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Dimension Calculation for Permanent Mold Casting of Gray Iron

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Abstract

The purpose of this study is to investigate the shrinkage in the permanent mold casting, and to determine sizes of the permanent mold in order to produce economical castings with high dimensional accuracy.

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Dimension calculation for permanent mold casting of gray iron

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CHAPTER 1

INTRODUCTION

The metal casting is a technology of pouring molten metal into a mold to produce an object of desired shape. There are many methods of metal casting today. However, they are not perfect because casted parts can have defects relative to microstructure, surface, dimensions, and many others. The fewer defects there are, the higher the quality of the output.

One of the indicators of quality is dimensional accuracy, which is closeness of the dimension of the casted part to the desired dimension. There are two reasons why we need to control the dimensional accuracy. The first reason is the leading cost of the casting processes. The way to cut cost is to produce a product close to the minimum allowable dimension value, which will save money as well as materials. The second reason is the production of casted parts used in complex mechanisms, which need higher geometrical tolerances. In both cases, the dimensional accuracy has to be within the tolerance average. The tolerance depends on the kind of process and material, which is used to produce this product, and is also determined by the importance of the usage of the product. However, close limits on tolerances that are not critical to the parts function can increase tooling cost, casting cost, or both without providing any benefit.

This paper presents a method of specifying dimensional accuracy of two specific gray iron castings using permanent mold casting.

Statement of Purpose

The purpose of this study is to investigate the shrinkage in the permanent mold casting, and to determine sizes of the permanent mold in order to produce economical castings with high dimensional accuracy.

Statement of Problem

The problem of this study is that it is difficult to predict the shrinkage value for permanent mold casting of gray iron with high probability.

Statement of Need

This particular study is of great importance because it concerns the production of casted parts for air conditioners. One of the most important requirements for production of parts of this nature is their high dimensional accuracy. Development of casted parts with high dimensional accuracy can lead to a cost effective production process that is based on manufacturing parts in the negative tolerance limit. This principle will lead to a more economic use of raw materials and improve quality of the final product.

This statement is illustrated by the following example.

For a steel cylinder with length 8 in, diameter 0.8 in, and density 0.285 pound/in^3, 0.04 in reduction in diameter will reduce weight of the part by almost 0.11 pounds. In the production of one million air conditioners the amount of metal saved would be about 111,687 pounds.

The overall importance and economic efficiency of the implementation of such a research study is well outlined by the results of the example and conceptual description that preceded it.

Statement of Hypothesis

The hypothesis of this study is that the determination of the shrinkage shows how the shape of the casted part is changed, and as a result it helps to increase dimensional accuracy of the foundry product by changing the sizes of the mold.

Assumptions

The following assumptions are made in pursuit of this study: chemical compositions of casted parts are identical, solidification conditions in the mold are the same, and thickness of a mold coating and pouring temperature are constant.

Limitations/Delimitations

Since only certain materials and cast configurations will be investigated in this study, the following parameters obtained from the study cannot be applied to any production cycle directly: limited to permanent mold (PM) casting of gray iron, dimensional study will be done on two castings-representatives of high value parts, metallurgical parameters (hypereutectic gray iron, PM temperature 200-500° F).

For this reason, this research will be able to check the hypothesis and can only serve as a guide for the real mold design due to unlimited variety of real types of castings.

Statement of Methodology

The objective of this study is to determine shrinkage for two different parts of the air conditioner: crankshaft and cylinder, which are shown in Figure 1. The material for the parts is gray iron. The chemical composition accords with ASTM Standard A823-99.

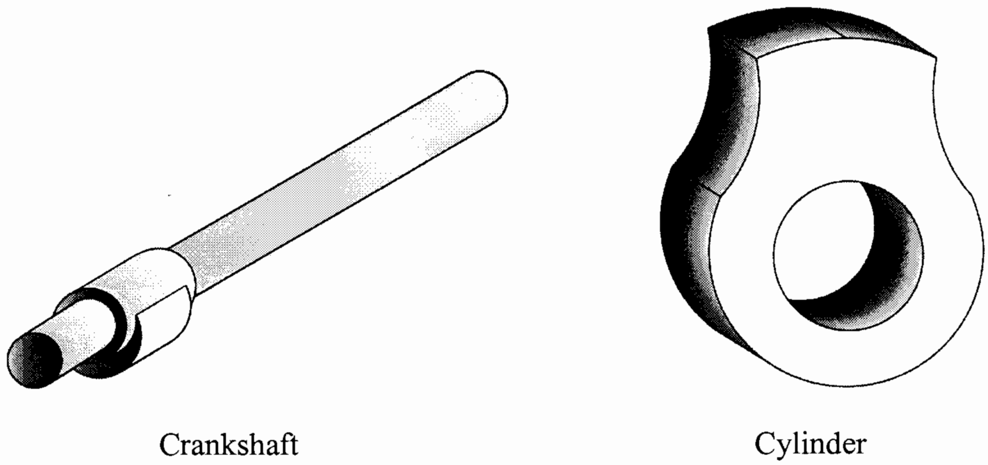

Figure 1. Typical parts.

The sizes of these parts are presented in Figures 2 and 3.

The testing procedure for this study is as follows: approximate determination of the mold dimensions, casting of 100 parts in each group, heat treating of parts, measuring of the casting dimensions, graphical interpretation of obtained results, determination of average shrinkage for two typical parts, and analysis of results.

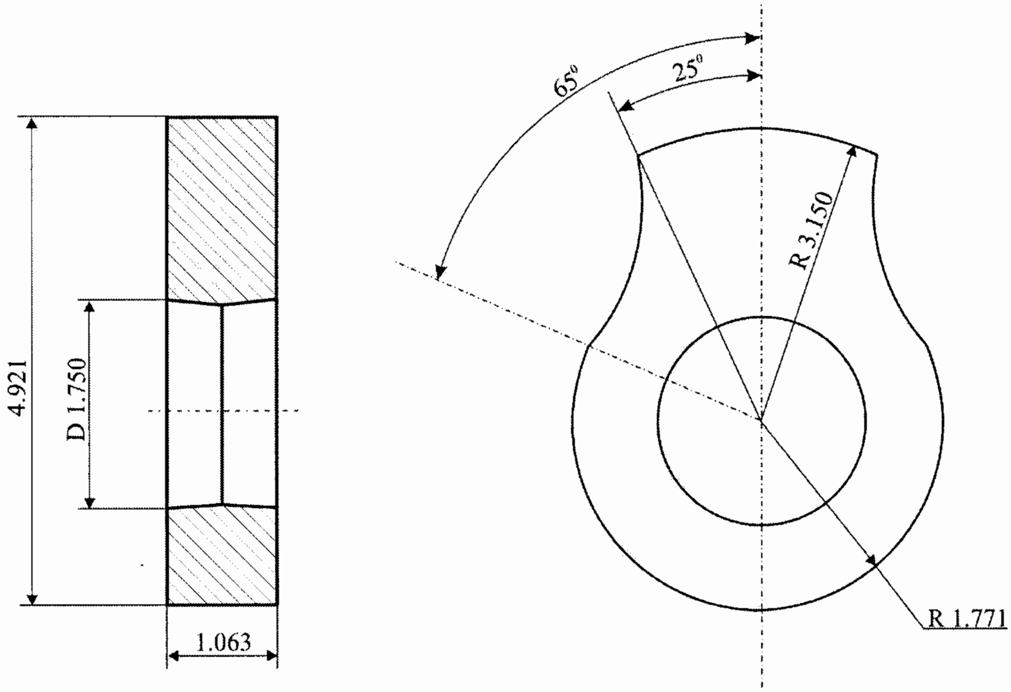

Figure 2. Typical sizes of the cylinder

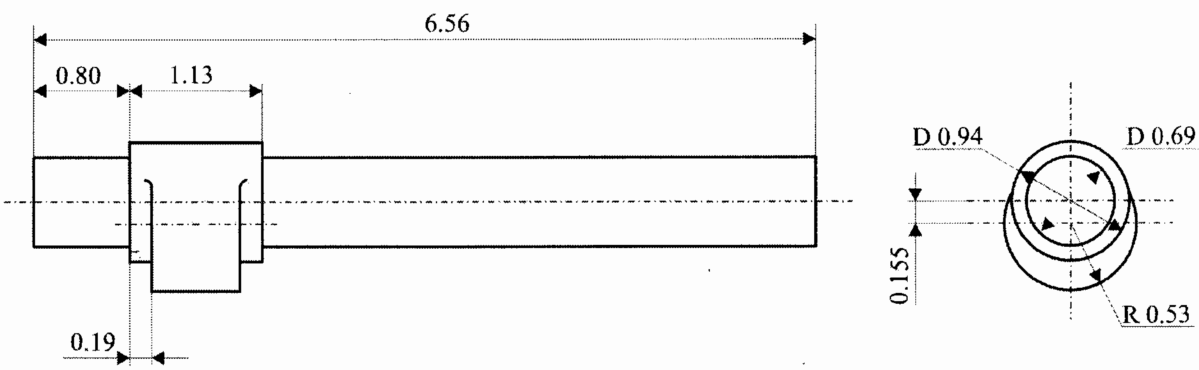

Figure 3. Typical sizes of the crankshaft

The equipment used in the experiment is permanent mold, permanent mold machine, melting furnace with ladle, and coordinate measuring machine.

Definitions of Terms

Alloy - A metallic material formed by mixing two or more chemical elements. Usually possesses properties different from those of the components (ASM handbook, 1992).

Shrinkage - The volume change that occurs in metals and alloys upon solidification and cooling to room temperature (ASM handbook, 1992).

Core - Separable part of the mold, usually made of sand, to create openings and various shaped cavities in the casting (ASM handbook, 1992).

Solidification - Formation of crystals as a metal solidifies. The atoms assume defined positions in the crystal lattice (Brandt, 1992).

Gate - End of the runner in a mold where molten metal enters the casting or mold cavity. Sometimes applies to entire assembly of connected channels (Investment casting handbook, 1968).

Graphite - carbon precipitated as graphite flakes while the iron cools through the freezing eutectic in which austenite, graphite, molten iron, and carbide exist together. (ASM handbook, 1992).

Macroshrinkage - Isolated, clustered, or interconnected voids in a casting that are detectable macroscopically. Such voids are usually associated with abrupt changes in section size and are caused by feeding that is insufficient to compensate for solidification shrinkage (Beeley, 2001).

Microshrinkage - A casting imperfection, not detectable microscopically, consisting of interdendritic voids. It results from contraction during solidification where the opportunity to supply filler material is inadequate to compensate for shrinkage. Alloys with wide ranges in solidification temperature are particularly susceptible (Beeley, 2001).

Mold - The form, usually of sand, containing the cavity into which molten metal is poured to make the casting (ASM handbook, 1992).

Mold Cavity - The impression in a mold produced by removal of the pattern. It is filled with molten metal to form the casting. Gates and risers are not considered part of the mold cavity (Investment casting handbook, 1968).

Pour - Discharge of molten metal from the Ladle into the mold (ASM handbook, 1992).

Riser - A reservoir of molten metal provided to compensate for internal contraction of the casting as it solidifies (Investment casting handbook, 1968).

Runner - The portion of the mold cavity between sprue cavity and ingate; applies to same portions of pattern set up and cast cluster (Investment casting handbook, 1968).

Stress - The intensity of the internal distributed forces or components of force, which resist deformation of a body. Stress is measured in force per unit area, for example pounds per square inch (psi) (Walton, 1971).

Budget Considerations

This study is based on the costs of the measurements of the molds and casted parts sizes as well as cost of materials. We need to produce two hundred of castings (100 crankshafts and 100 cylinders). In this case about one hundred and seventy kilograms of gray iron are needed.

CHAPTER 2

LITERATURE REVIEW

There is some information about system of geometrical tolerances, dimensional accuracy and permanent mold casting in this chapter. At first, we should take a look at this information in order to better understand the permanent mold process and the difference between the dimensional accuracy and dimensional tolerance.

Tolerance

Every engineering dimension deviates from its nominal value. Tolerances are being used to cover the variations expected in the normal course of production. Tolerances should be commensurate with the capabilities of the process (Liggett, 1993). The engineering tolerance is an allowance made for imperfections in a manufactured object. For example, gray irons usually contain 2.5 to 4% carbon (C), 1 to 3% silicium (Si), and additions of manganese (Mn), depending on the desired microstructure (as low as 0.1% manganese in ferritic gray irons and as high as 1.2% in pearlitics). Sulphur (S) and phosphorus (P) are also present in small amounts as residual impurities. The chemical composition of gray iron 100 is 3.5 to 3.8% carbon, 2.3 to 2.8% silicium, 0.4 to 0.8% manganese, 0.2% phosphorus, and 0.06 to 0.15% sulphur. It means that the tolerance of carbon chemical composition is 3.65±0.15%. It would not be reasonable to specify the concentration with an exact value of 3.65%, because such an iron cannot be made.

Another type of engineering tolerance is geometrical tolerance. The geometrical tolerance includes tolerances such as linearity, straightness, circularity, flatness, parallelism, perpendicularity, concentricity, and symmetry. The geometrical tolerance can also be called dimensional tolerance.

This research will emphasize linear tolerance, which can be described as an interval of allowable variations in size from the nominal dimension of a casted part. The interval limits define the upper and lower control limits for a product to work correctly. For example, a manufacturer needs to produce ten steel parts with the height of 3.5 and the length of 5 inches, as presented in Figure 4. The linear tolerance of this part is ± 0.1 inches, which means that they are allowed to produce parts with variation in length from 4.9 to 5.1 inches.

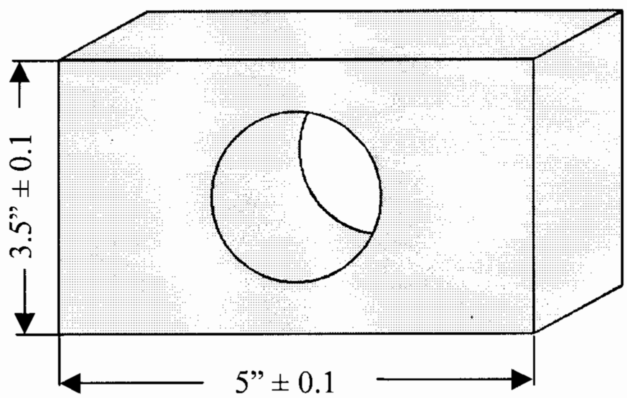

Figure 4. Example of a linear tolerance.

After the production of these ten parts, the lengths are measured and the results are presented in Figure 5. Even though all the lengths are different, they are all accepted because they are all within the acceptable interval limits. Some casted parts could have a length that is too large or too small. This would place the length of the part outside the interval limit, hence making it unacceptable.

Simply, observance of the linear tolerance is not a sufficient factor for the production of these parts because there are a few geometrical tolerances to be observed. Therefore, a special system of geometrical tolerances for different casting types was created in order to standardize all types of castings in the world. The name of this standard is ISO 8062. This international standard is based on measurements made on castings in different countries, such as France, Germany, Japan, Poland and Sweden. The second part of ISO 8062 relates to a system of geometrical tolerance grades for castings made in all metals and their alloys. As an example, casting geometrical tolerances on straightness are shown in Table 1 for different casting methods and materials.

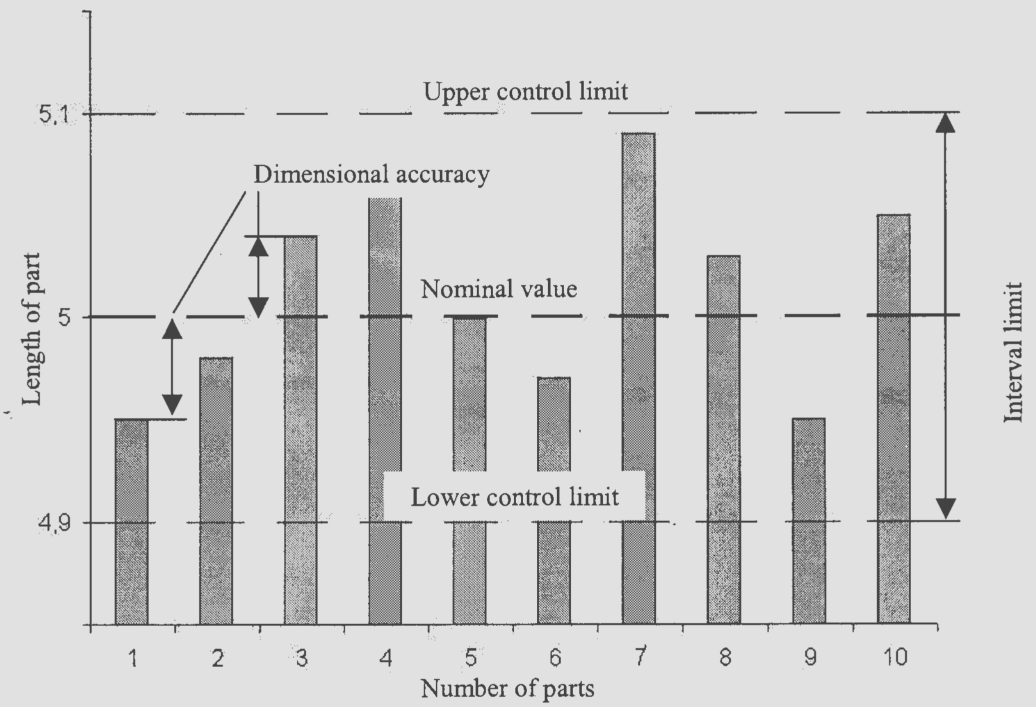

Figure 5. Graph of interval limit of linear tolerance.

Table 1

Casting geometrical tolerances on straightness (ISO 8062)

Raw casting nominal length of the cast parts, mm		Material						
From	To	Steel	Gray iron	Ductile iron	Malleable iron	Light metal alloys	Cu alloys	Zn alloys
Sand cast, hand molding								
>0	10	0.4-0.9	0.27-0.6	0.27-0.6	0.27-0.6	0.27-0.6	0.27-0.6	0.27-0.6
10	30	0.6-1.4	0.4-0.9	0.4-0.9	0.4-0.9	0.4-0.9	0.4-0.9	0.4-0.9
30	100	0.9-2.0	0.6-1.4	0.6-1.4	0.6-1.4	0.6-1.4	0.6-1.4	0.6-1.4
100	300	1.4-3.0	0.9-2.0	0.9-2.0	0.9-2.0	0.9-2.0	0.9-2.0	0.9-2.0
1000	3000	2.0-4.6	1.4-3.0	1.4-3.0	1.4-3.0	1.4-3.0	1.4-3.0	1.4-3.0
Sand cast, machine mold and shell molding								
>0	10	0.27-0.6	0.18-0.4	0.18-0.4	0.18-0.4	0.18-0.4	0.18-0.4	0.18-0.4
10	30	0.4-0.9	0.27-0.6	0.27-0.6	0.27-0.6	0.27-0.6	0.27-0.6	0.27-0.6
30	100	0.6-1.4	0.4-0.9	0.4-0.9	0.4-0.9	0.4-0.9	0.4-0.9	0.4-0.9
100	300	0.9-2.0	0.6-1.4	0.6-1.4	0.6-1.4	0.6-1.4	0.6-1.4	0.6-1.4
1000	3000	1.4-3.0	0.9-2.0	0.9-2.0	0.9-2.0	0.9-2.0	0.9-2.0	0.9-2.0

Similar data for other casting methods, such as permanent mold casting is not available. Meanwhile consultation should take place between the foundry and the customer to agree upon values used. However, we can make a conclusion from the Table1 that attainable accuracy for castings depends partly on the process and partly on the nature of each dimension, which means that errors in a casting may be statistical or systematic in their occurrence. Therefore, geometrical tolerances can be calculated in any type of casting as demonstrated below.

Every dimension is subject to innate differences due to process of variable adjustments. The outcome is a statistical spread of measurements about a mean value, portrayed by the normal distribution curve as shown in Figure 6a. Characteristics of the distribution curve determine the tolerances largely on the methods used in mold and core making, presuming that the mean can be made to correspond with the nominal dimension.

The second type of deviation is shown in Figure 6b, where the peak value is moved in one direction from the target value. Some of the reasons for these deviations are contraction uncertainty and errors in mold dimensions. The first is the shrinkage allowance, which is based on a standard value for an alloy. If there is interference to a contraction the value can be subjected to a significant error due to plastic deformation. This type of error is approximately proportional to the size of the dimension.

The two types of dimensional variation can be represented by an expression for casting tolerances (P.R. Beeley, 2001):

$$T = \pm\ (aD+b), \tag{1}$$

where D is the dimension and a and b are constants for particular casting conditions.

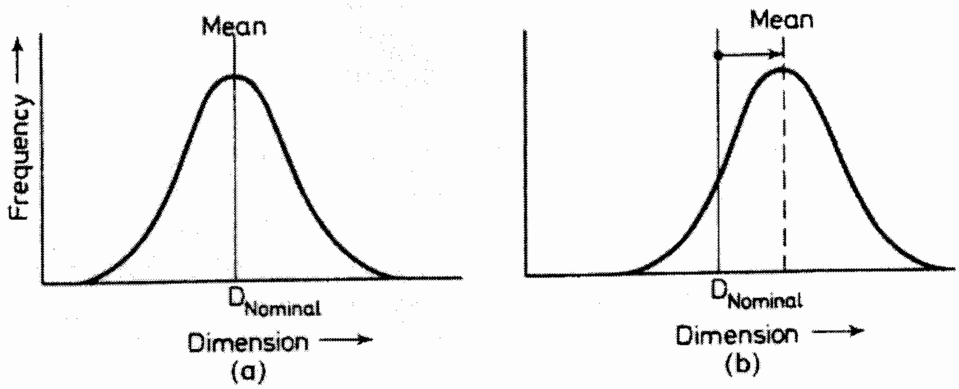

Figure 6. Alignment dimensional variation: (a) statistical spread of measurements, (b) systematic displacement from nominal dimension.

The term aD represents the shrinkage and can be substantial. Sometimes the differences in shrinkage behaviour can be equal to a considerable proportion of the total normal allowance. The constant b and the normal spread of the dimensional curve (Figure 6a) represent reproducibility of dimensions. The constant b is specific for one particular process and dimension.

Dimensional Accuracy

The dimensional accuracy is how close the dimension of the casted part is to the desired dimension. It can be presented as a variation in a size from the nominal dimension of a product. Therefore the dimensional accuracy can be called as a quality coefficient of the production. The dimensional accuracy was shown in Figure 5. The dimensional accuracy can have both positive and negative variations. In other words, the dimensions of parts can be above or below the nominal value, but they cannot exceed the maximum value or be below the minimum value.

The dimensional accuracy can be calculated as a difference between the size of the produced part and the nominal value of the production process.

There is a paradox in this example: on one hand, the production process is correct because the dimensional accuracies are within the interval limit of the process. On the other hand, this production process is not economical because the dimensional accuracies of 3rd, 4th, 7th, 8th, and 10th parts (Figure 5) are closer to the upper control limit. It is obvious that if the lengths of the parts were closer to the lower control limit that this production process would be economical, because in this case we would use less raw material to produce these parts. For these reasons, the dimensional accuracy is one of the critical attributes of casting.

Permanent Mold Process Overview

In permanent mold (PM) casting, also called "gravity die casting", molten metal is poured by the force of gravity into a reusable metallic mold. This is one of the various precision casting methods utilizing permanent mold, in which rapid solidification dynamics permits almost the immediate shakeout of castings. This greatly reduces production cycle time and improves mechanical properties of the casted parts.

A typical design of a permanent mold with a vertical parting line is to cast connecting rods and cover for forging presses of ductile iron. Figure 7 shows a mold cavity with a central sand core having two core prints located in each half of the mold, sand pouring cup, which also acts as the riser, ejection and water-cooling systems. Molten metal is poured into a pouring cup, which then passes through the ceramic filter and openings at the bottom, filling the mold cavity previously coated with a protective coating.

The thermal impact of molten metal flow in the mold is the major factor determining mold life as well as the casting quality. The permanent mold process typically operates at a temperature range of about 300 to 600° F (150° to 300°C), and the mold material is subjected to significant molten metal erosion and thermal stresses. For the conventional PM casting of irons, molds are usually made from iron or steel. Gray cast iron with Type A graphite is a recognized mold material that offers good thermal conductivity and heat resistance.

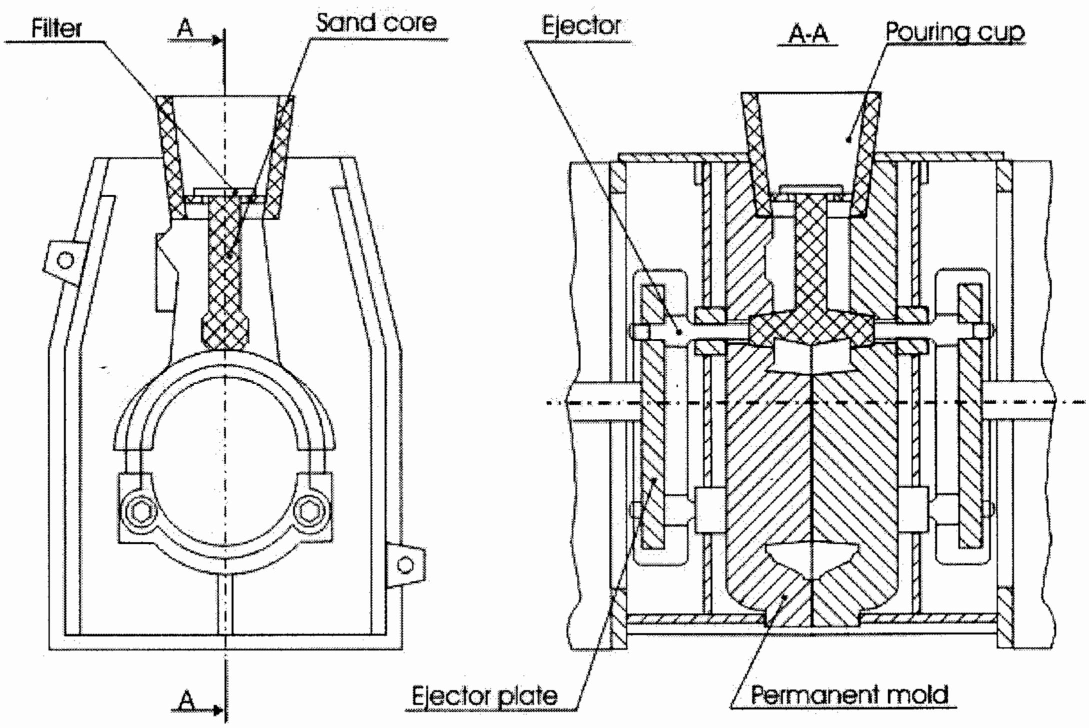

Figure 7. A typical design of a permanent mold with a vertical parting line

A protective coating is typically used to provide an insulating barrier between the molten metal and the metallic mold. This is to protect it from thermal shock and to keep the metal from adhering to the mold.

The coating also reduces friction and thermal losses that in turn prevents premature solidification of the metal in the mold. The protective coating drastically extends the mold life.

Dimensional Calculation of Molds

The dimensional calculation of the molds for production of parts with desired dimensional accuracy is based on prediction of material shrinkage and consideration of all sources of errors that might exist in the production process.

Errors in mold dimensions include mold cavity expansion and mold coating thickness. The mold's dimensional errors depend on the tolerance of equipment, which are used to make this mold. We cannot control these errors, but we have to take them into account to calculate the sizes of the mold. Typically a variation in size of a mold is about ±0.01 inches.

The next source of error is the variation in the thickness of coating. Usually soot is used as coating in PM casting and the volume of coating thickness varies from 0.005 inches to 0.01 inches, but we should take into account this source of error because the coating is burnt out during the pouring. This means the source of this error is insignificant, that is why we can leave out this source. However, we should periodically clean a mold in order to keep this error constant.

The main source of errors in permanent mold casting is shrinkage. Typical shrinkage allowance for small gray iron casted parts (up to 10") in PM casting is from 0.7 to 1%, which depends on the casting geometry.

Therefore, the permanent mold is purposely made larger to compensate for these variables. Thus, the dimensions of the mold can be presented by the expression:

$$D_{mold} = D + Shrinkage \cdot D \pm 0.01 \text{, or } D_{mold} = (1 + Shrinkage)D \pm 0.01, \quad (2)$$

where D is a desired dimension of casted part.

The application of the expression helps us to calculate dimensions of experimental molds taking into account the mold cavity expansion and shrinkage.

CHAPTER 3

EXPERIMENTAL PROCEDURES

Dimension Calculation of Experimental Molds

Analyses of the sources of errors in permanent mold casting showed us two sources of errors are mold cavity expansion and shrinkage. With aid of these errors we can devise the formula 2. The value of mold cavity error is a constant (±0.01), and so the expression includes shrinkage as the only independent variable. It is obvious now, that a desired dimensional accuracy can be reached by only using the well-defined value of shrinkage. Assuming the value of shrinkage (from 0.7 to 1%) we then have the opportunity to calculate the approximate molds' dimensions that will be used to make two experimental molds to cast 100 crankshafts and 100 cylinders. It is clear that the dimensions of these casted parts will not be accurate, however they will be close to desired dimensions, thus we can use these data in order to define the actual value of shrinkage.

Assuming the value of the shrinkage as 0.85% for both cases, the expression 2 can be represented as:

$$D_{mold(ex)} = 1.0085D \pm 0.01 \quad (3)$$

where $D_{mold(ex)}$ is a dimension of experimental mold;

D is a desired dimension of casted part.

This new expression will be used to calculate all dimensions of two experimental molds to produce two types of desired parts, crankshafts and cylinders.

Crankshaft

The crankshaft has few overall dimensions, as shown in Figure 8. There are three cylindrical parts with different diameters and lengths. The formula 3 is used in order to define these dimensions. The desired sizes of the crankshaft are shown in Figure 3.

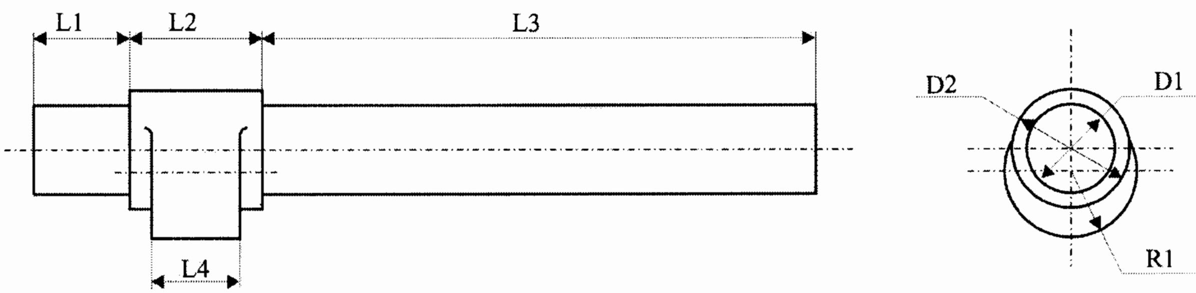

Figure 8. General dimensions of the experimental mold to produce the crankshaft

Inputting the desired sizes of the crankshaft to formula 3, the dimensions of the experimental mold can be calculated as shown.

$L = L1 + L2 + L3 = 1.0085 \cdot (0.8 + 1.13 + 4.63) = 6.62 \pm 0.01$ in.

Therefore, the length dimensions are $L1 = 0.81$ in.; $L2 = 1.14$ in.; $L3 = 4.67$ in.

$L4 = 1.0085 \cdot 0.75 \pm 0.01 = 0.76 \pm 0.01$ in;

$D1 = 1.0085 \cdot 0.69 \pm 0.01 = 0.70 \pm 0.01$ in;

$D2 = 1.0085 \cdot 0.94 \pm 0.01 = 0.95 \pm 0.01$ in;

$R1 = 1.0085 \cdot 0.53 \pm 0.01 = 0.53 \pm 0.01$ in.

According to the above calculation, the experimental mold for production of 100 crankshafts was made.

Cylinder

The overall dimensions of the cylinder are length (diameter) and height, as shown in Figure 9. The length of this part can be represented as a sum of two radiuses (R_1 and R_2).

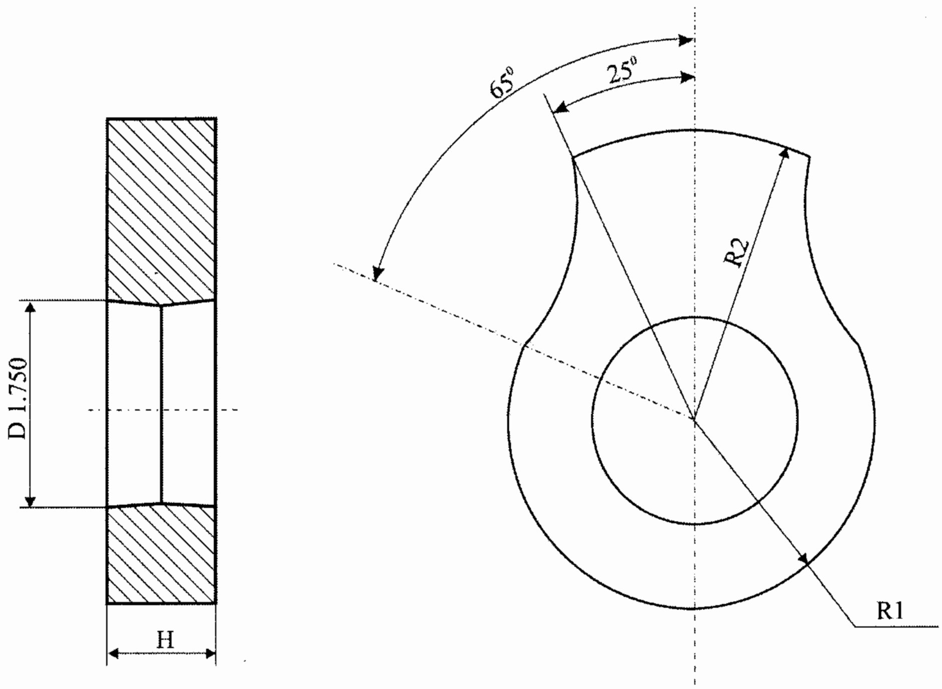

Figure 9. General dimensions of the experimental mold in order to produce the cylinder

The dimensions of the desired casted part are presented in Figure 2. Inputing these dimensions to formula 3 we have:

$R1 = (1.771 - 1.750/2)1.0085 + 0.005 + 1.75/2 = 1.784 \pm 0.01\,\text{in};$

$R2 = (3.150 - 1.750/2)1.0085 + 0.005 + 1.75/2 = 3.174 \pm 0.01\,\text{in};$

$H = 1.063 \cdot 1.0085 + 0.01 = 1.082 \pm 0.01\,\text{in}.$

According to the above calculation, the experimental mold to produce 100 cylinders was made.

Permanent Mold Casting

Experimental molds were made in compliance with the calculated dimensions. The next step of this study was to produce parts using permanent mold casting. Experimental castings were produced in an operating iron permanent mold foundry (Grede Perm Cast). The base iron was melted in a hot blast cupola from a charge consisting of pig iron, scrap iron and steel. Appropriate ferroalloy additions were made to produce a nominal chemical composition as follows: (wt%): 3.55-3.65 % carbon, 2.4-2.6 % silicon, 0.45-0.55 % manganese, 0.2-0.3 % phosphorous and 0.06-0.07 % titanium. High carbon equivalent (CE) is needed to regulate the chill depth and reduce sink/lap type defects. Titanium is essential for providing the undercooling required to meet ASTM specification A-823-84 that calls for predominately type D graphite with some Types A, B, or C graphite being associated with the casting center or in the vicinity of sand cores in a metallic matrix of ferrite, or pearlite, or their mixture. This specific microstructure has been found as a most desirable microstructure, ensuring relatively high tensile strength, good pressure tightness and excellent machinability.

Iron from the cupola was poured into a channel induction furnace, periodically tapped at 2580-2620 ^{0}F into 1000 lb transfer ladles, tapped into 220 lb pouring ladles, and then poured into vertically-parted permanent molds mounted on indexing or continuously-rotated, 12-station carousels. All parts were poured at 2420-2460 ^{0}F into soot-coated air-cooled molds.

Heat Treatment

A fixed metallic matrix is inherent in the permanent mold process, because of the mandatory heat treatment for all castings in order to stabilize the microstructure after the pouring. All experimental castings were subject to normalizing consisting of austenization at 1550 - 1700 ^{0}F for at least one hour and then air quenching. A microstructure of normalized PM castings contains up to 30% pearlite.

Data Measurement

The next step was measuring the dimensions of the casted parts by the Coordinate Measuring Machine (CMM). The spreads of measurements are depicted graphically for all dimensions of both casted parts (Appendix A, B). Minimal and maximal values were figured out by the machine and mean dimension was calculated.

The results of the experiment for the crankshaft are given for five dimensions in Table 2. Upper and lower control limits were defined by the customer.

Table 2

The results of the experiment for the crankshaft

Tip of dimension	Nominal value, in	Upper control limit, in	Lower control limit, in	Mean,. in	Maximum value, in	Minimum value, in
L	6.560	6.580	6.540	6.574	6.583	6.562
D1	0.690	0.700	0.680	0.696	0.699	0.692
D2	0.940	0.950	0.930	0.945	0.949	0.942
R1	0.530	0.540	0.520	0.528	0.531	0.526
L4	0.750	0.760	0.740	0.754	0.758	0.749

The results of the experiment for the crankshaft are given for three dimensions in Table 3.

Table 3

The results of the experiment for the cylinder

Tip of dimension	Nominal value, in	Upper control limit, in	Lower control limit, in	Mean, in	Maximum value, in	Minimum value, in
R1	1.771	1.781	1.761	1.776	1.780	1.771
R2	3.150	3.160	3.140	3.157	3.162	3.153
H	1.063	1.073	1.053	1.062	1.065	1.058

It can be noticed from the above tables, that all the dimensions produced are closer to the upper control limit and the actual spread of the dimensions is much smaller than the total allowed deviation. We will use this information to redesign the permanent molds to save the raw material. The actual curves are given in Appendixes A and B.

CHAPTER 4

DATA ANALYSIS AND CORRECTION OF THE MOLDS

Basically, the curves of spreads of measurements are located close to the upper control limit as shown in Figure 10 by a continuous line. In other words, they are to the right of the nominal value in both cases. This means that the dimensions of the experimental molds are slightly bigger than we need because we had assumed the value of shrinkage with a small level error, but now we know the dimensions of the casted parts and the experimental molds, so that the actual value of shrinkage can be calculated. Thus, the next step of this research is the dimensional corrections of the experimental molds.

According to the purpose of the study, we need to correct the dimensions of the experimental molds in such a way as to produce the parts with high dimensional accuracy and reduce the quantity of the raw material. It means that the curves of spreads of measurements should be as close to lower control limits as possible, as shown in Figure 10 by a dotted line. Furthermore, the curves must be to the right of lower control limits, otherwise some casted parts will be defined as defective goods because their dimensions will be outside of the tolerance limit.

The goal of the study can be reached by substituting the value of the lower control limit for the nominal value (desired dimension) in Formula 3. In this case, dimensions of the casted parts will be around the lower control limit. It is necessary but, still not enough because dimensions of all casted parts have to be within the tolerance limit

(Figure 10). Thus, we need to coincide the minimal values of spreads of measurements with lower control limits. It can be done by using the maximum value of shrinkage for each dimension of the casted parts.

By doing these changes, the actual dimensions of the produced castings will be closer to the lower control limit thereby decreasing material required.

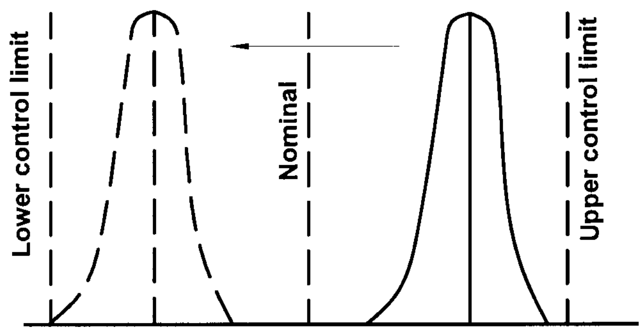

Figure 10. Minimization of the mold dimensions

Using the maximum value of shrinkage for each dimension and lower control limit instead of the nominal dimension will transform the formula 3 as shown:

$$D_{mold} = (1 + Shrinkage(\max))LCL, \tag{4}$$

where Shrinkage(max) is the maximum value of shrinkage;

LCL is lower control limit.

The maximum value of shrinkage conforms to the minimal value of spread of measurements so that it can be calculated by using formula:

$$Shrinkage(\max) = \frac{\left| D_{mold(ex)} - D_{\min} \right|}{D_{\min}} \cdot 100\%, \tag{5}$$

where D_{min} is a minimal dimension of spread of measurements,

$D_{mold(ex)}$ is the dimension of the experimental mold.

Crankshaft

The equations for maximum value of shrinkage are as follows:

$$Shrinkage(\max)_L = \frac{6.62-6.562}{6.562}\cdot 100\% = 0.88\%;$$

$$Shrinkage(\max)_{D1} = \frac{0.7-0.692}{0.692}\cdot 100\% = 1.16\%;$$

$$Shrinkage(\max)_{D2} = \frac{0.95-0.942}{0.942}\cdot 100\% = 0.85\%;$$

$$Shrinkage(\max)_{R1} = \frac{0.53-0.526}{0.526}\cdot 100\% = 0.76\%;$$

$$Shrinkage(\max)_{L4} = \frac{0.75-0.749}{0.749}\cdot 100\% = 0.13\%.$$

Now, we can use formula 4 to calculate the new dimensions of the mold for production of the crankshaft.

$$L_{mold} = (1+0.0088)\cdot 6.54 = 6.60 \text{ in.}$$

Therefore, the dimensions of the particular parts of the length are $L1 = 0.805$ in; $L2 = 1.137$ in.; $L3 = 4.658$ in.

$$D1 = (1+0.0116)\cdot 0.68 = 0.688 \text{ in;}$$

$$D2 = (1+0.0085)\cdot 0.93 = 0.938 \text{ in;}$$

$$R1 = (1+0.0076)\cdot 0.52 = 0.524 \text{ in;}$$

$$L4 = (1+0.0013)\cdot 0.74 = 0.741.$$

The dimensions of this mold are shown in Figure 11.

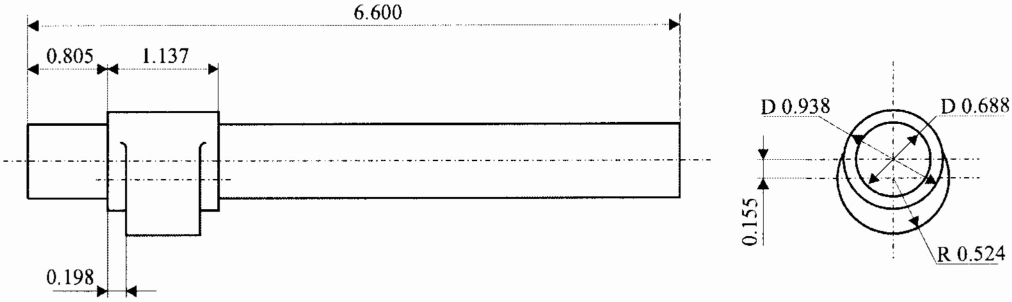

Figure 11. General calculated dimensions of the mold for production the crankshaft

Cylinder

The equations for maximum value of shrinkage in cylinder are as follows:

$$Shrinkage(\max)_{R1} = \frac{1.784 - 1.771}{1.771} \cdot 100\% = 0.73\%;$$

$$Shrinkage(\max)_{R2} = \frac{3.174 - 3.150}{3.150} \cdot 100\% = 0.76\%;$$

$$Shrinkage(\max)_{H} = \frac{1.082 - 1.058}{1.058} \cdot 100\% = 2.27\%.$$

Input calculated meanings of shrinkage to formula 4 results in the new dimensions of the mold for production of the cylinder.

$$R1 = (1 + 0.0073) \cdot 1.760 = 1.773 \text{ in};$$

$$R2 = (1 + 0.0076) \cdot 3.140 = 3.164 \text{ in};$$

$$H = (1 + 0.0227) \cdot 1.053 = 1.077 \text{ in}.$$

The dimensions of this mold are shown in Figure 12.

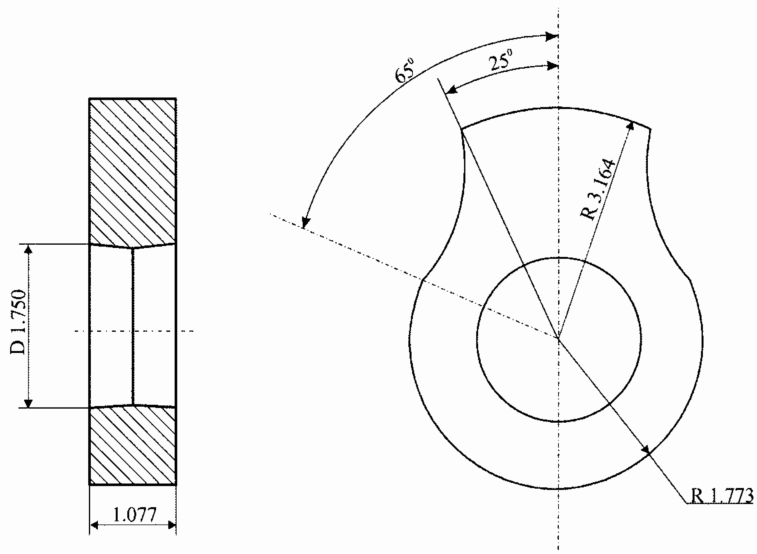

Figure 12. General dimensions of the calculated mold in order to produce the cylinder

Using the corrected molds dimensions will guarantee the production of the crankshafts and the cylinders with high dimensional accuracy. The dimensions of these castings will be closer to the lower control limit, thereby saving substantial amount of raw material.

CONCLUSIONS

Experiments were conducted to identify the actual value of shrinkage due to solidification of two different parts in permanent mold casting of gray iron. The theoretical calculation of geometrical dimensions of two molds resulted in production of castings with high dimensional accuracy and economical use of raw material.

The results of the experiments showed that the produced dimensions are closer to the upper control limit and the actual spread of dimensions is smaller as it is compared to the allocated tolerance.

Based on the results of the experiments, the maximum value of shrinkage for each dimension is established. Using this shrinkage value, new dimensions of the molds are calculated that will guarantee the production of the parts closer to the lower control limit.

This procedure would ensure a substantial saving in the cost of material used for mass production of these parts.

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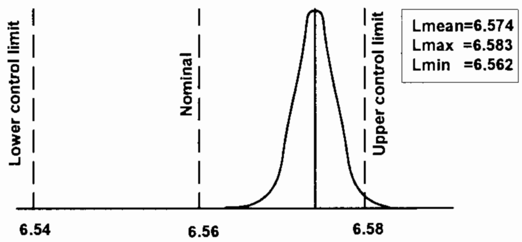
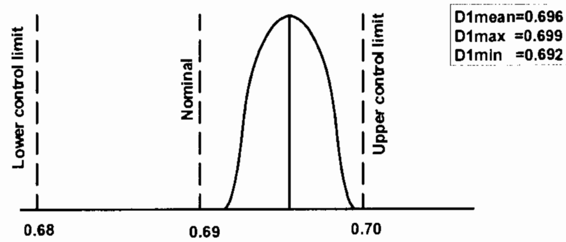
APPENDIX A

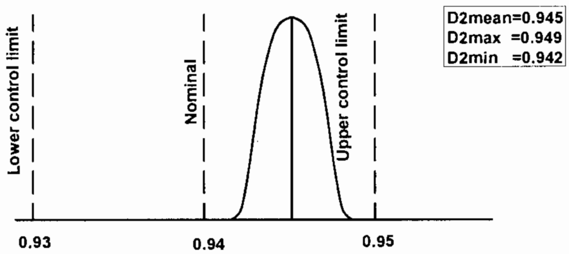
CURVES OF SPREADS OF MEASUREMENTS FOR THE CRANKSHAFT



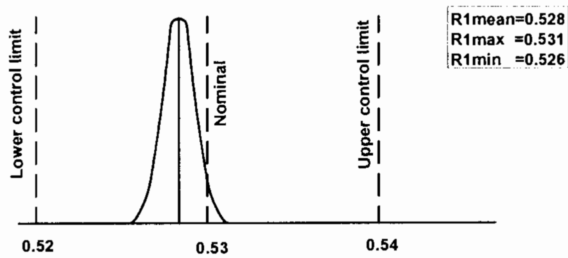
a)



b)



c)



d)

a) curve of spreads of measurements for the dimension L;

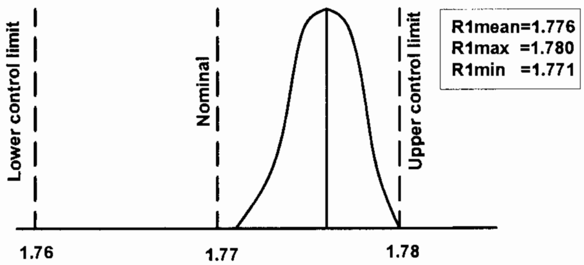
b) curve of spreads of measurements for the dimension D1;

c) curve of spreads of measurements for the dimension D2;

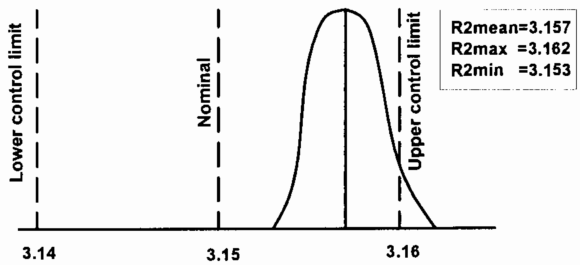
d) curve of spreads of measurements for the dimension R1.

APPENDIX B

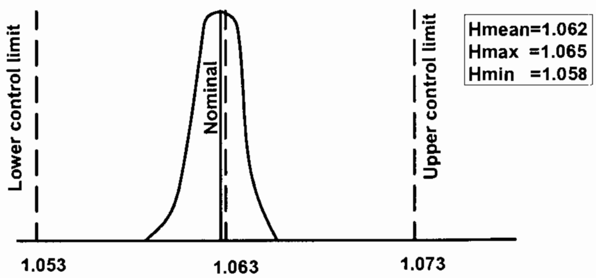
CURVES OF SPREADS OF MEASUREMENTS FOR THE CYLINDER



a)



b)



c)

a) curve of spreads of measurements for the dimension R1;

b) curve of spreads of measurements for the dimension R2;

c) curve of spreads of measurements for the dimension H.