold, die casting, slush mold, centrifugal, permanent mold, die casting and plaster mold casting processes. Ferrous metals are generally used for sand casting, shell-mold casting, and investment casting. Nonferrous materials may be used for any of these processes [Owusu, 1996].

Sand mold casting is the most popular casting process. Due to its low cost and high temperature resistance, ninety percent of all castings are produced via sand mold casting. Common metal candidates include iron and steel as well as, aluminum, brass, bronze and magnesium. The basic foundry supplies for sand castings (materials and equipment necessary to produce a casting) include molding materials, molding equipment, foundry tools, patterns and melting equipment. The general procedure for sand casting process is shown in Figure 2.2.

2.2.1 Core

The core is a body of material, usually sand, used to produce a cavity in or on a casting. A core is used to create passageways (holes) in a casting and may be used to form the water jacket in a water-cooled engine block. For example, a hole on a casting may be used to form air space between the cooling fins of an air-cooled cylinder. The characteristics of a sand core are that they must have dry strength, must give off minimal gas, must crumble easily, and it must be collapsible, permeable, temperature resistant (high), durable and formable. Cores are often made of dry sand/baked sand. Cores are made similar to molds. They are shaped by a core box and are dried in dryers. Grooves or vents are cut into cores that do not naturally have vents. A mold assembly with a core is shown in Figure 2.3.

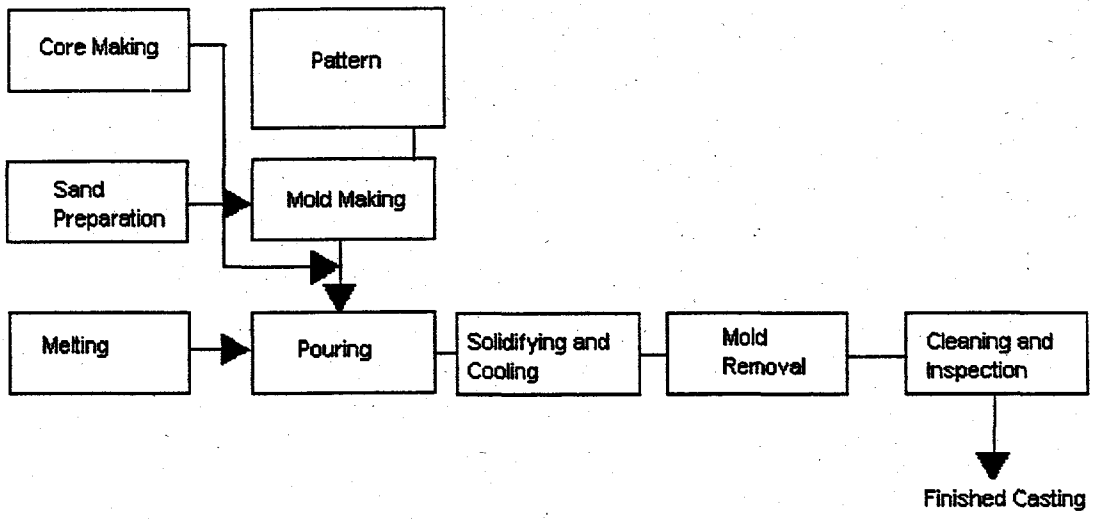


Figure 2.2 Flow Diagram Showing General Procedure for Sand Casting Process

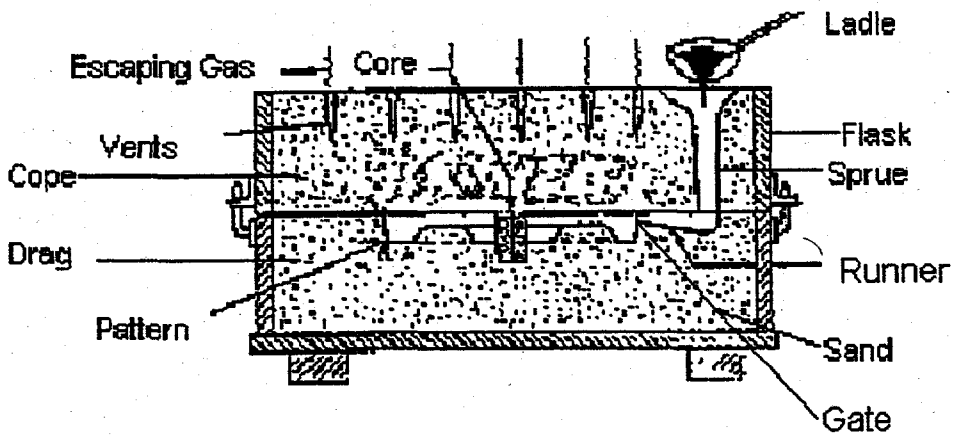


Figure 2.3 Sand Mold Assembly with a Core

2.2.2 Patterns

The pattern is used to prepare and produce a mold cavity. The different types of patterns are loose pattern and mounted patterns. The loose pattern contains not only the shape of the casting, but also, the sprue and riser. It is made of one or two parts split between the cope and the drag. A mounted pattern is permanently fastened to a board. It is easier than a loose pattern to store. Also, the gating system is often mounted on a match plate. A pattern may be solid or split. Patterns are often made of wood. Other materials may include metal, plaster, sand, and plastic.

2.2.3 Mold

The sand mold is made in a flask. The flask is the wood or metal frame in which the mold is made. The flask must be strong enough to withstand the sand ramming. It must resist the pressure of the molten metal. The flask is comprised of two parts to include: cope (top section) and the drag (bottom section). If the depth of the cope or drag is needed to increase, an intermediary section is used. It uses what is called the cheek. The components in the mold are the gates, risers, chills, pouring basin, etc. or gating system. The basic gating system is shown in Figure 2.4. The gating system introduces the liquid metal with minimal movement (turbulence), regulates the rate of entry, allows complete filling of the cavity and promote a temperature gradient within the casting to help the metal solidify evenly. The gate delivers the liquid to the mold cavity. The riser feeds the metal by gravity into the casting to keep it from shrinking. The choke aids in the metal distribution by causing certain sections of the casting to solidify faster than other parts. The sprue acts as a reservoir from the pour basin. The runner connects the sprue to the skim bob and gate. The skim bob is used to trap the slag. Figure 2.5 shows the sand mold and its main features.

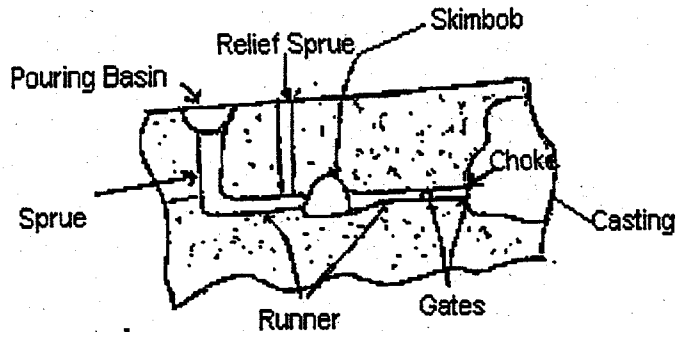


Figure 2.4. A Detailed Gating System

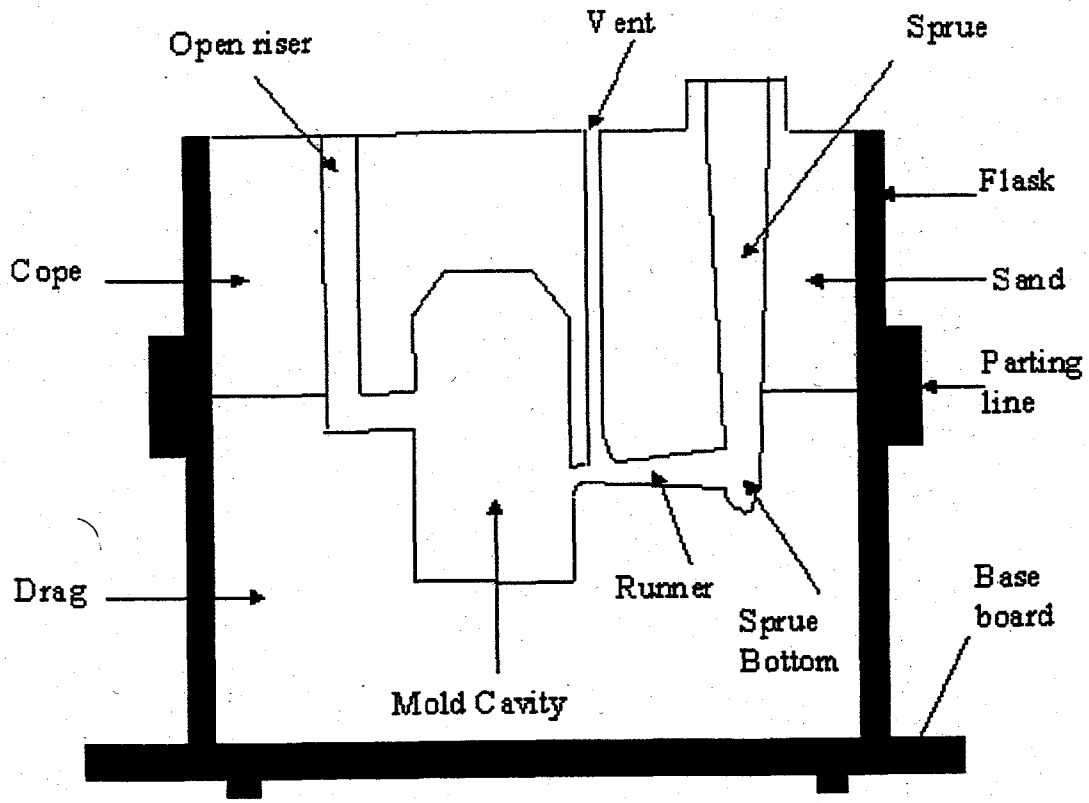


Figure 2.5 Sand Mold and Main Features

2.2.4 Mold Making Procedure

Tools used for this process include a flask, rammer and riddle. Clay and water bond green sand, while organic or inorganic chemicals bond dry sand. Figure 2.6 is a pictorial of the mold making procedure. The molding sand is filled into the lower flask, and the pattern is put down on the molding board. The upper and lower flask are put together with some parts to make the gate and the gas vents and filled with the sand as shown in Figure 2.6a. The sand is then rammed with a wedge shaped rammer as shown in Figure 2.6b. The remainder of the sand is scraped off the mold as shown in Figure 2.6c. The mold may be hardened chemically, see Figure 2.6d. The flask is then removed. Figures 2.6(f-g) show sand mold examples. The metal is melted in an induction furnace to over 1500 degrees C. The metal is then poured. After the casting solidifies, it is then hammered out of the mold.

2.3 Types of Molding and Casting Processes

There are several kinds of molding processes. The bonding method, mold forming method, and sand types are the distinction between them.

1. Sand molding (or sand casting)
    a. Green-sand molding
    b. Dry-sand molding
    c. Core-sand molding
    d. Shell molding.

Miscellaneous sand-molding processes: pit and floor molding, cement-bonded sand, air-set sand, loam molding, CO_2 process, hot box, etc.

2. Investment (or precision) molding
3. Ceramic molding

4. Plaster molding

5. Graphite molding

The major casting processes are classified as follows:

1. Sand casting

2. Permanent-mold casting

3. Die casting

4. Centrifugal casting

6. Precision investment casting

Each of these processes has their own field of appropriate application, with certain advantages and limitations. In this study, the focus is on sand casting. The sand aggregates studied were resin-bonded sand (rbs), lost foam silica sand (lfss), and lost foam low expansion (lfle).

2.3.1 Resin Bonded Sand

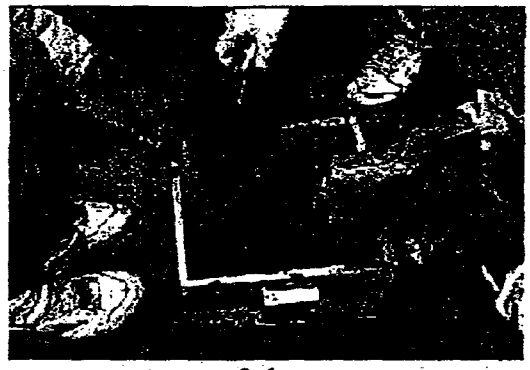
Resin bonded sand is chemically bonded. In the process, a reactive binder and a catalyst are mixed with the sand prior to molding. The hardening reaction takes place without further treatment. The mold strengthens over time. This process is carried out within a limited period before hardening occurs.

Advantage: More accurate castings than green sand molds

Disadvantage: More expensive than green sand casting.

2.3.2 Lost Foam Casting

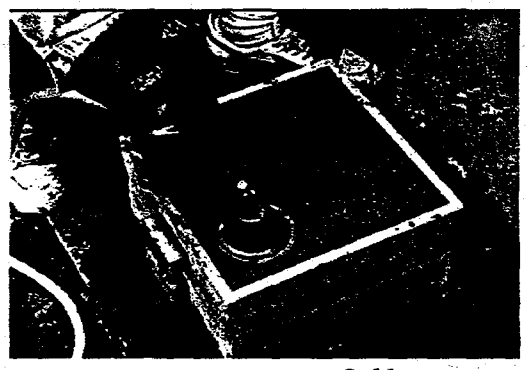
H.F. Shroyer was granted a patent for the lost foam casting process. The patent was for a cavity-less casting method, using a polystyrene foam pattern embedded in traditional green sand. The method is characterized by a polystyrene foam pattern left in the sand that is decomposed and



2.6a

2.6b

2.6c



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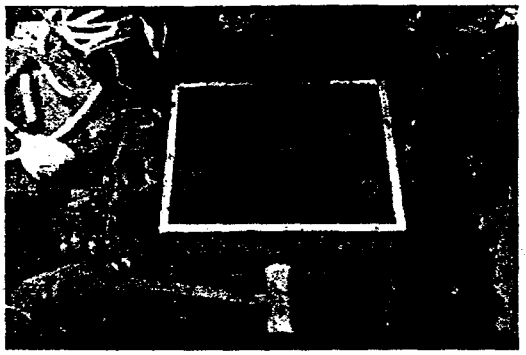

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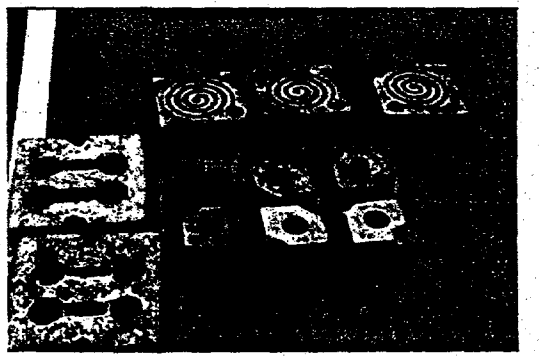
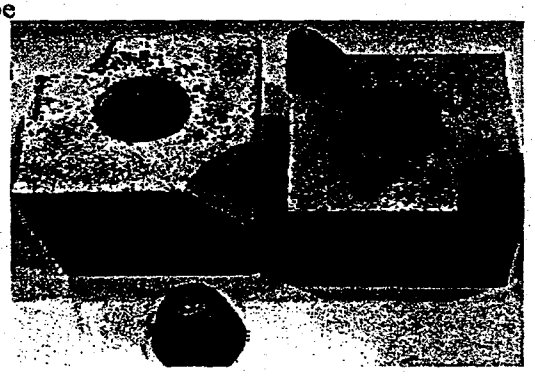


2.6f



2.6g

Figure 2.6. Pictorial Illustration of Sand Casting Process

evaporated by the molten metal. As the molten metal is poured it replaces the foam pattern, precisely duplicating all of the features of the pattern.

This casting process requires that a foam pattern be produced for every casting made. The polystyrene pattern requires a lot of energy to degrade, the metal-polymer interface has large thermal gradients. This means that the molten metal cools faster than it would if it were poured into an empty cavity. Accordingly, the fluidity of the molten metal is less than in sand casting.

The polystyrene pattern is made using a preheated die (usually aluminum). Heat is applied to fuse and bond the beads together. The pattern is then coated with a water-based refractory slurry, dried and placed in a flask. The flask is filled with loose fine sand, which surrounds and supports the pattern. The sand may be dried or mixed with bonding agents to give it additional strength. Then, without removing the polystyrene pattern, the molten metal is poured into the mold. The pattern vaporizes and the metal fills the mold cavity. The heat degrades the polystyrene and the degraded pattern evaporates and is vented into the surrounded sand and into the atmosphere. Basically, the shape desired is carved in the foam, the foam is covered with layers of fiberglass and epoxy, and then the foam is melted away when the metal is poured.

Advantages:

1. It is simple because there are no parting lines, cores, riser systems; hence it has design flexibility.
2. Inexpensive flasks can be used.
3. Polystyrene is inexpensive and can be designed into complex shapes and fine details.
4. The resulting casting requires minimum finishing and cleaning operations.
5. This process is economical for long production runs.
6. It can easily be automated.

7. Fast

8. Easy to Repair

Disadvantages:

1. Energy Cost:
   a. Die Cost: Application of heat to fuse and bond the beads together to make the pattern
   b. High heat gradients required for vaporizing the pattern
2. Flimsy on flat areas
3. Pattern destroyed
4. Can easily become heavy

2.3.2.1 Lost Foam Applications

Lost foam casting process may be applied in automotive, marine, aerospace, and construction industries, requiring x-ray and other soundness testing.

2.3.2.2 Tolerance

Depending on size, geometry, and complexity, a linear tolerance of +/- 0.005 in./in. is standard for the lost foam casting process. Silica sand is not the sand type of choice in terms of tolerance. Eliminating the use of silica sand in the lost foam casting system will result in tighter tolerances. This can be achieved by a concerted effort by the foam pattern producer, the casting producer, and the casting user and will often result in a lost foam casting that substantially reduces or completely eliminates post casting machining. Carbon sand is considered to be low expansion sand and will result in tighter tolerance specifications.

2.3.2.3 Types of Metals

Aluminum:	356	319	355	333	
Copper Based Alloys:	Gray Iron	Class 25	Class 30	Class 35	Class 50

Ductile Iron
Steel and Low Carbon Steel

2.3.2.4 Cost

The cost savings offset the cost increase for the lost foam casting process. This cost savings is due to the reduction in machining of the raw casting because of the tighter, near-net shape and net shape tolerances achieved. Many parts that often require milling, turning, drilling, and grinding can be cast with only minimal finish stock. Also, combining multiple components and casting them as one casting results in great cost reduction.

2.4 Coordinate Measuring Machine (CMM) and Point Cloud Data

Coordinate Measuring Machines (CMM) generate point cloud data from an object, such as: the casting surface. This data may be processed and parameter calculations may be made. There are many different methods of data processing, yet, their accuracy is questionable. The most popular algorithm, least squares method, is said to not give the minimum tolerance zone as required by ANSI standards. Some of the other alternatives do not always give the minimum zone. Ineffective methods open the door to producer's risk (α error): accepting that a part is within specifications when it is not. This error results in money and confidence loss. A possible method of data processing is capturing the point cloud data and doing form calculations on a computer using cutting edge algorithms.

2.5 Statistical Methods for Evaluation of Geometric and Dimensional Variations

There is much research in the arena of tolerance evaluation or metrology of manufactured parts. Minimum zone is a popular method of determining tolerance deviations. The methodology of minimum zone is calculating the maximum dimensional error by locating the minimum deviation among all the sampled coordinates using various optimization schemes. Yet, this

method requires that the entire deviation space be examined. However, CMM assigns point clouds to a sample of the data. Therefore, errors often occur. For example, all sampled deviations may be found to be within tolerance, but since all the data have not been examined some non-sampled deviations may in fact be out of bound. Therefore, minimum zone is not an effective method for tolerance evaluation of CMM sampled data [Menq et. al 1990]. Since CMM sampling does not meet the criteria, different number of sampling points at different measurement locations will always yield different results.

Some work has been done to construct models to attack this problem. Sobh and his colleagues attempted a probabilistic approach [Sobh *et al.* 1994].. In their research, they constructed geometric entities using uncertainty models for the objects that contained noisy measurements and proceeded to do reasoning on the uncertain geometries. Menq and his research team's method assumed normally distributed points in which the sampling space is related to the process capability [Menq *et al.* 1990]. This method proves that the sampling intensity (number of sampled points) does not depend on the tolerance or manufacturing alone, but depends on a combination of both factors. Thus, the number of sampled points is reduced as the process capability increases.

There has also been an attempt to solve the problem by modeling uncertain geometry. Kendall and Moran studied the theories of stochastic geometry [Kendall and Moran 1963]. They examined a method of choosing distributions on geometric elements that provide a consistent interpretation of physical geometric elements. Robotics research also presents some usable theories for dealing with uncertain geometry. Durrant-Whyte modeled a sensor in a manner that explicitly accounts for the uncertainty encountered in robot operations [Durrant-Whyte 1984 and 1986].

2.5.1 Dimensional and Form Variation Evaluation

It would be ideal to manufacture parts to exact size. Yet, because it is often impractical, a tolerance range is established. The form tolerance is the permitted deviation of the actual part feature from the nominal feature. These forms include lines, planes, circles, and cylinders. Other form features include curves and free-form surfaces. The tolerances that correspond to these forms are straightness, flatness, circularity (roundness), cylindricity, and profile of curves or surfaces. The standards by which the tolerance zones are specified are set by the American National Standard Institute (ANSI), and International Standard Organization (ISO).

In order to evaluate tolerance error, an ideal feature must first be established from the actual measurements such that deviations of the feature can be determined. In general, form features and errors can be expressed as follows [Menq, 1990]

$$X(\theta) = N(\theta) + \varepsilon(\theta) \tag{2.1}$$

where θ is a set of independent variables, $X(\theta)$ is the measurement value at θ, $N(\theta)$ is the ideal value of the form feature at θ, and $\varepsilon(\theta)$ is the deviation at θ.

The ideal form can be the nominal design value or the best least-square fit. For CMM sampling, the corresponding θ_i for each point is not really known. Therefore, the deviation of a sample point is minimized by

$$|\varepsilon_i| = \min |X_i - N(t,\theta)| \tag{2.2}$$

where, the point error ε_i is found by minimizing the difference between the measured value X_i and the nominal value $N(t,\theta)$, and t represents the tolerance allowed in the designed.

2.5.2 Linear Dimensions

The Euclidean distance is the linear distance between two coordinate points (x_1, y_1, z_1) and

(x_2, y_2, z_2). It is calculated using equation 2.3.

$$DIST = SQRT[(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2] \quad (2.3)$$

In this expression, DIST is the desired linear distance, SQRT is the square root, and x, y, z are the coordinates for points 1 and 2.

2.5.3 Surface Flatness Evaluation

Since sampled inspection does not measure all data points. It is possible to infer that a surface is flat when it actually is not. A result of all the measured sampled points being within the tolerance limit that does not necessarily indicate a flat surface. If any point is outside the tolerance, the surface is not considered flat since it is assumed that the CMM machine has negligible measurement error. Therefore, it is necessary to calculate the variance of the sample points to see if the variation of the surface is acceptable [Menq, *et al.* 1990]. This examination is based on a hypothesis test by

$$H_0 = \sigma = \sigma_m \quad (2.4)$$

and

$$H_1 = \sigma = \sigma_t \quad (2.5)$$

The null hypothesis states that the feature variation, σ, equals the expected variation σ_m of the process in control, while the alternative hypothesis states that the feature error, σ, reaches the tolerance limit, σ_t. Therefore, a critical value (L) must be defined and set up such that

$$s \leq L \text{ (Accept)}$$

and

$$s > L \text{ (Not Accepted).}$$

The selection of L along with the estimator s (sampled deviation) provides sufficient confidence in the test such that

$$P(s \leq L \mid \sigma = \sigma_m) = 1 - \gamma \quad (2.6)$$

And

$$P(s > L \mid \sigma = \sigma_t) = 1 - \delta. \tag{2.7}$$

where γ is the risk of rejection of a surface that is good and δ is the risk that a bad surface which is not satisfactory is selected. This is illustrated in Figure 2.7. The relationship between the sample variance s^2 and the true variance is given by

$$\chi_n^2 = ns^2/\sigma^2 \tag{2.8}$$

where χ_n^2 is a chi-square distribution with n degrees of freedom.

Therefore, equation 2.6 becomes

$$P(s^2 \leq L^2 \mid \sigma = \sigma_m) = P(\chi_n^2 \leq L^2 n/\sigma_m^2) = 1 - \gamma \tag{2.9}$$

which gives

$$L^2 = (\chi^2_{n:\gamma}\, \sigma^2_m)/n. \tag{2.10}$$

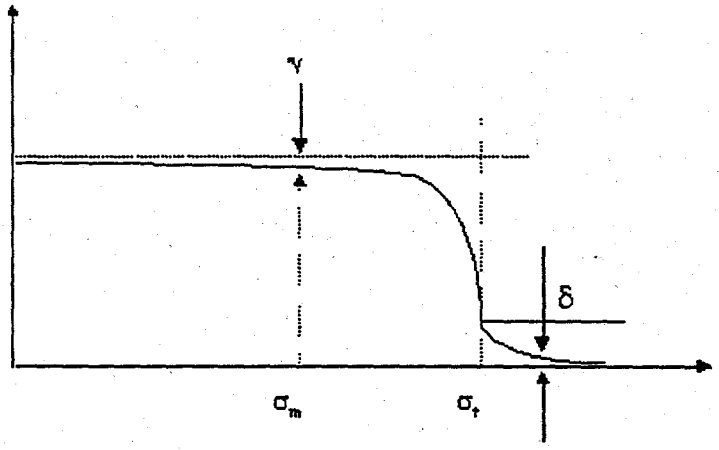


Figure 2.7. Sampling Plan Determined by Operating Characteristic Curve

Similarly, equation 2.7 becomes

$$P(s^2 > L^2 \mid \sigma = \sigma_t) = P(\chi_n^2 \leq L^2 n/\sigma_t^2) = 1 - \delta \tag{2.11}$$

and

$$L^2 = (\chi^2_{n:1-\gamma}\, \sigma^2_t)/n. \tag{2.12}$$

Setting equations 2.10 and 2.12 equal, the following equation is obtained

$$(\chi^2_{n:\gamma} / \chi^2_{n:1-\gamma}) = (\sigma_t/\sigma_m) . \tag{2.13}$$

Knowing that for $n \geq 30$, the quantity $\sqrt{2\chi_n^2}$ is distributed approximately normal with mean of $\mu = \sqrt{2n}$ and variance of σ^2 = unity [Bendat and Piersol, 1983]. Then

$$\sqrt{2\chi^2} = \sqrt{2n}\frac{s}{\sigma} \rightarrow N(\sqrt{2n}, 1) \tag{2.14}$$

and having

$$z = \frac{s-\sigma}{\sigma/\sqrt{2n}} \tag{2.15}$$

and

$$s = \frac{s\sigma}{\sqrt{2n}} + \sigma \quad . \tag{2.16}$$

Thus,

$$P(s^2 \leq L^2 \,|\, \sigma = \sigma_m) = P(z \leq \frac{L-\sigma_m}{\sigma_m/\sqrt{2n}}) = 1 - \gamma \tag{2.17}$$

and

$$L = \frac{z_\gamma \sigma_m}{\sqrt{2n}} + \sigma_m. \tag{2.18}$$

Let $\sigma_t = k\sigma_m$, $(k > 1)$, where k is the process capability ratio

$$P(s^2 > L^2 \,|\, \sigma = \sigma_t) = P(z > \frac{L-k\sigma_m}{k\sigma_m/\sqrt{2n}}) = 1 - \delta \tag{2.19}$$

and

$$L = \frac{z_{1-\delta} k\sigma_m}{\sqrt{2n}} + k\sigma_m. \tag{2.20}$$

By setting equations 2.18 and 2.20 equal, the relationship between sample size and process capability (given that the process is normally distributed) is obtained, such that

$$n = \frac{1}{2}\left[\frac{kz_{1-\delta} - z_\gamma}{1-k}\right]^2 \tag{2.21}$$

And the critical value L becomes

$$L = \frac{(1-k)z_\gamma \sigma_m}{kz_{1-\delta} - z_\gamma} + \sigma_m \quad . \tag{2.22}$$

Figure 2.8 shows the relationship between the sample size and the process capability. The sample size can be greatly reduced to estimate the value of the form tolerance when the process capability is high.

2.5.4 Flatness Error Evaluation using Non-linear Optimization Technique

Flatness is defined as "a condition of a surface having all elements in one plane" according to ANSI Y14.5M standards. This method of calculating flatness error of the casting is similar to a mathematical model developed by Cheraghi *et al.* at the Wichita State University (Cheraghi *et al*,1996). This method uses a non-linear optimization approach to calculate the exact values of flatness errors as defined by the ANSI Y14.5M standards on geometric dimensioning and tolerance. The measurements are taken in *x, y, z* coordinates on the walls' surface with the *z*-axis representing the direction in which the flatness will be measured. The *z* coordinates measure the variation on the surface of the casting as shown in Figure 2.9.

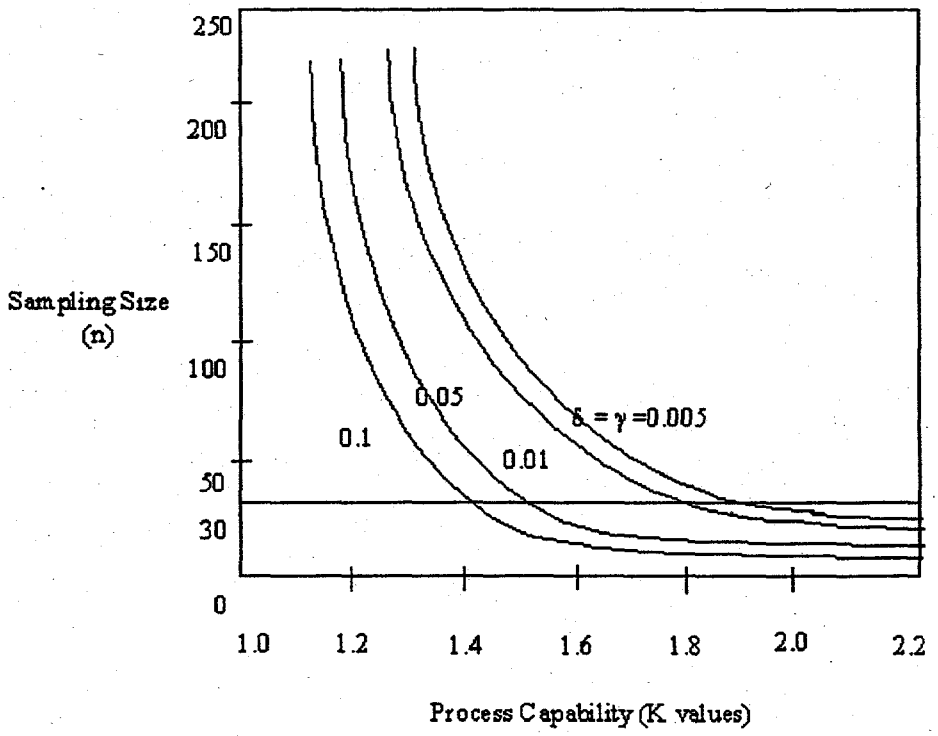


Figure 2.8 Sampling Size vs. Process Capability [Menq, et al 1990]

To obtain the exact value of the surface flatness, two planes parallel to the *x-y* plane (representing the ideal surface of the walls) a distance of t_f apart must be found to define the flatness tolerance zone. The nonlinear optimization problem is expressed

$$\text{Minimize } t_f = -\bar{z}_{\min} + \bar{z}_{\max} \tag{2.23}$$

Subject to:

$$\bar{z}_i = t_f \tag{2.24}$$

$$\bar{z}_i = 0 \qquad i = 1, 2, \ldots, n \tag{2.25}$$

where, $\bar{z}_i = -x_i \cos\theta \sin\gamma + y_i \sin\theta + z_i \cos\theta \cos\gamma + z$

and t_f is the distance representing the flatness error.

This method provides exact flatness error values and has a short computational time.

2.5.5 Evaluation of Parallel Surfaces

In order to evaluate the parallelism error of surfaces, it is necessary to find the distance between the points on opposite locations of the planes that are being evaluated. From these distances, the difference between the shortest distance and the longest distance gives the parallelism error. Mathematically, it is expressed as

$$\varepsilon_{\text{parallelism}} = \max(\text{dist}_{AB}) - \min(\text{dist}_{AB}) \tag{2.26}$$

where, $\varepsilon_{\text{parallelism}}$ is the difference between the maximum distance between planes A and B. The distance is computed using equation 2.3. Figure 2.10 illustrates the parallelism error between two planes.

2.5.6 Calculation of the Tapered Angle

The euclidean distance, equation 2.3, and $\tan\theta = \dfrac{\text{opposite side}}{\text{adjacent side}}$

were used to calculate the tapered angle; yielding

$$\cos\theta = \frac{\sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2 + (z_1 - z_0)^2}}{\sqrt{(x_3 - x_2)^2 + (y_3 - y_2)^2 + (z_3 - z_2)^2}} \tag{2.27}$$

Figure 2.11 shows the parameters used in this equation. These angles are based on the assumption that the walls of the casting are fairly straight.

2.6 Statistical Analysis of Dimensional Data

The statistical analysis of the dimensional data includes the factorial analysis of variance and the tests on means.

2.6.1 Analysis of Variance

Analysis of variance (ANOVA) procedures separate the variation observable on a response into two basic components: variation due to assignable causes and random or chance variation. Assignable causes refer to known or suspected sources of variation that could be corrected during the conduct of the experiment. Random or chance variation includes the effects of all other sources that could not be controlled or measured during the experiment except by statistical modeling. The statistical model for the sand casting dimensional data are

$$y_{ijklr} = \mu_{ijkl} + e_{ijkl.} \tag{2.28}$$

In this equation, y_{ijklr} is the measured dimensions of the sand casting due to the different factor level combinations. The number of repeat tests are represented by $r = 1, 2, 3$. The levels for the molding method are represented by $i = 1, 2, 3$. Similarly, $j = 1, 2, 3$; $k = 1, 2, 3$; $l = 1, 2, 3$, represent the levels for the gating system, the casting orientation and thickness, respectively. In this model μ_{ijkl} is the effect of the assignable causes and e_{ijkl} is the random error of the experiment. The assignable cause portion of the model can be further decomposed into terms representing the main effects and the interactions among the four model factors

$$\mu_{ijklr} = \mu + \alpha_i + \beta_j + \gamma_k + \delta_l + (\alpha\beta)_{ij} + (\alpha\gamma)_{jk} + (\alpha\delta)_{kl} + (\beta\gamma)_{ik}$$

$$+ (\beta\delta)_{jl} + (\gamma\delta)_{kl} + (\alpha\beta\gamma)_{ijk} + (\alpha\beta\delta)j_{kl} + (\beta\gamma\delta)_{ikl} + (\alpha\beta\gamma\delta)_{ijkl}. \qquad (2.29)$$

The subscript i in 2.29 represents molding material level, the subscript j represents the gating system levels, the subscript k represents the orientation levels, the subscript l represents the thickness levels, the r represents the three replicates. The parameters in 2.29 having a single subscript representing main effects for the factor identified by the subscript. Two-factor interactions are modeled by the terms having two subscripts, and the three-factor interaction by terms having three subscripts, and so on. The first term in the equation 2.29 represents, the over all response mean. The interaction component in 2.29 models the joint effects that cannot be suitably accounted for by the main effects. Each interaction effect measures the incremental joint over what can be measured by the main effects and lower-ord0er interactions. Thus, a two-factor interaction is present in a model only if the main effects cannot adequately model the effects of two factors on the response. Similarly, a three-factor interaction is included only if the three main effects and the three two-factor interactions do not satisfactorily model the effects of the factors on the response. In order for the parameters in 2.29 to be unique the following constraints are imposed:

$$\sum_i \alpha_i = 0, \qquad \sum_j \beta_j = 0, \qquad \sum_k \gamma_k = 0, \ldots, \quad \sum_i (\beta\alpha)ij = 0, \sum_j (\beta\alpha)ij = 0, \ldots, . \qquad (2.30)$$

Thus, the constraints require that each of the parameters in 2.30 be equal to zero. The ANOVA table shows the sum of squares (SS) for each of the factors. They are computed and their degrees of freedom are obtained by subtracting one in the case of the main factors and multiplying the degrees of freedom of the interaction factors. The mean square error is the ratio between the sum

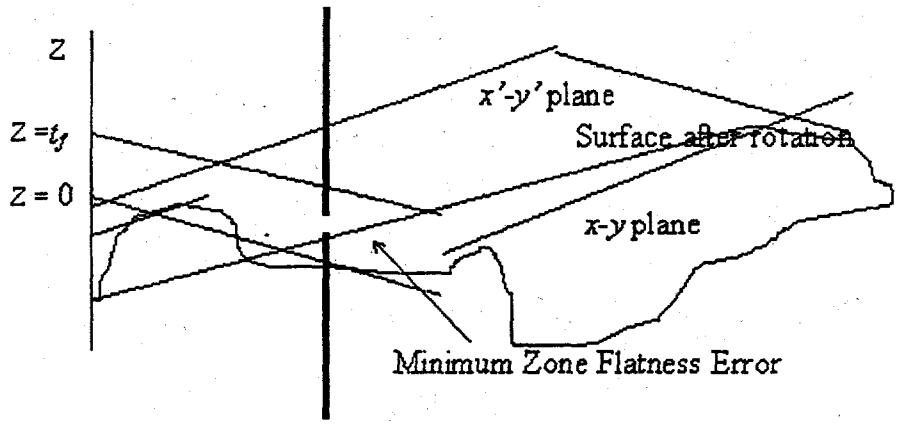


Figure 2.9 Flatness Error Evaluation using Non-linear Optimization Technique

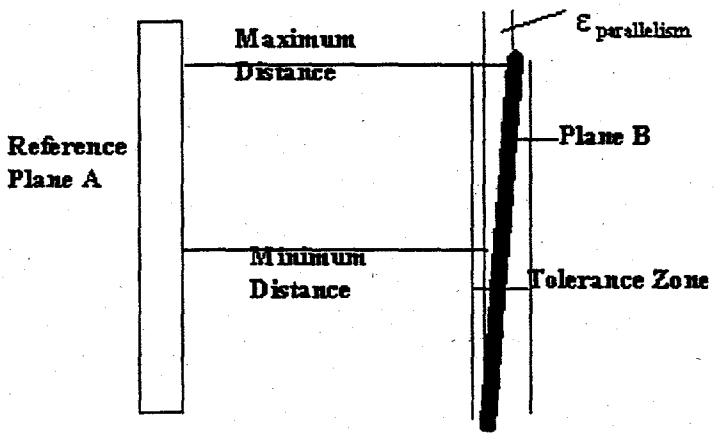


Figure 2.10 Parallelism Error between Two Planes

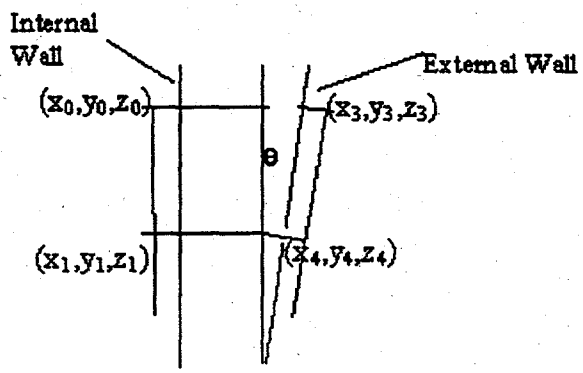


Figure 2.11 Parameters to Compute Tapered Angle

of squares and the degrees of freedom for each factor-level combination. The symbolic analysis of variance for the four factors is the shown in Table 2.1.

2.6.2 The F -Test

In order to find out if the differences on casting dimensions are due to assignable causes or random error, the F-test was implemented. The F-test distribution function tests the hypothesis that a particular main effect or interaction is zero. The corresponding F-ratio should be around one, since both the numerator and the denominator of the F-statistic are estimating the same quantity, which is the error variance. If the null hypothesis is false, the numerator mean square will tend to be larger that the error mean square. Thus, large F-ratios lead to rejection of the hypothesis of no factor effects. The F-test applies under the assumptions that both sampled populations are normally distributed, and the samples are random and independent.

Table 2.1. Symbolic Analysis of Variance Table

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F-Value
A	SS_A	a - 1	$SS_A/df(A)$	MS_A/MS_E
B	SS_B	b - 1	$SS_B/df(B)$	MS_B/MSE
C	SS_C	c - 1	$SS_C/df(C)$	MS_C/MS_E
D	SS_D	d - 1	$SS_D/df(D)$	MS_D/MS_E
AB	SS_{AB}	(a - 1)(b -1)	$SS_{AB}/df(AB)$	MS_{AB}/MS_E
AC	SS_{AC}	(a - 1)(c -1)	$SS_{AC}/df(AC)$	MS_{AC}/MS_E
AD	SS_{AD}	(a - 1)(d - 1)	$SS_{AD}/df(AD)$	MS_{AD}/MS_E
BC	SS_{BC}	(b - 1)(c - 1)	$SS_{BC}/df(BC)$	MS_{BC}/MS_E
BD	SS_{BD}	(b - 1)(d - 1)	$SS_{BD}/df(BD)$	MS_{BD}/MS_E
CD	SS_{CD}	(c - 1)(d - 1)	$SS_{CD}/df(CD)$	MS_{CD}/MS_E
ABC	SS_{ABC}	(a - 1)(b -1) (c -1)	$SS_{ABC}/df(ABC)$	MS_{ABC}/MS_E
ABD	SS_{ABD}	(a - 1)(b -1) (d - 1)	$SS_{ABD}/df(ABD)$	MS_{ABD}/MS_E
ACD	SS_{ACD}	(a - 1)(c - 1)(d - 1)	$SS_{ACD}/df(ACD)$	MS_{ACD}/MS_E
BCD	SS_{BCD}	(b - 1)(c - 1)(d - 1)	$SS_{BDC}/df(BCD)$	MS_{BDC}/MS_E
ABCD	SS_{ABCD}	(a - 1)(b -1) (c -1) (d - 1)	$SS_{ABCD}/df(ABC)$	MS_{ABCD}/MS_E
Error	abcd (m -1)	SS_E	$SS_E/df(Error)$	
Total	abcdm - 1	TSS		

Mathematically the F-ratio is expressed

$$F = (s_1^2/\sigma_2^2)/(s_2^2/\sigma_1^2). \quad (2.31)$$

In this equation, s^2 is the sample variance and σ^2 is the population variance. This equation is reduced to the ratio of the sample variances because it is assumed that the population variances are equal. Therefore, their ratio is unity.

The hypothesis tests procedure as follows:

One tailed test	Two-tailed test	
H_o: $\sigma_2^2 = \sigma_1^2$	H_o: $\sigma_2^2 = \sigma_1^2$	(2.32)
H_a: $\sigma_1^2 < \sigma_2^2$	H_a: $\sigma_1^2 \neq \sigma_2^2$	(2.33)
Test statistic:	Test statistic:	
$F = s_1^2/s_2^2$	$F = s_1^2/s_2^2$ *when* $s_1^2 > s_2^2$	(2.34)
	$F = s_2^2/s_1^2$ *when* $s_2^2 > s_1^2$	(2.35)
Rejection region:	Rejection region:	
$F > F_\alpha$	$F > F_{\alpha/2}$ when $s_1^2 > s_2$	(2.36)
	or $F > F_{\alpha/2}$ when $s_1^2 > s_2$	(2.37)

where F_α and $F_{\alpha/2}$ are based on ν_1 = numerator degrees of freedom and ν_2 = denominator degrees of freedom; ν_1 and ν_2 are the degrees of freedom for the numerator and denominator sample variances, respectively.

2.6.3 Tests on Means

If the F-test results in the rejection of the null hypothesis, the treatment means are equal. Yet, it is required to know which of the means differ and by how much. Confidence intervals can be placed on the difference between the various pairs of treatment means in an experiment.

For p treatment means, then $c = p\,(p\text{-}1)/2.$ (2.38)

where c pairs of means that can be compared. If it is necessary to have $100(1 - \alpha)$ percent confidence that each of the c confidence intervals contains the true difference, multiple intervals will have to be formed using a smaller value of α than would a single interval. There are a number of procedures available for making multiple comparisons. Among the procedures are Duncan's multiple range test, Tukey's procedure, Newman-Keuls test and Scheffe's test.

2.6.3.1 Duncan's Multiple Range Test.

Application of Duncan's multiple-range test requires that the averages be ordered from smallest to largest. Each based on sample size n. They are considered significantly different if

$$| \bar{y}_i - \bar{y} | > R_p \tag{2.39}$$

where,

$$R_p = q(\alpha_p;p,\nu) (MS_E/n)^{1/2} \tag{2.40}$$

and $q(\alpha_p;p,\nu)$ is the studentized-range critical point based on comparing the largest and the smallest of p averages, MS_E is the mean squared error based on ν degrees of freedom, and the experimentwise significance level is α_p and n is the number of observations in the treatment being compared. The experimentwise significance level is related to a comparisonwise level α through the equation:

$$\alpha_p = 1 - (1 - \alpha)^{p-1}. \tag{2.41}$$

In this procedure, the two most extreme averages are compared first. The difference between the largest and the smallest of p = k factor-level or interaction averages is compared using R_k in equation 2.40 with the experimentwise significance level of α_k. If this averages are not found significantly different with k = p, testing stops and all the averages are declared not significantly different at the $100\alpha_k$ percent significance level.

This is equivalent to the non-rejection of H_o: $\mu_1 = \mu_2 = \ldots = \mu_k$. If the two extreme averages are significantly different, testing continues.

The next step is to compare the largest average with the second smallest and the smallest average with the second largest, each test using 2.40 and 2.41 with $p = k - 1$. If neither of these tests is statistically significant, testing ceases and only the two extreme averages are judged significantly different. If one or both of the tests are statistically significant, testing continues with the group(s) of averages for which the two extremes have been declared significantly different. Testing continues in this fashion until no further significant differences are obtained.

2.6.3.2 Tukey's Least Significance Difference (TSD)

Tukey's procedure controls the experimentwise error rate for multiple comparisons when all averages are based on the same number of observations. The stated experimentwise error rate is very close to the correct value even when the sample sizes are not equal. The critical value used in the TSD formula is the upper 100α percent point for the difference between the largest and smallest of k averages. This difference is the range of k averages, and the critical point is obtained from the distribution of range statistic.

In Tukey's procedure, two averages, $\bar{y}_i$ and $\bar{y}_j$, based on n_i and n_j observations respectively, are significantly different if

$$|y_i - \bar{y}_j| > \text{TSD} \tag{2.42}$$

where

$$\text{TSD} = q(\alpha;p,\nu)(MS_E [(n_i^{-1} + n_j^{-1})]/2)^{\frac{1}{2}}, \tag{2.43}$$

in which $q(\alpha;p,\nu)$ is the studentized range statistic, k is the number of averages being compared, MS_E is the mean squared error from an ANOVA fit to the data based on ν degrees of freedom, and α is the experimentwise error rate.

2.6.3.3 Newman-Keuls Range Test.

The computational steps are the same as Duncan's procedure. However, the values that determine the critical ranges are different. Application of the Newman-Keuls range test requires that the averages be ordered from smallest to largest. Each based on sample size n. They are considered significantly different if

$$| \bar{y}_i - \bar{y}_j | > N_p, \tag{2.44}$$

where

$$N_p = q(\alpha_p;p,\nu)\,(MS_E/n)^{1/2}, \tag{2.45}$$

and $q(\alpha_p;p,\nu)$ is the studentized-range critical point based on comparing the largest and the smallest of p averages, MS_E is the mean squared error based on ν degrees of freedom, and the experimentwise significance level is α_p and n is the number of observations in the treatment being compared. The experimentwise significance level is related to a comparisonwise level α through equation 2.46

$$\alpha_p = 1 - (1 - \alpha)^{p-1}. \tag{2.46}$$

In this procedure, the two most extreme averages are compared first. The difference between the largest and the smallest of p = k factor-level or interaction averages is compared using N_k in equation 2.45 with the experimentwise significance level of α_k. If these averages are not found significantly different with k = p, testing stops and all the averages are declared not significantly different at the $100\alpha_k$ percent significance level. This is equivalent to non-rejection of H_o: $\mu_1 = \mu_2 = \ldots = \mu_k$. If the two extreme averages are significantly different, testing continues.

The next step is to compare the largest average with the second smallest and the smallest average with the second largest, each test using equations 2.45 and 2.46 with p = k - 1. If neither

of these tests are statistically significant, testing ceases and only the two extreme averages are judged significantly different. If one or both of the tests are statistically significant, testing continues with the group(s) of averages for which the two extremes have been declared significantly different. Testing continues in this fashion until no further significant differences are obtained.

2.6.3.4 Scheffe's Test

The Scheffe's test is similar to the Tukey's test in that a single critical difference value is computed regardless of whether the means to be compared are immediately adjacent, or if several other means fall between those being compared. The major computational difference is that Scheffe's test makes use of the F table versus the studentized range tables for the other tests. The Scheffe's test is also more stringent than Tukey's test and thus the probability of Type I error is lower.

Two means are considered significantly different if equation 2.47 is true when

$$| \bar{y}_i - \bar{y}_j | > S_p \tag{2.47}$$

where,

$$S_p = [(N - 1)F_{kv}]^{1/2} [2MS_E / n] \tag{2.48}$$

in which N is the number of groups and F is the F value for k degrees of freedoms within the group, $(N-1)$, and v is the degrees of freedom of the error in the analysis of variance. MS_E is the mean square error and n is the number of observations.

CHAPTER 3

DATA COLLECTION, EVALUATION AND ANALYSIS

In the project entitled, "Application of Statistical Methods for Analyzing the Relationship between Casting Distortion, Mold Filling, and Interfacial Heat Transfer in Sand Molds", the effect of gating, thickness, orientation and sand type on form and dimensional errors is analyzed. In the project, aluminum metal was poured. The four variable factors involved in the investigation have been summarized below and the same have been delineated in Table 3.1.

	Variable Factor	Level of Factor
1.	Molding Method (M):	Resin bonded sand molding method Lost foam molding with silica bonded sand method Lost foam with low expansion (carbon)sand molding method
2.	Gating System (G):	Top-gated system Bottom-gated system Side-gated system
3.	Casting Orientation (O):	Up, Down, Sideways
4.	Casting Thickness (T):	¼, ½, and ¾ inch.

The four variable factors have three levels each and each level has three replications. The letters M, G, O, and T as defined above represent the variable factors. The subscripts 1, 2, and 3 represent levels of the factors and the X's represent three replications at each level. A few of the design of experiment tables for the calculated parameters are located in Appendix A.

The statistical analysis used in this investigation includes Analysis of Variance (ANOVA) for full factorial randomized experiment. Randomized complete block design technique was used

Table 3.1. Experimental Design of the Project (casting data received)

		Mold Type																											
		M1									M2										M3									
		Thickness																											
Orientation	Gating	T1			T2			T3			T1			T2			T3				T1			T2			T3		
	G1	0.045	0.038	0.021	0.025	0.043	0.027	0.036	0.032	0.04	0.014	0.026	0.016	0.008	0.011	0.008	0.007	0.007	0.005	0.02	0.02	0.01	0.02	0.02	**0.02**	0.014	0.01	0.0101
O1	G2	0.015	0.02	0.016	0.038	0.04	0.029	0.046	0.039	0.05	0.018	0.012	0.007	0.01	0.008	0.014	0.011	0.018	0.018	0.01	0.03	0.02	**0.11**	0.2	0.02	0.008	0.019	0.0065
	G3	-	-	-	-	-	-	-	-	-	0.009	0.019	0.029	0.011	0.009	0.011	0.011	0.013	0.008	0.02	0.02	**0.02**	0.01	0.02	0.02	0.009	0.01	0.0057
	G1	0.037	0.041	0.037	0.029	0.032	0.03	0.029	0.033	0.029	0.026	0.015	0.025	0.013	0.005	0.013	0.007	0.01	0.008	0.01	0.02	0.02	0.02	0.01	0.02	0.013	0.01	0.006
O2	G2	0.013	0.028	0.033	0.04	0.04	0.055	0.039	0.03	0.038	0.017	0.017	**0.033**	0.017	0.006	0.01	0.018	0.005	0.023	0.02	0.02	0.02	0.02	0.01	0.02	0.013	0.009	**0.0106**
	G3	-	-	-	-	-	-	-	-	-	0.008	0.011	0.011	0.011	0.007	0.008	0.017	0.013	0.02	0.02	0.02	**0.02**	0.01	0.02	0.01	0.008	0.016	0.0073
	G1	0.033	0.014	0.019	0.02	0.033	0.013	0.022	0.026	0.018	0.009	0.014	0.013	0.011	0.013	0.014	0.012	0.018	0.015	0.01	0.02	0.02	0.01	0.01	0.02	0.01	0.014	0.0077
O3	G2	0.021	0.043	0.072	0.026	0.026	0.03	0.032	0.027	0.041	0.007	0.009	0.018	0.009	0.008	0.014	0.005	0.01	0.01	**0.02**	**0.02**	0.02	0.01	0.02	0.01	0.017	0.01	**0.013**
	G3	-	-	-	-	-	-	-	-	-	0.01	0.007	0.01	0.008	0.012	0.006	-	-	-	0.01	0.02	0.02	0.01	0.01	0.02	0.007	0.014	0.0198

G1 = Top gating O1=Down T1= 3/4 inch thickness M1=Resin Bonded Sand
G2 = Bottom gating O2=Up T2= 1/2 inch thickness M2=Lost Foam Low Expansion
G3 = Side gating O3=Side T3= 1/4 inch thickness M3=Lost Foam Silica Sand

for controlling experimental variability due to parallelism. Newman-Keuls Test of Means was performed to obtain the effect of differences of means for the sample data.

The data received for the resin-bonded castings included: three orientations, namely opening up, opening down and opening laterally. The opening up and opening down castings had two gating systems, top and bottom. The opening laterally castings used four gating systems: top, bottom, and two side gating systems, one filling through the flanges and the other side gating filling through the top ridge. All the orientation and gating combinations were cast in three different levels of thickness. There were three replicates made of each casting combination, but not all proved viable. There were no side-gated data received from the resin-bonded sand castings (rbs). The data received for the lost foam with low expansion carbon sand molding method and lost foam with silica sand molding (lfle and lfss) included all three orientations, gating systems (top, bottom, and side), and three levels of thickness (¼, ½, ¾ inch). There were three replicates made of each combination.

Figure 3.1 provides schematic diagrams of the orientation and gating systems examined in this research work. The ANOVA was performed on the three data sets. In addition to the analysis of variance, Newman-Keuls statistical tests of means were performed where statistical significance was observed. Finally, a group of charts including scatter plots, histograms, normal probability diagrams and box plots were used to graphically confirm the analytical results from ANOVA and Test of Means.

Scatter plots made it possible to visualize the trend of the data and its distribution around the mean. Similarly, the histograms revealed the frequency distribution of the data.

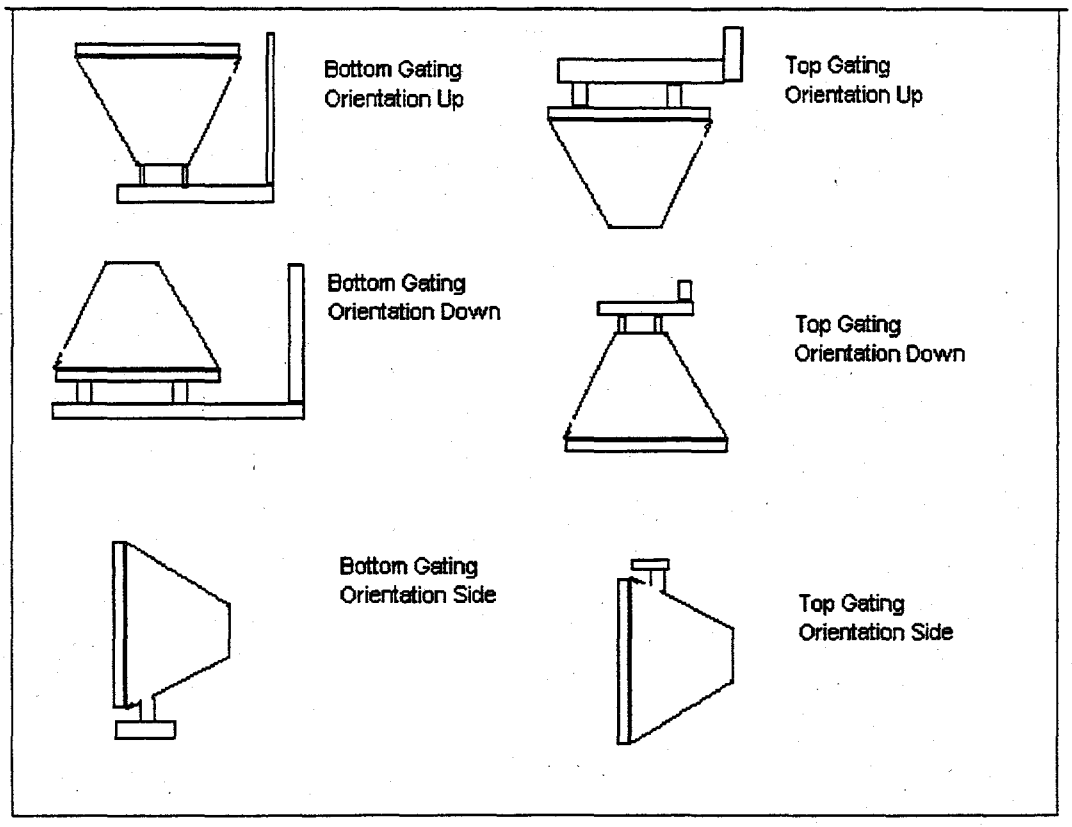


Figure 3.1 Schematic of Orientation and Gating Systems

The normal probability diagrams showed whether the data normally distributed. The box plot was used to view the range of the data points as well as the mean.

In order to study the variation of the distortion on sand castings, casting characteristics were analyzed. These characteristics include flatness, thickness, parallelism, casting angle, length, and height. Figure 3.2 is a four view drawing of the casting. The hash marks indicate where the Coordinate Measuring Machine (CMM) measured surface coordinates for the point cloud data.

3.1 Data Collection: Preprocessing of Data for Statistical Analysis

CMI Test Center (CMI) used a CMM to measure the point cloud data. Table 3.2 shows a sample of the point cloud data sent from CMI. In order to get the data into a functional format, it was necessary to preprocess the data.

The steps used in preprocessing the data for statistical analysis are as listed below.

1. The point cloud data were received in comma delimited form in Microsoft Excel files.
2. The files were edited so that only the point cloud coordinates were in the files. These coordinates were arranged in a long row with each set of x, y, z coordinates after the other (x_1, y_1, z_1, x_2, y_2, z_2,. . .).
3. The files were opened in a text editor and separated into the ordered triple sets so that when viewed in Excel, there were three columns of data corresponding to the coordinate axes(x, y, z). There were 180 rows and 3 columns.
4. When opened in Excel, the data were separated into 3 sections with 60 points in each. Each section contained the points for each replicate (1, 2, 3).
5. The data were broken down into the individual replicates on separate worksheets within each workbook.
6. Each set of point cloud data for the replicates were divided up into the respective geometrical entity represented (e.g. edge points, right flange, inner left wall, etc.)
7. Each file (workbook) is representative of one casting orientation, gating, thickness, and sand type.

Table 3.2 Sample CMM Point Cloud Data from CMI

Part Program	mlbx75							
Inspector	JS							
AFSWS								
MLBX								
Nominal	-0.46267	2.46322	-0.35968	0	2.15707	8.41401	-0.76627	0
#NAME?	0	0	0	0.5	0	0	0	0.5
#NAME?	0	0	0	0.5	0	0	0	0.5
Seq# Datatype	1X	1Y	1Z	1DS	2X	2Y	2Z	2DS
6/10/97 20:08	-0.46508	2.465562	-0.34047	0.019518	2.15495	8.416134	-0.74892	0.017639
6/10/97 20:35	-0.46586	2.46634	-0.33414	0.025951	2.147165	8.423862	-0.686	0.081507
6/10/97 20:54	-0.46648	2.466955	-0.32912	0.031037	2.151773	8.419288	-0.72324	0.043705

3.2 Data Analysis

Data Analysis is the evaluation of the data variations, associated with the calculated parameters, such as: flatness, casting tapered angle, parallelism, and linear distances (length, thickness, and height) of the castings.

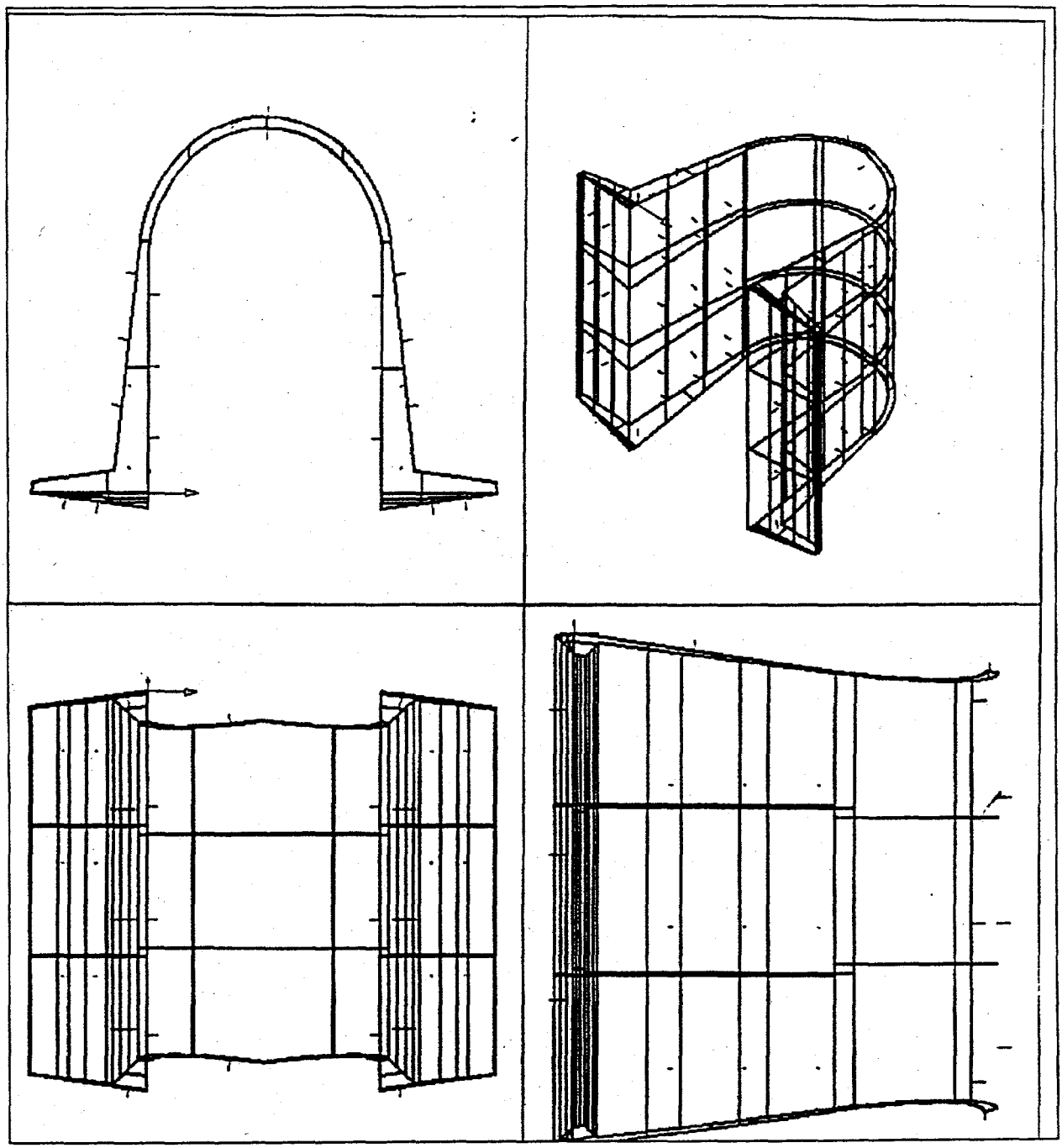


Figure 3.2 Four View Drawing of the Casting (Mailbox)

The nominal values as provided in conjunction with the project are indicated as follows

Length (inch)	=	6^{+1}
Height (inch)	=	8^{+1}
Parallelism (inch)	=	0
Thickness (inch)	=	¼ , ½, ¾
Flatness (inch)	=	0
Casting Angle (degrees)	=	8^{+2} .

3.2.1 Flatness Evaluation

The flatness of the plane surfaces was calculated using the Nonlinear Optimization method as detailed in the Literature Survey section. The nonlinear program was coded in C programming language. This method requires that the evaluation plane be relatively parallel with the xz plane, meaning that the flatness error is measured in the y direction. Therefore, some of the data needed to be rearranged. The arrangement of data for the flanges was fine, but the data for the inner walls of the casting were in the yz plane and needed to be manipulated. This was remedied simply by switching the x and y columns (basically a rotation of axes) in the data files. In order for the program to read the data, the data must be in a text file, thus the raw data for the flanges and walls were copied from Excel and placed into a text file so that the program could read the data. The flatness indices generated by the program were stored in text files and copied back into Excel

Table 3.3 Flatness Worksheet (0.25 inch)

Left Flange Flatness				Right Flange Flatness			
OG	Rep 1	Rep2	Rep3	OG	Rep 1	Rep2	Rep3
DT	0.012935	0.013662	0.014674	DT	0.036616	0.074457	0.03629
DB	0.03245	0.02176	0.014237	DB	0.181809	0.122948	0.058175
LT	0.008781	0.009309	0.024521	LT	0.007408	0.040378	0.053052
LB	0.007215	0.027715	0.016905	LB	0.018779	0.042132	0.031649
UT	0.011571	0.006366	0.012523	UT	0.134544	0.073681	0.044145
UB	0.009505	0.036035	0.010901	UB	0.013127	0.051024	0.030049
DT	0.008961	0.005837	**0.007399**	DT	0.619931	0.039233	**0.329582**
DB	0.006735	0.005149	0.008138	DB	0.019637	0.023701	0.030751
LT	0.007212	0.004631	0.010762	LT	0.080055	0.077857	0.12408
LB	0.011588	0.009577	0.006972	LB	0.019526	0.03902	0.063054
UT	0.013515	0.010137	0.008043	UT	0.008154	0.010423	0.019614
UB	0.005749	0.008792	0.003127	UB	0.090187	0.03024	0.029533
DT	0.005029	0.007252	0.009229	DT	0.032293	0.041927	0.039602
DB	0.005894	0.021856	0.004864	DB	0.030441	0.024383	0.018511
LT	0.008773	0.008492	0.004029	LT	0.089748	0.02361	0.068788
LB	0.001428	0.003593	0.009957	LB	0.004139	0.050933	0.021718
UT	0.00607	0.002988	0.00524	UT	0.021058	0.02367	0.009404
UB	0.003384	0.010898	0.010458	UB	0.052951	0.06347	0.076058

Left Wall Flatness				Right Wall Flatness			
OG	Rep1	Rep2	Rep3	OG	Rep1	Rep2	Rep3
DT	0.010207	0.007854	0.013675	DT	0.025197	0.013263	0.093224
DB	0.018216	0.011647	0.007128	DB	0.032088	0.040024	0.177846
LT	0.010528	0.017995	0.018362	LT	0.022667	0.041416	0.050389
LB	0.009471	0.018852	0.029116	LB	0.042769	0.060123	0.118547
UT	0.014219	0.02607	0.015715	UT	0.011941	0.004608	0.106884
UB	0.007994	0.011009	0.008176	UB	0.057124	0.048472	0.024532
DT	0.016619	0.016787	**0.016703**	DT	0.054214	0.027195	**0.040704**
DB	0.00682	0.00742	0.005181	DB	0.016604	0.023969	0.006156
LT	0.016712	0.005816	0.009716	LT	0.018055	0.012279	0.028918
LB	0.017762	0.004841	0.023283	LB	0.03102	0.019873	0.014762
UT	0.01681	0.013218	0.020062	UT	0.032457	0.031188	0.014697
UB	0.025717	0.014637	0.024603	UB	0.050625	0.110769	0.065259
DT	0.007319	0.009923	0.007847	DT	0.010203	0.010705	0.015612
DB	0.013375	0.005343	0.013257	DB	0.030328	0.045034	0.038702
LT	0.006586	0.009263	0.018357	LT	0.084529	0.088799	0.114245
LB	0.008553	0.007586	0.013787	LB	0.018066	0.043239	0.028038
UT	0.007974	0.011638	0.006394	UT	0.035637	0.013439	0.01297
UB	0.008971	0.014418	0.013464	UB	0.100449	0.069747	0.030077

3.2.2 Evaluation of Parallelism

The first step in calculating the parallelism was to place the point cloud data representing the inner walls into the Parallelism worksheet within each workbook. Then the data points were sorted for each replicate so that the points from the right inner wall lined up next to the points on the left inner wall (mirror points). Thus, the y-axis was sorted. Then, the distance between these mirror points was calculated using the Euclidean distance formula as given in equation 2.3. The average of the difference between the maximum and minimum distances of each replicate is the parallelism index. The index was calculated automatically in Excel by writing a simple cell formula. Table 3.4 is a Parallelism Calculation Worksheet and Table 3.5 shows the indices.

3.2.3 Calculation of Tapered Angle

Equation 2.27 requires that the distance in the *y*-axis be relatively the same on the inner and outer walls in order to maintain the trigonometric relationship. This can be seen in Figure 2.11. Further, if the vertical distance is represented by the *y*-axis, it can be seen that $(y_1 - y_0)$ must equal (y_3-y_2) for the cosine relationship to hold. Upon viewing the data (inner and outer wall data pasted into the Casting Angle worksheet), the y-coordinates of the inner wall were a greater distance apart in the *y* direction than the y-coordinates on the outer wall. Consequently, if the points were input directly into equation 2.27, there would be a mathematical error since the inverse cosine of a number greater than one does not exist. Therefore, an additional point on the inner wall was determined using linear interpolation. This would give an inner wall *y* displacement similar to the y displacement of the outer wall making equation 2.27 valid. The linear interpolation equation requires that two points be known and that one of the coordinates for the desired point be known.

Table 3.4 Parallelism Calculation Worksheet

Inner Right Wall			Inner Left Wall						
X	Y	Z	x	y	Z	Xdiff sq	ydiff sq	zdiff sq	distance
6.088231	1.2689	-7.9344	0.003227	1.2689	-7.9344	37.02727368	0	0	6.085004
6.097964	1.2689	-5.2896	-0.011662	1.2689	-5.2896	37.32752986	0	0	6.109626
6.091801	1.2689	-2.6448	-0.01047	1.2689	-2.6448	37.23771136	0	0	6.102271
6.080119	2.9099	-7.9344	-0.006811	2.9099	-7.9344	37.05071682	0	0	6.08693
6.083248	2.9099	-5.2896	-0.006431	2.9099	-5.2896	37.08419032	0	0	6.089679
6.087119	2.9099	-2.6448	-0.010985	2.9099	-2.6448	37.18687239	0	0	6.098104
6.070778	4.5508	-7.9344	-0.005117	4.5508	-7.9344	36.91650005	0	0	6.075895
6.071899	4.5508	-5.2896	-0.001905	4.5508	-5.2896	36.89109503	0	0	6.073804
6.072398	4.5508	-2.6448	-0.002328	4.5508	-2.6448	36.90229598	0	0	6.074726
X	Y	z	x	y	Z	Xdiff sq	ydiff sq	zdiff sq	distance
6.047667	1.2689	-7.9344	0.007978	1.2689	-7.9344	36.47784322	0	0	6.039689
6.070028	1.2689	-5.2896	-0.012193	1.2689	-5.2896	36.99341229	0	0	6.082221
6.068419	1.2689	-2.6448	-0.010648	1.2689	-2.6448	36.95505559	0	0	6.079067
6.059741	2.9099	-7.9344	0.008082	2.9099	-7.9344	36.62257665	0	0	6.051659
6.060069	2.9099	-5.2896	-0.003938	2.9099	-5.2896	36.7721809	0	0	6.064007
6.06194	2.9099	-2.6448	-0.007241	2.9099	-2.6448	36.83495801	0	0	6.069181
6.058674	4.5508	-7.9344	0.008233	4.5508	-7.9344	36.60783629	0	0	6.050441
6.059531	4.5508	-5.2896	0.002081	4.5508	-5.2896	36.6927005	0	0	6.05745
6.054229	4.5508	-2.6448	0.006308	4.5508	-2.6448	36.57734842	0	0	6.047921
X	Y	z	x	y	Z	Xdiff sq	ydiff sq	zdiff sq	distance
6.065334	1.2689	-7.9344	0.004808	1.2689	-7.9344	36.7299754	0	0	6.060526
6.077377	1.2689	-5.2896	-0.008461	1.2689	-5.2896	37.03742416	0	0	6.085838
6.067954	1.2689	-2.6448	-0.011365	1.2689	-2.6448	36.9581195	0	0	6.079319
6.069826	2.9099	-7.9344	0.002698	2.9099	-7.9344	36.81004217	0	0	6.067128
6.068131	2.9099	-5.2896	-0.007543	2.9099	-5.2896	36.91381455	0	0	6.075674
6.059585	2.9099	-2.6448	-0.008425	2.9099	-2.6448	36.82074536	0	0	6.06801
6.061953	4.5508	-7.9344	0.00641	4.5508	-7.9344	36.66960102	0	0	6.055543
6.056711	4.5508	-5.2896	0.004976	4.5508	-5.2896	36.62349651	0	0	6.051735
6.049223	4.5508	-2.6448	0.0015	4.5508	-2.6448	36.57495348	0	0	6.047723

Table 3.5 Parallelism Index

Replicate	Max dist	min dist	parallelism
1	6.109626	6.073804	**0.035822**
2	6.082221	6.039689	**0.042532**
3	6.085838	6.047723	**0.038115**

The y coordinate was the desired coordinate, therefore the x coordinate was the point to be interpolated. Given this, the linear interpolation equation is shown in equation 3.1

$$x_m = \frac{(x_u - x_l)(y_m - y_l)}{(y_u - y_l)} + x_l \tag{3.1}$$

where u, l, and m represent the upper, lower and middle points, respectively. This formula was entered into the Casting Angle worksheet to determine the normalized point that would be input into (2.27). Equation (2.27) was entered into the Casting Angle worksheet and the cell formula interpolated the point and determined the casting angle index. The angle was converted to degrees from radians my multiplying the angle by $180/\pi$. Table 3.6 shows the Casting Angle Calculation worksheet.

3.2.4 Calculations of Casting Dimensions

The equations for calculating the linear distances (i.e. the thickness of the castings at the top ridge, height, and the length of the castings) were entered into the CMM point cloud data worksheet. The worksheet contained the data for all three replicates. The distances were calculated using the linear distance formula (x_2-x_1). The length was calculated using the z-distance between the center edge point (EP) and back edge point (BEP) for each replicate. The formula is (EP_z-BEP_z). The height is calculated by using the following formula:

Average (Rp_y-Average(min(Fp_y)).

where RP_y denotes the ridge points in the y-direction and min FP_y denotes the lowest flange points in the y-direction. The thickness was calculated by averaging the y-distance of the ridge points and inner walls and taking the difference. Table 3.7 is a Height, Length, and Thickness calculation worksheet.

Table 3.6 Casting Angle Calculation Worksheet

Right Casting Angle Calculation(Replicate 1)									
Replicate 1									**Casting**
Outer right wall			**inner right wall**						**Angle**
6.820275	2.026755	-7.8129	6.088231	1.2689	-7.9344	6.088231	1.2689	-7.9344	**10.12**
6.627267	3.52851	-7.8129	6.080119	2.9099	-7.9344	6.0723776	4.25	-7.9344	
6.42457	5.029088	-7.8129	6.070778	4.5508	-7.9344				
6.422561	5.028841	-5.2653	6.071899	4.5508	-5.2896	6.097964	1.2689	-5.2896	**10.12**
6.621888	3.52785	-5.2653	6.083248	2.9099	-5.2896	6.074288	4.25	-5.2896	
6.815204	2.026132	-5.2653	6.097964	1.2689	-5.2896				
6.814022	2.025987	-2.7177	6.091801	1.2689	-2.6448	6.091801	1.2689	-2.6448	**10.12**
6.623176	3.528008	-2.7177	6.087119	2.9099	-2.6448	6.0741764	4.25	-2.6448	
6.416798	5.028133	-2.7177	6.072398	4.5508	-2.6448				
							Right Casting Angle(Rep1)		**10.12**
Right Casting Angle Calculation(Replicate 1)									
Replicate 1									
outer left wall			**inner left wall**						
-0.351678	5.020136	-7.8129	-0.005117	4.5508	-7.9344	0.003227	1.2689	-7.9344	**10.15**
-0.519308	3.515252	-7.8129	-0.006811	2.9099	-7.9344	-0.0043522	4.25	-7.9344	
-0.674892	2.008901	-7.8129	0.003227	1.2689	-7.9344				
-0.681185	2.009674	-5.2653	-0.011662	1.2689	-5.2896	-0.011662	1.2689	-5.2896	**10.14**
-0.519442	3.515268	-5.2653	-0.006431	2.9099	-5.2896	-0.0027993	4.25	-5.2896	
-0.351543	5.020119	-5.2653	-0.001905	4.5508	-5.2896				
-0.357016	5.020791	-2.7177	-0.002328	4.5508	-2.6448	-0.01047	1.2689	-2.6448	**10.14**
-0.524397	3.515877	-2.7177	-0.010985	2.9099	-2.6448	-0.0030742	4.25	-2.6448	
-0.687111	2.010401	-2.7177	-0.01047	1.2689	-2.6448				
							Left Casting Angle(Rep1)		**10.15**

Table 3.7 Height, Length, and Thickness Calculation Worksheet

	Length										
		Edge points(z-values)				**back edge points(z-values)**					
	Replicate 1	**Replicate 2**	**Replicate 3**		**Replicate 1**	**Replicate 2**	**Replicate 3**				
	-0.447461	-0.373175	-0.376152		-9.258259	-9.1825	-9.194202	**Length 1**	**Length 2**	**Length 3**	
middle	**-0.774418**	**-0.779279**	**-0.763303**		**-8.566546**	**-8.52613**	**-8.520512**	**7.79**	**7.75**	**7.76**	
	-0.414694	-0.342567	-0.356066		-9.2738	-9.185958	-9.183904				
	Height										
	ridge points(y-values)				**right flange(y-values)**				**left flange(y-values)**		
	Replicate 1	**Replicate 2**	**Replicate 3**		**Replicate 1**	**Replicate 2**	**Replicate 3**	**Replicate 1**	**Replicate 2**	**Replicate 3**	
	8.818637	8.776808	8.805258		-0.038625	-0.119717	-0.085829	-0.125554	-0.131836	-0.118149	
	8.831355	8.783336	8.812826		-0.037679	-0.119969	-0.079898	-0.122384	-0.124316	-0.116732	
	8.843286	8.789744	8.820552		-0.021643	-0.147657	-0.079773	-0.114303	-0.127921	-0.114424	
average	**8.83109267**	**8.783296**	**8.8128787**								
	Ridge points(y-values),averages				**Flange average**			**Height1**	**Height2**	**Height3**	
	8.83718933	**8.78652**	**8.8167153**		-0.076698	-0.128569333	-0.099134167	**8.91**	**8.92**	**8.92**	
						Thickness					
		ridge points(y-values)				**Inner wall ridge(y-values)**					
	Replicate 1	**Replicate 2**	**Replicate 3**		**Replicate 1**	**Replicate 2**	**Replicate 3**	**Thickness 1**	**Thickness 2**	**Thickness 3**	
	8.818637	8.776808	8.805258		8.520976	8.464262	8.50427	0.297661	0.312546	0.300988	
	8.831355	8.783336	8.812826		8.548627	8.477321	8.517008	0.282728	0.306015	0.295818	
	8.843286	8.789744	8.820552		8.548036	8.47589	8.51755	0.29525	0.313854	0.303002	
							Thickness	**0.29**	**0.31**	**0.30**	

CHAPTER 4

METHOD IMPLEMENTATION AND ANALYSIS

The implementation of the methodology involved many steps. Initially, the data was preprocessed. Then, the form parameters were calculated from the point cloud data collected from the castings. The analysis of variance (ANOVA) statistical analysis was then performed. Finally, the Newman Keuls Test of Means was performed. The characteristic parameters of the castings that were analyzed in this research are summarized in the following statements.

1. Flatness of the flanges and inner walls of the casting
2. Parallelism of the inside walls of the casting
3. The tapered angle of the outside walls of the casting
4. Casting height
5. Wall thickness of the top of the casting
7. Length of the top ridge of the casting

4.1 Statistical Analysis

The statistical analysis was performed in order to determine the effect of the factors (gating, orientation, thickness, and sand type) on the form parameters. Tables 4.1 – 4.4 are samples of the factorial analysis of variance (ANOVA) performed on the data. Samples of the remaining Tables are located in Appendix C. The ANOVA results were analyzed for significant contributors at the 95 percent confidence level.

The index being analyzed in Table 4.1 is the left flange flatness of the entire set of ¼ inch casting data. According to the analysis of variance (ANOVA) of this index, the mold type (M) factor and orientation-mold type (OM) factor interaction are affecting the left flange flatness at the 95 percent confidence level. Newman Keuls is performed on the mold type (M) due to the significance indicated at the mold factor; thus, mold type (M) has a more significant contribution to the distortion than orientation (O). Table 4.2 is the ANOVA for the height of the ¼ inch lost foam low expansion castings. According to the table, neither gating (G) or orientation (O) significantly affects the height of the lost foam low expansion castings; thus, no test of means was performed. Table 4.3 is the ANOVA for the left wall flatness of the resin-bonded castings. The factor interaction of gating-orientation (GO) is significantly affecting the left wall flatness. Since there was no significance indicated for the single factors (G and O), both gating (G) and orientation (O) were affecting left wall flatness equally; therefore, the Newman Keuls test was unnecessary. Table 4.4 is the ANOVA for the parallelism of the lost foam silica sand castings. The factor interaction of gating and orientation (GO) and gating (G) are affecting the parallelism of the lost foam silica sand castings. Since there was significance for the single factor gating, gating has a greater effect on the parallelism error. Newman Keuls must be performed in this case.

The Newman Keuls test of mean was performed on the significant factors found in the analysis of the ANOVA tables at the 95 percent confidence level. The purpose of the test of means is to determine which factor levels have the greatest effect on the distortion. Tables 4.5 and 4.6 are the Newman Keuls test of means (5 percent significance level) performed based on the analysis of ANOVA Tables 4.1-4.4. Table 4.5 is the Newman Keuls on the mold type of all of the ¼" left flange flatness data. The Newman Keuls test of means indicates that M1 is the mold

factor level that is contributing to the left flange flatness error of all of the ¼ inch casting data; therefore, resin-bonded sand is the mold type contributing to the left flange flatness error for this data set. Basically the way the table is interpreted is M1 is more significant than M2, M1 is more significant than M3, and M2 is more significant than M3; therefore, M1 is most significant. Table 4.6 is the Newman Keuls on the gating of the ¼ inch lost foam silica sand parallelism data. The test of means indicates that top gating (G1) is the gating type contributing most to the ¼ inch lost foam silica sand parallelism error. The analysis performed on the ½" and ¾" data is similar. Chapter 5 details the full results of the ANOVA and Newman Keuls test of means.

Table 4.1 Factorial Analysis of Variance of Left Flange Flatness of all ¼ inch castings

		Number of Factors = 3				Number of Replicates = 3			
		Factor				Levels			
		G=Gating System				2			
		O=Orientation				3			
		M=Sand Type				3			
Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOM	4.02E-05	4	1.01E-05	0.5479	0.7017	3.890307	FALSE	2.633534	FALSE
GO	7.03E-05	2	3.52E-05	1.9162	0.1619	5.247898	FALSE	3.259444	FALSE
GM	0.0001	2	5.87E-05	3.1998	0.0526	5.247898	FALSE	3.259444	FALSE
G	1.07E-05	1	1.07E-05	0.5812	0.4508	7.395556	FALSE	4.113161	FALSE
OM	0.0003	4	6.79E-05	3.7023	0.0127	3.890307	FALSE	2.633534	TRUE
O	6.88E-05	2	3.44E-05	1.8739	0.1682	5.247898	FALSE	3.259444	FALSE
M	0.0002	2	0.0001	5.997	5.70E-03	5.247898	TRUE	3.259444	TRUE
Error	0.0007	36	1.84E-05						
Total	0.0015	53							

Table 4.2 Factorial Analysis of Variance of Height of Lost Foam Low Expansion Castings (¼ in.)

		Number of Factors=2		Number of Replicates=3					
		Factor		Levels					
		G=Gating		2					
		O=Orientation		3					
Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0096	2	0.0048	2.2083	0.1525	6.926598	FALSE	3.88529	FALSE
G	0.0083	1	0.0083	3.809	0.0747	9.330279	FALSE	4.747221	FALSE
O	0.0088	2	0.0044	2.0252	0.1747	6.926598	FALSE	3.88529	FALSE
Error	0.026	12	0.0022						
Total	0.0526	17							

Table 4.3 Factorial Analysis of Variance: Left Wall Flatness of Resin Bonded Castings(¼ in.)

		Number of Factors=2		Number of Replicates=3					
		Factor		Levels					
		G=Gating		2					
		O=Orientation		3					
Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0002	2	0.0001	5.4367	0.0209	6.926598	FALSE	3.88529	TRUE
G	4.67E-05	1	4.67E-05	2.2668	0.158	9.330279	FALSE	4.747221	FALSE
O	2.33E-06	2	1.17E-06	0.0566	0.9452	6.926598	FALSE	3.88529	FALSE
Error	0.0002	12	2.06E-05						
Total	0.0005	17							

Table 4.4 Factorial Analysis of Variance: Parallelism of Lost Foam Silica Sand Castings(¼in.)

		Number of Factors		Number of Replicates					
		Factor		Levels					
		G=Gating		2					
		O=Orientation		3					
Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0208	4	0.0052	3.6063	0.0251	4.57902	FALSE	2.92775	TRUE
G	0.0227	2	0.0114	7.8834	0.0035	6.0129	TRUE	3.55456	TRUE
O	0.0042	2	0.0021	1.4484	0.2611	6.0129	FALSE	3.55456	FALSE
Error	0.0259	18	0.0014						
Total	0.0736	26							

Table 4.5 Newman Keuls Test of Means on Mold Type of the Left Flange Flatness Data(¼ in.)

Newman Keuls Test of Means on Mold Type for Left Flange Flatness Data(0.25 in.)

ColName	Count	Mean	Std.Dev.	Std.Err.
M1	18	0.01061111	0.00615619	0.00145103
M2	18	0.00822222	0.00479651	0.00113055
M3	18	0.01316667	0.00346834	0.00081750

Newman-Keuls' Test

Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
M1	Vs.	M2	0.00238889	0.00000000	YES
M1	Vs.	M3	0.00255556	0.00000000	YES
M2	Vs.	M3	0.00494444	0.00000000	YES

Table 4.6 Newman Keuls Test of Means on Gating System of Lost Foam Low Expansion Parallelism Data(¼ in.)

Newman Keuls Test of Means on Gating for Lost Foam Silica Sand Parallelism Data(0.25 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
G1	9	0.1314	0.0534	0.0178
G2	9	0.2012	0.0422	0.0141

Newman-Keuls' Test

Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
G1	Vs.	G2	0.0698	0.0000	YES

CHAPTER 5

RESULTS

5.1 Data Analysis

From the charts and analysis, there were differences noted between the nominal and calculated values. Overall, the nominal values of the resin bonded casting parameters varied more than the lost foam processes parameters. The lost foam low expansion casting parameters varied the least. Samples of the figures used in these analyses included surface plots (Figure 5.1), box plots (Figure 5.2), histograms (Figure 5.3) and scatter plots (Figure 5.4). The surface plot of flatness shows the three-dimensional variations in flatness. Box plots show the spread of the data around the mean. Histograms show the normal distribution features of the data. Scatter Plots show the two-dimensional variation in the data.

5.2 Statistical Analysis Results

The statistical analysis showed that the factors (gating, orientation, sand mold type, and thickness) definitely have an effect on casting distortion. Factorial analysis of variance was performed on all of the data for each mold type separately and collectively. The analysis was performed on three orientation levels (down, up, and left), three thickness levels (¾, ½ , and ¼ inch) and three mold type levels (resin bonded sand, lost foam low expansion, and lost foam silica sand). Two gating systems (top and bottom) were analyzed for all three-sand types and analysis for variations due to side gating was performed solely on the lost foam processes (since this was the only side gating data available. Newman Keuls test of means was performed on the significant

factors as determined by the ANOVA. The results of the analyses are summarized in Tables 5.1-5.4. The tables outline the significant contributors to the distortion of the parameters (left wall flatness, height, etc.) at $\alpha = 5$ percent level.). In the tables, ALL indicates that "all" factor levels contributed equally to the casting distortion. The dash "-" means that from the ANOVA analysis, the effect of the factor was not significant. The complete set of factorial analysis of variance (ANOVA) and Newman Keuls is located in Appendix B.

Table 5.1 shows the results of the analysis performed on all of the ¼ inch castings. According to the analysis, the significant contributors to the distortion are the resin-bonded sand, orientation down and top gating (See Table 5.1 a). From Table 5.1 b and d, it can be seen that the ¼ inch lost foam silica sand and resin bonded sand castings are distorted by orientation down and top gating, while the distortion of the low expansion castings are primarily due to orientation down (Table 5.1 c). Table 5.2a-d shows the analysis performed on all of the ½ inch castings. The analysis indicated that all gating levels equally affected the height and right flange flatness of the lost foam silica sand castings, left flange flatness and left wall flatness of the resin bonded castings and the right flange flatness of the of the lost foam low expansion castings. All orientation levels equally affected the right flange flatness of the lost foam silica sand castings, height of the resin bonded castings, and length, parallelism, left wall flatness, and right wall flatness and right flange flatness of the lost foam low expansion castings. Top gating affected the right wall flatness of the resin-bonded castings and orientation up affected the length of the lost foam low expansion castings. The analysis performed on the ¾ inch castings indicated that orientation down and top gating characterized the distortion of the lost foam silica sand castings (See Table 5.3). The low expansion and resin bonded castings are equally affected by all orientation and gating levels. The low expansion castings are mostly affected by the orientation.

Table 5.4 shows the results of the all of the castings. The results for all of the resin-bonded sand castings are shown in Table 5.4a. According to the analysis, all orientation configurations equally affected the thickness, height, length, left casting angle, and left flange flatness. The thickness, length, and parallelism was affected by the ¾ inch thickness, while the ½ inch thickness significantly affected the left and right casting angle, and right flange flatness. Top gating contributed significantly to the height distortion. All gating configurations equally affected the left casting angle and left flange flatness.

Table 5.4b shows the results for all of the lost foam low expansion castings. The parallelism and left casting angle were affected by ½ inch thickness, the right flange flatness and right wall flatness were affected by the ¼ inch thickness and the thickness was affected by ¾ inch thickness. All orientation configuration configurations equally affected the height, length, and right flange flatness. Down orientation significantly contributed to the distortion of the left flange flatness. All gating configurations affected the right flange flatness equally.

Table 5.4c shows the results for all of the lost foam silica sand castings. The thickness, height, parallelism, left casting angle, right casting angle were affected by the ¾ inch thickness. All thickness levels contributed equally to the right flange flatness, left wall flatness, and right wall flatness. Orientation down affected the thickness, height, length, and right casting angle. Side orientation affected the left flange flatness. Top gating affected the thickness and parallelism. All gating, orientation, and thickness levels affected the right flange flatness.

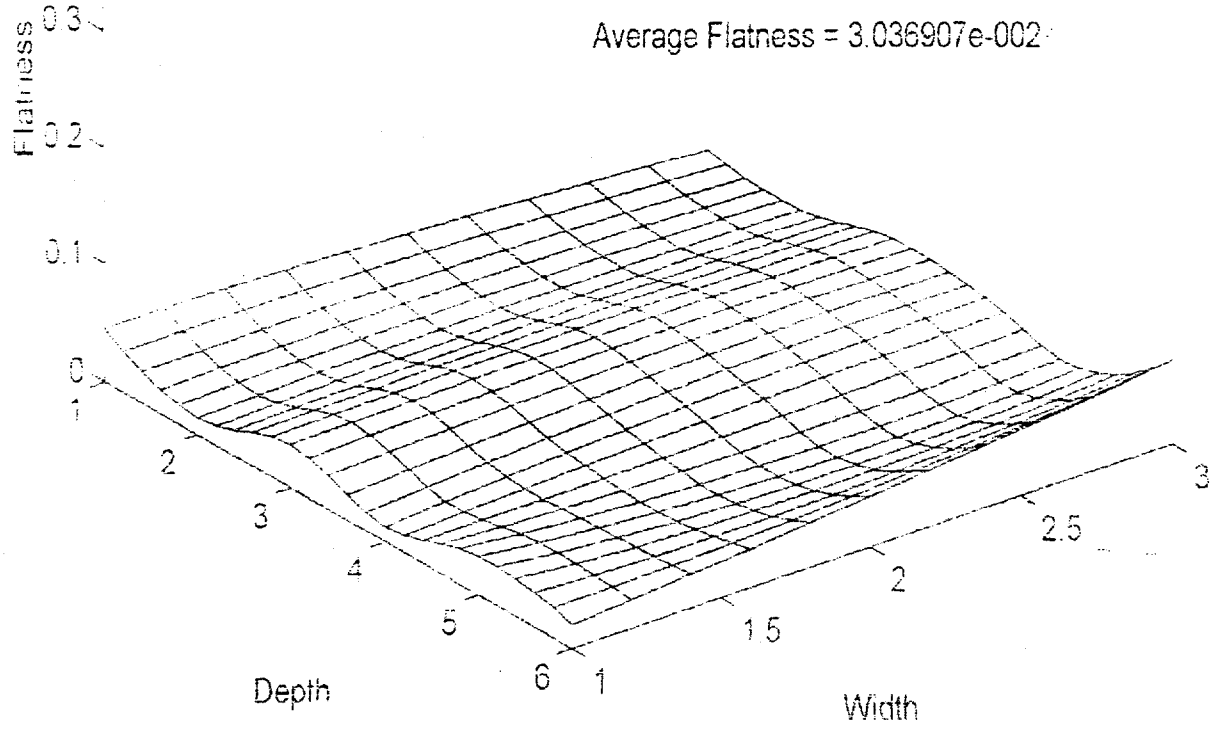


Figure 5.1 Surface Plot of Flatness

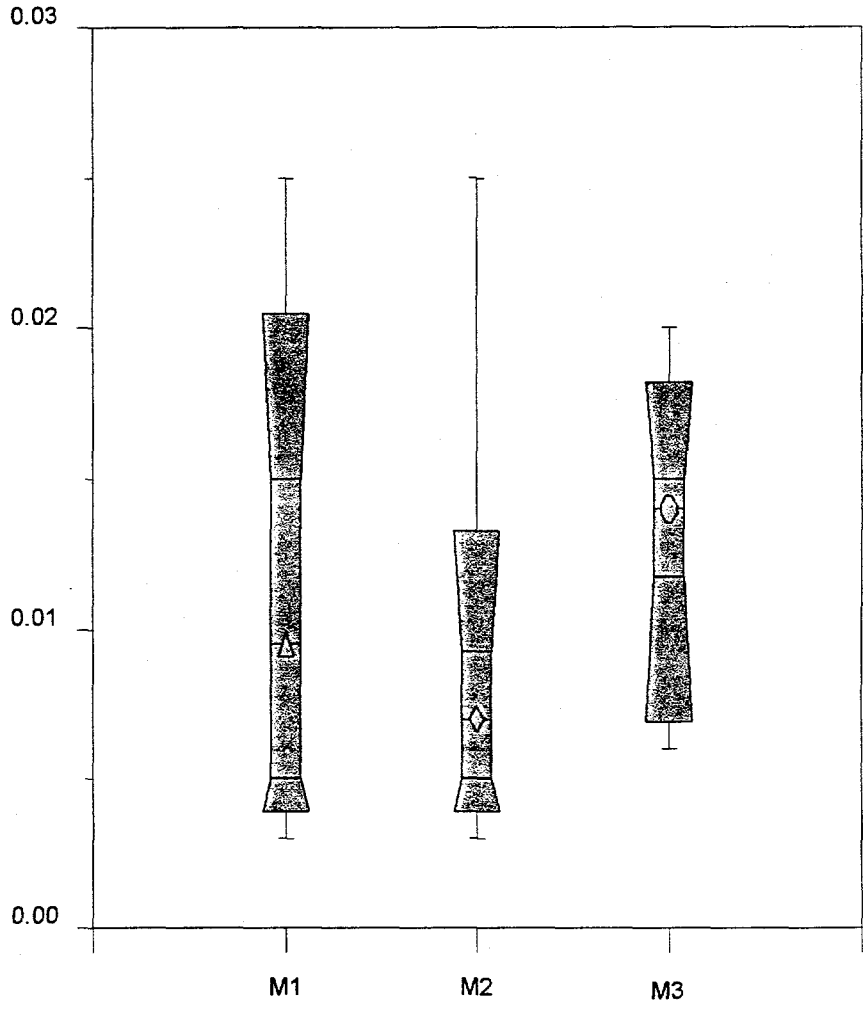


Figure 5.2 Box Plot of Left Flange Flatness of all 0.25 inch castings

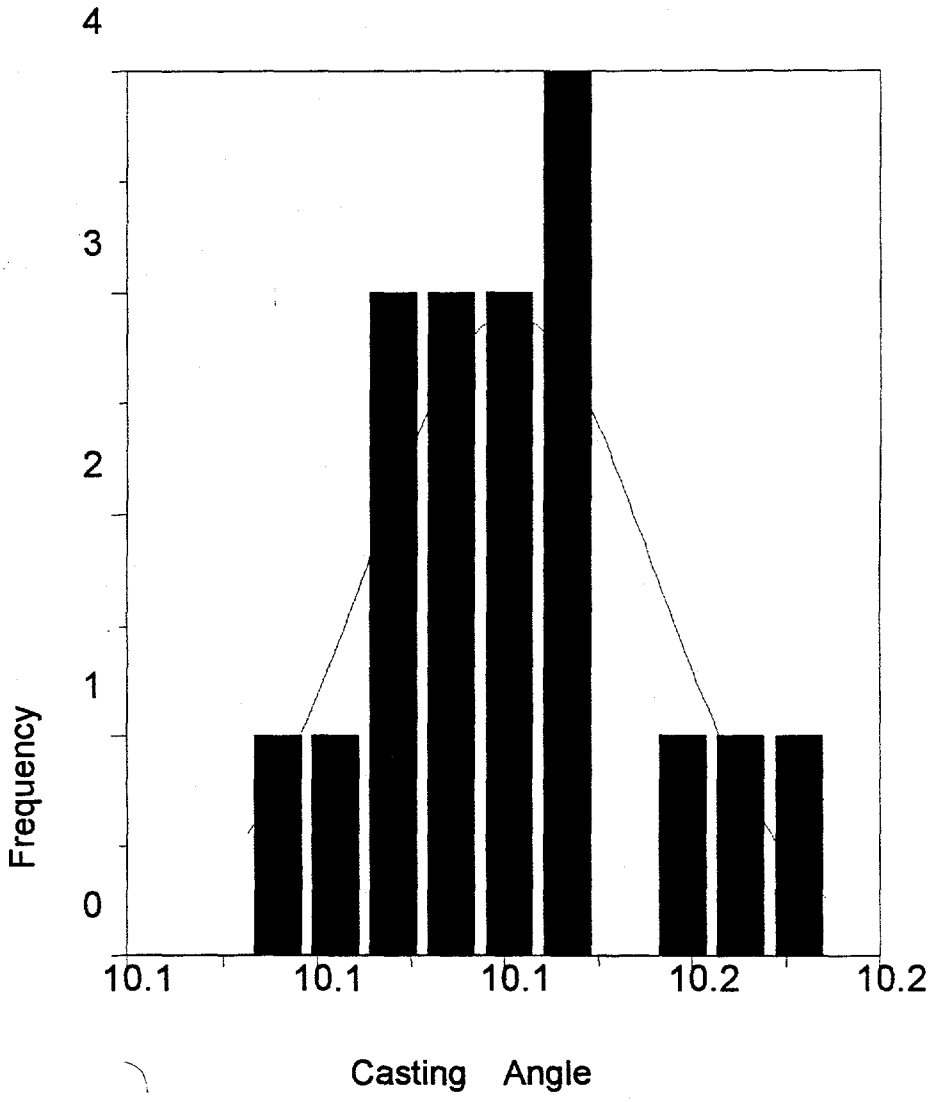


Figure 5.3 Histogram of Left Casting Angle Resin Bonded Sand (0.25 inch)

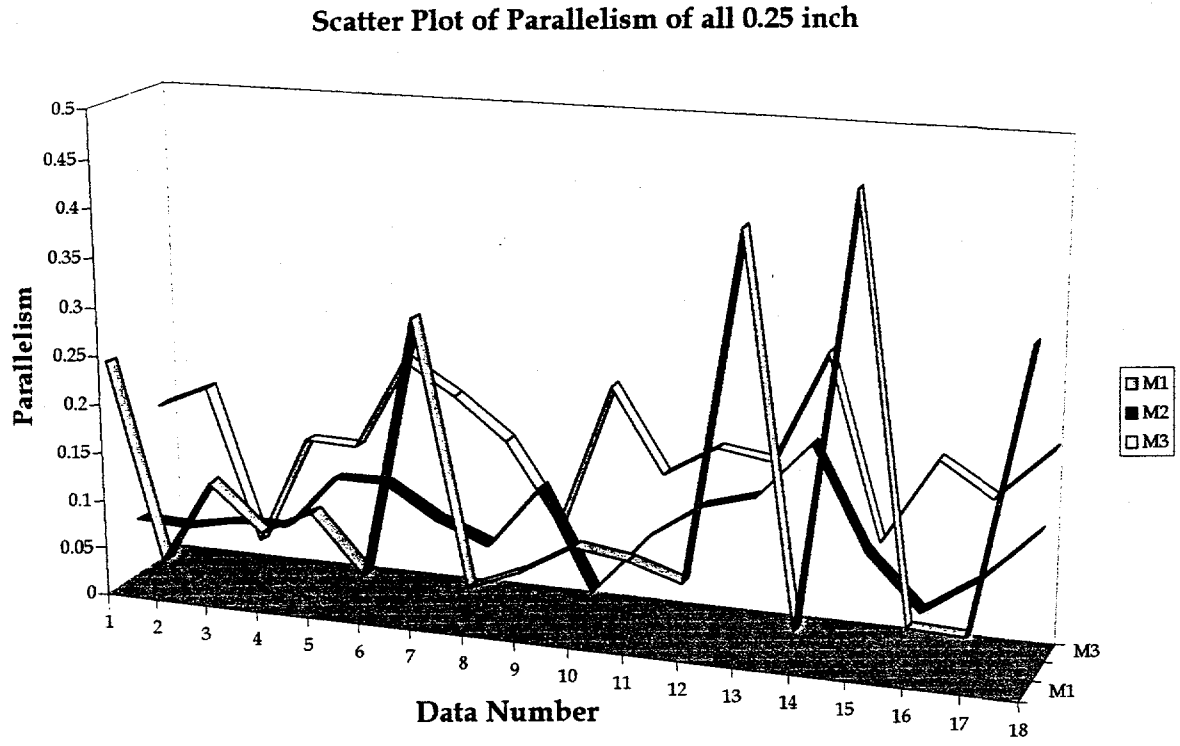


Figure 5.4 Scatter Plot of Parallelism of all 0.25 inch Castings

Table 5.1 Significant Contributors to Distortion of ¼ inch Casting ($\alpha = 0.05$)

(Results of Statistical Analysis)

Significant Factor Effect seen for 0.25 inch

a: All 0.25 inch castings			
Characteristic	**Gating**	**Orientation**	**Mold Type**
Thickness	-	-	-
Height	-	-	Resin Bond
Length	-	Down	Resin Bond
Parallelism	-	-	LF Silica
Left Casting Angle	-	-	-
Right Casting Angle	-	-	Resin Bond
Left Flange Flatness	-	-	Resin Bond
Right Flange Flatness	-	-	Resin Bond
Left Wall Flatness	Top	Down	Resin Bond
Right Wall Flatness	Top	Down	-

b: Lost Foam Silica Sand		
Characteristic	**Gating**	**Orientation**
Thickness	Top	Down
Height	-	Down
Length	-	Down
Parallelism	Top	-
Left Casting Angle	-	-
Right Casting Angle	-	-
Left Flange Flatness	-	Down
Right Flange Flatness	-	-
Left Wall Flatness	-	-
Right Wall Flatness	-	-

c: Lost Foam Low Expansion		
Characteristic	**Gating**	**Orientation**
Thickness	-	-
Height	-	-
Length	-	Down
Parallelism	-	-
Left Casting Angle	-	-
Right Casting Angle	-	-
Left Flange Flatness	-	-
Right Flange Flatness	-	Down
Left Wall Flatness	-	-
Right Wall Flatness	-	-

d: Resin Bonded Sand		
Characteristic	**Gating**	**Orientation**
Thickness	-	Down
Height	Top	-
Length	-	-
Parallelism	-	-
Left Casting Angle	-	-
Right Casting Angle	-	-
Left Flange Flatness	-	-
Right Flange Flatness	-	-
Left Wall Flatness	Top	Down
Right Wall Flatness	Top	-

Table 5.2 Significant Contributors to Distortion on 0.50 inch Castings ($\alpha = 0.05$)

(Results of Statistical Analysis)

Significant Factor Effect seen for 0.50 inch Castings

a: All 0.50 inch Castings			
Characteristic	**Gating**	**Orientation**	**Mold Type**
Thickness	-	-	ALL
Height			Resin Bonded
Length	-	ALL	Resin Bonded
Parallelism	-	-	Low-Expan.
Left Casting Angle	-	-	Resin Bonded
Right Casting Angle	-	-	-
Left Flange Flatness	-	-	-
Right Flange Flatness	ALL	-	Silica Sand
Left Wall Flatness	ALL	ALL	ALL
Right Wall Flatness	-	-	Low-Expan.

b: Lost Foam Silica Sand		
Characteristic	**Gating**	**Orientation**
Thickness	-	-
Height	ALL	-
Length	-	-
Parallelism	-	-
Left Casting Angle	-	-
Right Casting Angle	-	-
Left Flange Flatness	-	-
Right Flange Flatness	ALL	ALL
Left Wall Flatness	-	-
Right Wall Flatness	-	-

c: Resin Bonded Sand		
Characteristic	**Gating**	**Orientation**
Thickness	-	-
Height	-	ALL
Length	-	ALL
Parallelism	-	ALL
Left Casting Angle	-	-
Right Casting Angle	-	-
Left Flange Flatness	ALL	-
Right Flange Flatness	-	-
Left Wall Flatness	ALL	ALL
Right Wall Flatness	Top	ALL

d: Lost Foam Low Expansion		
Characteristic	**Gating**	**Orientation**
Thickness	-	-
Height	-	-
Length	-	Up
Parallelism	-	-
Left Casting Angle	-	-
Right Casting Angle	-	-
Left Flange Flatness	-	-
Right Flange Flatness	ALL	ALL
Left Wall Flatness	-	-
Right Wall Flatness	-	-

Table 5.3 Significant Contributors to Distortion on 0.75 inch castings ($\alpha = 0.05$)

(Results of Statistical Analysis

Significant Factor Effect seen for 0.75 inch Castings

a: All 0.75 inch castings			
Characteristic	**Gating**	**Orientation**	**Mold Type**
Thickness	-	-	Resin-Bond
Height	-	ALL	Resin-Bond
Length	-	-	Resin-Bond
Parallelism	-	-	Resin-Bond
Left Casting Angle	ALL		ALL
Right Casting Angle	-	ALL	Resin-Bond
Left Flange Flatness	-	-	-
Right Flange Flatness	-	ALL	ALL
Left Wall Flatness	-	-	Resin-Bond
Right Wall Flatness	-	-	Resin-Bond

b: Lost Foam Silica Sand		
Characteristic	**Gating**	**Orientation**
Thickness	Top	-
Height	-	Down
Length	-	Down
Parallelism	-	Down
Left Casting Angle	-	-
Right Casting Angle	Top	-
Left Flange Flatness	-	ALL
Right Flange Flatness	-	-
Left Wall Flatness	-	ALL
Right Wall Flatness	-	-

c: Lost Foam Low Expansion		
Characteristic	**Gating**	**Orientation**
Thickness	ALL	ALL
Height	ALL	ALL
Length	-	-
Parallelism	-	-
Left Casting Angle	-	-
Right Casting Angle	-	-
Left Flange Flatness	-	ALL
Right Flange Flatness	-	-
Left Wall Flatness	-	ALL
Right Wall Flatness	-	-

d: Resin Bonded Sand		
Characteristic	**Gating**	**Orientation**
Thickness	-	-
Height	ALL	ALL
Length	-	-
Parallelism	ALL	ALL
Left Casting Angle	ALL	ALL
Right Casting Angle	-	ALL
Left Flange Flatness	ALL	ALL
Right Flange Flatness	-	-
Left Wall Flatness	-	-
Right Wall Flatness	ALL	-

Table 5.4 Significant Contributors to Distortion on all castings ($\alpha = 0.05$)

(Results of Statistical Analysis)

Significant Factor Effect seen for ALL :

a: Resin Bonded Sand Castings			
Characteristic	**Gating**	**Orientation**	**Thickness**
Thickness	-	ALL	0.75
Height	Top	ALL	ALL
Length	-	ALL	0.75
Parallelism	-	-	0.75
Left Casting Angle	ALL	ALL	0.5
Right Casting Angle	-	-	0.5
Left Flange Flatness	ALL	ALL	-
Right Flange Flatness	-	-	0.5
Left Wall Flatness	-	-	-
Right Wall Flatness	-	-	-

b: Lost Foam Silica Sand			
Characteristic	**Gating**	**Orientation**	**Thickness**
Thickness	Top	Down	0.75
Height	-	Down	0.75
Length	-	Down	-
Parallelism	Top	-	0.75
Left Casting Angle	-	-	0.75
Right Casting Angle	-	Down	0.75
Left Flange Flatness	-	Side	-
Right Flange Flatness	ALL	ALL	ALL
Left Wall Flatness	-	-	ALL
Right Wall Flatness	-	-	ALL

c: Lost Foam Low Expansion			
Characteristic	**Gating**	**Orientation**	**Thickness**
Thickness	-	ALL	0.75
Height	-		ALL
Length	-	ALL	ALL
Parallelism	-	-	0.5
Left Casting Angle	-	-	0.5
Right Casting Angle	-	-	-
Left Flange Flatness	-	Down	-
Right Flange Flatness	ALL	ALL	0.25
Left Wall Flatness	-	-	-
Right Wall Flatness	-	-	0.25

CHAPTER 6

CONCLUSIONS

The purpose of this work was to use statistical analysis as a viable tool in the foundry industry. The primary objective was to determine the effect of gating, orientation, mold type, and thickness on casting distortion. The use of the analysis methodologies in this work has proven that statistical analysis may be used with confidence in the foundry as well as other industries.

The statistical analysis confirmed that the type of gating systems, orientation, mold type, and thickness indeed influence the quality of the casting. The factorial analysis of variance determined the effect of each factor on each parameter (length, height, thickness, parallelism, casting angle, and flatness). The test of means was an effective method for determining the factor level effects. It is noted that there may have been errors introduced to the castings in association with process error, human error, batch error, multiple mold error, etc. Yet, for this analysis, it was assumed that all of the parameter variations found were solely due to the gating, orientation, thickness, and mold type.

For all of the castings, the thickness levels, orientation, and gating significant contributed to the distortion of the parameters. For all of the resin-bonded castings, ¾ and ½ inch thickness played a significant role in casting distortion. Gating and orientation also played crucial roles in the distortion. Orientation down, ¾ inch thickness, and top gating affected the lost foam silica sand castings. The thickness level (¾, ½ , ¼ inch) most significantly affected the lost foam low expansion castings compared with the orientation and gating.

Resin bonded sand, orientation down, and top-gating most affected all of the ¼ inch castings. The most significant contributor to the distortion the ½ and ¾ inch castings was resin bonded sand. Also, the analysis indicated that side gating did not significantly contribute to the distortion of the castings. In conclusion, resin bonded sand, orientation down, and top gating were the significant contributors to the distortion of the castings.

6.1 Future Work

A gap formation model may now be developed based upon the findings that gating, orientation, mold type, and thickness affect casting distortion. This model may be used to control casting distortion. The information may be used in casting solidification simulation software. The algorithms used to calculate the dimensional variations may be coded into the coordinate-measuring machine. The understanding of point cloud data combined with neural networks may be used in a foundry setting to determine, classify, alleviate, and remedy dimensional variation errors. By controlling and measuring the errors associated with the process, batches, etc., it is possible to more accurately determine the effect of gating, orientation, thickness, and mold type on the parameter distortion. The same study may be performed on different ferrous metals such as cast iron and steel.

REFERENCES

Batista, Casimiro, Application of Statistical Methods for Improvement of Metal Casting Dimensional Accuracy in Sand Molds, Masters Thesis, The Florida State University, 1997

Cattanach, Robert., etal, The Handbook for Environmentally Conscious Manufacturing: From Design and Production to Labeling and Recycling, Chicago: 1996.

Cheraghi, S. Hossein, *Straightness and flatness tolerance evaluation: and optimization approach*, Precision Engineering, New York: Elsevier Science, Inc., 1996.

Dargan, Tarsha, Statistical Analysis of Point Cloud Data from a Coordinate Measuring Machine and the Application of Green Quality Function Deployment II on Sand Casting Processes, Masters Thesis, Florida Agricultural and Mechanical University,1998.

Dionne, Louis, "Lost Foam Technique for Making Fiberglass Parts", http:// www.ezone.com, October 1998

DiSylvestro, G., *"Dimensional Stability of Castings Made in High Density Green Sand Molding: Phase I —Factors Which Affect Dimensional Stability"*, AFS Transactions, Vol. 84, pp. 745, 1976.

Doyle, Lawrence E, etal, Manufacturing Processes and Materials for Engineers, Prentice-Hall 1985, page 120-173.

Ehrenfield, John, "Moving Toward Loop-Closing Structures: Systems Issues in Achieving Environmentally Conscious Manufacturing", Center for Technology, Policy & Industrial Development Massachusetts Institute of Technology.

Elmography, W. H., Wu, H. A., Elmography, H. A., *"Evaluation of Actual Geometric Tolerance Using Coordinate Measuring Data"*, Advances in Design and Automation.

EPA, "Environmental Accounting Case Studies: Green Accounting at AT&T," EPA 742- R-95-003

Gess, David, *Life Cycle Cost Management,* Perspectives, http: www.dfi.com/lccm.html: Autumn 1994

Govers, C.P.M., *What and how about quality function deployment(QFD)*, International Journal of Production Economics, Netherlands: 1996

Heine, R. W., Loper Jr., C. R., and Rosenthal, P. C., *Principles of Metal Casting*, Second Edition, McGraw-Hill Book Company, 1967.

Henry, J. Glynn, etal, Environmental Science and Engineering, New Jersey: Prentice-Hall, Inc., 1996, pg. 693

Ho K., Pehlke R. D., *"Mechanisms of Heat Transfer at a Metal-Mold Interface"*, AFS Transactions, Vol. 61, pp. 587 - 598, 1984.

Kalpakjian, S., *Manufacturing Engineering and Technology*, Third Edition, Adison-Wesley Publishing Company, New York, 1995.

Masor, R.L., Gunst, R.F., Statistical Design and Analysis of Experiments: with applications to Engineering and Science, John Wiley & Sons, New York, 1989.

Menq, C. H., Yau, H. T., Lai, G. Y., Miller, R. A. "Statistical Evaluation of Form Tolerances Using Discrete Measurement Data", *Advances in Integrated Product Design and Manufacturing*, American Society of Mechanical Engineers, (Production Engineering Division (Publication), PED, Vol. 47, 1990, p. 135-149.

Murphy, T. S. R., and Abdin, S. Z., 1980, *"Minimum Zone Evaluation of Surfaces"*, *International Journal of Machine Tool Design and Research*, Vol. 20, No. 2, 1989.

Nishida, Y., Journal of Japan Institute of Metals, Vol. 34, pp. 1135 - 1139, 1970.

Owusu, Yaw, "Short Course on Metal Casting Technology" , Argonne National Laboratory, Chicago, August 13, 1996.

Owusu, Yaw A., Sodium Silicate Bonding in Foundry Sands, PhD Dissertation, The Pennsylvania State University, 1980.

Owusu, Yaw, Systems Approach to Concurrent Engineering: Design, Manufacturing, and Product Support, January 1998.

Owusu, Yaw A., and Batista, Casimiro, *Statistical Analysis of Casting Distortion using Geometrical and Dimensional Tolerance Evaluation Technique*, 1997.

Piwonka, T, Owusu, Y.A., Woodbury, K., and Parker, T., The Relationship between Casting Distortions, Mold Filling and Interfacial Heat Transfer in Sand Molds, Research Sponsored by U.S. Department of Energy, March 13, 1996.

Piwonka, T. S., "*Improve Dimensional Accuracy—Is It Worth Anything to The Casting Buyer?*", The Crucible, Non-Ferrous Founders Society, pp. 10, March/April 1990.

Piwonka, T. S., "Heat Transfer at the Mold-Metal Interface in Investment Castings", *Proceedings of the 41st Annual Technical Meeting*, Investment Casting Institute, paper #15, Chicago, IL, October 1993.

Richmond, O., Hector, L. G., and Friday, J. M., "*Growth Instability During Non-Uniform Directional Solidification of Pure Metals*", Ibid, Vol. 57, pp. 529, 1990.

Rosenau, Milton D and Moran, John J, Managing the Development of New Products, New York: Van Nostrand Reinhold, 1993.

Sobh, T. M., Zhu, X., Brudelin, B., "Analysis of Tolerance for Manufacturing Geometric Objects from Sensed Data", http://www.cs.utah.edu/~sobh/jmachine/paper.html, 1994.

Tien, R. H., and Richmond, O., "Theory of Maximum Tesile Stresses in the Solidifying Shell of a Constrained Rectangular Casting", Journal of Applied Mechanics, Vol. 49, pp. 481, 1982.

Turner, etal, Introduction to Industrial System Engineering, Prentice-Hall, New Jersey: 1978, pp. 73-76

Woodbury, K. A., Parker, J. K., Owusu, Y. A., Piwonka, T. S., *"The Relationship Between Casting Distortion, Mold Filling, and Interfacial Heat Transfer in Sand Molds"*, A Proposal from the Metal Casting Distortion Technology Center at The University of Alabama and Florida A & M University, 1995.

http://www.tcbi.com/archiesr/secondary/

http://inaba.nrim.go.jp:8080/movie/CAST/cast.html, Metal casting by the sand mold

APPENDIX A

(Experimental Design of the Project)

Table A. 1 Experimental Design of the Project
(Thickness)

		Mold Type																											
		M1									M2										M3								
		Thickness																											
Orientation	Gating	T1			T2			T3			T1			T2			T3				T1			T2			T3		
	G1	0.8	0.8	0.8	0.5	0.5	0.5	0.3	0.3	0.3	0.826	0.834	0.782	0.52	0.62	0.584	0.318	0.258	0.248	0.74	0.75	0.74	0.51	0.51	0.5	0.242	0.246	0.2428
O1	G2	0.8	0.8	0.8	0.6	0.5	0.5	0.3	0.3	0.3	0.747	0.755	0.754	0.535	0.521	0.507	0.231	0.231	0.234	0.75	0.74	0.74	0.5	0.49	0.51	0.239	0.239	0.2476
	G3	-	-	-	-	-	-	-	-	-	0.77	0.75	0.75	0.508	0.515	0.509	0.246	0.24	0.251	0.74	0.74	**0.74**	0.51	0.51	0.5	0.241	0.239	0.2344
	G1	0.8	0.9	0.8	0.5	0.5	0.5	0.3	0.3	0.3	0.755	0.756	0.749	0.512	0.503	0.515	0.239	0.239	0.243	0.75	0.75	0.74	0.5	0.5	**0.5**	0.239	0.235	0.2278
O2	G2	0.8	0.8	0.8	0.5	0.5	0.5	0.3	0.3	0.3	0.751	0.753	0.749	0.507	0.51	0.519	0.227	0.239	0.232	0.73	0.73	0.74	**0.5**	0.5	0.5	0.244	0.246	0.2453
	G3	-	-	-	-	-	-	-	-	-	0.753	0.748	0.75	0.506	0.52	0.519	0.234	0.24	0.244	0.74	0.73	0.74	0.5	0.5	0.51	0.237	0.242	0.2435
	G1	0.8	0.8	0.8	0.5	0.5	0.5	0.3	0.3	0.3	0.752	0.751	0.748	0.503	0.51	0.511	0.237	0.246	0.229	0.74	0.74	0.74	0.5	0.49	0.51	0.241	0.242	0.2385
O3	G2	0.8	0.8	0.8	0.5	0.5	0.6	0.3	0.3	0.3	0.78	0.777	0.772	0.547	0.64	0.502	0.255	0.309	0.282	**0.74**	**0.74**	0.74	0.5	0.5	0.5	0.436	0.382	0.4095
	G3	-	-	-	-	-	-	-	-	-	0.75	0.75	0.76	0.51	0.51	0.5	-	-	-	0.74	0.74	0.74	0.49	0.49	0.5	0.242	0.246	0.2428

G1 = Top gating O1=Down T1= 3/4 inch thickness M1=Resin Bonded Sand
G2 = Bottom gating O2=Up T2= 1/2 inch thickness M2=Lost Foam Low Expansion
G3 = Side gating O3=Side T3= 1/4 inch thickness M3=Lost Foam Silica Sand

Table A. 2 Experimental Design of the Project
(Height)

		Mold Type																								
		M1									M2									M3						
		Thickness																								
Orientation	Gating	T1			T2			T3			T1			T2			T3			T1			T2			T3		
	G1	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.8	8.8	8.7	8.707	8.672	8.673	8.766	8.688	8.696	8.658	8.71	8.63	8.63	8.61	8.59	8.62	8.61	8.745	8.644	8.7979
O1	G2	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.578	8.632	8.616	8.645	8.632	8.636	8.656	8.656	8.656	8.63	8.62	8.6	8.59	8.6	8.59	8.651	8.686	8.6194
	G3	-	-	-	-	-	-	-	-	-	8.634	8.631	8.622	8.638	8.635	8.625	8.62	8.652	8.712	8.62	8.64	**8.63**	8.61	8.61	8.6	8.678	8.699	8.6631
	G1	8.9	8.9	8.9	8.9	8.8	8.9	8.9	8.9	8.9	8.623	8.621	8.608	8.586	8.596	8.653	8.698	8.677	8.672	8.61	8.63	8.61	8.61	8.61	**8.61**	8.742	8.721	8.6914
O2	G2	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.611	8.613	8.59	8.639	8.625	8.637	8.669	8.667	8.668	8.59	8.61	8.6	**8.61**	8.6	8.61	8.671	8.601	8.6357
	G3	-	-	-	-	-	-	-	-	-	8.614	8.631	8.604	8.596	8.637	8.607	8.613	8.72	8.704	8.61	8.61	8.6	8.61	8.61	8.59	8.655	8.621	8.6377
	G1	8.9	8.9	8.9	8.9	8.8	8.9	8.9	8.9	8.9	8.616	8.614	8.606	8.618	8.778	8.617	8.598	8.638	8.609	8.62	8.62	8.63	8.6	8.61	8.6	8.696	8.683	8.6884
O3	G2	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.8	8.66	8.644	8.658	8.583	8.617	8.576	8.61	8.643	8.841	**8.63**	**8.63**	8.63	8.6	8.6	8.6	8.795	8.771	8.783
	G3	-	-	-	-	-	-	-	-	-	8.615	8.614	8.612	8.641	8.618	8.629	-	-	-	8.61	8.62	8.61	8.6	8.61	8.59	8.708	8.651	8.7029

G1 = Top gating O1=Down T1= 3/4 inch thickness M1=Resin Bonded Sand
G2 = Bottom gating O2=Up T2= 1/2 inch thickness M2=Lost Foam Low Expansion
G3 = Side gating O3=Side T3= 1/4 inch thickness M3=Lost Foam Silica Sand

Table A. 3 Experimental Design of the Project
(Length)

		Mold Type																											
		M1									M2									M3									
		Thickness																											
Orientation	Gating	T1			T2			T3			T1			T2			T3			T1			T2			T3		
	G1	7.744	7.782	7.815	7.847	7.79	7.779	7.774	7.76	7.73	6.478	6.479	6.47	6.496	6.485	6.494	6.425	6.421	6.427	6.43	6.44	6.45	6.44	6.44	6.45	6.29	6.15	6.3924
O1	G2	7.74	7.821	7.73	7.78	7.821	7.788	7.792	7.747	7.757	6.455	6.488	6.482	6.48	6.479	6.499	6.458	6.458	6.41	6.44	6.44	6.44	6.4	6.44	6.44	6.413	6.436	5.803
	G3	-	-	-	-	-	-	-	-	-	6.484	6.489	6.475	6.518	6.484	6.473	6.449	6.459	6.433	6.42	6.46	**6.44**	6.43	6.44	6.44	6.279	6.414	6.3795
	G1	7.759	7.775	7.837	7.799	7.834	7.82	7.774	7.821	7.721	6.482	6.484	6.461	6.479	6.472	6.477	6.452	6.416	6.433	6.4	6.44	6.41	6.44	6.44	**6.44**	6.424	6.442	6.4364
O2	G2	7.799	7.747	7.784	7.808	7.819	7.823	7.793	7.807	7.785	6.464	6.468	6.482	6.485	6.475	6.478	6.442	6.436	6.438	6.42	6.43	6.44	**6.43**	6.43	6.44	6.357	7.028	6.6925
	G3	-	-	-	-	-	-	-	-	-	6.473	6.462	6.467	6.488	6.496	6.489	6.435	6.434	6.442	6.44	6.43	6.44	6.44	6.43	6.44	6.432	6.406	6.3577
	G1	7.761	7.743	7.771	7.735	7.794	7.741	7.747	7.751	7.771	6.484	6.462	6.46	6.452	6.449	6.443	6.396	6.392	6.417	6.44	6.44	6.45	6.45	6.45	6.44	6.426	6.435	6.3945
O3	G2	7.781	7.748	7.787	7.796	7.809	7.82	7.767	7.782	7.757	6.464	6.463	6.467	6.47	6.472	6.464	6.419	6.419	6.418	**6.45**	**6.45**	6.45	6.44	6.45	6.43	6.03	6.201	6.116
	G3	-	-	-	-	-	-	-	-	-	6.466	6.465	6.47	6.478	6.497	6.462	-	-	-	6.43	6.45	6.43	6.44	6.45	6.43	6.408	6.443	6.4482

G1 = Top gating
G2 = Bottom gating
G3 = Side gating

O1=Down
O2=Up
O3=Side

T1= 3/4 inch thickness
T2= 1/2 inch thickness
T3= 1/4 inch thickness

M1=Resin Bonded Sand
M2=Lost Foam Low Expansion
M3=Lost Foam Silica Sand

Table A. 4 Experimental Design of the Project
(Parallelism)

		Mold Type																												
		M1									M2										M3									
		Thickness																												
Orientation	Gating	T1			T2			T3			T1			T2			T3			T1			T2			T3				
	G1	0.103	0.089	0.087	0.062	0.114	0.105	0.24	0.311	0.422	0.059	0.092	0.148	0.059	0.05	0.141	0.058	0.077	0.052	0.03	0.03	0.04	0.06	0.04	0.04	0.166	0.204	0.1682		
O1	G2	0.088	0.071	0.065	0.099	0.116	0.076	0.036	0.043	0.038	0.056	0.069	0.207	0.027	0.022	0.096	0.065	0.044	0.09	0.04	0.04	0.05	0.02	0.03	0.03	0.189	0.163	0.2816		
	G3	-	-	-	-	-	-	-	-	-	0.052	0.068	0.088	0.184	0.067	0.029	0.062	0.08	0.204	0.04	0.03	0.03	0.02	0.03	0.03	0.111	0.12	0.196		
	G1	0.056	0.067	0.058	0.07	0.122	0.067	0.124	0.065	0.466	0.066	0.136	0.105	0.141	0.072	0.061	0.047	0.064	0.03	0.05	0.05	0.06	0.03	0.03	0.03	0.029	0.082	0.0958		
O2	G2	0.058	0.065	0.09	0.126	0.11	0.121	0.077	0.097	0.053	0.067	0.5	0.034	0.019	0.025	0.033	0.055	0.039	0.091	0.06	0.05	0.07	0.04	0.03	0.05	0.931	0.952	0.9418		
	G3	-	-	-	-	-	-	-	-	-	0.056	0.046	0.036	0.111	0.073	0.062	0.04	0.086	0.049	0.05	0.05	0.07	0.05	0.04	0.04	0.173	0.206	0.1808		
	G1	0.048	0.039	0.034	0.054	0.071	0.059	0.105	0.089	0.05	0.123	0.093	0.087	0.077	0.054	0.07	0.036	0.054	0.068	0.02	0.04	0.02	0.07	0.05	0.03	0.142	0.143	0.1531		
O3	G2	0.088	0.073	0.095	0.042	0.062	0.098	0.044	0.072	0.336	0.123	0.132	0.141	0.118	0.064	0.063	0.038	0.073	0.016	0.03	0.03	0.03	0.03	0.05	0.03	0.237	0.176	0.206		
	G3	-	-	-	-	-	-	-	-	-	0.075	0.025	0.06	0.045	0.107	0.042	-	-	-	0.05	0.04	0.05	0.04	0.05	0.06	0.095	0.186	0.1252		

G1 = Top gating O1=Down T1= 3/4 inch thickness M1=Resin Bonded Sand
G2 = Bottom gating O2=Up T2= 1/2 inch thickness M2=Lost Foam Low Expansion
G3 = Side gating O3=Side T3= 1/4 inch thickness M3=Lost Foam Silica Sand

Table A. 5 Experimental Design of the Project
(Left Casting Angle)

		Mold Type																											
		M1									M2										M3								
		Thickness																											
Orientation	Gating	T1			T2			T3			T1			T2			T3			T1			T2			T3		
	G1	10.1	10.1	10.13	10.11	10.11	10.11	10.11	10.11	10.12	10.12	10.12	10.12	10.12	10.12	10.12	10.12	10.13	10.14	10.1	10.1	10.1	10.1	10.1	10.1	10.12	10.13	10.117
O1	G2	10.1	10.09	10.1	10.1	10.1	10.1	10.15	10.12	10.12	10.11	10.12	10.11	10.12	10.12	10.12	10.12	10.12	10.12	10.1	10.1	10.1	10.1	10.1	10.1	10.12	10.12	10.12
	G3	-	-	-	-	-	-	-	-	-	10.12	10.12	10.12	10.12	10.11	10.12	10.13	10.12	10.13	10.1	10.1	**10.1**	10.1	10.1	10.1	10.12	10.12	10.122
	G1	10.11	10.11	10.11	10.1	10.11	10.11	10.13	10.12	10.14	10.12	10.11	10.12	10.12	10.12	10.12	10.15	10.12	10.13	10.1	10.1	10.1	10.1	10.1	**10.1**	10.14	10.12	10.122
O2	G2	10.11	10.11	10.11	10.11	10.11	10.11	10.12	10.12	10.12	10.12	10.12	10.12	10.12	10.12	10.12	10.12	10.12	10.12	10.1	10.1	10.1	**10.1**	10.1	10.1	10.12	10.12	10.116
	G3	-	-	-	-	-	-	-	-	-	10.11	10.11	10.11	10.12	10.12	10.12	10.12	10.14	10.13	10.1	10.1	10.1	10.1	10.1	10.1	10.12	10.12	10.122
	G1	10.13	10.13	10.13	10.11	10.1	10.13	10.14	10.11	10.12	10.11	10.11	10.11	10.12	10.11	10.12	10.13	10.12	10.12	10.1	10.1	10.1	10.1	10.1	10.1	10.12	10.12	10.12
O3	G2	10.1	10.11	10.11	10.11	10.11	10.11	10.12	10.11	10.1	10.12	10.12	10.12	10.12	10.12	10.12	10.13	10.14	10.13	**10.1**	**10.1**	10.1	10.1	10.1	10.1	10.12	10.12	10.1
	G3	-	-	-	-	-	-	-	-	-	10.12	10.12	10.12	10.12	10.12	10.12	-	-	-	10.1	10.1	10.1	10.1	10.1	10.1	10.12	10.12	10.118

G1 = Top gating O1=Down T1= 3/4 inch thickness M1=Resin Bonded Sand
G2 = Bottom gating O2=Up T2= 1/2 inch thickness M2=Lost Foam Low Expansion
G3 = Side gating O3=Side T3= 1/4 inch thickness M3=Lost Foam Silica Sand

Table A. 6 Experimental Design of the Project
(Right Casting Angle)

		Mold Type																											
		M1									M2										M3								
		Thickness																											
Orientation	Gating	T1			T2			T3			T1			T2			T3				T1			T2			T3		
	G1	10.11	10.11	10.1	10.12	10.1	10.11	9.828	9.877	10.02	10.11	10.11	10.12	10.12	10.13	10.07	10.1	10.06	10.16	10.1	10.1	10.1	10.1	10.1	10.1	10.29	10.26	10.275
O1	G2	10.12	10.13	10.12	10.13	10.1	10.13	10.12	10.12	10.11	10.11	10.12	10.11	10.12	10.12	10.12	10.11	10.11	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.19	10.22	10.148
	G3	-	-	-	-	-	-	-	-	-	10.12	10.12	10.12	10.12	10.12	10.12	10.11	10.11	10.14	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.16	10.19	10.168
	G1	10.13	10.13	10.11	10.11	10.08	10.11	10.08	10.1	9.899	10.11	10.11	10.12	10.07	10.12	10.14	10.11	10.17	10.13	10.1	10.1	10.1	10.1	10.1	10.1	10.12	10.17	10.205
O2	G2	10.12	10.11	10.11	10.08	10.1	10.1	10.08	10.07	10.13	10.13	10.11	10.1	10.11	10.11	10.12	10.11	10.11	10.18	10.1	10.1	10.1	10.1	10.1	10.1	10.22	10.25	10.234
	G3	-	-	-	-	-	-	-	-	-	10.12	10.14	10.12	10.12	10.12	10.12	10.11	10.13	10.14	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.21	10.25	10.188
	G1	10.14	10.14	10.15	10.11	10.14	10.1	10.09	10.11	10.11	10.12	10.12	10.11	10.11	10.15	10.12	10.13	10.14	10.17	10.1	10.1	10.1	10.1	10.1	10.1	10.15	10.17	10.151
O3	G2	10.12	10.12	10.13	10.12	10.11	10.1	10.13	10.12	9.636	10.11	10.12	10.12	10.15	10.12	10.11	10.09	10.08	10.14	10.1	10.1	10.1	10.1	10.1	10.1	10.25	10.22	10.2
	G3	-	-	-	-	-	-	-	-	-	10.11	10.12	10.12	10.11	10.11	10.11	-	-	-	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.18	10.21	10.19

G1 = Top gating
G2 = Bottom gating
G3 = Side gating

O1=Down
O2=Up
O3=Side

T1= 3/4 inch thickness
T2= 1/2 inch thickness
T3= 1/4 inch thickness

M1=Resin Bonded Sand
M2=Lost Foam Low Expansion
M3=Lost Foam Silica Sand

Table A. 7 Experimental Design of the Project
(Left Flange Flatness)

		Mold Type																											
		M1									M2									M3									
		Thickness																											
Orientation	Gating	T1			T2			T3			T1			T2			T3			T1			T2			T3		
	G1	0.007	0.006	0.019	0.006	0.02	0.016	0.003	0.005	0.009	0.012	0.006	0.013	0.01	0.036	0.011	0.007	0.005	0.008	0.008	0.007	0.009	0.005	0.005	**0.005**	0.006	0.007	0.014
O1	G2	0.01	0.008	0.003	0.009	0.01	0.019	0.006	0.01	0.004	0.032	0.022	0.014	0.013	0.014	0.015	0.009	0.009	0.025	**0.003**	**0.009**	**0.006**	**0.006**	0.007	0.004	0.012	0.012	0.014
	G3	-	-	-	-	-	-	-	-	-	0.007	0.028	0.017	0.013	0.011	0.005	0.006	0.018	0.018	**0.005**	**0.092**	**0.048**	0.013	0.007	0.012	0.016	0.024	0.013
	G1	0.008	0.004	0.014	0.006	0.008	0.006	0.02	0.006	0.015	0.006	0.009	0.003	0.006	0.022	0.005	0.005	0.007	0.009	0.006	0.008	0.012	0.011	0.02	0.011	0.02	0.015	0.014
O2	G2	0.003	0.004	0.02	0.016	0.004	0.005	0.016	0.005	0.007	0.009	0.006	**0.015**	0.007	0.005	0.011	0.012	0.01	0.007	0.013	0.015	0.03	0.014	0.037	0.013	0.013	0.018	**0.015**
	G3	-	-	-	-	-	-	-	-	-	0.019	0.016	0.016	0.009	0.014	0.007	0.014	0.01	0.008	0.05	0.01	**0.03**	0.007	0.003	0.026	0.015	0.017	0.03
	G1	0.034	0.028	0.022	0.033	0.067	0.024	0.025	0.015	0.012	0.003	0.011	0.01	0.004	0.011	0.005	0.004	0.003	0.01	0.008	0.017	0.01	0.015	0.017	0.01	0.011	0.012	0.009
O3	G2	0.008	0.004	0.013	0.005	0.009	0.004	0.005	0.013	0.015	0.009	0.008	0.004	0.001	0.004	0.01	0.005	0.006	0.007	**0.008**	**0.008**	0.008	0.013	0.012	0.01	0.015	0.015	**0.015**
	G3	-	-	-	-	-	-	-	-	-	0.014	0.01	0.01	0.006	0.003	0.005	-	-	-	0.014	0.011	0.01	0.019	0.028	0.008	0.008	0.012	0.008

G1 = Top gating
G2 = Bottom gating
G3 = Side gating

O1=Down
O2=Up
O3=Side

T1= 3/4 inch thickness
T2= 1/2 inch thickness
T3= 1/4 inch thickness

M1=Resin Bonded Sand
M2=Lost Foam Low Expansion
M3=Lost Foam Silica Sand

Table A. 8 Experimental Design of the Project
(Right Flange Flatness)

		Mold Type																											
		M1									M2										M3								
		Thickness																											
Orientation	Gating	T1			T2			T3			T1			T2			T3			T1			T2			T3		
	G1	0.022	0.01	0.067	0.009	0.009	0.012	0.012	0.021	0.008	0.135	0.074	0.044	0.013	0.051	0.03	0.02	0.024	0.031	0.01	0.01	0.06	0.02	0.02	**0.02**	0.021	0.08	0.0872
O1	G2	0.019	0.027	0.008	0.007	0.002	0.023	0.01	0.008	0.017	0.182	0.123	0.058	0.037	0.074	0.036	0.007	0.04	0.053	0.13	0.04	0.07	**0.03**	0.03	0.02	0.054	0.05	0.0518
	G3										0.019	0.042	0.032	0.073	0.067	0.048	0.061	0.127	0.072	0.01	0.01	**0.01**	0.06	0.03	0.01	0.065	0.125	0.0362
	G1	0.009	0.008	0.115	0.006	0.034	0.006	0.021	0.008	0.019	0.09	0.03	0.03	0.03	0.024	0.019	0.032	0.042	0.04	0.17	0.03	0.02	0.04	0.01	0.04	0.035	0.028	0.2081
O2	G2	0.017	0.017	0.069	0.02	0.006	0.021	0.013	0.017	0.037	0.62	0.039	**0.659**	0.08	0.078	0.124	0.02	0.039	0.063	0.01	0.02	0.17	0.01	0.02	0.03	0.139	0.044	**0.0911**
	G3										0.17	0.043	0.084	0.016	0.029	0.017	0.008	0.01	0.02	0.02	0.03	**0.03**	0.05	0.03	0.02	0.063	0.145	0.047
	G1	0.038	0.036	0.014	0.019	0.024	0.009	0.019	0.031	0.019	0.053	0.063	0.076	0.019	0.021	0.02	0.01	0.013	0.007	0.03	0.02	0.01	0.03	0.03	0.02	0.026	0.099	0.0347
O3	G2	0.023	0.018	0.043	0.007	0.004	0.006	0.009	0.018	0.01	0.09	0.024	0.069	0.004	0.051	0.022	0.008	0.003	0.006	**0.02**	**0.02**	0.02	0.04	0.06	0.02	0.037	0.118	**0.071**
	G3	-	-	-	-	-	-	-	-	-	0.016	0.048	0.007	0.021	0.024	0.009	-	-	-	0.01	0.01	0.01	0.02	0.03	0.01	0.092	0.154	0.129

G1 = Top gating O1=Down T1= 3/4 ir M1=Resin Bonded Sand M1=Resin Bonded Sand
G2 = Bottom gating O2=Up T2= 1/2 ir M2=Lost Foam Low Expansion M2=Lost Foam Low Expansion
G3 = Side gating O3=Side T3= 1/4 ir M3=Lost Foam Silica Sand M3=Lost Foam Silica Sand

Table A. 9 Experimental Design of the Project
(Left Wall Flatness)

		Mold Type																											
		M1									M2										M3								
		Thickness																											
Orientation	Gating	T1			T2			T3			T1			T2			T3				T1			T2			T3		
	G1	0.045	0.038	0.021	0.025	0.043	0.027	0.036	0.032	0.04	0.014	0.026	0.016	0.008	0.011	0.008	0.007	0.007	0.005		0.025	0.02	0.014	0.017	0.017	**0.017**	0.01	0.01	0.01
O1	G2	0.015	0.02	0.016	0.038	0.04	0.029	0.046	0.039	0.05	0.018	0.012	0.007	0.01	0.008	0.014	0.011	0.018	0.018		0.015	0.026	0.021	**0.107**	0.196	0.018	0.01	0.02	0.007
	G3	-	-	-	-	-	-	-	-	-	0.009	0.019	0.029	0.011	0.009	0.011	0.011	0.013	0.008		0.018	0.017	**0.017**	0.015	0.018	0.016	0.01	0.01	0.006
	G1	0.037	0.041	0.037	0.029	0.032	0.03	0.029	0.033	0.029	0.026	0.015	0.025	0.013	0.005	0.013	0.007	0.01	0.008		0.014	0.016	0.017	0.016	0.014	0.022	0.01	0.01	0.006
O2	G2	0.013	0.028	0.033	0.04	0.04	0.055	0.039	0.03	0.038	0.017	0.017	**0.033**	0.017	0.006	0.01	0.018	0.005	0.023		0.017	0.022	0.019	0.018	0.011	0.022	0.01	0.01	**0.011**
	G3	-	-	-	-	-	-	-	-	-	0.008	0.011	0.011	0.011	0.007	0.008	0.017	0.013	0.02		0.018	0.02	**0.019**	0.012	0.02	0.014	0.01	0.02	0.007
	G1	0.033	0.014	0.019	0.02	0.033	0.013	0.022	0.026	0.018	0.009	0.014	0.013	0.011	0.013	0.014	0.012	0.018	0.015		0.011	0.021	0.017	0.011	0.014	0.021	0.01	0.01	0.008
O3	G2	0.021	0.043	0.072	0.026	0.026	0.03	0.032	0.027	0.041	0.007	0.009	0.018	0.009	0.008	0.014	0.005	0.01	0.01		**0.023**	**0.023**	0.023	0.01	0.016	0.01	0.02	0.01	**0.013**
	G3	-	-	-	-	-	-	-	-	-	0.01	0.007	0.01	0.008	0.012	0.006	-	-	-		0.013	0.021	0.019	0.012	0.014	0.016	0.01	0.01	0.02

G1 = Top gating O1=Down T1= 3/4 inch thickness M1=Resin Bonded Sand
G2 = Bottom gating O2=Up T2= 1/2 inch thickness M2=Lost Foam Low Expansion
G3 = Side gating O3=Side T3= 1/4 inch thickness M3=Lost Foam Silica Sand

Table A. 10 Experimental Design of the Project
(Right Wall Flatness)

		Mold Type																											
		M1									M2										M3								
		Thickness																											
Orientation	Gating	T1			T2			T3			T1			T2			T3			T1			T2			T3		
	G1	0.035	0.031	0.09	0.022	0.039	0.036	0.031	0.024	0.024	0.012	0.005	0.107	0.057	0.048	0.025	0.017	0.024	0.006	0.018	0.019	0.02	0.023	0.023	**0.023**	0.023	0.04	0.04
O1	G2	0.01	0.022	0.014	0.046	0.047	0.037	0.037	0.033	0.042	0.032	0.04	0.178	0.025	0.013	0.093	0.023	0.041	0.05	0.017	0.021	0.02	**0.015**	0.018	0.012	0.042	0.03	0.1
	G3	-	-	-	-	-	-	-	-	-	0.043	0.06	0.119	0.139	0.06	0.009	0.049	0.06	0.06	0.021	0.022	**0.02**	0.02	0.017	0.143	0.025	0.03	0.03
	G1	0.027	0.017	0.112	0.021	0.038	0.022	0.02	0.025	0.02	0.051	0.111	0.065	0.03	0.045	0.039	0.01	0.011	0.016	0.024	0.01	0.01	0.017	0.016	0.013	0.008	0.04	0.01
O2	G2	0.01	0.013	0.02	0.046	0.032	0.036	0.033	0.028	0.04	0.054	0.027	**0.081**	0.018	0.012	0.029	0.031	0.02	0.015	0.015	0.018	0.02	0.013	0.012	0.017	0.01	0.01	**0.01**
	G3	-	-	-	-	-	-	-	-	-	0.021	0.06	0.03	0.042	0.037	0.034	0.032	0.031	0.015	0.02	0.01	**0.02**	0.015	0.022	0.018	0.015	0.03	0.05
	G1	0.044	0.064	0.029	0.018	0.018	0.012	0.026	0.023	0.02	0.1	0.07	0.03	0.055	0.046	0.018	0.018	0.038	0.043	0.018	0.015	0.02	0.016	0.016	0.013	0.017	0.01	0.03
O3	G2	0.024	0.029	0.054	0.028	0.033	0.037	0.045	0.028	0.044	0.085	0.089	0.114	0.018	0.043	0.028	0.009	0.026	0.011	**0.011**	**0.011**	0.01	0.012	0.019	0.019	0.052	0.02	**0.04**
	G3	-	-	-	-	-	-	-	-	-	0.043	0.029	0.038	0.036	0.013	0.013	-	-	-	0.018	0.011	0.01	0.013	0.016	0.012	0.02	0.04	0.05

G1 = Top gating
G2 = Bottom gating
G3 = Side gating

O1=Down
O2=Up
O3=Side

T1= 3/4 inch thickness
T2= 1/2 inch thickness
T3= 1/4 inch thickness

M1=Resin Bonded Sand
M2=Lost Foam Low Expansion
M3=Lost Foam Silica Sand

APPENDIX B

(ANOVA and Newman Keuls)

Table B.1 Factorial Analysis of Variance Thickness of Resin Bonded Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0027	4	0.0007	2.1275	0.0974	3.890307	FALSE	2.633534	FALSE
GO	0.0006	2	0.0003	0.9464	0.3976	5.247898	FALSE	3.259444	FALSE
GT	0.0001	2	5.86E-05	0.1868	0.8304	5.247898	FALSE	3.259444	FALSE
G	0.0004	1	0.0004	1.3099	0.26	7.395556	FALSE	4.113161	FALSE
OT	0.0015	4	0.0004	1.181	0.3356	3.890307	FALSE	2.633534	FALSE
O	0.0037	2	0.0018	5.8593	0.0063	5.247898	TRUE	3.259444	TRUE
T	2.4372	2	1.2186	3885.551	0	5.247898	TRUE	3.259444	TRUE
Error	0.0113	36	0.0003						
Total	2.4575	53							

Table B.2 Factorial Analysis of Variance Height of Resin Bonded Castings
(all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0014	4	0.0003	1.2769	0.2971	3.890307	FALSE	2.633534	FALSE
GO	0.0044	2	0.0022	8.2081	0.0012	5.247898	TRUE	3.259444	TRUE
GT	0.0008	2	0.0004	1.5904	0.2178	5.247898	FALSE	3.259444	FALSE
G	0.0043	1	0.0043	16.0489	0.0003	7.395556	TRUE	4.113161	TRUE
OT	0.005	4	0.0013	4.7338	0.0036	3.890307	TRUE	2.633534	TRUE
O	0.002	2	0.001	3.7013	0.0345	5.247898	FALSE	3.259444	TRUE
T	0.0041	2	0.0021	7.7584	0.0016	5.247898	TRUE	3.259444	TRUE
Error	0.0096	36	0.0003						
Total	0.0316	53							

Table B.3 Factorial Analysis of Variance Length of Resin Bonded Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0005	4	0.0001	0.9149	0.4658	3.890307	FALSE	2.633534	FALSE
GO	0.0002	2	0.0001	0.9595	0.3927	5.247898	FALSE	3.259444	FALSE
GT	0.0006	2	0.0003	2.3997	0.1051	5.247898	FALSE	3.259444	FALSE
G	0.0004	1	0.0004	3.1504	0.0844	7.395556	FALSE	4.113161	FALSE
OT	0.0011	4	0.0003	2.1631	0.093	3.890307	FALSE	2.633534	FALSE
O	0.0044	2	0.0022	17.0789	6.08E-06	5.247898	TRUE	3.259444	TRUE
T	0.0263	2	0.0131	102.6046	1.35E-15	5.247898	TRUE	3.259444	TRUE
Error	0.0046	36	0.0001						
Total	0.0381	53							

Table B.4 Factorial Analysis of Variance Parallelism of Resin Bonded Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0549	4	0.0137	2.8689	0.0368	3.890307	FALSE	2.633534	TRUE
GO	0.0445	2	0.0223	4.6524	0.016	5.247898	FALSE	3.259444	TRUE
GT	0.0532	2	0.0266	5.557	0.0079	5.247898	TRUE	3.259444	TRUE
G	0.013	1	0.013	2.7127	0.1083	7.395556	FALSE	4.113161	FALSE
OT	0.0054	4	0.0013	0.2797	0.8892	3.890307	FALSE	2.633534	FALSE
O	0.0141	2	0.0071	1.4735	0.2426	5.247898	FALSE	3.259444	FALSE
T	0.0599	2	0.03	6.2606	0.0046	5.247898	TRUE	3.259444	TRUE
Error	0.1723	36	0.0048						
Total	0.4174	53							

Table B.5 Factorial Analysis of Variance Left Casting Angle of Resin Bonded Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0006	4	0.0002	2.2933	0.0783	3.890307	FALSE	2.633534	FALSE
GO	0.0005	2	0.0002	3.4268	0.0434	5.247898	FALSE	3.259444	TRUE
GT	0.0002	2	8.36E-05	1.2268	0.3052	5.247898	FALSE	3.259444	FALSE
G	0.0004	1	0.0004	6.4986	0.0152	7.395556	FALSE	4.113161	TRUE
OT	0.0005	4	0.0001	1.9545	0.1225	3.890307	FALSE	2.633534	FALSE
O	0.0005	2	0.0002	3.5362	0.0396	5.247898	FALSE	3.259444	TRUE
T	0.0014	2	0.0007	10.5837	0.0002	5.247898	TRUE	3.259444	TRUE
Error	0.0025	36	6.81E-05						
Total	0.0066	53							

Table B.6 Factorial Analysis of Variance Right Casting Angle of Resin Bonded Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0534	4	0.0134	2.272	0.0805	3.890307	FALSE	2.633534	FALSE
GO	0.0403	2	0.0201	3.4242	0.0435	5.247898	FALSE	3.259444	TRUE
GT	0.0069	2	0.0034	0.5868	0.5614	5.247898	FALSE	3.259444	FALSE
G	0.0023	1	0.0023	0.3966	0.5328	7.395556	FALSE	4.113161	FALSE
OT	0.0076	4	0.0019	0.3252	0.8592	3.890307	FALSE	2.633534	FALSE
O	0.0017	2	0.0008	0.1427	0.8675	5.247898	FALSE	3.259444	FALSE
T	0.0783	2	0.0391	6.658	0.0035	5.247898	TRUE	3.259444	TRUE
Error	0.2116	36	0.0059						
Total	0.4021	53							

Table B.7 Factorial Analysis of Variance Left Flange Flatness of Resin Bonded Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0005	4	0.0001	2.1872	0.09	3.890307	FALSE	2.633534	FALSE
GO	0.0011	2	0.0006	9.5365	0.0005	5.247898	TRUE	3.259444	TRUE
GT	0.0002	2	8.03E-05	1.3571	0.2703	5.247898	FALSE	3.259444	FALSE
G	0.0008	1	0.0008	12.898	0.001	7.395556	TRUE	4.113161	TRUE
OT	0.0003	4	7.81E-05	1.3205	0.281	3.890307	FALSE	2.633534	FALSE
O	0.001	2	0.0005	8.7834	0.0008	5.247898	TRUE	3.259444	TRUE
T	0.0002	2	8.39E-05	1.4172	0.2556	5.247898	FALSE	3.259444	FALSE
Error	0.0021	36	5.92E-05						
Total	0.0062	53							

Table B.8 Factorial Analysis of Variance Right Flange Flatness of Resin Bonded Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	3.79E-05	4	9.46E-06	0.123	0.9733	3.890307	FALSE	2.633534	FALSE
GO	0.0005	2	0.0002	3.0883	0.0578	5.247898	FALSE	3.259444	FALSE
GT	6.26E-06	2	3.13E-06	0.0407	0.9602	5.247898	FALSE	3.259444	FALSE
G	0.0001	1	0.0001	1.6584	0.206	7.395556	FALSE	4.113161	FALSE
OT	3.03E-05	4	7.57E-06	0.0985	0.9823	3.890307	FALSE	2.633534	FALSE
O	0.0003	2	0.0001	1.8519	0.1716	5.247898	FALSE	3.259444	FALSE
T	0.0002	2	9.87E-05	1.2829	0.2896	5.247898	FALSE	3.259444	FALSE
Error	0.0028	36	7.69E-05						
Total	0.0039	53							

Table B.9 Factorial Analysis of Variance Left Wall Flatness of Resin Bonded Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0011	4	0.0003	3.3953	0.0187	3.890307	FALSE	2.633534	TRUE
GO	0.0005	2	0.0003	3.2831	0.049	5.247898	FALSE	3.259444	TRUE
GT	0.0004	2	0.0002	2.1825	0.1275	5.247898	FALSE	3.259444	FALSE
G	0.0003	1	0.0003	3.5081	0.0692	7.395556	FALSE	4.113161	FALSE
OT	0.0009	4	0.0002	2.7857	0.041	3.890307	FALSE	2.633534	TRUE
O	0.0003	2	0.0002	1.8673	0.1692	5.247898	FALSE	3.259444	FALSE
T	0.0001	2	5.17E-05	0.6266	0.5401	5.247898	FALSE	3.259444	FALSE
Error	0.003	36	8.25E-05						
Total	0.0066	53							

Table B.10 Factorial Analysis of Variance Right Wall Flatness of Resin Bonded Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0003	4	8.18E-05	0.2999	0.8761	3.890307	FALSE	2.633534	FALSE
GO	0.0005	2	0.0002	0.8513	0.4353	5.247898	FALSE	3.259444	FALSE
GT	0.0051	2	0.0025	9.2658	0.0006	5.247898	TRUE	3.259444	TRUE
G	7.41E-06	1	7.41E-06	0.0271	0.8701	7.395556	FALSE	4.113161	FALSE
OT	0.0007	4	0.0002	0.6568	0.626	3.890307	FALSE	2.633534	FALSE
O	0.0001	2	5.36E-05	0.1965	0.8224	5.247898	FALSE	3.259444	FALSE
T	0.0003	2	0.0002	0.5754	0.5676	5.247898	FALSE	3.259444	FALSE
Error	0.0098	36	0.0003						
Total	0.0168	53							

Table B.11 Factorial Analysis of Variance: Height of Lost Foam Low Expansion Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0179	4	0.0045	2.5664	0.0546	3.890307	FALSE	2.633534	FALSE
GO	0.0149	2	0.0075	4.2839	0.0214	5.247898	FALSE	3.259444	TRUE
GT	0.0069	2	0.0034	1.9726	0.1539	5.247898	FALSE	3.259444	FALSE
G	0.0036	1	0.0036	2.0684	0.159	7.395556	FALSE	4.113161	FALSE
OT	0.0058	4	0.0014	0.827	0.5168	3.890307	FALSE	2.633534	FALSE
O	0.0089	2	0.0045	2.5538	0.0918	5.247898	FALSE	3.259444	FALSE
T	0.0125	2	0.0063	3.5968	0.0377	5.247898	FALSE	3.259444	TRUE
Error	0.0627	36	0.0017						
Total	0.1332	53							

Table B.12 Factorial Analysis of Variance: Right Wall Flatness of Lost Foam Low Expansion Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0026	4	0.0006	0.516	0.7244	3.890307	FALSE	2.633534	FALSE
GO	0.0021	2	0.001	0.8295	0.4444	5.247898	FALSE	3.259444	FALSE
GT	0.0017	2	0.0008	0.6774	0.5143	5.247898	FALSE	3.259444	FALSE
G	0.0005	1	0.0005	0.4222	0.52	7.395556	FALSE	4.113161	FALSE
OT	0.0039	4	0.001	0.772	0.5506	3.890307	FALSE	2.633534	FALSE
O	0.0016	2	0.0008	0.6393	0.5336	5.247898	FALSE	3.259444	FALSE
T	0.0133	2	0.0067	5.308	0.0095	5.247898	TRUE	3.259444	TRUE
Error	0.0451	36	0.0013						
Total	0.0708	53							

Table B.13 Factorial Analysis of Variance: Right Flange Flatness of Lost Foam Low Expansion Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0805	4	0.0201	2.74	0.0435	3.890307	FALSE	2.633534	TRUE
GO	0.063	2	0.0315	4.2875	0.0214	5.247898	FALSE	3.259444	TRUE
GT	0.0483	2	0.0241	3.2857	0.0489	5.247898	FALSE	3.259444	TRUE
G	0.0455	1	0.0455	6.1969	0.0176	7.395556	FALSE	4.113161	TRUE
OT	0.0516	4	0.0129	1.7574	0.1589	3.890307	FALSE	2.633534	FALSE
O	0.0653	2	0.0327	4.4467	0.0188	5.247898	FALSE	3.259444	TRUE
T	0.1307	2	0.0654	8.8957	0.0007	5.247898	TRUE	3.259444	TRUE
Error	0.2645	36	0.0073						
Total	0.7495	53							

Table B.14 Factorial Analysis of Variance: Left Wall Flatness of Lost Foam Low Expansion Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0002	4	4.69E-05	1.9366	0.1254	3.890307	FALSE	2.633534	FALSE
GO	8.81E-05	2	4.41E-05	1.8174	0.177	5.247898	FALSE	3.259444	FALSE
GT	6.74E-05	2	3.37E-05	1.3911	0.2618	5.247898	FALSE	3.259444	FALSE
G	1.50E-06	1	1.50E-06	0.0619	0.805	7.395556	FALSE	4.113161	FALSE
OT	0.0002	4	5.93E-05	2.4461	0.064	3.890307	FALSE	2.633534	FALSE
O	0.0001	2	5.61E-05	2.3155	0.1132	5.247898	FALSE	3.259444	FALSE
T	0.0004	2	0.0002	7.2429	0.0023	5.247898	TRUE	3.259444	TRUE
Error	0.0009	36	2.42E-05						
Total	0.0019	53							

Table B.15 Factorial Analysis of Variance: Left Flange Flatness of Lost Foam Low Expansion Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0001	4	2.71E-05	0.7888	0.5401	3.890307	FALSE	2.633534	FALSE
GO	7.81E-05	2	3.91E-05	1.1363	0.3322	5.247898	FALSE	3.259444	FALSE
GT	0.0002	2	9.09E-05	2.6444	0.0848	5.247898	FALSE	3.259444	FALSE
G	4.27E-05	1	4.27E-05	1.2414	0.2726	7.395556	FALSE	4.113161	FALSE
OT	9.23E-05	4	2.31E-05	0.6713	0.6162	3.890307	FALSE	2.633534	FALSE
O	0.0006	2	0.0003	9.2365	0.0006	5.247898	TRUE	3.259444	TRUE
T	6.86E-05	2	3.43E-05	0.9978	0.3786	5.247898	FALSE	3.259444	FALSE
Error	0.0012	36	3.44E-05						
Total	0.0024	53							

Table B.16 Factorial Analysis of Variance: Left Casting Angle of Lost Foam Low Expansion Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0002	4	4.53E-05	2.1153	0.099	3.890307	FALSE	2.633534	FALSE
GO	0.0002	2	8.91E-05	4.159	0.0237	5.247898	FALSE	3.259444	TRUE
GT	3.10E-05	2	1.55E-05	0.7226	0.4924	5.247898	FALSE	3.259444	FALSE
G	2.67E-07	1	2.67E-07	0.0125	0.9117	7.395556	FALSE	4.113161	FALSE
OT	6.42E-05	4	1.61E-05	0.7491	0.5651	3.890307	FALSE	2.633534	FALSE
O	1.90E-07	2	9.50E-08	0.0044	0.9956	5.247898	FALSE	3.259444	FALSE
T	0.0013	2	0.0006	30.238	1.97E-08	5.247898	TRUE	3.259444	TRUE
Error	0.0008	36	2.14E-05						
Total	0.0025	53							

Table B.17 Factorial Analysis of Variance: Right Casting Angle of Lost Foam Low Expansion Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0011	4	0.0003	0.4982	0.7372	3.890307	FALSE	2.633534	FALSE
GO	0.0008	2	0.0004	0.7756	0.468	5.247898	FALSE	3.259444	FALSE
GT	0.0013	2	0.0007	1.2253	0.3056	5.247898	FALSE	3.259444	FALSE
G	8.66E-05	1	8.66E-05	0.1583	0.6931	7.395556	FALSE	4.113161	FALSE
OT	0.0018	4	0.0005	0.8278	0.5163	3.890307	FALSE	2.633534	FALSE
O	0.0016	2	0.0008	1.503	0.2361	5.247898	FALSE	3.259444	FALSE
T	0.0007	2	0.0004	0.6777	0.5141	5.247898	FALSE	3.259444	FALSE
Error	0.0197	36	0.0005						
Total	0.0273	53							

Table B.18 Factorial Analysis of Variance: Length of Lost Foam Low Expansion Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0005	4	0.0001	0.9149	0.4658	3.890307	FALSE	2.633534	FALSE
GO	0.0002	2	0.0001	0.9595	0.3927	5.247898	FALSE	3.259444	FALSE
GT	0.0006	2	0.0003	2.3997	0.1051	5.247898	FALSE	3.259444	FALSE
G	0.0004	1	0.0004	3.1504	0.0844	7.395556	FALSE	4.113161	FALSE
OT	0.0011	4	0.0003	2.1631	0.093	3.890307	FALSE	2.633534	FALSE
O	0.0044	2	0.0022	17.0789	6.08E-06	5.247898	TRUE	3.259444	TRUE
T	0.0263	2	0.0131	102.6046	1.35E-15	5.247898	TRUE	3.259444	TRUE
Error	0.0046	36	0.0001						
Total	0.0381	53							

Table B.19 Factorial Analysis of Variance: Parallelism of Lost Foam Low Expansion Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0061	4	0.0015	1.3167	0.2823	3.890307	FALSE	2.633534	FALSE
GO	0.0049	2	0.0024	2.0834	0.1393	5.247898	FALSE	3.259444	FALSE
GT	0.0025	2	0.0012	1.0706	0.3535	5.247898	FALSE	3.259444	FALSE
G	0.0013	1	0.0013	1.0948	0.3024	7.395556	FALSE	4.113161	FALSE
OT	0.0037	4	0.0009	0.8013	0.5324	3.890307	FALSE	2.633534	FALSE
O	0.003	2	0.0015	1.2954	0.2862	5.247898	FALSE	3.259444	FALSE
T	0.0189	2	0.0094	8.0851	0.0013	5.247898	TRUE	3.259444	TRUE
Error	0.042	36	0.0012						
Total	0.0825	53							

Table B.20 Factorial Analysis of Variance: Thickness of Lost Foam Low Expansion Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0005	4	0.0001	0.2179	0.9267	3.890307	FALSE	2.633534	FALSE
GO	0.0203	2	0.0101	16.6954	7.41E-06	5.247898	TRUE	3.259444	TRUE
GT	0.0005	2	0.0002	0.3939	0.6773	5.247898	FALSE	3.259444	FALSE
G	0.0003	1	0.0003	0.4514	0.506	7.395556	FALSE	4.113161	FALSE
OT	0.0014	4	0.0003	0.5604	0.6928	3.890307	FALSE	2.633534	FALSE
O	0.0075	2	0.0037	6.1471	0.0051	5.247898	TRUE	3.259444	TRUE
T	2.4048	2	1.2024	1982.49	0	5.247898	TRUE	3.259444	TRUE
Error	0.0218	36	0.0006						
Total	2.457	53							

Table B.21 Factorial Analysis of Variance: Height of Lost Foam Silica Sand Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0177	4	0.0044	7.7947	0.0001	3.890307	TRUE	2.633534	TRUE
GO	0.013	2	0.0065	11.4652	0.0001	5.247898	TRUE	3.259444	TRUE
GT	0.0008	2	0.0004	0.7462	0.4813	5.247898	FALSE	3.259444	FALSE
G	0.0015	1	0.0015	2.7087	0.1085	7.395556	FALSE	4.113161	FALSE
OT	0.0068	4	0.0017	3.0185	0.0303	3.890307	FALSE	2.633534	TRUE
O	0.0061	2	0.003	5.3521	0.0092	5.247898	TRUE	3.259444	TRUE
T	0.1018	2	0.0509	89.8565	1.01E-14	5.247898	TRUE	3.259444	TRUE
Error	0.0204	36	0.0006						
Total	0.1332	53							

Table B.22 Factorial Analysis of Variance: Right Wall Flatness of Lost Foam Silica Sand Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0026	4	0.0006	0.516	0.7244	3.890307	FALSE	2.633534	FALSE
GO	0.0021	2	0.001	0.8295	0.4444	5.247898	FALSE	3.259444	FALSE
GT	0.0017	2	0.0008	0.6774	0.5143	5.247898	FALSE	3.259444	FALSE
G	0.0005	1	0.0005	0.4222	0.52	7.395556	FALSE	4.113161	FALSE
OT	0.0039	4	0.001	0.772	0.5506	3.890307	FALSE	2.633534	FALSE
O	0.0016	2	0.0008	0.6393	0.5336	5.247898	FALSE	3.259444	FALSE
T	0.0133	2	0.0067	5.308	0.0095	5.247898	TRUE	3.259444	TRUE
Error	0.0451	36	0.0013						
Total	0.0708	53							

Table B.23 Factorial Analysis of Variance: Right Flange Flatness of Lost Foam Silica Sand Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0805	4	0.0201	2.74	0.0435	3.890307	FALSE	2.633534	TRUE
GO	0.063	2	0.0315	4.2875	0.0214	5.247898	FALSE	3.259444	TRUE
GT	0.0483	2	0.0241	3.2857	0.0489	5.247898	FALSE	3.259444	TRUE
G	0.0455	1	0.0455	6.1969	0.0176	7.395556	FALSE	4.113161	TRUE
OT	0.0516	4	0.0129	1.7574	0.1589	3.890307	FALSE	2.633534	FALSE
O	0.0653	2	0.0327	4.4467	0.0188	5.247898	FALSE	3.259444	TRUE
T	0.1307	2	0.0654	8.8957	0.0007	5.247898	TRUE	3.259444	TRUE
Error	0.2645	36	0.0073						
Total	0.7495	53							

Table B.24 Factorial Analysis of Variance: Left Wall Flatness of Lost Foam Silica Sand Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0002	4	4.69E-05	1.9366	0.1254	3.890307	FALSE	2.633534	FALSE
GO	8.81E-05	2	4.41E-05	1.8174	0.177	5.247898	FALSE	3.259444	FALSE
GT	6.74E-05	2	3.37E-05	1.3911	0.2618	5.247898	FALSE	3.259444	FALSE
G	1.50E-06	1	1.50E-06	0.0619	0.805	7.395556	FALSE	4.113161	FALSE
OT	0.0002	4	5.93E-05	2.4461	0.064	3.890307	FALSE	2.633534	FALSE
O	0.0001	2	5.61E-05	2.3155	0.1132	5.247898	FALSE	3.259444	FALSE
T	0.0004	2	0.0002	7.2429	0.0023	5.247898	TRUE	3.259444	TRUE
Error	0.0009	36	2.42E-05						
Total	0.0019	53							

Table B.25 Factorial Analysis of Variance: Left Flange Flatness of Lost Foam Silica Sand Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0001	4	2.71E-05	0.7888	0.5401	3.890307	FALSE	2.633534	FALSE
GO	7.81E-05	2	3.91E-05	1.1363	0.3322	5.247898	FALSE	3.259444	FALSE
GT	0.0002	2	9.09E-05	2.6444	0.0848	5.247898	FALSE	3.259444	FALSE
G	4.27E-05	1	4.27E-05	1.2414	0.2726	7.395556	FALSE	4.113161	FALSE
OT	9.23E-05	4	2.31E-05	0.6713	0.6162	3.890307	FALSE	2.633534	FALSE
O	0.0006	2	0.0003	9.2365	0.0006	5.247898	TRUE	3.259444	TRUE
T	6.86E-05	2	3.43E-05	0.9978	0.3786	5.247898	FALSE	3.259444	FALSE
Error	0.0012	36	3.44E-05						
Total	0.0024	53							

B.26 Factorial Analysis of Variance: Left Casting Angle of Lost Foam Silica Sand Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0001	4	3.39E-05	2.3151	0.076	3.890307	FALSE	2.633534	FALSE
GO	5.32E-05	2	2.66E-05	1.8161	0.1772	5.247898	FALSE	3.259444	FALSE
GT	2.58E-05	2	1.29E-05	0.8798	0.4236	5.247898	FALSE	3.259444	FALSE
G	4.39E-05	1	4.39E-05	2.9985	0.0919	7.395556	FALSE	4.113161	FALSE
OT	5.51E-05	4	1.38E-05	0.941	0.4515	3.890307	FALSE	2.633534	FALSE
O	8.25E-05	2	4.12E-05	2.8148	0.0731	5.247898	FALSE	3.259444	FALSE
T	0.0001	2	7.13E-05	4.8647	0.0135	5.247898	FALSE	3.259444	TRUE
Error	0.0005	36	1.47E-05						
Total	0.0011	53							

Table B.27 Factorial Analysis of Variance: Right Casting Angle of Lost Foam Silica Sand Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0184	4	0.0046	22.3856	2.38E-09	3.890307	TRUE	2.633534	TRUE
GO	0.009	2	0.0045	21.7871	6.30E-07	5.247898	TRUE	3.259444	TRUE
GT	0.0014	2	0.0007	3.5252	0.04	5.247898	FALSE	3.259444	TRUE
G	0.0004	1	0.0004	1.9512	0.171	7.395556	FALSE	4.113161	FALSE
OT	0.0026	4	0.0006	3.1607	0.0252	3.890307	FALSE	2.633534	TRUE
O	0.0016	2	0.0008	3.7821	0.0323	5.247898	FALSE	3.259444	TRUE
T	0.1021	2	0.051	248.5019	8.56E-22	5.247898	TRUE	3.259444	TRUE
Error	0.0074	36	0.0002						
Total	0.1428	53							

Table B.28 Factorial Analysis of Variance: Length of Lost Foam Silica Sand Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.1562	4	0.0391	2.6478	0.0491	3.890307	FALSE	2.633534	TRUE
GO	0.0818	2	0.0409	2.7731	0.0758	5.247898	FALSE	3.259444	FALSE
GT	0.0036	2	0.0018	0.1229	0.8847	5.247898	FALSE	3.259444	FALSE
G	0.0024	1	0.0024	0.1629	0.6889	7.395556	FALSE	4.113161	FALSE
OT	0.2663	4	0.0666	4.5141	0.0047	3.890307	TRUE	2.633534	TRUE
O	0.111	2	0.0555	3.7641	0.0328	5.247898	FALSE	3.259444	TRUE
T	0.0739	2	0.0369	2.5039	0.0959	5.247898	FALSE	3.259444	FALSE
Error	0.531	36	0.0147						
Total	1.2262	53							

Table B.29 Factorial Analysis of Variance: Parallelism of Lost Foam Silica Sand Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0029	4	0.0007	1.4093	0.2506	3.890307	FALSE	2.633534	FALSE
GO	0.0034	2	0.0017	3.2427	0.0507	5.247898	FALSE	3.259444	FALSE
GT	0.0151	2	0.0075	14.4775	2.43E-05	5.247898	TRUE	3.259444	TRUE
G	0.0074	1	0.0074	14.2065	0.0006	7.395556	TRUE	4.113161	TRUE
OT	0.0149	4	0.0037	7.1702	0.0002	3.890307	TRUE	2.633534	TRUE
O	0.0022	2	0.0011	2.1543	0.1307	5.247898	FALSE	3.259444	FALSE
T	0.1887	2	0.0944	181.2317	1.61E-19	5.247898	TRUE	3.259444	TRUE
Error	0.0187	36	0.0005						
Total	0.2534	53							

Table B.30 Factorial Analysis of Variance: Thickness of Lost Foam Silica Sand Castings (all)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3
T=Thickness	3

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GOT	0.0176	4	0.0044	74.355	6.78E-17	3.890307	TRUE	2.633534	TRUE
GO	0.0096	2	0.0048	80.9879	4.73E-14	5.247898	TRUE	3.259444	TRUE
GT	0.0118	2	0.0059	99.9961	2.00E-15	5.247898	TRUE	3.259444	TRUE
G	0.0043	1	0.0043	72.2434	3.96E-10	7.395556	TRUE	4.113161	TRUE
OT	0.0199	4	0.005	84.0902	9.40E-18	3.890307	TRUE	2.633534	TRUE
O	0.0084	2	0.0042	71.254	3.05E-13	5.247898	TRUE	3.259444	TRUE
T	1.9984	2	0.9992	16923.77	0	5.247898	TRUE	3.259444	TRUE
Error	0.0021	36	5.90E-05						
Total	2.072	53							

Table B.31 Factorial Analysis of Variance

Resin Bonded Castings

(0.25 inch)

Number of Factors = 2	Number of Replicates = 3
Factor	Levels
G=Gating System	2
O=Orientation	3

Left Flange Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	4.31E-05	2	2.16E-05	0.728	0.503	6.926598	FALSE	3.88529	FALSE
G	4.67E-05	1	4.67E-05	1.5779	0.233	9.330279	FALSE	4.747221	FALSE
O	0.0002	2	9.96E-05	3.3621	0.0693	6.926598	FALSE	3.88529	FALSE
Error	0.0004	12	2.96E-05						
Total	0.0006	17							

Right Flange Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	2.00E-04	2	1.00E-04	1.8406	0.2008	6.926598	FALSE	3.88529	FALSE
G	2.01E-05	1	2.01E-05	0.3406	0.5703	9.330279	FALSE	4.747221	FALSE
O	0.0001	2	6.95E-05	1.1802	0.3405	6.926598	FALSE	3.88529	FALSE
Error	0.0007	12	5.89E-05						
Total	0.0011	17							

Left Wall Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0001	2	5.07E-05	0.958	0.4112	6.926598	FALSE	3.88529	FALSE
G	0.0003	1	0.0003	5.4454	0.0378	9.330279	FALSE	4.747221	TRUE
O	0.0005	2	0.0003	5.0294	0.0259	6.926598	FALSE	3.88529	TRUE
Error	0.0006	12	5.29E-05						
Total	0.0016	17							

Right Wall Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	2.10E-05	2	1.05E-05	0.3474	0.7134	6.926598	FALSE	3.88529	FALSE
G	8.00E-04	1	8.00E-04	25.1636	0.0003	9.330279	TRUE	4.747221	TRUE
O	5.83E-05	2	2.92E-05	0.9651	0.4087	6.926598	FALSE	3.88529	FALSE
Error	0.0004	12	3.02E-05						
Total	0.0012	17							

Table B.32 Factorial Analysis of Variance
Resin Bonded Castings
(0.25 inch)

Number of Factors = 2	Number of Replicates = 3
Factor	Levels
G=Gating System	2
O=Orientation	3

Height

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0033	2	1.70E-03	3.1661	0.0787	6.926598	FALSE	3.88529	FALSE
G	0.0038	1	0.0038	7.1934	0.02	9.330279	FALSE	4.747221	TRUE
O	0.0035	2	0.0018	3.3673	0.0691	6.926598	FALSE	3.88529	FALSE
Error	0.0063	12	0.0005						
Total	0.0169	17							

Length

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0002	2	7.98E-05	0.3691	0.6989	6.926598	FALSE	3.88529	FALSE
G	0.0008	1	0.0008	3.7416	0.077	9.330279	FALSE	4.747221	FALSE
O	0.0024	2	0.0012	5.493	0.0202	6.926598	FALSE	3.88529	TRUE
Error	0.0026	12	0.0002						
Total	0.0059	17							

Left Casting Angle

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0008	2	4.00E-04	3.7114	0.0556	6.926598	FALSE	3.88529	FALSE
G	2.84E-05	1	2.84E-05	0.2789	0.6071	9.330279	FALSE	4.747221	FALSE
O	0.0002	2	0.0001	1.1281	0.3557	6.926598	FALSE	3.88529	FALSE
Error	0.0012	12	0.0001						
Total	0.0022	17							

Right Casting Angle

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0922	2	4.61E-02	2.6597	0.1106	6.926598	FALSE	3.88529	FALSE
G	9.10E-03	1	9.10E-03	0.5254	0.4824	9.330279	FALSE	4.747221	FALSE
O	0.007	2	0.0035	0.2007	0.8208	6.926598	FALSE	3.88529	FALSE
Error	0.208	12	0.0173						
Total	0.3163	17							

Table B.33 Factorial Analysis of Variance
Resin Bonded Castings
(0.25 inch)

Number of Factors = 2	Number of Replicates = 3
Factor	Levels
G=Gating System	2
O=Orientation	3

Parallelism

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0957	2	0.0478	3.4831	0.0642	6.926598	FALSE	3.88529	FALSE
G	0.0646	1	0.0646	4.7028	0.0509	9.330279	FALSE	4.747221	FALSE
O	0.0129	2	0.0065	0.4714	0.6352	6.926598	FALSE	3.88529	FALSE
Error	0.1648	12	0.0137						
Total	0.3379	17							

Thickness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	1.18E-05	2	5.89E-06	0.0341	0.9666	6.926598	FALSE	3.88529	FALSE
G	1.80E-05	1	1.80E-05	0.1044	0.7522	9.330279	FALSE	4.747221	FALSE
O	0.0025	2	0.0013	7.3535	0.0082	6.926598	TRUE	3.88529	TRUE
Error	0.0021	12	0.0002						
Total	0.0046	17							

Table B.34 Factorial Analysis of Variance

Resin Bonded Castings

(0.50 inch)

Number of Factors = 2	Number of Replicates = 3
Factor	Levels
G=Gating System	2
O=Orientation	3

Left Flange Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0013	2	0.0006	5.8537	0.0168	6.926598	FALSE	3.88529	TRUE
G	0.0006	1	0.0006	5.6597	0.0348	9.330279	FALSE	4.747221	TRUE
O	0.0008	2	0.0004	3.7161	0.0555	6.926598	FALSE	3.88529	FALSE
Error	0.0013	12	0.0001						
Total	0.004	17							

Right Flange Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0001	2	7.41E-05	0.8617	0.447	6.926598	FALSE	3.88529	FALSE
G	5.69E-05	1	5.69E-05	0.6619	0.4317	9.330279	FALSE	4.747221	FALSE
O	8.81E-05	2	4.41E-05	0.5126	0.6115	6.926598	FALSE	3.88529	FALSE
Error	0.001	12	8.59E-05						
Total	0.0013	17							

Left Wall Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0001	2	5.07E-05	0.958	0.4112	6.926598	FALSE	3.88529	FALSE
G	0.0003	1	0.0003	5.4454	0.0378	9.330279	FALSE	4.747221	TRUE
O	0.0005	2	0.0003	5.0294	0.0259	6.926598	FALSE	3.88529	TRUE
Error	0.0006	12	5.29E-05						
Total	0.0016	17							

Right Wall Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	3.21E-05	2	1.61E-05	0.3345	0.7222	6.926598	FALSE	3.88529	FALSE
G	0.0007	1	0.0007	15.5741	0.0019	9.330279	TRUE	4.747221	TRUE
O	0.0006	2	0.0003	5.7789	0.0175	6.926598	FALSE	3.88529	TRUE
Error	0.0006	12	4.80E-05						
Total	0.0019	17							

Table B.35 Factorial Analysis of Variance
Resin Bonded Castings
(0.50 inch)

Number of Factors = 2		Number of Replicates = 3	
Factor		Levels	
G=Gating System		2	
O=Orientation		3	

Height

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0009	2	5.00E-04	3.6468	0.0579	6.926598	FALSE	3.88529	FALSE
G	0.0006	1	0.0006	4.4439	0.0567	9.330279	FALSE	4.747221	FALSE
O	0.0013	2	0.0006	5.1016	0.0249	6.926598	FALSE	3.88529	TRUE
Error	0.0015	12	0.0001						
Total	0.0043	17							

Length

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0005	2	0.0003	6.627	0.0115	6.926598	FALSE	3.88529	TRUE
G	0.0002	1	0.0002	4.0794	0.0663	9.330279	FALSE	4.747221	FALSE
O	0.0029	2	0.0014	35.2632	9.45E-06	6.926598	TRUE	3.88529	TRUE
Error	0.0005	12	4.08E-05						
Total	0.0041	17							

Left Casting Angle

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	3.60E-05	2	1.80E-05	0.3681	0.6996	6.926598	FALSE	3.88529	FALSE
G	7.36E-05	1	7.36E-05	1.5065	0.2432	9.330279	FALSE	4.747221	FALSE
O	0.0001	2	6.75E-05	1.3824	0.2882	6.926598	FALSE	3.88529	FALSE
Error	0.0006	12	4.89E-05						
Total	0.0008	17							

Right Casting Angle

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0002	2	0.0001	0.5	0.6186	6.926598	FALSE	3.88529	FALSE
G	6.81E-07	1	6.81E-07	0.0028	0.9583	9.330279	FALSE	4.747221	FALSE
O	0.0012	2	0.0006	2.5105	0.1228	6.926598	FALSE	3.88529	FALSE
Error	0.0029	12	0.0002						
Total	0.0043	17							

Table B.36 Factorial Analysis of Variance
Resin Bonded Castings
(0.50 inch)

Number of Factors = 2	Number of Replicates = 3
Factor	Levels
G=Gating System	2
O=Orientation	3

Parallelism

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0008	2	0.0004	0.7761	0.482	6.926598	FALSE	3.88529	FALSE
G	0.0009	1	0.0009	1.7801	0.2069	9.330279	FALSE	4.747221	FALSE
O	0.0049	2	0.0025	4.8467	0.0286	6.926598	FALSE	3.88529	TRUE
Error	0.0061	12	0.0005						
Total	0.0128	17							

Thickness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0005	2	0.0003	1.5315	0.2556	6.926598	FALSE	3.88529	FALSE
G	0.0004	1	0.0004	2.3155	0.154	9.330279	FALSE	4.747221	FALSE
O	0.0007	2	0.0004	2.1977	0.1537	6.926598	FALSE	3.88529	FALSE
Error	0.002	12	0.0002						
Total	0.0036	17							

Table B.37 Factorial Analysis of Variance
Resin Bonded Castings
(0.75 inch)

Number of Factors = 2	Number of Replicates = 3
Factor	Levels
G=Gating System	2
O=Orientation	3

Left Flange Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0003	2	0.0002	4.2353	0.0406	6.926598	FALSE	3.88529	TRUE
G	0.0003	1	0.0003	6.6681	0.024	9.330279	FALSE	4.747221	TRUE
O	0.0003	2	0.0002	4.3922	0.037	6.926598	FALSE	3.88529	TRUE
Error	0.0005	12	3.97E-05						
Total	0.0014	17							

Right Flange Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0001	2	7.41E-05	0.8617	0.447	6.926598	FALSE	3.88529	FALSE
G	5.69E-05	1	5.69E-05	0.6619	0.4317	9.330279	FALSE	4.747221	FALSE
O	8.81E-05	2	4.41E-05	0.5126	0.6115	6.926598	FALSE	3.88529	FALSE
Error	0.001	12	8.59E-05						
Total	0.0013	17							

Left Wall Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0015	2	0.0008	4.4897	0.035	6.926598	FALSE	3.88529	TRUE
G	3.20E-05	1	3.20E-05	0.1874	0.6727	9.330279	FALSE	4.747221	FALSE
O	0.0002	2	9.82E-05	0.575	0.5775	6.926598	FALSE	3.88529	FALSE
Error	0.002	12	0.0002						
Total	0.0038	17							

Right Wall Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0007	2	0.0004	0.4989	0.6192	6.926598	FALSE	3.88529	FALSE
G	0.0036	1	0.0036	4.803	0.0489	9.330279	FALSE	4.747221	TRUE
O	0.0002	2	0.0001	0.1425	0.8686	6.926598	FALSE	3.88529	FALSE
Error	0.0089	12	0.0007						
Total	0.0134	17							

Table B.38 Factorial Analysis of Variance
Resin Bonded Castings
(0.75 inch)

Number of Factors = 2	Number of Replicates = 3
Factor	Levels
G=Gating System	2
O=Orientation	3

Height

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0015	2	0.0007	5.019	0.0261	6.926598	FALSE	3.88529	TRUE
G	0.0008	1	0.0008	5.3251	0.0396	9.330279	FALSE	4.747221	TRUE
O	0.0022	2	0.0011	7.3818	0.0081	6.926598	TRUE	3.88529	TRUE
Error	0.0018	12	0.0001						
Total	0.0063	17							

Length

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	1.42E-05	2	7.12E-06	0.056	0.9458	6.926598	FALSE	3.88529	FALSE
G	4.29E-05	1	4.29E-05	0.337	0.5723	9.330279	FALSE	4.747221	FALSE
O	0.0002	2	0.0001	0.908	0.4293	6.926598	FALSE	3.88529	FALSE
Error	0.0015	12	0.0001						
Total	0.0018	17							

Left Casting Angle

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0003	2	0.0002	2.7953	0.1008	6.926598	FALSE	3.88529	FALSE
G	0.0005	1	0.0005	9.4517	0.0096	9.330279	TRUE	4.747221	TRUE
O	0.0006	2	0.0003	6.0455	0.0153	6.926598	FALSE	3.88529	TRUE
Error	0.0006	12	5.37E-05						
Total	0.0021	17							

Right Casting Angle

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0012	2	0.0006	10.0607	0.0027	6.926598	TRUE	3.88529	TRUE
G	0.0001	1	0.0001	1.98	0.1848	9.330279	FALSE	4.747221	FALSE
O	0.0012	2	0.0006	9.5522	0.0033	6.926598	TRUE	3.88529	TRUE
Error	0.0007	12	6.09E-05						
Total	0.0032	17							

Table B.39 Factorial Analysis of Variance
Resin Bonded Castings
(0.75 inch)

Number of Factors = 2	Number of Replicates = 3
Factor	Levels
G=Gating System	2
O=Orientation	3

Parallelism

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.003	2	0.0015	12.6439	0.0011	6.926598	TRUE	3.88529	TRUE
G	0.0007	1	0.0007	5.896	0.0318	9.330279	FALSE	4.747221	TRUE
O	0.0016	2	0.0008	6.5426	0.012	6.926598	FALSE	3.88529	TRUE
Error	0.0014	12	0.0001						
Total	0.0067	17							

Thickness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0027	2	0.0014	2.275	0.1453	6.926598	FALSE	3.88529	FALSE
G	0.0001	1	0.0001	0.2125	0.653	9.330279	FALSE	4.747221	FALSE
O	0.0019	2	0.0009	1.5697	0.248	6.926598	FALSE	3.88529	FALSE
Error	0.0072	12	0.0006						
Total	0.012	17							

Table B.40 Factorial Analysis of Variance
Lost Foam Low Expansion Castings
(0.25 inch)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3

Left Flange Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	4.21E-05	2	2.11E-05	1.1147	0.3597	6.926598	FALSE	3.8852903	FALSE
G	5.69E-05	1	5.69E-05	3.0118	0.1082	9.3302788	FALSE	4.7472213	FALSE
O	6.54E-05	2	3.27E-05	1.7324	0.2183	6.926598	FALSE	3.8852903	FALSE
Error	0.0002	12	1.89E-05						
Total	0.0004	17							

Right Flange Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0001	2	6.04E-05	0.3291	0.7259	6.926598	FALSE	3.8852903	FALSE
G	2.22E-05	1	2.22E-05	0.1211	0.7339	9.3302788	FALSE	4.7472213	FALSE
O	0.0031	2	0.0016	8.4508	0.0051	6.926598	TRUE	3.8852903	TRUE
Error	0.0022	12	0.0002						
Total	0.0054	17							

Left Wall Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0002	2	0.0001	5.4367	0.0209	6.926598	FALSE	3.8852903	TRUE
G	4.67E-05	1	4.67E-05	2.2668	0.158	9.3302788	FALSE	4.7472213	FALSE
O	2.33E-06	2	1.17E-06	0.0566	0.9452	6.926598	FALSE	3.8852903	FALSE
Error	0.0002	12	2.06E-05						
Total	0.0005	17							

Right Wall Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.001	2	0.0005	0.4538	0.6457	6.926598	FALSE	3.8852903	FALSE
G	0.0006	1	0.0006	0.5482	0.4733	9.3302788	FALSE	4.7472213	FALSE
O	0.0035	2	0.0018	1.6136	0.2395	6.926598	FALSE	3.8852903	FALSE
Error	0.0132	12	0.0011						
Total	0.0183	17							

Table B.41 Factorial Analysis of Variance
Lost Foam Low Expansion Castings
(0.25 inch)

Height

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0096	2	0.0048	2.2083	0.1525	6.926598	FALSE	3.8852903	FALSE
G	0.0083	1	0.0083	3.809	0.0747	9.3302788	FALSE	4.7472213	FALSE
O	0.0088	2	0.0044	2.0252	0.1747	6.926598	FALSE	3.8852903	FALSE
Error	0.026	12	0.0022						
Total	0.0526	17							

Length

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0002	2	7.98E-05	0.3691	0.6989	6.926598	FALSE	3.8852903	FALSE
G	0.0008	1	0.0008	3.7416	0.077	9.3302788	FALSE	4.7472213	FALSE
O	0.0024	2	0.0012	5.493	0.0202	6.926598	FALSE	3.8852903	TRUE
Error	0.0026	12	0.0002						
Total	0.0059	17							

Left Casting Angle

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0003	2	0.0002	2.5673	0.118	6.926598	FALSE	3.8852903	FALSE
G	2.33E-05	1	2.33E-05	0.3754	0.5515	9.3302788	FALSE	4.7472213	FALSE
O	4.19E-05	2	2.09E-05	0.3365	0.7208	6.926598	FALSE	3.8852903	FALSE
Error	0.0007	12	6.22E-05						
Total	0.0011	17							

Right Casting Angle

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0018	2	0.0009	0.8531	0.4504	6.926598	FALSE	3.8852903	FALSE
G	0.0012	1	0.0012	1.169	0.3009	9.3302788	FALSE	4.7472213	FALSE
O	0.0026	2	0.0013	1.2592	0.3188	6.926598	FALSE	3.8852903	FALSE
Error	0.0123	12	0.001						
Total	0.0179	17							

Table B.42 Factorial Analysis of Variance
Lost Foam Low Expansion Castings
(0.25 inch)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3

Parallelism

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0056	2	0.0028	1.5301	0.2559	6.926598	FALSE	3.8852903	FALSE
G	5.20E-05	1	5.20E-05	0.0284	0.8691	9.3302788	FALSE	4.7472213	FALSE
O	0.0052	2	0.0026	1.4118	0.2814	6.926598	FALSE	3.8852903	FALSE
Error	0.022	12	0.0018						
Total	0.0328	17							

Thickness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0058	2	0.0029	7.6652	0.0072	6.926598	TRUE	3.8852903	TRUE
G	1.99E-05	1	1.99E-05	0.0523	0.8229	9.3302788	FALSE	4.7472213	FALSE
O	0.0017	2	0.0009	2.2622	0.1467	6.926598	FALSE	3.8852903	FALSE
Error	0.0046	12	0.0004						
Total	0.0121	17							

Lost Foam Low Expansion Castings

(0.50 inch)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3

Left Flange Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	8.33E-06	2	4.17E-06	0.0707	0.9321	6.926598	FALSE	3.8852903	FALSE
G	5.00E-05	1	5.00E-05	0.8483	0.3752	9.3302788	FALSE	4.7472213	FALSE
O	0.0004	2	0.0002	3.0094	0.0872	6.926598	FALSE	3.8852903	FALSE
Error	0.0007	12	5.89E-05						
Total	0.0011	17							

Right Flange Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0035	2	0.0017	4.9576	0.027	6.926598	FALSE	3.8852903	TRUE
G	0.0043	1	0.0043	12.3498	0.0043	9.3302788	TRUE	4.7472213	TRUE
O	0.004	2	0.002	5.6589	0.0186	6.926598	FALSE	3.8852903	TRUE
Error	0.0042	12	0.0004						
Total	0.016	17							

Left Wall Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	1.30E-05	2	6.50E-06	0.5043	0.6162	6.926598	FALSE	3.8852903	FALSE
G	0	1	0	8.11E-28	1	9.3302788	FALSE	4.7472213	FALSE
O	8.33E-06	2	4.17E-06	0.3233	0.7299	6.926598	FALSE	3.8852903	FALSE
Error	0.0002	12	1.29E-05						
Total	0.0002	17							

Right Wall Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0003	2	0.0001	0.2815	0.7595	6.926598	FALSE	3.8852903	FALSE
G	0.0004	1	0.0004	0.8413	0.3771	9.3302788	FALSE	4.7472213	FALSE
O	0.0007	2	0.0003	0.7022	0.5148	6.926598	FALSE	3.8852903	FALSE
Error	0.0056	12	0.0005						
Total	0.0069	17							

Table B.45 Factorial Analysis of Variance
Lost Foam Low Expansion Castings
(0.50 inch)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3

Parallelism

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0049	2	0.0025	2.0413	0.1726	6.926598	FALSE	3.8852903	FALSE
G	0.0037	1	0.0037	3.0491	0.1063	9.3302788	FALSE	4.7472213	FALSE
O	0.0007	2	0.0004	0.3074	0.741	6.926598	FALSE	3.8852903	FALSE
Error	0.0145	12	0.0012						
Total	0.0239	17							

Thickness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0088	2	0.0044	3.3953	0.0678	6.926598	FALSE	3.8852903	FALSE
G	7.36E-06	1	7.36E-06	0.0057	0.9413	9.3302788	FALSE	4.7472213	FALSE
O	0.0042	2	0.0021	1.613	0.2396	6.926598	FALSE	3.8852903	FALSE
Error	0.0156	12	0.0013						
Total	0.0287	17							

Table B.46 Factorial Analysis of Variance

Lost Foam Low Expansion Castings

(0.50 inch)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3

Left Flange Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0001	2	6.81E-05	2.6923	0.1082	6.926598	FALSE	3.8852903	FALSE
G	0.0001	1	0.0001	4.6505	0.052	9.3302788	FALSE	4.7472213	FALSE
O	0.0003	2	0.0002	6.0725	0.0151	6.926598	FALSE	3.8852903	TRUE
Error	0.0003	12	2.53E-05						
Total	0.0009	17							

Right Flange Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.1399	2	0.07	3.2531	0.0743	6.926598	FALSE	3.8852903	FALSE
G	0.0895	1	0.0895	4.1596	0.064	9.3302788	FALSE	4.7472213	FALSE
O	0.1099	2	0.055	2.5554	0.119	6.926598	FALSE	3.8852903	FALSE
Error	0.2581	12	0.0215						
Total	0.5974	17							

Left Wall Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	3.88E-05	2	1.94E-05	0.4943	0.6219	6.926598	FALSE	3.8852903	FALSE
G	2.22E-05	1	2.22E-05	0.5666	0.4661	9.3302788	FALSE	4.7472213	FALSE
O	0.0003	2	0.0002	4.3187	0.0387	6.926598	FALSE	3.8852903	TRUE
Error	0.0005	12	3.92E-05						
Total	0.0009	17							

Right Wall Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0034	2	0.0017	0.7757	0.4822	6.926598	FALSE	3.8852903	FALSE
G	0.0012	1	0.0012	0.5616	0.4681	9.3302788	FALSE	4.7472213	FALSE
O	0.0013	2	0.0006	0.2912	0.7525	6.926598	FALSE	3.8852903	FALSE
Error	0.0264	12	0.0022						
Total	0.0323	17							

Table B.47 Factorial Analysis of Variance
Lost Foam Low Expansion Castings
(0.50 inch)

Height

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0119	2	0.006	24.5254	5.77E-05	6.926598	TRUE	3.8852903	TRUE
G	0.0015	1	0.0015	6.3565	0.0268	9.3302788	FALSE	4.7472213	TRUE
O	0.0047	2	0.0023	9.6696	0.0032	6.926598	TRUE	3.8852903	TRUE
Error	0.0029	12	0.0002						
Total	0.021	17							

Length

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	1.42E-05	2	7.12E-06	0.056	0.9458	6.926598	FALSE	3.8852903	FALSE
G	4.29E-05	1	4.29E-05	0.337	0.5723	9.3302788	FALSE	4.7472213	FALSE
O	0.0002	2	0.0001	0.908	0.4293	6.926598	FALSE	3.8852903	FALSE
Error	0.0015	12	0.0001						
Total	0.0018	17							

Left Casting Angle

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	4.00E-05	2	2.00E-05	15.8325	0.0004	6.926598	TRUE	3.8852903	TRUE
G	5.01E-06	1	5.01E-06	3.967	0.0697	9.3302788	FALSE	4.7472213	FALSE
O	1.71E-05	2	8.53E-06	6.7468	0.0109	6.926598	FALSE	3.8852903	TRUE
Error	1.52E-05	12	1.26E-06						
Total	7.73E-05	17							

Right Casting Angle

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	1.52E-05	2	7.59E-06	0.1021	0.9037	6.926598	FALSE	3.8852903	FALSE
G	1.66E-05	1	1.66E-05	0.2237	0.6447	9.3302788	FALSE	4.7472213	FALSE
O	6.45E-05	2	3.22E-05	0.4337	0.6579	6.926598	FALSE	3.8852903	FALSE
Error	0.0009	12	7.43E-05						
Total	0.001	17							

Table B.48 Factorial Analysis of Variance
Lost Foam Low Expansion Castings
(0.50 inch)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3

Parallelism

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0005	2	0.0002	0.5048	0.6159	6.926598	FALSE	3.8852903	FALSE
G	3.64E-05	1	3.64E-05	0.0792	0.7832	9.3302788	FALSE	4.7472213	FALSE
O	0.0008	2	0.0004	0.9219	0.4242	6.926598	FALSE	3.8852903	FALSE
Error	0.0055	12	0.0005						
Total	0.0069	17							

Thickness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0061	2	0.0031	22.3388	0.0072	6.926598	TRUE	3.8852903	TRUE
G	0.0007	1	0.0007	5.2988	0.8229	9.3302788	FALSE	4.7472213	TRUE
O	0.0029	2	0.0014	10.5852	0.1467	6.926598	TRUE	3.8852903	TRUE
Error	0.0016	12	0.0001						
Total	0.0114	17							

Table B.49 Factorial Analysis of Variance
Lost Foam Silica Sand Castings
(0.25 inch)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3

Left Flange Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0001	4	3.64E-05	2.2837	0.1002	4.579022	FALSE	2.927749	FALSE
G	6.90E-05	2	3.45E-05	2.1651	0.1437	6.012897	FALSE	3.554561	FALSE
O	0.0002	2	8.14E-05	5.1093	0.0175	6.012897	FALSE	3.554561	TRUE
Error	0.0003	18	1.59E-05						
Total	0.0007	26							

Right Flange Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0053	4	0.0013	0.5215	0.7211	4.579022	FALSE	2.927749	FALSE
G	0.0035	2	0.0018	0.6934	0.5128	6.012897	FALSE	3.554561	FALSE
O	0.0034	2	0.0017	0.6727	0.5227	6.012897	FALSE	3.554561	FALSE
Error	0.046	18	0.0026						
Total	0.0583	26							

Left Wall Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	2.77E-05	4	6.93E-06	0.3929	0.811	4.579022	FALSE	2.927749	FALSE
G	9.19E-06	2	4.59E-06	0.2605	0.7735	6.012897	FALSE	3.554561	FALSE
O	2.96E-05	2	1.48E-05	0.8403	0.4478	6.012897	FALSE	3.554561	FALSE
Error	0.0003	18	1.76E-05						
Total	0.0004	26							

Right Wall Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0019	4	0.0005	1.5623	0.2271	4.579022	FALSE	2.927749	FALSE
G	0.0007	2	0.0003	1.0697	0.364	6.012897	FALSE	3.554561	FALSE
O	0.0015	2	0.0007	2.3988	0.1192	6.012897	FALSE	3.554561	FALSE
Error	0.0056	18	0.0003						
Total	0.0097	26							

Table B.50 Factorial Analysis of Variance
Lost Foam Silica Sand Castings
(0.25 inch)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3

Height

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0316	4	0.0079	6.5195	0.002	4.579022	TRUE	2.927749	TRUE
G	0.0086	2	0.0043	3.5415	0.0505	6.012897	FALSE	3.554561	FALSE
O	0.0141	2	0.0071	5.8292	0.0112	6.012897	FALSE	3.554561	TRUE
Error	0.0218	18	0.0012						
Total	0.0762	26							

Length

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.3633	4	0.0908	3.0186	0.0455	4.579022	FALSE	2.927749	TRUE
G	0.0137	2	0.0068	0.2272	0.799	6.012897	FALSE	3.554561	FALSE
O	0.2588	2	0.1294	4.3	0.0298	6.012897	FALSE	3.554561	TRUE
Error	0.5417	18	0.0301						
Total	1.1775	26							

Left Casting Angle

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0002	4	4.17E-05	2.2304	0.1063	4.579022	FALSE	2.927749	FALSE
G	6.20E-05	2	3.10E-05	1.6569	0.2185	6.012897	FALSE	3.554561	FALSE
O	4.93E-05	2	2.46E-05	1.3169	0.2926	6.012897	FALSE	3.554561	FALSE
Error	0.0003	18	1.87E-05						
Total	0.0006	26							

Right Casting Angle

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0331	4	0.0083	15.0229	1.46E-05	4.579022	TRUE	2.927749	TRUE
G	0.0031	2	0.0016	2.8134	0.0865	6.012897	FALSE	3.554561	FALSE
O	0.001	2	0.0005	0.8909	0.4276	6.012897	FALSE	3.554561	FALSE
Error	0.0099	18	0.0006						
Total	0.0471	26							

Table B.51 Factorial Analysis of Variance
Lost Foam Silica Sand Castings
(0.25 inch)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3

Parallelism

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0208	4	0.0052	3.6063	0.0251	4.579022	FALSE	2.927749	TRUE
G	0.0227	2	0.0114	7.8834	0.0035	6.012897	TRUE	3.554561	TRUE
O	0.0042	2	0.0021	1.4484	0.2611	6.012897	FALSE	3.554561	FALSE
Error	0.0259	18	0.0014						
Total	0.0736	26							

Thickness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0355	4	0.0089	97.5895	6.03E-12	4.579022	TRUE	2.927749	TRUE
G	0.0208	2	0.0104	114.1509	5.95E-11	6.012897	TRUE	3.554561	TRUE
O	0.0197	2	0.0099	108.2233	9.27E-11	6.012897	TRUE	3.554561	TRUE
Error	0.0016	18	9.10E-05						
Total	0.0777	26							

Table B.52 Factorial Analysis of Variance
Lost Foam Silica Sand Castings
(0.50 inch)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3

Height

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0002	2	7.65E-05	2.8389	0.0978	6.926598	FALSE	3.88529	FALSE
G	0.0001	1	0.0001	4.916	0.0467	9.330279	FALSE	4.747221	TRUE
O	0.0002	2	7.99E-05	2.9682	0.0897	6.926598	FALSE	3.88529	FALSE
Error	0.0003	12	2.69E-05						
Total	0.0008	17							

Length

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	6.15E-05	2	3.07E-05	0.2451	0.7865	6.926598	FALSE	3.88529	FALSE
G	0.0005	1	0.0005	3.6286	0.081	9.330279	FALSE	4.747221	FALSE
O	0.0002	2	0.0001	0.919	4.25E-01	6.926598	FALSE	3.88529	FALSE
Error	0.0015	12	1.00E-04						
Total	0.0023	17							

Parallelism

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0006	2	0.0003	3.123	0.0809	6.926598	FALSE	3.88529	FALSE
G	0.0003	1	0.0003	2.5752	0.1345	9.330279	FALSE	4.747221	FALSE
O	0.0002	2	8.03E-05	0.8097	0.4679	6.926598	FALSE	3.88529	FALSE
Error	0.0012	12	9.92E-05						
Total	0.0022	17							

Thickness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	2.37E-05	2	1.18E-05	0.3544	0.7087	6.926598	FALSE	3.88529	FALSE
G	2.56E-05	1	2.56E-05	0.7657	0.3987	9.330279	FALSE	4.747221	FALSE
O	8.82E-05	2	4.41E-05	1.3207	0.3031	6.926598	FALSE	3.88529	FALSE
Error	0.0004	12	3.34E-05						
Total	0.0005	17							

Table B.53 Factorial Analysis of Variance
Flatness of Lost Foam Silica Sand Castings
(0.50 inch)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3

Left Flange Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	8.33E-06	2	4.17E-06	0.0707	0.9321	6.926598	FALSE	3.88529	FALSE
G	5.00E-05	1	5.00E-05	0.8483	0.3752	9.330279	FALSE	4.747221	FALSE
O	0.0004	2	0.0002	3.0094	0.0872	6.926598	FALSE	3.88529	FALSE
Error	0.0007	12	5.89E-05						
Total	0.0011	17							

Right Flange Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0035	2	0.0017	4.9576	0.027	6.926598	FALSE	3.88529	TRUE
G	0.0043	1	0.0043	12.3498	0.0043	9.330279	TRUE	4.747221	TRUE
O	0.004	2	0.002	5.6589	0.0186	6.926598	FALSE	3.88529	TRUE
Error	0.0042	12	0.0004						
Total	0.016	17							

Left Wall Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	1.30E-05	2	6.50E-06	0.5043	0.6162	6.926598	FALSE	3.88529	FALSE
G	0	1	0	8.11E-28	1	9.330279	FALSE	4.747221	FALSE
O	8.33E-06	2	4.17E-06	0.3233	0.7299	6.926598	FALSE	3.88529	FALSE
Error	0.0002	12	1.29E-05						
Total	0.0002	17							

Right Wall Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0003	2	0.0001	0.2815	0.7595	6.926598	FALSE	3.88529	FALSE
G	0.0004	1	0.0004	0.8413	0.3771	9.330279	FALSE	4.747221	FALSE
O	0.0007	2	0.0003	0.7022	0.5148	6.926598	FALSE	3.88529	FALSE
Error	0.0056	12	0.0005						
Total	0.0069	17							

Table B.54 Factorial Analysis of Variance
Lost Foam Silica Sand Castings
(0.50 inch)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3

Left Casting Angle

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	2.50E-05	2	1.25E-05	1.8202	0.204	6.926598	FALSE	3.88529	FALSE
G	1.15E-05	1	1.15E-05	1.6696	0.2206	9.330279	FALSE	4.747221	FALSE
O	7.48E-05	2	3.74E-05	5.4527	0.0207	6.926598	FALSE	3.88529	TRUE
Error	8.23E-05	12	6.86E-06						
Total	2.00E-04	17							

Right Casting Angle

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	7.52E-06	2	3.76E-06	0.1056	0.9006	6.926598	FALSE	3.88529	FALSE
G	3.07E-05	1	3.07E-05	0.8606	0.3718	9.330279	FALSE	4.747221	FALSE
O	6.58E-05	2	3.29E-05	0.9236	0.4236	6.926598	FALSE	3.88529	FALSE
Error	0.0004	12	3.56E-05						
Total	0.0005	17							

Table B.55 Factorial Analysis of Variance
Lost Foam Silica Sand Castings
(0.75 inch)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3

Height

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0004	2	0.0002	1.8332	2.02E-01	6.926598	FALSE	3.88529	FALSE
G	0.0001	1	0.0001	0.8333	0.3793	9.330279	FALSE	4.747221	FALSE
O	0.0013	2	0.0006	5.3338	0.022	6.926598	FALSE	3.88529	TRUE
Error	0.0014	12	0.0001						
Total	0.0033	17							

Thickness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	9.42E-05	2	4.71E-05	4.0103	4.64E-02	6.926598	FALSE	3.88529	TRUE
G	6.78E-05	1	6.78E-05	5.7757	0.0333	9.330279	FALSE	4.747221	TRUE
O	5.26E-06	2	2.63E-06	0.2241	0.8025	6.926598	FALSE	3.88529	FALSE
Error	0.0001	12	1.17E-05						
Total	0.0003	17							

Parallelism

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	5.60E-06	2	2.80E-06	0.0398	0.9611	6.926598	FALSE	3.88529	FALSE
G	3.00E-04	1	3.00E-04	4.0336	0.0677	9.330279	FALSE	4.747221	FALSE
O	0.0023	2	0.0012	16.6647	0.0003	6.926598	TRUE	3.88529	TRUE
Error	0.0008	12	7.04E-05						
Total	0.0035	17							

Length

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0002	2	7.55E-05	0.6796	0.5253	6.926598	FALSE	3.88529	FALSE
G	0.0001	1	0.0001	0.9669	0.3449	9.330279	FALSE	4.747221	FALSE
O	0.0014	2	0.0007	6.4315	0.0126	6.926598	FALSE	3.88529	TRUE
Error	0.0013	12	0.0001						
Total	0.003	17							

Table B.56 Factorial Analysis of Variance
Flatness of Lost Foam Silica Sand Castings
(0.75 inch)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3

Left Flange Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0001	2	6.81E-05	2.6923	0.1082	6.926598	FALSE	3.88529	FALSE
G	0.0001	1	0.0001	4.6505	0.052	9.330279	FALSE	4.747221	FALSE
O	0.0003	2	0.0002	6.0725	0.0151	6.926598	FALSE	3.88529	TRUE
Error	0.0003	12	2.53E-05						
Total	0.0009	17							

Right Flange Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.1399	2	0.07	3.2531	0.0743	6.926598	FALSE	3.88529	FALSE
G	0.0895	1	0.0895	4.1596	0.064	9.330279	FALSE	4.747221	FALSE
O	0.1099	2	0.055	2.5554	0.119	6.926598	FALSE	3.88529	FALSE
Error	0.2581	12	0.0215						
Total	0.5974	17							

Left Wall Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	3.88E-05	2	1.94E-05	0.4943	0.6219	6.926598	FALSE	3.88529	FALSE
G	2.22E-05	1	2.22E-05	0.5666	0.4661	9.330279	FALSE	4.747221	FALSE
O	0.0003	2	0.0002	4.3187	0.0387	6.926598	FALSE	3.88529	TRUE
Error	0.0005	12	3.92E-05						
Total	0.0009	17							

Right Wall Flatness

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	0.0034	2	0.0017	0.7757	0.4822	6.926598	FALSE	3.88529	FALSE
G	0.0012	1	0.0012	0.5616	0.4681	9.330279	FALSE	4.747221	FALSE
O	0.0013	2	0.0006	0.2912	0.7525	6.926598	FALSE	3.88529	FALSE
Error	0.0264	12	0.0022						
Total	0.0323	17							

Table B.57 Factorial Analysis of Variance
Lost Foam Silica Sand Castings
(0.75 inch)

Number of Factors	Number of Replicates
Factor	Levels
G=Gating	2
O=Orientation	3

Left Casting Angle

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	1.19E-05	2	5.93E-06	0.521	0.6067	6.926598	FALSE	3.88529	FALSE
G	2.28E-07	1	2.28E-07	0.0201	0.8896	9.330279	FALSE	4.747221	FALSE
O	2.17E-05	2	1.09E-05	0.9543	0.4125	6.926598	FALSE	3.88529	FALSE
Error	1.00E-04	12	1.14E-05						
Total	2.00E-04	17							

Right Casting Angle

Source	SS	DF	MS	F	P	F 0.01	significant?	F 0.05	significant?
GO	2.38E-05	2	1.19E-05	0.7692	0.4849	6.926598	FALSE	3.88529	FALSE
G	1.00E-04	1	1.00E-04	9.031	0.011	9.330279	FALSE	4.747221	TRUE
O	1.70E-05	2	8.52E-06	0.55	0.5909	6.926598	FALSE	3.88529	FALSE
Error	0.0002	12	1.55E-05						
Total	0.0004	17							

Newman Keuls Test of Means on Mold Type of Height Data (0.25 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
M1	18	8.8862	0.0315	0.0074
M2	18	8.6424	0.0556	0.0131
M3	18	8.7012	0.0605	0.0143

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
M1	Vs.	M2	0.2438	0.0000	YES
M1	Vs.	M3	0.1850	0.0000	YES
M2	Vs.	M3	0.0588	0.0000	YES

Newman Keuls Test of Means on Mold Type of Length Data (all 0.25 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
M1	18	7.7686	0.0256	0.0060
M2	18	6.4266	0.0187	0.0044
M3	18	6.3593	0.2598	0.0612

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
M1	Vs.	M2	1.3421	0.1296	YES
M1	Vs.	M3	1.4093	0.1638	YES
M2	Vs.	M3	0.0673	0.1296	NO

Newman Keuls Test of Means on Mold Type for Parallelism Data(all 0.25 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
M1	18	0.1482	0.1410	0.0332
M2	18	0.0994	0.0439	0.0104
M3	18	0.1663	0.0589	0.0139

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
M1	Vs.	M2	0.0488	0.0000	YES
M1	Vs.	M3	0.0181	0.0000	YES
M2	Vs.	M3	0.0669	0.0000	YES

Newman Keuls Test of Means on Mold Type for Right Casting Angle Data(all 0.25 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
M1	18	10.0357	0.1364	0.0321
M2	18	10.1225	0.0324	0.0076
M3	18	10.2086	0.0484	0.0114

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
M1	Vs.	M2	0.0868	0.0000	YES
M1	Vs.	M3	0.1730	0.0000	YES
M2	Vs.	M3	0.0861	0.0000	YES

Newman Keuls Test of Means on Gating for Right Wall Flatness Data(all 0.25 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
G1	27	0.0226	0.0101	0.0019
G2	27	0.0322	0.0185	0.0036

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
G1	Vs.	G2	0.0096	0.0000	YES

Newman Keuls Test of Means on Orientation for Right Wall Flatness Data(all 0.25 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	18	0.0344	0.0194	0.0046
O2	18	0.0199	0.0099	0.0023
O3	18	0.0279	0.0128	0.0030

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.0145	0.0000	YES
O1	Vs.	O3	0.0065	0.0000	YES
O2	Vs.	O3	0.0080	0.0000	YES

Newman Keuls Test of Means on Orientation for Lost Foam Silica Sand Height Data(0.25 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	6	8.6905	0.0683	0.0279
O2	6	8.6770	0.0529	0.0216
O3	6	8.7360	0.0520	0.0212

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.0135	0.0000	YES
O1	Vs.	O3	0.0455	0.0000	YES
O2	Vs.	O3	0.0590	0.0000	YES

Newman Keuls Test of Means on Orientation of Lost Foam Silica Sand Length Data (0.25 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	6	6.2475	0.2420	0.0988
O2	6	6.5633	0.2551	0.1041
O3	6	6.2672	0.1751	0.0715

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.3158	0.0000	YES
O1	Vs.	O3	0.0197	0.0000	YES
O2	Vs.	O3	0.2961	0.0000	YES

Newman Keuls Test of Means on Orientation of Lost Foam Silica Sand Left Flange Flatness Data(all 0.25 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	6	0.0108	0.0035	0.0014
O2	6	0.0158	0.0026	0.0011
O3	6	0.0128	0.0026	0.0010

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.0050	0.0000	YES
O1	Vs.	O3	0.0020	0.0000	YES
O2	Vs.	O3	0.0030	0.0000	YES

Newman Keuls Test of Means on Gating for
Lost Foam Silica Sand Parallelism Data(0.25 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
G1	9	0.1314	0.0534	0.0178
G2	9	0.2012	0.0422	0.0141

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
G1	Vs.	G2	0.0698	0.0000	YES

Newman Keuls Test of Means on Orientation of
Lost Foam Low Expansion Length Data (0.25 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	6	6.4330	0.0202	0.0082
O2	6	6.4362	0.0119	0.0049
O3	6	6.4104	0.0128	0.0052

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.0032	0.0000	YES
O1	Vs.	O3	0.0226	0.0000	YES
O2	Vs.	O3	0.0258	0.0000	YES

Newman Keuls Test of Means on Orientation for
Lost Foam Low Expansion Right Flange Flatness Data(0.25 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	6	0.0292	0.0161	0.0066
O2	6	0.0393	0.0141	0.0058
O3	6	0.0078	0.0034	0.0014

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.0102	0.0000	YES
O1	Vs.	O3	0.0213	0.0000	YES
O2	Vs.	O3	0.0315	0.0000	YES

Newman Keuls Test of Means on Gating for
Resin Bonded Sand Height Data (0.25 in.)

ColName	Count	Mean	Std.Dev.	Std.Err.
G1	9	8.8717	0.0294	0.0098
G2	9	8.9006	0.0279	0.0093

Newman-Keuls' Test
Significance Level: 0.05

Variables	Mean Diff	Critical Value	Significant
G1 Vs. G2	0.0289	0.0000	YES

Newman Keuls Test of Means on Gating for
Resin Bonded Sand Castings of Left Wall Flatness Data(0.25 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
G1	9	0.0294	0.0068	0.0023
G2	9	0.0380	0.0074	0.0025

Newman-Keuls' Test
Significance Level: 0.05

Variables	Mean Diff	Critical Value	Significant
G1 Vs. G2	0.0086	0.0000	YES

Newman Keuls Test of Means on Orientation of
Resin Bonded Sand Casting Left Wall Flatness Data (0.25 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	6	0.0405	0.0066	0.0027
O2	6	0.0330	0.0045	0.0018
O3	6	0.0277	0.0081	0.0033

Newman-Keuls' Test
Significance Level: 0.05

Variables	Mean Diff	Critical Value	Significant
O1 Vs. O2	0.0075	0.0000	YES
O1 Vs. O3	0.0128	0.0000	YES
O2 Vs. O3	0.0053	0.0000	YES

Newman Keuls Test of Means on Mold Type of Thickness Data (all 0.50 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
M1	18	10.1106	0.0111	0.0026
M2	18	10.1151	0.0021	0.0005
M3	18	10.1163	0.0032	0.0007

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
M1	Vs.	M2	0.0046	0.0058	NO
M1	Vs.	M3	0.0057	0.0074	NO
M2	Vs.	M3	0.0012	0.0058	NO

Newman Keuls Test of Means on Mold Type of Height Data (all 0.50 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
M1	18	8.8712	0.0159	0.0037
M2	18	8.6424	0.0556	0.0131
M3	18	8.6024	0.0067	0.0016

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
M1	Vs.	M2	0.2288	0.0288	YES
M1	Vs.	M3	0.2688	0.0365	YES
M2	Vs.	M3	0.0400	0.0288	YES

Newman Keuls Test of Means on Orientation of Length Data (all 0.50 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	18	6.9081	0.6502	0.1532
O2	18	6.9111	0.6594	0.1554
O3	18	6.8947	0.6462	0.1523

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.0030	0.5594	NO
O1	Vs.	O3	0.0134	0.5594	NO
O2	Vs.	O3	0.0164	0.7069	NO

Newman Keuls Test of Means on Mold Type of Length Data (0.50 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
M1	18	7.8000	0.0292	0.0069
M2	18	6.4748	0.0155	0.0036
M3	18	6.4390	0.0115	0.0027

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
M1	Vs.	M2	1.3252	0.0173	YES
M1	Vs.	M3	1.3611	0.0219	YES
M2	Vs.	M3	0.0358	0.0173	YES

Newman Keuls Test of Means on Mold Type of Parallelism Data (0.50 inch)

ColName	Count	Mean	Std.Dev.	Std.Err
M1	18	0.0874	0.0274	0.0065
M2	18	0.0663	0.0375	0.0088
M3	18	0.0394	0.0114	0.0027

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
M1	Vs.	M2	0.0211	0.0237	NO
M1	Vs.	M3	0.0479	0.0299	YES
M2	Vs.	M3	0.0268	0.0237	YES

Newman Keuls Test of Means on Mold Type of Left Casting Angle Data (0.50 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
M1	18	10.1086	0.0070	0.0016
M2	18	10.1165	0.0010	0.0002
M3	18	10.1175	0.0034	0.0008

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
M1	Vs.	M2	0.0079	0.0039	YES
M1	Vs.	M3	0.0089	0.0049	YES
M2	Vs.	M3	0.0010	0.0039	NO

Newman Keuls Test of Means on Gating of Right Flange Flatness Data (0.50 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
G1	27	0.0221	0.0113	0.0022
G2	27	0.0323	0.0294	0.0056

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
G1	Vs.	G2	0.0101	0.0156	NO

Newman Keuls Test of Means on Mold Type of Right Flange Flatness Data(0.50 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
M1	18	0.0124	0.0088	0.0021
M2	18	0.0407	0.0307	0.0072
M3	18	0.0284	0.0121	0.0029

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
M1	Vs.	M2	0.0283	0.0214	YES
M1	Vs.	M3	0.0161	0.0169	NO
M2	Vs.	M3	0.0123	0.0169	NO

Newman Keuls Test of Means on Gating of Left Wall Flatness Data(0.50 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
G1	27	0.0185	0.0089	0.0017
G2	27	0.0306	0.0391	0.0075

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
G1	Vs.	G2	0.0121	0.0199	NO

Newman Keuls Test of Means on Orientation of Left Wall Flatness Data(0.50 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	18	0.0352	0.0464	0.0109
O2	18	0.0219	0.0134	0.0031
O3	18	0.0166	0.0076	0.0018

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.0133	0.0242	NO
O1	Vs.	O3	0.0186	0.0306	NO
O2	Vs.	O3	0.0053	0.0242	NO

Newman Keuls Test of Means on Mold Type of Left Wall Flatness Data(0.50 inch)

ColName	Count	Mean	Std.Dev.	Std.Err
M1	18	0.0319	0.0095	0.0022
M2	18	0.0106	0.0032	0.0008
M3	18	0.0311	0.0466	0.0110

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
M1	Vs.	M2	0.0213	0.0299	NO
M1	Vs.	M3	0.0009	0.0236	NO
M2	Vs.	M3	0.0204	0.0236	NO

Newman Keuls Test of Means on Mold Type of Right Wall Flatness Data(0.50 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
M1	18	0.0316	0.0106	0.0025
M2	18	0.0357	0.0202	0.0048
M3	18	0.0164	0.0038	0.0009

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
M1	Vs.	M2	0.0041	0.0114	NO
M1	Vs.	M3	0.0152	0.0114	YES
M2	Vs.	M3	0.0193	0.0145	YES

Newman Keuls Test of Means on Mold Type of Thickness Data(0.75 inch)

ColName	Count	Mean	Std.Dev.	Std.Err
M1	18	0.8153	0.0266	0.0063
M2	18	0.7661	0.0259	0.0061
M3	18	0.7403	0.0043	0.0010

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
M1	Vs.	M2	0.0492	0.0185	YES
M1	Vs.	M3	0.0750	0.0234	YES
M2	Vs.	M3	0.0257	0.0185	YES

Newman Keuls Test of Means on Orientation of Height Data(0.75 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	18	8.72599898	0.13568314	0.03198082
O2	18	8.70201522	0.13657236	0.03219041
O3	18	8.71321281	0.12243775	0.02885886

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.02398376	0.14281819	NO
O1	Vs.	O3	0.01278617	0.11301266	NO
O2	Vs.	O3	0.01119759	0.11301266	NO

Newman Keuls Test of Means on Mold Type of Height Data(0.75 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
M1	18	8.89197778	0.01920126	0.00452578
M2	18	8.63164534	0.03518775	0.00829383
M3	18	8.61760390	0.01384923	0.00326430

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
M1	Vs.	M2	0.26033244	0.02100777	YES
M1	Vs.	M3	0.27437388	0.02654828	YES
M2	Vs.	M3	0.01404144	0.02100777	NO

Newman Keuls Test of Means on Mold Type of Length Data(0.75 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
M1	18	7.77364889	0.03022763	0.00712472
M2	18	6.47175056	0.01033537	0.00243607
M3	18	6.43646533	0.01333097	0.00314214

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
M1	Vs.	M2	1.30189833	0.01714657	YES
M1	Vs.	M3	1.33718356	0.02166874	YES
M2	Vs.	M3	0.03528522	0.01714657	YES

Newman Keuls Test of Means on Mold Type of Parallelism Data(0.75 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
M1	18	0.07070522	0.01992391	0.00469611
M2	18	0.12436383	0.10281243	0.02423312
M3	18	0.04243789	0.01430679	0.00337214

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
M1	Vs.	M2	0.05365861	0.05235652	YES
M1	Vs.	M3	0.02826733	0.05235652	NO
M2	Vs.	M3	0.08192594	0.06616483	YES

Newman Keuls Test of Means on Gating of Left Casting Angle Data(0.75 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
G1	25	1.012E+001	0.00786165	0.00157233
G2	25	1.011E+001	0.00649340	0.00129868

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
G1	Vs.	G2	0.00369429	0.00412415	NO

Newman Keuls Test of Means on Mold Type of Left Casting Angle Data(0.75 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
M1	18	1.011E+001	0.01112025	0.00262107
M2	18	1.012E+001	0.00213178	0.00050246
M3	18	1.012E+001	0.00316470	0.00074593

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
M1	Vs.	M2	0.00456111	0.00582358	NO
M1	Vs.	M3	0.00574732	0.00735946	NO
M2	Vs.	M3	0.00118621	0.00582358	NO

Newman Keuls Test of Means on Orientation of Right Casting Angle Data(0.75 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	18	1.011E+001	0.00777704	0.00183307
O2	18	1.012E+001	0.00922293	0.00217387
O3	18	1.012E+001	0.01209642	0.00285115

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.00125561	0.00846248	NO
O1	Vs.	O3	0.00768896	0.01069435	NO
O2	Vs.	O3	0.00643335	0.00846248	NO

Newman Keuls Test of Means on Mold Type of Right Casting Angle Data(0.75 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
M1	18	1.012E+001	0.01380946	0.00325492
M2	18	1.011E+001	0.00762451	0.00179711
M3	18	1.011E+001	0.00464524	0.00109489

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
M1	Vs.	M2	0.00922778	0.01029377	NO
M1	Vs.	M3	0.00880602	0.00814550	YES
M2	Vs.	M3	0.00042175	0.00814550	NO

Newman Keuls Test of Means on Orientation of Right Flange Flatness Data(0.75 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	18	0.06009427	0.05137171	0.01210843
O2	18	0.11766073	0.19680023	0.04638626
O3	18	0.03767907	0.02304666	0.00543215

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.05756646	0.10139447	NO
O1	Vs.	O3	0.02241520	0.10139447	NO
O2	Vs.	O3	0.07998166	0.12813587	NO

Newman Keuls Test of Means on Mold Type of Right Flange Flatness Data(0.75 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
M1	18	0.03107550	0.02768484	0.00652538
M2	18	0.13656749	0.18748411	0.04419043
M3	18	0.04779109	0.05273101	0.01242882

Newman-Keuls' Test
Significance Level: 0,05

Variables			Mean Diff	Critical Value	Significant
M1	Vs.	M2	0.10549199	0.12314061	NO
M1	Vs.	M3	0.01671560	0.09744170	NO
M2	Vs.	M3	0.08877639	0.09744170	NO

Newman Keuls Test of Means on Mold Type of Left Wall Flatness Data(0.75 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
M1	18	0.03036907	0.01497323	0.00352923
M2	18	0.01643461	0.00717842	0.00169197
M3	18	0.01911688	0.00415048	0.00097828

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
M1	Vs.	M2	0.01393446	0.01071422	YES
M1	Vs.	M3	0.01125219	0.00847821	YES
M2	Vs.	M3	0.00268227	0.00847821	NO

Newman Keuls Test of Means on Mold Type of Right Wall Flatness Data (0.75 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
M1	18	0.03575841	0.02814753	0.00663444
M2	18	0.06948364	0.04357828	0.01027150
M3	18	0.01661418	0.00433221	0.00102111

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
M1	Vs.	M2	0.03372522	0.02578687	YES
M1	Vs.	M3	0.01914424	0.02578687	NO
M2	Vs.	M3	0.05286946	0.03258780	YES

Newman Keuls Test of Means on Gating for Lost Foam Silica Sand Height Data(0.50 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
G1	9	8.6051	0.0059	0.0020
G2	9	8.5997	0.0067	0.0022

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
G1	Vs.	G2	0.0054	0.0076	NO

Newman Keuls Test of Means on Orientation for Lost Foam Silica Sand Left Casting Angle Data (0.50 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	6	10.1178	0.0037	0.0015
O2	6	10.1198	0.0028	0.0011
O3	6	10.1148	0.0014	0.0006

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.0020	0.0000	YES
O1	Vs.	O3	0.0030	0.0000	YES
O2	Vs.	O3	0.0050	0.0000	YES

Newman Keuls Test of Means on Gating for Lost Foam Silica Sand Thickness Data (0.75 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
G1	9	0.7423	0.0037	0.0012
G2	9	0.7384	0.0040	0.0013

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
G1	Vs.	G2	0.0039	0.0000	YES

Newman Keuls Test of Means on Orientation for Lost Foam Silica Sand Height Data (0.75 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	6	8.6205	0.0125	0.0051
O2	6	8.6061	0.0143	0.0058
O3	6	8.6261	0.0060	0.0025

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.0144	0.0000	YES
O1	Vs.	O3	0.0056	0.0000	YES
O2	Vs.	O3	0.0200	0.0000	YES

Newman Keuls Test of Means on Orientation for Lost Foam Silica Sand Length Data (0.75 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	6	6.4402	0.0067	0.0027
O2	6	6.4242	0.0162	0.0066
O3	6	6.4450	0.0032	0.0013

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.0160	0.0000	YES
O1	Vs.	O3	0.0049	0.0000	YES
O2	Vs.	O3	0.0209	0.0000	YES

Newman Keuls Test of Means on Orientation for Lost Foam Silica Sand Parallelism Data (0.75 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	6	0.0380	0.0090	0.0037
O2	6	0.0581	0.0102	0.0042
O3	6	0.0312	0.0064	0.0026

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.0201	0.0000	YES
O1	Vs.	O3	0.0068	0.0000	YES
O2	Vs.	O3	0.0269	0.0000	YES

Newman Keuls Test of Means on Gating for Lost Foam Silica Sand Right Casting Angle Data (0.75 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
G1	9	10.1170	0.0034	0.0011
G2	9	10.1115	0.0041	0.0014

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
G1	Vs.	G2	0.0056	0.0000	YES

Newman Keuls Test of Means on Gating for Lost Foam Silica Sand Thickness Data (all)

ColName	Count	Mean	Std.Dev.	Std.Err.
G1	27	0.4949	0.2094	0.0403
G2	27	0.5127	0.1889	0.0364

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
G1	Vs.	G2	0.0178	0.0000	YES

Newman Keuls Test of Means on Orientation for Lost Foam Silica Sand Thickness Data (all)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	18	0.4953	0.2094	0.0494
O2	18	0.4946	0.2103	0.0496
O3	18	0.5214	0.1825	0.0430

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.0007	0.0000	YES
O1	Vs.	O3	0.0261	0.0000	YES
O2	Vs.	O3	0.0268	0.0000	YES

Newman Keuls Test of Means on Thickness for Lost Foam Silica Sand Thickness Data (all)

ColName	Count	Mean	Std.Dev.	Std.Err.
T1	18	0.7403	0.0043	0.0010
T2	18	0.5020	0.0056	0.0013
T3	18	0.2691	0.0654	0.0154

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
T1	Vs.	T2	0.2384	0.0000	YES
T1	Vs.	T3	0.4712	0.0000	YES
T2	Vs.	T3	0.2329	0.0000	YES

Newman Keuls Test of Means on Orientation for Lost Foam Silica Sand Height Data (all)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	18	8.6366	0.0554	0.0131
O2	18	8.6297	0.0455	0.0107
O3	18	8.6548	0.0663	0.0156

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.0069	0.0000	YES
O1	Vs.	O3	0.0183	0.0000	YES
O2	Vs.	O3	0.0251	0.0000	YES

Newman Keuls Test of Means on Thickness for Lost Foam Silica Sand
Height Data (all)

ColName	Count	Mean	Std.Dev.	Std.Err.
T1	18	8.6176	0.0138	0.0033
T2	18	8.6024	0.0067	0.0016
T3	18	8.7012	0.0606	0.0143

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
T1	Vs.	T2	0.0152	0.0000	YES
T1	Vs.	T3	0.0836	0.0000	YES
T2	Vs.	T3	0.0988	0.0000	YES

Newman Keuls Test of Means on Orientation for Lost Foam Silica Sand
Length Data (all)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	18	6.3741	0.1607	0.0379
O2	18	6.4754	0.1528	0.0360
O3	18	6.3853	0.1281	0.0302

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.1013	0.0000	YES
O1	Vs.	O3	0.0111	0.0000	YES
O2	Vs.	O3	0.0901	0.0000	YES

Newman Keuls Test of Means on Thickness for Lost Foam Silica Sand
Parallelism Data (all)

ColName	Count	Mean	Std.Dev.	Std.Err.
T1	18	0.0424	0.0143	0.0034
T2	18	0.0394	0.0114	0.0027
T3	18	0.2922	0.3042	0.0717

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
T1	Vs.	T2	0.0030	0.0000	YES
T1	Vs.	T3	0.2498	0.0000	YES
T2	Vs.	T3	0.2528	0.0000	YES

Newman Keuls Test of Means on Gating for Lost Foam Silica Sand
Parallelism Data (all)

ColName	Count	Mean	Std.Dev.	Std.Err.
T1	18	10.1163	0.0032	0.0007
T2	18	10.1175	0.0034	0.0008
T3	18	10.1192	0.0075	0.0018

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
T1	Vs.	T2	0.0012	0.0000	YES
T1	Vs.	T3	0.0028	0.0000	YES
T2	Vs.	T3	0.0017	0.0000	YES

Newman Keuls Test of Means on Thickness for Lost Foam Silica Sand
Left Casting Angle Data (all)

ColName	Count	Mean	Std.Dev.	Std.Err.
T1	18	10.1163	0.0032	0.0007
T2	18	10.1175	0.0034	0.0008
T3	18	10.1192	0.0075	0.0018

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
T1	Vs.	T2	0.0012	0.0000	YES
T1	Vs.	T3	0.0028	0.0000	YES
T2	Vs.	T3	0.0017	0.0000	YES

Newman Keuls Test of Means on Orientation for Lost Foam Silica Sand
Right Casting Angle Data (all)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	18	10.1548	0.0623	0.0147
O2	18	10.1428	0.0484	0.0114
O3	18	10.1421	0.0421	0.0099

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.0120	0.0000	YES
O1	Vs.	O3	0.0127	0.0000	YES
O2	Vs.	O3	0.0007	0.0000	YES

Newman Keuls Test of Means on Thickness for Lost Foam Silica Sand
Right Casting Angle Data (all)

ColName	Count	Mean	Std.Dev.	Std.Err.
T1	18	10.1143	0.0046	0.0011
T2	18	10.1188	0.0056	0.0013
T3	18	10.2066	0.0479	0.0113

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
T1	Vs.	T2	0.0045	0.0000	YES
T1	Vs.	T3	0.0924	0.0000	YES
T2	Vs.	T3	0.0879	0.0000	YES

Newman Keuls Test of Means on Orientation for Lost Foam Silica Sand
Left Flange Flatness Data (all)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	19	0.0078	0.0033	0.0007
O2	19	0.0151	0.0077	0.0018
O3	19	0.0115	0.0036	0.0008

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.0073	0.0055	YES
O1	Vs.	O3	0.0038	0.0044	NO
O2	Vs.	O3	0.0036	0.0044	NO

Newman Keuls Test of Means on Orientation for Lost Foam Silica Sand
Right Flange Flatness Data (all)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	18	0.0446	0.0316	0.0074
O2	18	0.0621	0.0638	0.0150
O3	18	0.0402	0.0290	0.0068

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.0174	0.0381	NO
O1	Vs.	O3	0.0044	0.0381	NO
O2	Vs.	O3	0.0218	0.0481	NO

Newman Keuls Test of Means on Orientation for Lost Foam Silica Sand
Left Flange Flatness Data (0.75 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	6	0.0071	0.0022	0.0009
O2	6	0.0139	0.0085	0.0035
O3	6	0.0100	0.0037	0.0015

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.0068	0.0103	NO
O1	Vs.	O3	0.0029	0.0081	NO
O2	Vs.	O3	0.0039	0.0081	NO

Newman Keuls Test of Means on Orientation for Lost Foam Silica Sand
Left Wall Flatness Data (0.75 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	6	0.0200	0.0048	0.0020
O2	6	0.0177	0.0027	0.0011
O3	6	0.0197	0.0049	0.0020

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.0023	0.0080	NO
O1	Vs.	O3	0.0003	0.0064	NO
O2	Vs.	O3	0.0020	0.0064	NO

Newman Keuls Test of Means on Orientation for Lost Foam Silica Sand
Right Flange Flatness Data (0.50 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
O1	6	0.0243	0.0046	0.0019
O2	6	0.0263	0.0127	0.0052
O3	6	0.0347	0.0157	0.0064

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
O1	Vs.	O2	0.0020	0.0178	NO
O1	Vs.	O3	0.0104	0.0224	NO
O2	Vs.	O3	0.0084	0.0178	NO

Newman Keuls Test of Means on Thickness for Lost Foam Silica Sand
Right Flange Flatness Data (all)

ColName	Count	Mean	Std.Dev.	Std
T1	18	0.0477	0.0528	0
T2	18	0.0296	0.0114	0.0027
T3	18	0.0707	0.0481	0.0113

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
T1	Vs.	T2	0.0182	0.0358	NO
T1	Vs.	T3	0.0229	0.0358	NO
T2	Vs.	T3	0.0411	0.0452	NO

Newman Keuls Test of Means on Thickness for Lost Foam Silica Sand
Left Wall Flatness Data (all)

ColName	Count	Mean	Std.Dev.	Std.Err.
T1	18	0.0191	0.0042	0.0010
T2	18	0.0311	0.0466	0.0110
T3	18	0.0111	0.0034	0.0008

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
T1	Vs.	T2	0.0119	0.0232	NO
T1	Vs.	T3	0.0080	0.0232	NO
T2	Vs.	T3	0.0200	0.0294	NO

Newman Keuls Test of Means on Thickness for Lost Foam Silica Sand
Right Wall Flatness Data (all)

ColName	Count	Mean	Std.Dev.	Std.Err.
T1	18	0.0166	0.0043	0.0010
T2	18	0.0164	0.0038	0.0009
T3	18	0.0293	0.0218	0.0051

Newman-Keuls' Test
Significance Level: 0.05

Variables			Mean Diff	Critical Value	Significant
T1	Vs.	T2	0.0002	0.0112	NO
T1	Vs.	T3	0.0127	0.0112	YES
T2	Vs.	T3	0.0129	0.0141	NO

Newman Keuls Test of Means on Gating for Lost Foam Silica Sand
Right Flange Flatness Data (all)

ColName	Count	Mean	Std.Dev.	Std.Err.
G1	27	0.0452	0.0474	0.0091
G2	27	0.0527	0.0421	0.0081

Newman-Keuls' Test
Significance Level: 0.05

Variables	Mean Diff	Critical Value	Significant
G1 Vs. G2	0.0075	0.0314	NO

Newman Keuls Test of Means on Gating for Lost Foam Silica Sand
Right Flange Flatness Data (0.50 inch)

ColName	Count	Mean	Std.Dev.	Std.Err.
G1	9	0.0270	0.0096	0.0032
G2	9	0.0299	0.0147	0.0049

Newman-Keuls' Test
Significance Level: 0.05

Variables	Mean Diff	Critical Value	Significant
G1 Vs. G2	0.0029	0.0151	NO