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# Relationships between casting features and cavity fill time, gate velocity, and gate area for aluminum die castings

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# RELATIONSHIPS BETWEEN CASTING FEATURES AND CAVITY FILL TIME, GATE VELOCITY, AND GATE AREA FOR ALUMINUM DIE CASTINGS

An Abstract of a Dissertation

Submitted

In Partial Fulfillment

of the Requirements for the Degree of

Doctor of Industrial Technology

Approved:

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ABSTRACT

The purpose of this study was to investigate the relationships between casting features (including weight, average thickness, surface area, and outside diameter) and casting process variables (including cavity fill time, gate velocity, and gate area) for aluminum die castings. Historical data of good quality aluminum round castings of the Kiowa Corporation in Marshalltown, Iowa, were used in the correlation analysis. The correlation analysis consisted of determining the following:

1. the correlation of one casting process variable and one casting feature.

2. the multiple correlation of one casting process variable and a combination of several casting features.

The results of statistical analyses indicated that there are significant correlations between some casting features and casting process variables. Average thickness had the highest correlation with cavity fill time and gate velocity. Outside diameter had the highest correlation with gate area.

Since all six correlations between pairs of casting features were significant, the use of a second casting feature in the multiple regression equation for predicting

casting process variables from casting features does not result in a significant difference. Therefore, for round aluminum die castings of alloy A380 with the metal temperature 1220° F, in sizes of 2.7 to 16 inches, made by a horizontal cold chamber machine with a die temperature of 350° F, this study suggests that the design of gate area should be based on casting outside diameter, and that cavity fill time and gate velocity should be based on casting average thickness.

Casting cavity fill time can be predicted from casting average thickness by using the following linear regression equation:

$$\text{Cavity Fill Time (sec)} = 0.0059 + 0.3757 \times \text{Average Thickness (in)}$$

Gate velocity can be predicted from average thickness by using the following linear regression equation:

$$\text{Gate Velocity (ft/sec)} = 133.5828 - 152.2890 \times \text{Average Thickness (in)}$$

Gate area can be predicted from outside diameter by using the following linear regression equation:

$$\text{Gate Area (in}^2\text{)} = 0.0092 + 0.0345 \times \text{Outside Diameter (in)}$$

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# CHAPTER I

# INTRODUCTION

## Introduction to Aluminum Die Casting

### Description of Aluminum Die Casting Process

Die casting is a manufacturing process by which molten metal is mechanically injected into a reusable steel mold called a die. The die is divided into two halves called the cover die and the ejector die. The cover die is bolted to the front stationary platen, and the ejector die is bolted to the movable platen (see Figure 1). The die is opened and closed by a toggle mechanism driven by a clamping cylinder (American Die Casting Institute (ADCI), 1981).

Aluminum die castings are produced in cold chamber die casting machines. The casting cycle begins with the die in the closed and locked position. A quantity of molten aluminum is ladled manually or automatically through the pour hole into the cold chamber (see Figure 2). The operator actuates the shot, and the plunger tip, driven by the shot cylinder, travels forward pushing the molten metal from the cold chamber through the gating system and into the die cavity where it solidifies very quickly. After a preset period of time, the hydraulic pressure in the shot cylinder is reduced to

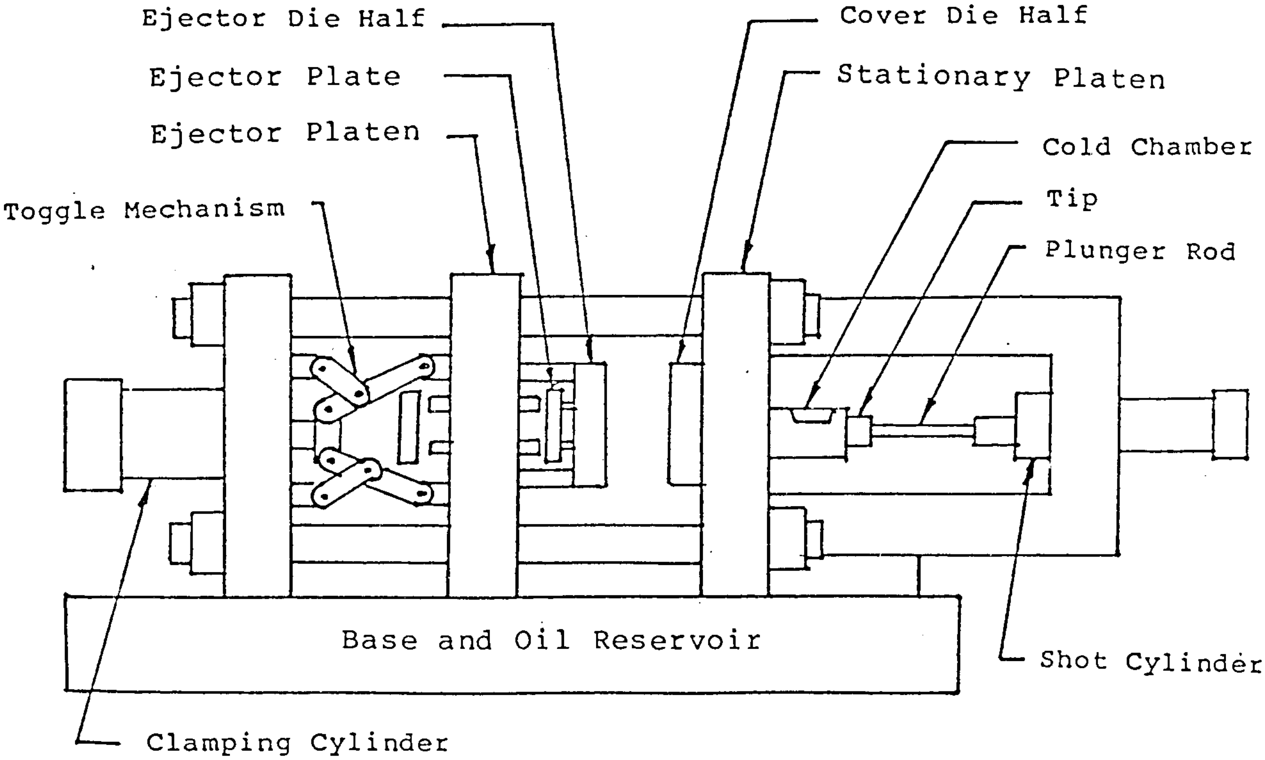



Figure 1. Horizontal cold chamber die casting machine.

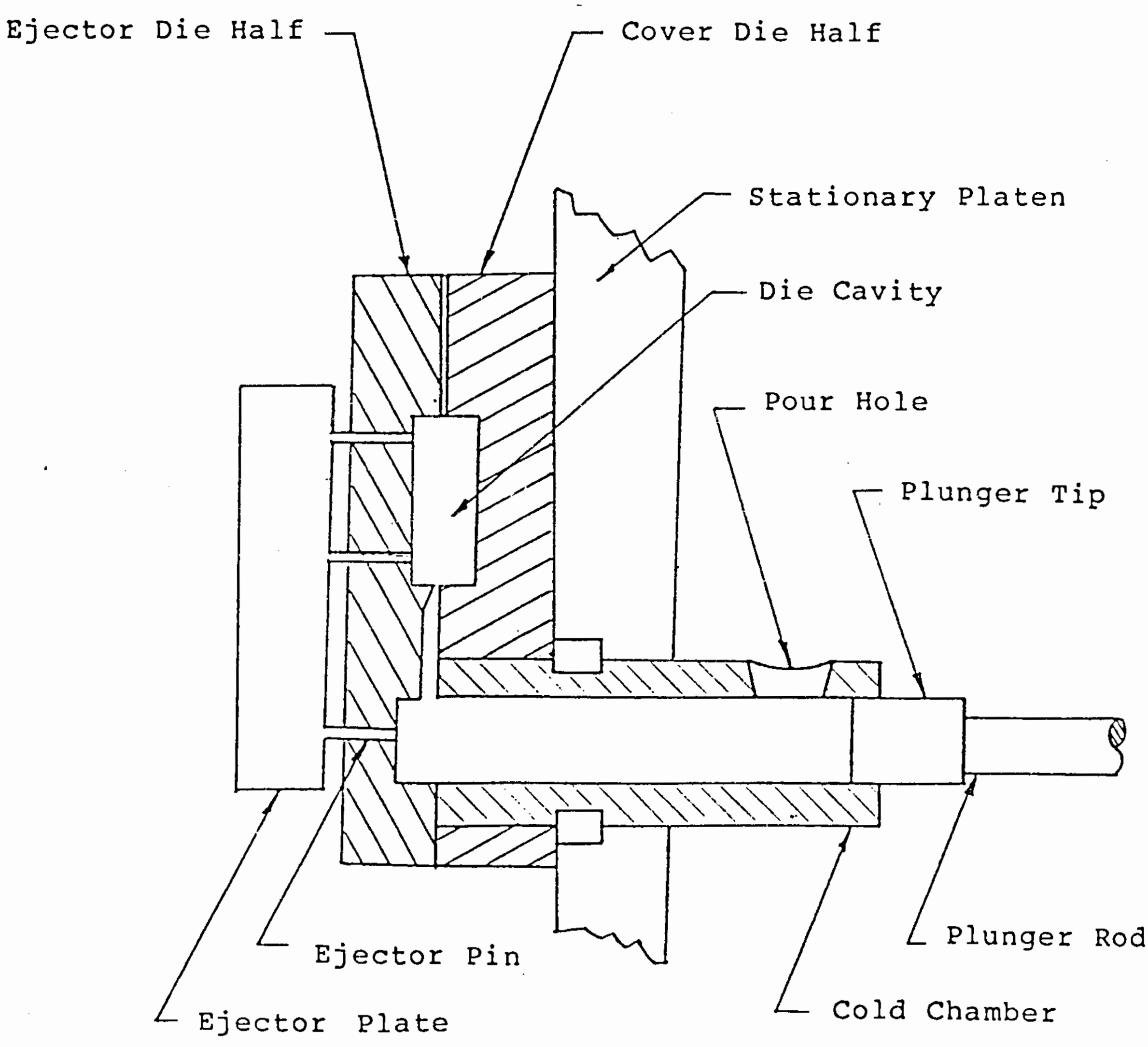



Figure 2. Diagram of die, cold chamber, and horizontal plunger.

zero. Then the movable platen travels back to open the die. Ejector pins in the ejector die travel forward to eject the casting from the die cavity. The operator removes the casting, cleans any excess metal from the cavity, and then applies parting agents to each die half. Finally, after the die is closed, the cycle is repeated (ADCI, 1981; Garber, 1979; Pokorny & Thukkaram, 1981).

The complete cycle of die casting is by far the fastest method known for producing non-ferrous metal castings. Compared to sand casting, which requires a new sand mold for each casting, die casting is more precise and less expensive. Aluminum, zinc, magnesium, lead, and copper alloys are commercially die cast. Aluminum and zinc are used most frequently (ADCI, 1981).

## Applications of Die Casting Design and Control Techniques

Because of the entrapment of gases and the solidification of the casting, die castings typically contain external and internal defects (Garber, 1979). Therefore, in order to reduce casting defects, research on the die casting process and die design for die casting has been carried out systematically around the world for at least 25 years (Cocks, 1980). Most authors agree that cavity fill time, gate velocity, and gate area are three of the most critical factors in assessing the process performance in a die casting process (Cocks, 1980; Cocks & Wall, 1983, 1984, 1985; Kolar, 1985; Robinson, 1977; Wall & Cocks, 1980; Zinc Development Association (ZDA), 1980).

Several methods for predicting the gate area and controlling the casting cavity fill time and gate velocity are available for die castings. Among these die casting design and process control guidelines, the Zinc Die Casting Die Design Aid which was developed by the Zinc Development Association, London, U.K. (see Appendix A) is the most recent technique. Because this technique provides a narrower range of cavity fill time, gate velocity, and gate area for casting trials, the American Die Casting Institute (ADCI) is introducing this new technique to the American die casting industry.

However, in order to apply this casting design and machine control technique to aluminum die casting, the best range of cavity fill time and gate velocity for aluminum casting must be determined first. The review of literature in Chapter II indicates that many reports have been found dealing with the best cavity fill time, gate velocity, and gate area for zinc die castings, but few were published which dealt with aluminum die castings. According to a summary report from British Non-Ferrous (BNF) Metal Technology Center (1980), most reports for predicting aluminum cavity fill time, gate velocity and gate area do not provide enough scientific data and also fail to consider the effects of different casting features.

Casting weight and surface area are used to calculate the best cavity fill time, gate velocity, and gate area in the Die Casting Research Foundation (DCRF) casting nomograph (see Appendix B). On the other hand, casting volume and casting thickness are used in calculating cavity fill time and gate area for zinc die casting by the British Non-Ferrous Metal Technology Center (BNF, 1980). In addition, casting size is commonly considered by most casting engineers in the design of gate area and the control of casting machine. However, no systematic research has been conducted on the effects of different weights, thicknesses, surface areas, and outside diameters on aluminum cavity fill time, gate velocity, and gate area.

## Purpose of the Study

The purpose of this study was to determine the relationships between aluminum casting features (including weight, average thickness, surface area, and outside diameter) and casting process variables (including cavity fill time, gate velocity, and gate area) for round A380 aluminum die castings to generate equations to predict cavity fill time, gate velocity, and gate area from casting features. These findings could also allow the Zinc Die Casting Die Design Aid to be utilized for aluminum die casting.

## Statement of the Problem

The problem of this investigation was to determine the relationship of aluminum casting features and aluminum die casting process variables.

The aluminum casting features included the following:

1. weight,
2. average thickness,
3. surface area, and
4. outside diameter.

The aluminum die casting process variables included the following:

1. aluminum die casting cavity fill time,
2. aluminum die casting gate velocity, and
3. aluminum die casting gate area.

## Research Questions

The information about the different aluminum die casting features and casting process variables was combined to obtain answers for the following research questions:

Question 1. What is the relationship between cavity fill time and the weight of aluminum die castings?

Question 2. What is the relationship between cavity fill time and the average thickness of aluminum die castings?

Question 3. What is the relationship between cavity fill time and the surface area of aluminum die castings?

Question 4. What is the relationship between cavity fill time and the outside diameter of aluminum die castings?

Question 5. What is the relationship between cavity fill time and a combination of several aluminum die casting features?

Question 6. What is the relationship between gate velocity and the weight of aluminum die castings?

Question 7. What is the relationship between gate velocity and the average thickness of aluminum die castings?

Question 8. What is the relationship between gate velocity and the surface area of aluminum die castings?

Question 9. What is the relationship between gate velocity and the outside diameter of aluminum die castings?

Question 10. What is the relationship between gate velocity and a combination of several aluminum die casting features?

Question 11. What is the relationship between gate area and the weight of aluminum die castings?

Question 12. What is the relationship between gate area and the average thickness of aluminum die castings?

Question 13. What is the relationship between gate area and the surface area of aluminum die castings?

Question 14. What is the relationship between gate area and the outside diameter of aluminum die castings?

Question 15. What is the relationship between gate area and a combination of several aluminum die casting features?

## Significance of the Study

In an effort to determine the best aluminum die casting cavity fill time, gate velocity, and gate area, the aluminum die casting industry commonly uses the trial-and-error method. This method is expensive and time-consuming. If relationships between casting features and cavity fill time, gate velocity, and gate area can be better understood, the prediction of casting process variables (including cavity fill time, gate velocity, and gate area) from aluminum casting features may become possible.

By analyzing the relationships between casting features and casting process variables, this study might generate the equations for predicting casting process variables from casting features. In addition, by summarizing the range of cavity fill time, gate velocity, and gate area, this study could allow the Zinc Die Casting Die Design Aid to be utilized by the aluminum die casting industry (see Appendix N). This technology can provide an optimal choice of cavity fill time, gate velocity, and gate area to match the capability of the casting machine.

Therefore, findings from this study could significantly reduce the time for die design and the number of trials for machine settings and increase production efficiency. Furthermore, a combination of the results of this study and a computer controlled hydraulic system can eventually lead to automation in the aluminum die casting process.

## Limitations

Because of the constraints of time, financial resources, and computer data, this study was conducted under the following limitations:

1. The shape of selected aluminum sample castings was limited to round aluminum die castings.

2. The sizes of selected aluminum sample castings were limited to casting sizes which were produced by the Kiowa Corporation not more than two years before the study (see Data Collection in Chapter III, p. 30).

3. The type of selected aluminum casting machine was limited to horizontal cold chamber die casting machines.

4. The type of aluminum alloy was limited to standard alloy A380.

## Delimitation

According to engineering records of the Kiowa Corporation, die temperature and metal temperature have always been set at 350° F and 1220° F, respectively. Therefore, this study did not attempt to evaluate differences in results which could be caused by differences in die temperature and molten aluminum temperature.

## Assumptions

The following assumptions were made in pursuit of this study:

1. Data obtained from the Kiowa Corporation are valid and reliable.

2. Casting weight, average thickness, surface area,

and outside diameter represented the major characteristics of aluminum die casting features.

3. Kiowa Corporation's casting inspection standard was reliable and consistent.

4. The casting features of each sample casting represented the casting features of the repective production lot.

## Definition of Terms

The following terms were defined to clarify their use in the context of this study. Most definitions adhere to the terminology standard set by the American Die Casting Institute, Inc. (1981):

Average thickness--average wall thickness of an aluminum die casting.

Cavity--the recess or impression in a die in which the casting is formed.

Casting features--the physical features of an aluminum casting including weight, average thickness, surface area, and outside diameter.

Casting process variables--the process variables of a die casting machine including cavity fill time, gate velocity, and gate area.

Cavity fill time--the amount of time needed to fill the die cavity with molten metal.

Cold chamber machine--a type of die casting machine in which metal is ladled into the injection cylinder each time the machine is cycled.

Die--a metal mold which includes the gating system, casting cavity, and over-flow well, if any.

Ejector plate--a plate to which ejector pins are attached and which actuates the ejector pins.

Gate (ingate)--passage for molten metal which connects the runner with the die cavity.

Gate velocity--the velocity of the molten metal which is being injected into a die through the gate area.

Gate area--the thinnest cross section of ingate which connects the runner to the casting cavity.

Injection--the process of forcing molten metal into a die.

Nomograph--graphic chart for helping die casting engineers to design the gating system for a die and to determine how to set certain machine controls (see Appendix A & B).

Plunger--Ram or piston which forces molten metal into a die.

Porosity--voids or pores resulting from trapped air or shrinkage in a casting.

Runner--die passage connecting sprue or plunger holes of a die to the gate where molten metal enters the cavity or cavities.

Shot--that segment of the casting cycle in which molten metal is forced into the die.

Shrinkage, solidification--dimensional reduction that accompanies the freezing (solidification) of metal passing from the molten to the solid states.

Vent--narrow passage at the die parting which permits air to escape from the die cavity as it is being filled with molten metal.

# CHAPTER II

# REVIEW OF LITERATURE

## Introduction

Because the capability of a casting machine has to match the kinds and sizes of castings produced, it is commonly believed that the quality of an aluminum die casting depends on the casting die design, the capability of the casting machine, and the machine controls (Kruszynski, 1986; Robinson, 1977). During the initial try-out stages, the casting die is often redesigned to improve casting quality. The casting die can be modified by cutting or welding. These trial-and-error processes usually need to be repeated until an acceptable casting quality is obtained. However, these processes are very costly and time-consuming.

> Traditionally, casting die design has been based on experience alone with modifications being carried out by the cut-and-weld technique until a visually acceptable casting is obtained. Assessment of the efficiency of the casting die design is based on a qualitative assessment of casting quality. This method may result in the eventual production of quality castings but it cannot be expected to maximize the profitability of the die casting operation. (Robinson, 1977, p. 1)

Once the machine type and die design have been decided, the quality and production rate of a given aluminum die casting depends heavily on the efficiency of casting machine control procedures (Cocks, 1980; Kruszynski, 1986; Robinson, 1977).

> Once the initial shots have been made with a new die and the necessary data has been collected and interpreted, it will probably be necessary to adjust the operating parameters of the machine to obtain the designed performance from the die. It is important, therefore, to appreciate the interaction between operating parameters, die performance and casting quality. (Robinson, 1977, p. 7)

The complete cycle of a casting process can be divided into two phases (see Appendix C): an initial slow shot phase followed by a fast shot phase (ADCI, 1981). The main purpose of the slow shot phase is to fill the cold chamber with molten aluminum. During the slow shot phase, air in the cold chamber escapes through vents in the parting plane of the die halves. The recommended slow shot plunger speed has been investigated by Garber (1979). It was shown that a slow shot velocity of less than 0.38 m/s (15 in/s) can improve aluminum die casting quality. In addition, nomographs developed by the Die Casting Research Foundation, Inc. are available to calculate the required length and speed of the slow shot by cold chamber diameter and its initial fill percentage. Recently, to avoid the variation in the amount of metal ladled, Professors LaRue and Pershing (1985) of the University of Northern Iowa developed a metal sensing device for a die casting machine that will ensure the activation of the fast shot so that the plunger will be moving at maximum velocity just as the metal arrives at the gate regardless of variations in the amount of metal ladled.

In the fast shot phase, cavity fill time, gate velocity, and gate area influence the quality of the casting (Cocks, 1980). A number of nomographs and tables have been produced for predicting the optimum cavity fill time, gate velocity, and gate area for the control of the plunger velocity and design of gate area (BNF, 1980). Examples include the nomograph developed by the Die Casting Research Foundation (DCRF, 1961), Des Plaines, Illinois (see Appendix B), the "Australian Gating Technology" developed by the Commonwealth Scientific Industrial Research Organization (CSIRO), Melbourne, Australia, and the Zinc Die Casting Die Design Aid published by the Zinc Development Association (ZDA), London, United Kingdom (see Appendix A). In order to determine which nomograph is the most reliable, a survey of different die casting technology from Europe, USA, and Australia has been published by BNF (1980). This summary report, called the BNF Manual of Pressure Diecasting Gating Design, has compared those different nomographs.

The results of this summary report showed that "no nomogram is significantly better than the others. Comparing the average difference between predicted and actual values, it suggests the original DCRF to be the better. However, the DCRF methods cannot be used on all the castings" (p. 10). In applying any of the above die casting gate design and machine control guidelines to aluminum die casting, the casting feature information, best cavity fill time, and gate velocity are needed.

## Review of Pertinent Studies

During the review of related literature, a computer data base called World Aluminum Abstracts (WAA) was searched in the library of the University of Northern Iowa. This data base, which is produced by the American Society for Metals (ASM), provides complete coverage of the world's technical literature on aluminum from 1968 to the present. About fifty pieces of literature were found dealing with casting features. One-third of these dealt with materials tests and heat treatment. The rest of the literature dealt with new casting materials, new die materials, and different shapes of gate systems. No report was found dealing with casting weight, average thickness, surface area, or outside diameter.

Although many pieces of literature were found dealing with the best cavity fill time or gate velocity or gate area for different kinds of die castings, most of the literature dealt with the gating system or cavity fill time individually or only dealt with zinc die casting. There was no literature in the WAA computer data base which dealt directly with the relationships between process variables and casting features.

In addition to the literature in the WAA data base, one dissertation was found dealing with aluminum die casting (Garber, 1979). There were three objectives in his study. The first two objectives were to investigate the effects of experimental manipulations and random variations of five process variables (including intensification pressure, fast shot velocity, die temperature, metal temperature, and die open time) on the internal quality of aluminum die castings. The first two objectives of Garber's study involved five factor experiments, each factor having two levels. From the total of 100 experimental castings, 11 castings were selected for density measurements. The remaining 89 castings were machined to reveal the internal structure of the castings. Only random variations in the plunger travel lengths and pressure-related variables were found to affect internal quality. The third objective was to determine whether entrapped air or internal solidification shrinkage is the principal cause of porosity within aluminum die castings. In his review of literature, he noted "although it is generally held that entrapped air is the principal cause of the great volume of porosity within aluminum die casting, no experimental evidence was found in the literature to support this view" (p. 202). Like those researchers he mentioned in his review of literature, Garber (1979) also did not conduct any experiment to address the cause of porosity. Instead, he answered the question concerning the third objective by "observations" of his two experiments together with his "theoretical considerations" and drew the following conclusion:

> Seven arguments were given from which it was concluded that internal solidification shrinkage is the principal cause of the greatest volume of porosity. Five of these arguments were based on experimental observations noted in the experiments and two arguments were based on theoretical considerations about the volume of entrapped gas porosity and the volume of shrinkage porosity. (p. 201)

As with the WAA computer data base, this dissertation included no discussion about the relationships between casting features and casting process variables.

The BNF Manual of Pressure Diecasting Gating Design (1980) provided several summary figures of optimal ranges of cavity fill time, gate velocity, and gate area for both zinc and aluminum die castings. However, they are too general to use for a specific casting. In addition, this manual concluded that most published works did not have sound experiments to support their recommendations (BNF, 1980).

> There has been a considerable number of papers published on gate velocity, cavity fill time and gate area. However, very few of the papers give experimental results or any evidence for the recommendations they make. Some of the recommendations made for gate velocity are beyond the capabilities of existing machines. (p. 1)

This manual also indicated that most published works did not consider the effects of casting features. "A further problem is that diecastings cover an enormous range of shapes and sizes, which means that what is applicable in one case may not apply in another" (p. 1).

Although there was no direct study dealing with the relationships between casting features and casting process variables, some reports were found to be useful in providing basic information for this study. These included the definition and calculation of casting process variables and some isolated information about the possible relationships between casting features and cavity fill time, gate velocity, and gate area.

## Cavity Fill Time and Aluminum Casting Features

Cavity fill time is the amount of time taken to fill the die cavity with molten metal. Therefore, it is the result of casting volume divided by the product of the inside diameter of the cold chamber and the speed of the plunger. Cavity fill time can be calculated by using the following formula (Garber, 1979):

$$t = \frac{Vc}{\pi r^2 Vp}$$

where

t = cavity fill time

Vc = volume of casting and overflow wells

r = inside radius of cold chamber

Vp = average plunger velocity during filling.

From practical experience, most authors agree that shortening the cavity fill time by increasing the fast shot velocity improves the surface quality of a casting (BNF, 1980; Cocks & Wall, 1983, 1984, 1985; Garber, 1979; ZDA, 1980). Therefore, most nomographs recommend using the shortest possible cavity fill time to obtain a good surface finish.

A popular method in determining possible cavity fill time is to calculate the cavity fill time from the weight to surface area ratio and the temperature differences between the casting die and the molten aluminum (see Appendix B). However, from interviews of casting engineers at the Kiowa Corporation (1985), most believe that in addition to average thickness, other casting features (especially weight, surface area, and size) should also be considered in determining the best cavity fill time. It seems clear that there are relationships between the cavity fill time and several casting features. Unfortunately, the exact nature of the relationships between cavity fill time and casting features have not yet been systematically investigated.

## Gate Velocity and Aluminum Casting Features

The metal flow rate can be calculated by dividing casting volume by cavity fill time. In calculating gate velocity, metal flow rate is divided by gate area (ZDA, 1980). Therefore, the following equations can be used to summarize the calculation:

$$\text{metal flow rate} = \frac{\text{casting volume}}{\text{cavity fill time}}$$

$$\text{gate velocity} = \frac{\text{metal flow rate}}{\text{gate area}}$$

Several studies, each recommending a wide range of different gate velocities for aluminum die casting, were reported in the BNF Manual of Pressure Diecasting Gating Design (1980). However, these studies did not consider the effects of different casting features on gate velocity. The effects of low and high gate velocities on the quality of aluminum die castings have been reported differently. Low gate velocities were found to produce castings of better quality by Luis and Draper (1966), and Stuhrke and Wallace (1965). On the other hand, based on production experience, reports from ADCI have indicated that high gate velocities were desirable (Cocks & Wall, 1983, 1984, 1985; ZDA, 1980). These contradictory reports might indicate that the effects of gate velocity depend on and interact with other process variables or casting features.

## Gate Area and Aluminum Casting Features

Several different gating nomographs have been developed for deciding gate area (BNF, 1980; Cope & Siauw, 1985; DCRF, 1961, 1986; Herman, 1973, 1979; Kolar, 1985; Pokorny & Thukkaram, 1981). The Society of Die Casting Engineers (SDCE) has developed a gating slide rule with which gate area, plunger velocity, and cold chamber area can be calculated based on the basic cavity fill time. The BNF Manual of Pressure Diecasting Gating

Design (1980) indicated that a very wide range of gate areas can be used on a casting. However, it also indicated that the bigger gate areas have a negligible effect on the surface finish of the castings.

In conclusion, this manual showed that most publications did not provide enough scientific evidence for their recommendations (BNF, 1980):

> A considerable amount of published work has appeared over the last 20 years on various aspects of gating design. Most of the papers have covered isolated aspects and have often been expressed without the support of any scientifically collected results. (p. 1)

Finally, this manual concluded that it is simpler and more accurate to relate the casting volume and casting wall thickness to the gate area and that the use of average thickness in calculations is more accurate than calculations using minimum wall thickness. The form of the equation used to obtain the best gate area was as follows:

$$A = \frac{K\,V^{n1}}{T^{n2}}$$

where A = gate area,

T = average wall thickness,

V = casting volume,

K, n1, n2 = constants.

## Summary

According to the literature reviewed in this chapter, there has been no systematic and detailed investigation into the precise relationships between aluminum die casting features and cavity fill time, gate velocity, and gate area. Several nomographs have been produced for predicting the optimum fill time, gate velocity, and gate area for the die casting industry. Predictions are commonly calculated based on some casting features. However, different nomographs may use different casting features for their calculations. In addition, in order to apply those techniques to aluminum die casting, the best ranges of cavity fill time, gate velocity, and gate area have yet to be determined for aluminum. Therefore, the precise nature of the relationships between casting features and cavity fill time, gate velocity, and gate area require further investigation.

# CHAPTER III

# METHODOLOGY

## Nature of the Data

Historical casting data from the Kiowa Corporation at Marshalltown, Iowa, were used in this study. Two categories of data were needed for solving the research questions: (a) casting features and (b) casting process variables. The casting features, which included casting weight, average thickness, surface area, and outside diameter, were measured directly from the collected samples. The casting process variables, which include cavity fill time, gate velocity, and gate area, were procured from the engineering records. These engineering records were collected systematically through years of die casting experience at the Kiowa Corporation.

Before production runs for a new casting were started, systematic experiments had always been conducted to set up the casting machine. After the experiments, the die casting process variables were always recorded for later use. In subsequent runs, the casting machines were set according to the previous engineering records. Usually, no further trials were needed for the later runs. This shows the engineering records to be very reliable and complete.

## Criteria for Acceptable Samples

The following criteria were used to select sample casting parts for the data analyses:

1. The sample casting was round.

2. Each sample casting part was different from others in at least one selected casting feature.

3. The sample casting must have been produced not more than two years before the time of the study.

4. The casting scrap rate of the selected sample was be less than five percent.

## Treatment of the Data

In order to determine the relationships between the aluminum die casting features and the casting process variables, the following correlation analyses were used:

1. The correlation of one dependent variable (casting process variable) and one independent variable (casting feature) for questions 1, 2, 3, 4, 6, 7, 8, 9, 11, 12, 13, and 14.

2. The multiple correlation of one dependent variable (casting process variable) and a combination of several independent variables (casting features) for questions 5, 10, and 15.

## Correlation Analysis of Two Variables

### Research Questions

Question 1. What is the relationship between aluminum cavity fill time and the weight of aluminum die castings?

Question 2. What is the relationship between aluminum cavity fill time and the average thickness of aluminum die castings?

Question 3. What is the relationship between aluminum cavity fill time and the surface area of aluminum die castings?

Question 4. What is the relationship between aluminum cavity fill time and the outside diameter of aluminum die castings?

Question 6. What is the relationship between gate velocity and the weight of aluminum die castings?

Question 7. What is the relationship between gate velocity and the average thickness of aluminum die castings?

Question 8. What is the relationship between gate velocity and the surface area of aluminum die castings?

Question 9. What is the relationship between gate velocity and the outside diameter of aluminum die castings?

Question 11. What is the relationship between gate area and the weight of aluminum die castings?

Question 12. What is the relationship between gate area and the average thickness of aluminum die castings?

Question 13. What is the relationship between gate area and the surface area of aluminum die castings?

Question 14. What is the relationship between gate area and the outside diameter of aluminum die castings?

## Data Needed

The data needed to solve the above questions consisted of 30 pairs of data for each casting feature and its corresponding casting process variable for each question.

## Data Collection

Round castings with different part numbers were identified from Kiowa's Casting Sample Center, which stores sample castings from the last production run of each casting part. Because of limitations in Kiowa's computer capacity, casting quality data have been kept for only two years. Therefore, castings which were produced more than two years before the study were eliminated because of the lack of quality data. The first thirty round castings which had a scrap rate of less than five percent were identified, collected, and measured individually to record the features of each selected casting. The corresponding casting process data were collected from engineering records in Kiowa's Information Center.

A data collection sheet (see Appendix D) was designed to record the measured casting features and the casting process data. The information included casting part number, casting scrap rate, casting machine number, plunger area, plunger velocity, gate area, gate velocity, flow rate, casting volume, casting weight, cavity fill time, and the average thickness, casting surface area, and outside diameter of the casting.

<u>Data Analysis</u>

The information for the data collection sheets was transferred onto a data matrix (see Appendix E) which contained 30 sets of seven variables (three casting process variables and four casting feature variables). This data matrix was used as the computer input for the correlation analysis. Each casting feature and its corresponding casting process data were plotted in a graphic form called a scattergram. The correlation between the independent variable (casting feature) and the dependent variable (casting process variable) was expressed as Pearson's correlation coefficient (r). A statistical computer program called Statistical Package for Social Sciences (SPSS), which was provided by Academic Computing Services of the University of Northern Iowa, was used to plot the scattergrams and calculate the correlation coefficients (r) and their significance level. If a significant correlation was found, the line of best fit and the regression equation, $Y' = \text{Constant} + B X$, was also included. If the correlation coefficient was not significantly different from zero, only the correlation coefficient (r) and significance level were reported. The scattergram and statistical summary for non-significant correlation are included in Appendix F through J.

## Data Interpretation

The correlation coefficient and its confidence level were used to interpret the nature and significance of the relationship between the dependent variable (casting process variable) and the independent variable (casting feature variable). Since the relationship between the dependent variable and the independent variable cannot be decided in advance, a two-tailed test at $p < .05$ was used. If there was a significant linear relationship (the value of r was not equal to zero, and the significance level was $p < .05$) between the two variables, the use of the regression line for predicting the casting process variable from the casting feature was also explained.

## Multiple Correlation Analysis

### Research Questions

Question 5. What is the relationship between cavity fill time and a combination of several aluminum die casting features?

Question 10. What is the relationship between gate velocity and a combination of several aluminum die casting features?

Question 15. What is the relationship between gate area and a combination of several aluminum die casting features?

### Data Needed

The data needed to solve any one of the above questions were one dependent variable (casting process variable) and four independent variables (casting features) for each question.

### Data Collection

The same data which were used in the two variable correlation analyses were also used in the multiple correlation analyses.

## Data Analysis

The multiple regression statistical computer program called "New Regression" was available from the SPSS. This program provided the correlation matrix for the expression of the correlation between every two variables. A correlation matrix which includes one casting process variable and four casting features was printed for each question.

For multiple regression analysis, the arbitrary inclusion of large numbers of variables increases the standard errors of all estimates without improving prediction (Norusis, 1982). Therefore, a stepwise selection method, which is the most commonly used method in multiple regression analysis, was used to determine the optimal number of independent predictor(s) (casting features) for a multiple regression model. The main purpose of the stepwise selection is to build a concise model that makes the best prediction possible.

The stepwise selection of independent variables is a combination of forward and backward selection (Norusis, 1982). In the forward selection, the first variable entered into the equation is the one with the largest positive or negative correlation with the dependent variable. The F-test for the hypothesis that the coefficient of the entered variable is 0 is then calculated. In order to judge whether this selected variable is important, a probability of .05 was used as the criterion. Therefore, a variable enters into the multiple regression equation only if the probability associated with the F-test is less than or equal to .05.

If the variable fails to meet entry requirement (pIN = .05), the procedure terminates with no independent variables in the equation. If it passes the criterion, the second variable is selected based on the highest partial correlation, and if it also passes entry criteria, it enters the equation. From this point, the backward elimination process examines whether or not the F value of the first variable is small enough to meet the removal criterion. A .10 backward elimination criterion (pOUT = .10) was used in this study. The next step is to examine the variables not in the equation for possible entry and then examine the variables in the equation for possible removal. Variables are removed until none remain that meet the removal criterion. Variable selection terminates when no more variables meet entry and removal criteria (Norusis, 1982).

After the stepwise selection, a final multiple regression equation was expressed. In addition, the table of the statistical summary was also included.

Data Interpretation

The criterion and process of stepwise selection, the number of optimal predictors, and the final multiple regression model, which predicts the casting process variable from one or more casting feature variables, were discussed.

# CHAPTER IV

## ANALYSES OF THE DATA

This study investigated the relationships between casting features (including casting weight, average thickness, surface area, and outside diameter) and casting process variables (including cavity fill time, gate velocity, and gate area for aluminum die casting) for aluminum die castings. The correlation analyses consisted of determining:

1. the correlation of one casting process variable and one casting feature.

2. the multiple correlation of one casting process variable and a combination of several casting features.

A statistical computer program called Statistical Package for Social Sciences (SPSS) was used to calculate the correlation coefficient (r), significance level, and linear regression equation for each research question.

For simple correlation analyses, the significant relationships were reported as a correlation coefficient (r), a significance level, and a scattergram with the line of best fit. If the correlation coefficient was not significantly different from zero, only the correlation coefficient (r) and significance level were reported.

The scattergram and statistical summary are included in the Appendices.

For multiple regression analyses, the default values (pIN = .05, pOUT = .10, and tolerance = .01) of SPSS stepwise selection (Norusis, 1982) were used as the criteria in determining the optimal number of casting feature variables. After the stepwise selection, the multiple regression coefficient (R) and final regression equation were reported for each multiple regression question. Detailed discussions about the variables in and not in the multiple regression equation were included.

## Results and Discussions of Findings

### Question 1

What is the relationship between cavity fill time and the casting weight of aluminum die castings?

#### Findings

The 30 pairs of cavity fill time and casting weight were analyzed to answer question 1. A non-significant correlation coefficient was found between cavity fill time and casting weight, $r = .3554$, $p = .0539 > .05$. The statistical summary of the relationship and the scattergram are in Appendix F.

## Question 2

What is the relationship between cavity fill time and the average thickness of aluminum die castings?

### Findings

The 30 pairs of cavity fill time and average thickness were analyzed to answer question 2. A significant correlation coefficient was found between cavity fill time and the average thickness, $r = .5411$, $p = .0020 < .05$. The statistical summary is shown in Table 1. The scattergram and the line of best fit are graphically presented in Figure 3.

The regression line for predicting cavity fill time from casting thickness was also plotted using the following linear equation:

$$\text{Cavity Fill Time (sec)} = .0059 + .3757 \times \text{Average Thickness (in)}$$

This regression line indicates that an increase in .1 inch of casting average thickness results in a .03757 second increase in cavity fill time.

Table 1

The Statistical Summary for the Relationship Between Cavity Fill Time and Average Thickness

| | | | |
|---|---|---|---|
| Correlation (r) | = .5411 | Intercept (A) | = .0059 |
| Significance | = .0020 | Slope (B) | = .3757 |
| Std Err of Est | = .1045 | Significance | = .0010 |

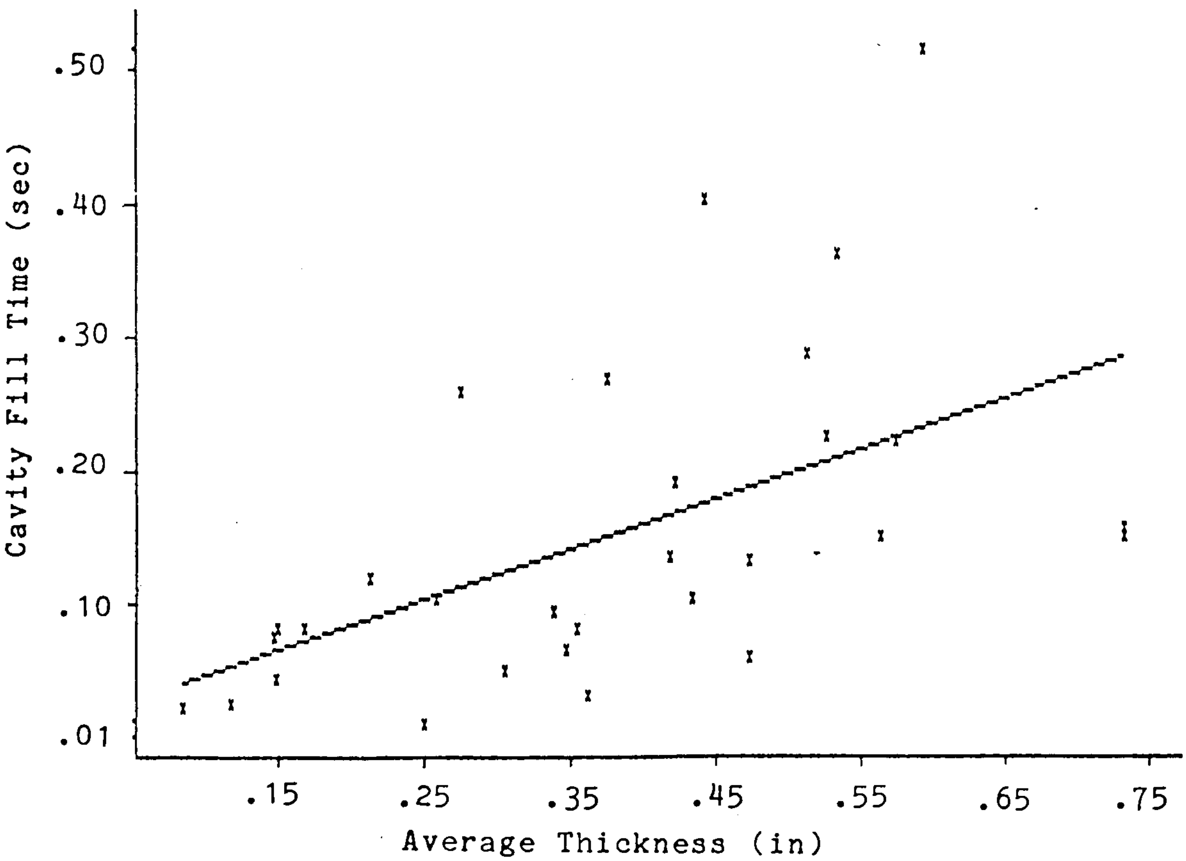



Figure 3. The scattergram and line of best fit for cavity fill time and average thickness.

Question 3

What is the relationship between cavity fill time and the surface area of aluminum die castings?

Findings

The 30 pairs of cavity fill time and surface area were analyzed to answer question 3. A non-significant correlation coefficient was found between cavity fill time and the surface area, $r = .1850$, $p = .3276 > .05$. The statistical summary of the relationship and the scattergram are presented in Appendix G.

Question 4

What is the relationship between cavity fill time and the outside diameter of aluminum die castings?

Findings

The 30 pairs of cavity fill time and outside diameter were analyzed to answer question 4. A significant correlation coefficient was found between cavity fill time and outside diameter, $r = .4249$, $p = .0193 < .05$. The statistical summary is shown in Table 2. The scattergram and line of best fit are graphically presented in Figure 4.

Table 2

The Statistical Summary for the Relationship Between Cavity Fill Time and Outside Diameter

| | | | |
|---|---|---|---|
| Correlation (r) | = .4249 | Intercept (A) | = .0499 |
| Significance | = .0193 | Slope (B) | = .0129 |
| Std Err of Est | = .1125 | Significance | = .0096 |

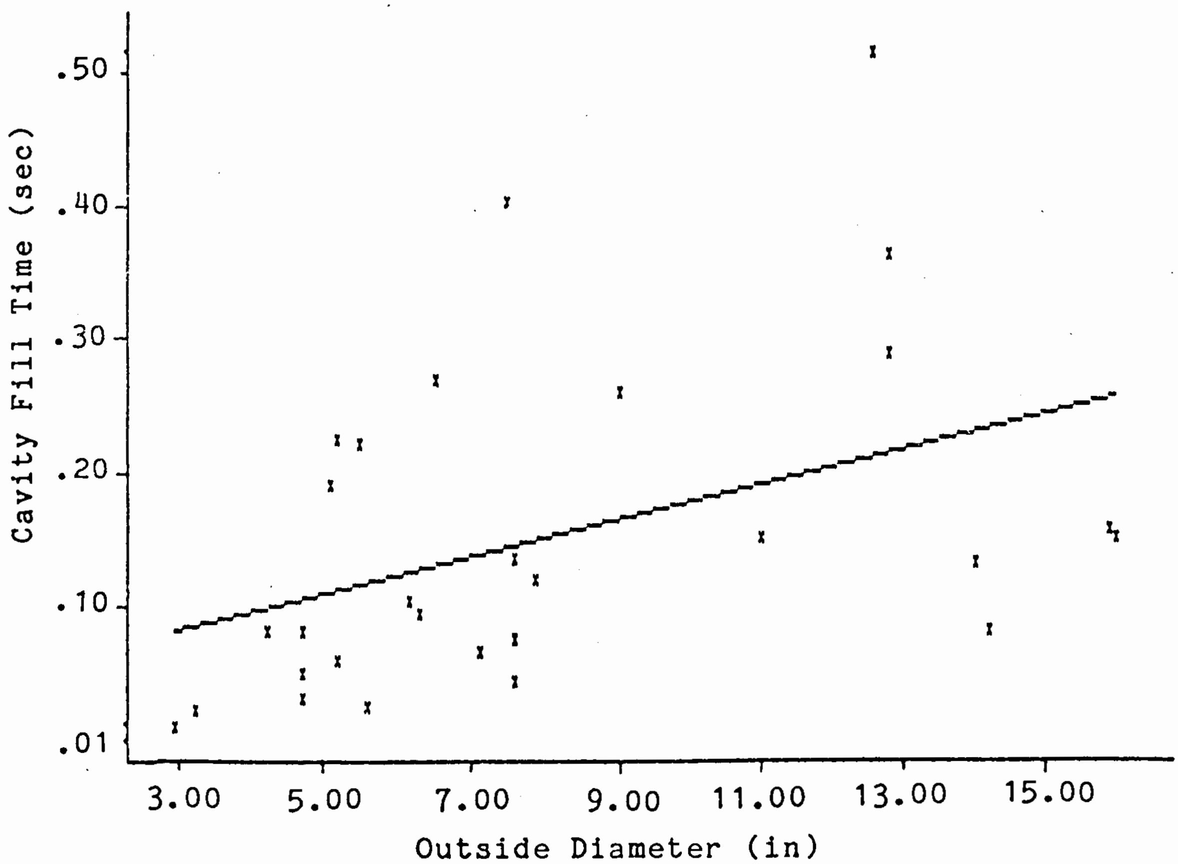



Figure 4. The scattergram and line of best fit for cavity fill time and outside diameter.

The regression line for predicting cavity fill time from outside diameter was also plotted using the following linear equation:

$$\text{Cavity Fill Time (sec)} = .0499 + .0129 \times \text{Outside Diameter (in)}$$

This regression line indicates that an increase in one inch of casting outside diameter results in a .0129-second increase in cavity fill time.

## Question 5

What is the relationship between cavity fill time and a combination of several aluminum die casting features?

### Findings

The 30 sets of cavity fill time, casting weight, average thickness, surface area, and outside diameter were analyzed to answer question 5. The correlation matrix shows the large correlations of the casting features in Table 3. After the stepwise selection, only casting thickness was accepted in the multiple regression model. The statistical summary is shown in Table 4.

Table 3

*The Correlation Matrix of Cavity Fill Time and Casting Features*

N = 30

| | Time | Weight | Thick | Surface | O.D. |
|---|---|---|---|---|---|
| Time | | | | | |
| Weight | .3554 | | | | |
| | p = .0539 | | | | |
| Thick | .5411 | .6208 | | | |
| | p = .0020 | p = .0000 | | | |
| Surface | .1850 | .8257 | .4177 | | |
| | p = .3276 | p = .0000 | p = .0220 | | |
| O.D. | .4249 | .9082 | .5479 | .7931 | |
| | p = .0193 | p = .0000 | p = .0020 | p = .0000 | |

*Note.* Time = cavity fill time; Weight = casting weight; Thick = average thickness; Surface = surface area; O.D. = outside diameter; N = number of total sample. upper value = correlation coefficient; lower value = significance level.

Table 4

The Statistical Summary of the Multiple Regression Analysis Between Cavity Fill Time and Casting Features

Dependent Variable: cavity fill time
Independent Variable(s) Entered on Stepwise Selection:
average thickness

Multiple R = .5411
R Square = .2928, Standard Error = .1045

Analysis of Variance

Variable in the equation

| Variable | B | T | Sig T |
|---|---|---|---|
| Thick | .3757 | 3.4050 | .0020 |
| (constant) | .0059 | .1260 | .9009 |

Variables not in the equation

| Variable | Partial | T | Sig T |
|---|---|---|---|
| Weight | .0295 | .1530 | .8792 |
| Surface | -.0537 | -.2790 | .7821 |
| O.D. | .1835 | .9650 | .3433 |

*Note.* Weight = casting weight; Thick = average thickness; Surface = surface area; O.D. = outside diameter.

<u>Discussion of Findings</u>

1. The SPSS stepwise selection with the default criteria (pIN = .05, pOUT = .10, and tolerance = .01) were used to select the important casting feature variable(s) and determine the optimal number of casting feature variables for the multiple regression equation. The casting feature with the largest partial correlation coefficient, average thickness, was selected and tested first. Because average thickness met the criterion for inclusion (pIN < .05), it was entered into the equation. The casting feature with the next largest partial correlation coefficient, outside diameter, was selected and tested next. However, because outside diameter did not meet the default criterion for inclusion, forward selection stopped. Therefore, only casting thickness was considered for predicting the cavity fill time from casting features (see Appendix K).

2. The multiple regression coefficient (R) may increase as casting weight, surface area, and outside diameter are included. However, it does not necessarily mean that the equation with more variables better fits the population (Norusis, 1982). This is because each time a variable is added to the equation, one degree of freedom is lost from the residual sum of squares and one is gained in the regression sum of squares.

3. The final multiple regression between cavity fill time and casting thickness is:

Cavity Fill Time (sec)

= .0059 + .3757 x Average Thickness (in)

This final multiple regression line was the same as the simple regression line between cavity fill time and average thickness (see Figure 3, p. 40).

## Question 6

What is the relationship between gate velocity and the casting weight of aluminum die castings?

### Findings

The 30 pairs of gate velocity and casting weight were analyzed to answer question 6. A non-significant correlation coefficient was found between cavity fill time and the surface area, $r = -.1827$, $p = .3338 > .05$. The statistical summary of the relationship and the scattergram are presented in Appendix H.

## Question 7

What is the relationship between gate velocity and the average thickness of aluminum die castings?

### Findings

The 30 pairs of gate velocity and average thickness were analyzed to answer question 7. A significant correlation coefficient was found between gate velocity and average thickness, $r = -.4055$, $p = .0262 < .05$. The statistical summary is shown in Table 5. The scattergram and line of best fit are graphically presented in Figure 5.

The regression line for predicting gate velocity from average thickness was also plotted using the following linear equation:

Gate Velocity (ft/sec)

= 133.5828 + (-152.2890) x Average Thickness (in)

This regression line indicates that an increase in .1 inch of casting average thickness results in a 15.2289-feet per second decrease in gate velocity.

Table 5

The Statistical Summary for the Relationship Between Gate Velocity and Average Thickness

| | | | | | |
|---|---|---|---|---|---|
| Correlation (r) | = | -.4055 | Intercept (A) | = | 133.5828 |
| Significance | = | .0262 | Slope (B) | = | -152.2890 |
| Std Err of Est | = | 61.4342 | Significance | = | .0131 |

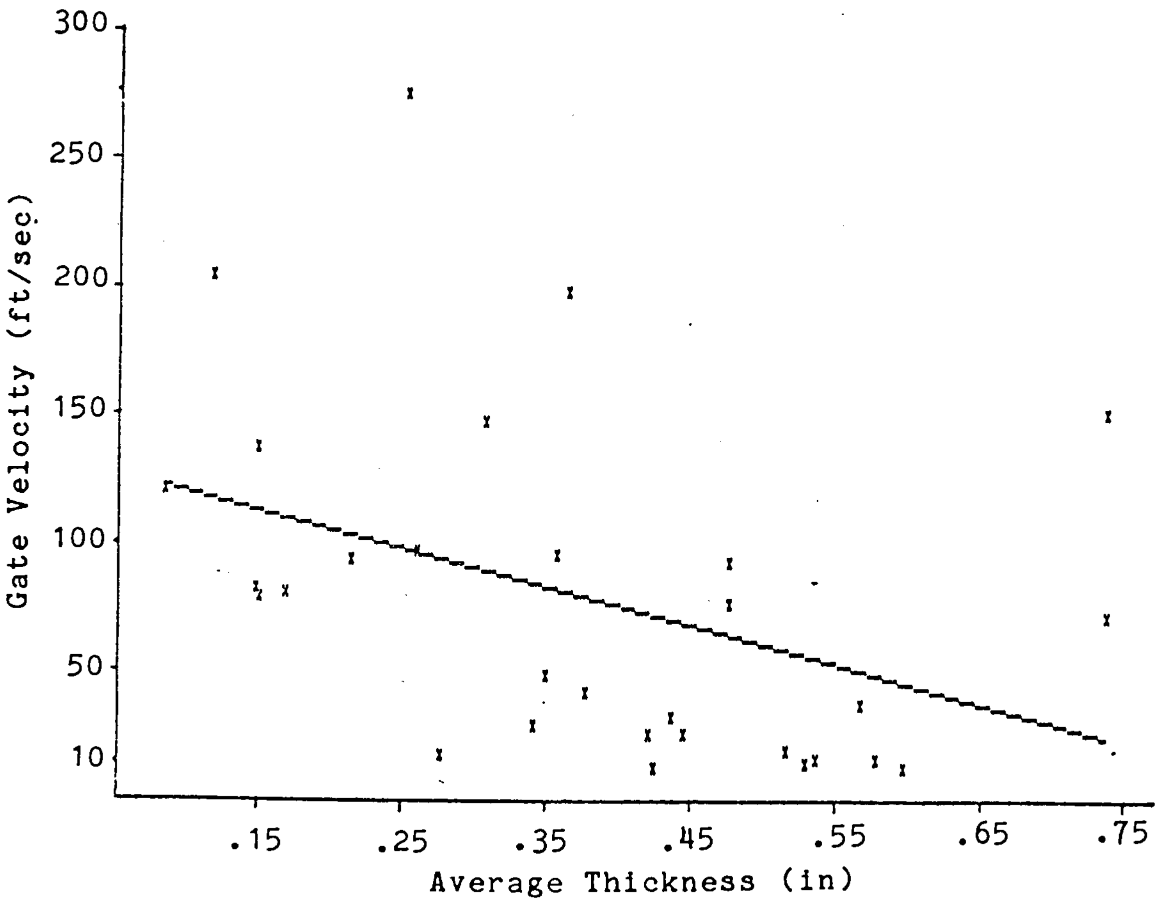



Figure 5. The scattergram and line of best fit for gate velocity and average thickness.

## Question 8

What is the relationship between gate velocity and the surface area of aluminum die castings?

### Findings

The 30 pairs of gate velocity and surface area were analyzed to answer question 8. A non-significant correlation coefficient was found between gate velocity and surface area, $r = -.2274$, $p = .2268 > .05$. The statistical summary of the relationship and the scattergram are presented in Appendix I.

## Question 9

What is the relationship between gate velocity and the outside diameter of aluminum die castings?

### Findings

The 30 pairs of gate velocity and outside diameter were analyzed to answer question 9. A non-significant correlation coefficient was found between gate velocity and outside diameter, $r = -.2997$, $p = .1080 > .05$. The statistical summary and the scattergram for the relationship are presented in Appendix J.

## Question 10

What is the relationship between gate velocity and a combination of several aluminum die casting features?

### Findings

The 30 sets of gate velocity, casting weight, average thickness, surface area, and outside diameter were analyzed to answer question 10. The correlation matrix shows the large correlations of the casting features in Table 6. After the stepwise selection, only casting thickness was accepted in the multiple regression model. The statistical summary is shown in Table 7.

### Discussion of Findings

1. The SPSS stepwise selection with the default criteria (pIN = .05, pOUT = .10, and tolerance = .01) were used to select the important casting feature variable(s) and determine the optimal number of casting feature variables for the regression equation. The casting features with the largest partial correlation, average thickness, was selected and tested first. Because average thickness met the criterion for inclusion (pIN < .05), it was entered into the equation.

The casting feature with the next largest partial coefficient, outside diameter, was selected next.

Table 6

*The Correlation Matrix of Gate Velocity and Casting Features*

N = 30

| | Velo | Weight | Thick | Surface | O.D. |
|---|---|---|---|---|---|
| Velo | | | | | |
| Weight | -.3554 | | | | |
| | p = .3338 | | | | |
| Thick | -.4055 | .6208 | | | |
| | p = .0262 | p = .0000 | | | |
| Surface | -.2274 | .8257 | .4177 | | |
| | p = .2268 | p = .0000 | p = .0220 | | |
| O.D. | .2997 | .9082 | .5479 | .7931 | |
| | p = .1080 | p = .0000 | p = .0020 | p = .0000 | |

*Note*. Velo = gate velocity; Weight = casting weight; Thick = average thickness; Surface = surface area; O.D. = outside diameter; N = number of total sample.
upper value = correlation coefficient; lower value = significance level.

Table 7

*The Statistical Summary of the Multiple Regression Analysis Between Gate Velocity and Casting Features*

Dependent Variable: gate velocity
Independent Variable(s) Entered on Stepwise Selection:
average thickness

Multiple R = .4055
R Square = .1644, Standard Error = 61.4342

Analysis of Variance

Variable(s) in the Equation

| Variable | B | T | Sig T |
|---|---|---|---|
| Thick | -152.2890 | -2.3470 | .0262 |
| (constant) | 133.5828 | 4.8840 | .0000 |

Variables Not in the Equation

| Variable | Partial | T | Sig T |
|---|---|---|---|
| Weight | .0963 | .5030 | .6192 |
| Surface | -.0699 | -.3640 | .7186 |
| O.D. | -.1013 | -.5290 | .6009 |

*Note.* Weight = casting weight; Thick = average thickness; Surface = surface area; O.D. = outside diameter.

However, because outside diameter did not meet the default criterion for inclusion, forward selection stopped. Therefore, only casting thickness was considered for predicting gate velocity from casting features (see Appendix L).

2. The multiple regression coefficient (R) may increase as casting weight, surface area, and outside diameter are included. However, it does not necessarily mean that the equation with more variables better fits the population (Norusis, 1982). This is because each time a variable is added to the equation, one degree of freedom is lost from the residual sum of squares and one is gained in the regression sum of squares.

3. The final multiple regression between cavity fill time and casting thickness is:

Gate Velocity (ft/sec)

= 133.5828 + (-152.2890) x Average Thickness (in)

This equation was the same as the simple regression line between gate velocity and average thickness (see Figure 5, p. 49).

## Question 11

What is the relationship between gate area and the casting weight of aluminum die castings?

### Findings

The 30 pairs of gate area and casting weight were analyzed to answer question 11. A significant correlation coefficient was found between gate area and casting weight, $r = .6150$, $p = .0001 < .05$. The statistical summary is shown in Table 8. The scattergram and line of best fit are graphically presented in Figure 6.

The regression line for predicting gate area from casting weight was also plotted using the following linear equation:

$$\text{Gate Area (in}^2\text{)} = .1495 + .0705 \times \text{Casting Weight (lb)}$$

This regression line indicates that an increase in one pound of casting weight results in a .0705-square inch increase in gate area.

Table 8

The Statistical Summary for the Relationship Between Gate Area and Casting Weight

| | | | |
|---|---|---|---|
| Correlation (r) | = .6150 | Intercept (A) | = .1495 |
| Significance | = .0001 | Slope (B) | = .0705 |
| Std Err of Est | = .1656 | Significance | = .0001 |

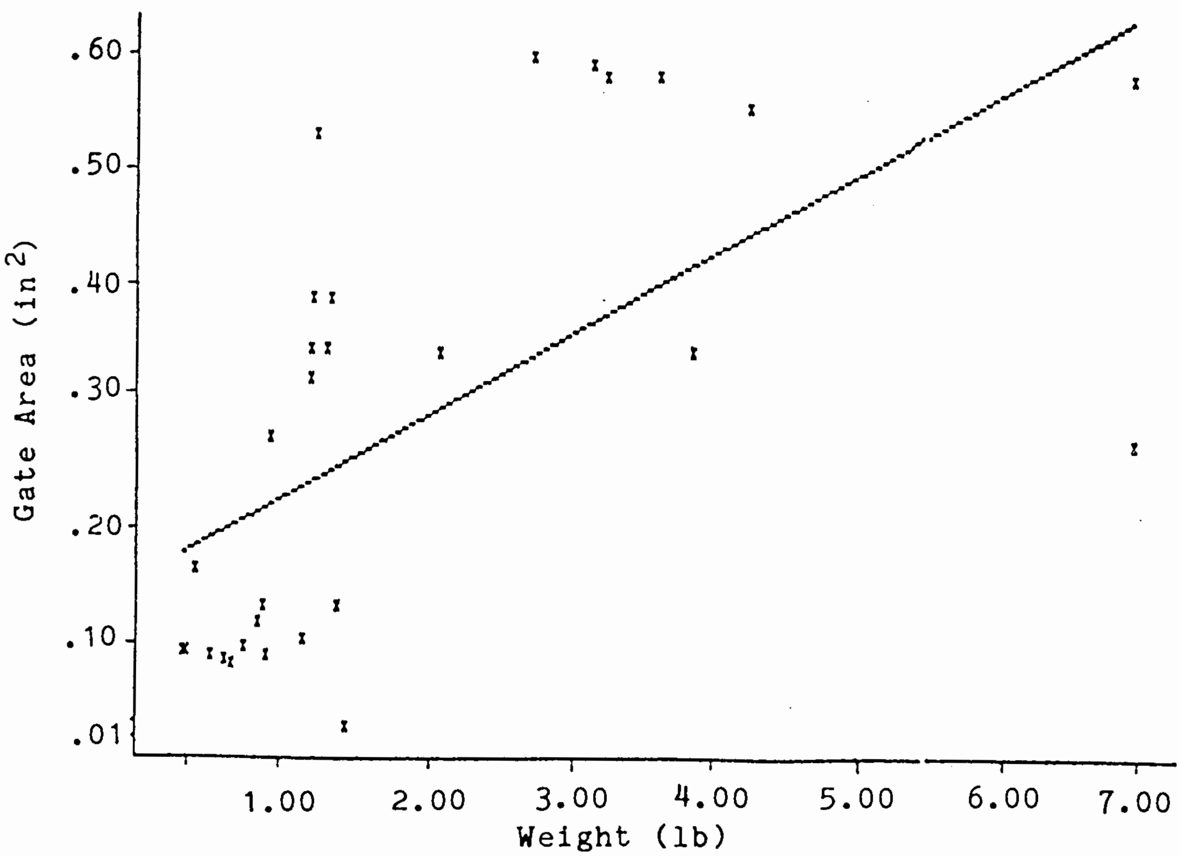



Figure 6. The scattergram and line of best fit for gate area and casting weight.

## Question 12

What is the relationship between gate area and the average thickness of aluminum die castings?

### Findings

The 30 pairs of gate area and average thickness were analyzed to answer question 12. A significant correlation coefficient was found between gate area and average thickness, $r = .5157$, $p = .0035 < .05$. The statistical summary is shown in Table 9. The scattergram and line of best fit are graphically presented in Figure 7.

The regression line for predicting gate area from average thickness was also plotted using the following linear equation:

$$\text{Gate Area (in}^2\text{)} = .0461 + .6050 \times \text{Average Thickness (in)}$$

This regression line indicates that an increase in .1 inch of average thickness results in a .0605-square inch increase in gate area.

Table 9

The Statistical Summary for the Relationship Between Gate Area and Average Thickness

| | |
|---|---|
| Correlation (r) = .5157 | Intercept (A) = .0461 |
| Significance = .0035 | Slope (B) = .6050 |
| Std Err of Est = .1799 | Significance = .0018 |

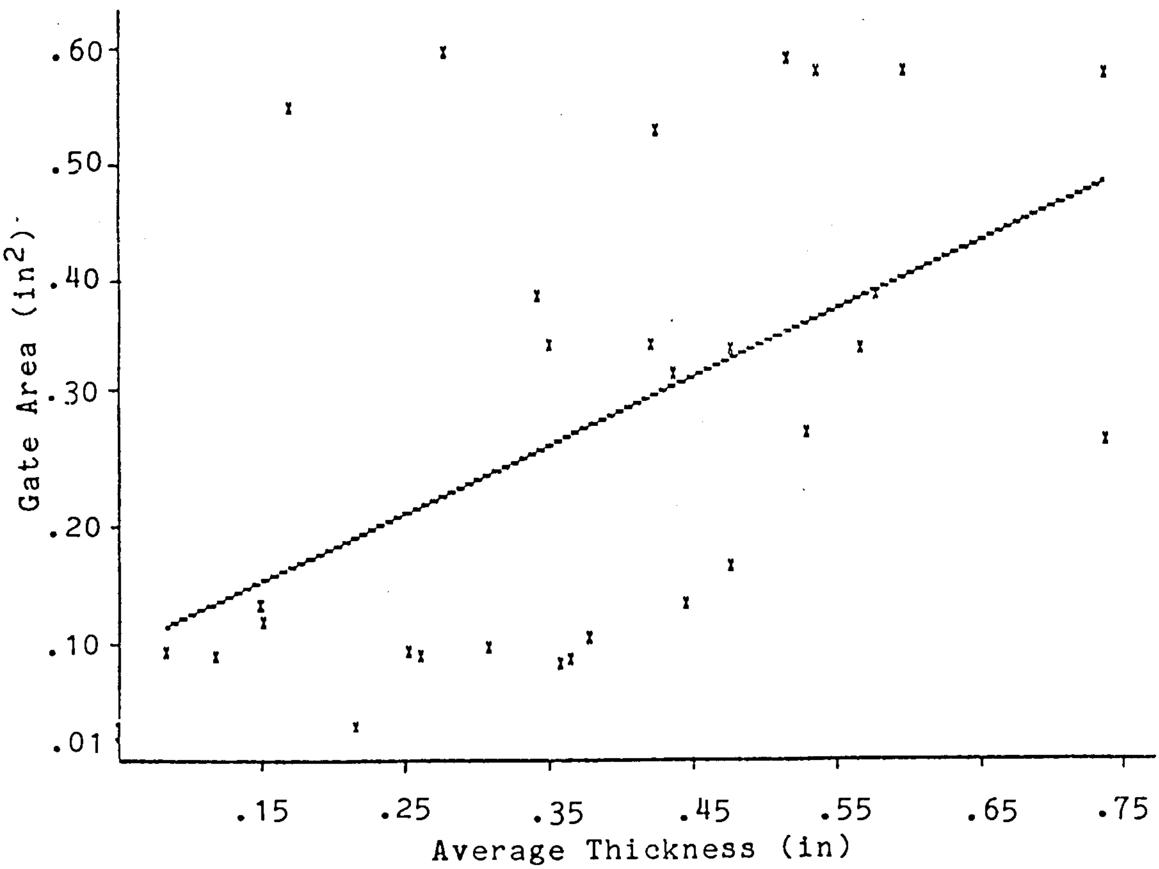



Figure 7. The scattergram and line of best fit for gate area and average thickness.

## Question 13

What is the relationship between gate area and the surface area of aluminum die castings?

### Findings

The 30 pairs of gate area and surface area were analyzed to answer question 13. A significant correlation coefficient was found between gate area and surface area, $r = .6021$, $p = .0001 < .05$. The statistical summary is shown in Table 10. The scattergram and line of best fit are graphically presented in Figure 8.

The regression line for predicting gate area from surface area was also plotted using the following linear equation:

$$\text{Gate Area (in}^2\text{)} = .1117 + .0013 \times \text{Surface Area (in}^2\text{)}$$

This regression line indicates that an increase in 50 square inch of surface area results in a .0650-square inch increase in gate area.

Table 10

The Statistical Summary for the Relationship Between Gate Area and Surface Area

| | |
|---|---|
| Correlation (r) = .6021 | Intercept (A) = .1117 |
| Significance = .0001 | Slope (B) = .0013 |
| Std Err of Est = .1676 | Significance = .0002 |

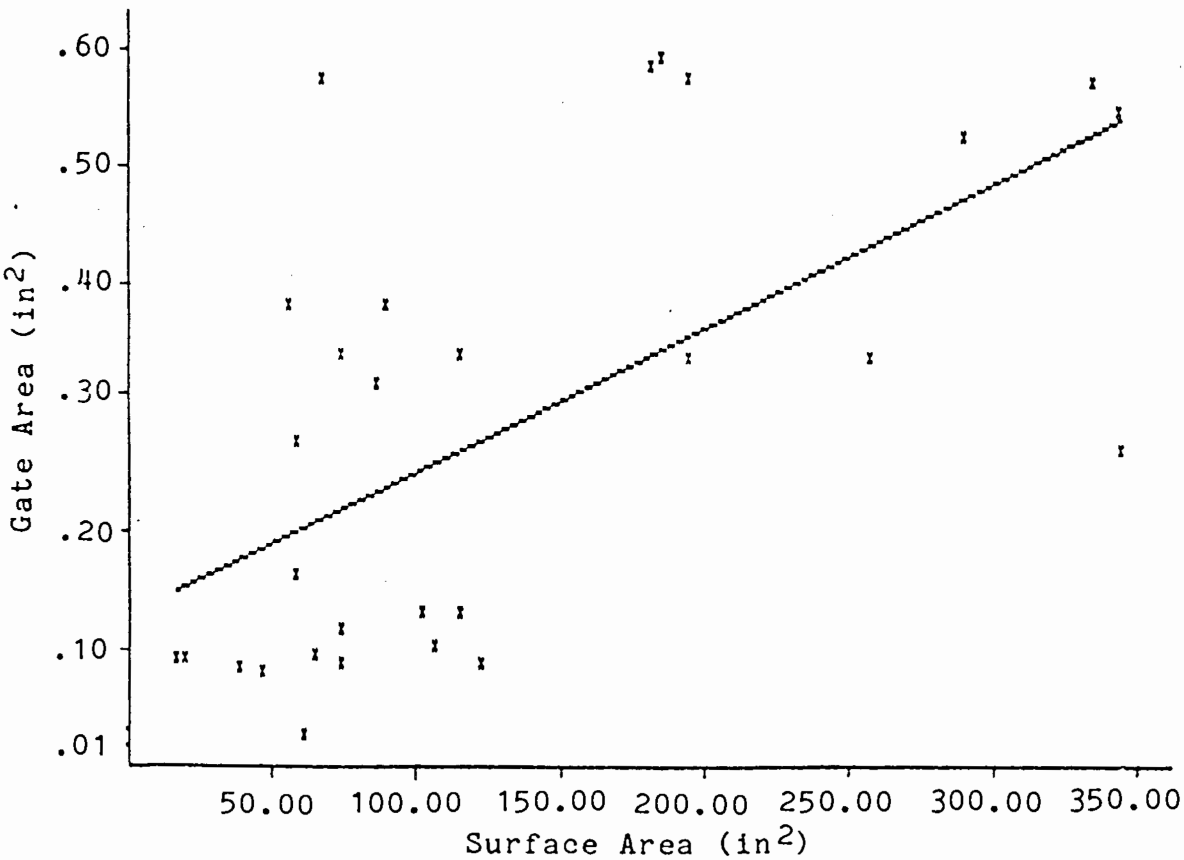



Figure 8. The scattergram and line of best fit for gate area and surface area.

## Question 14

What is the relationship between gate area and the outside diameter of aluminum die castings?

### Findings

The 30 pairs of gate area and outside diameter were analyzed to answer question 14. A significant correlation coefficient was found between gate area and outside diameter, $r = .6744$, $p = .0001 < .05$. The statistical summary is shown in Table 11. The scattergram and line of best fit are graphically presented in Figure 9.

The regression line for predicting gate area from outside diameter was also plotted using the following linear equation:

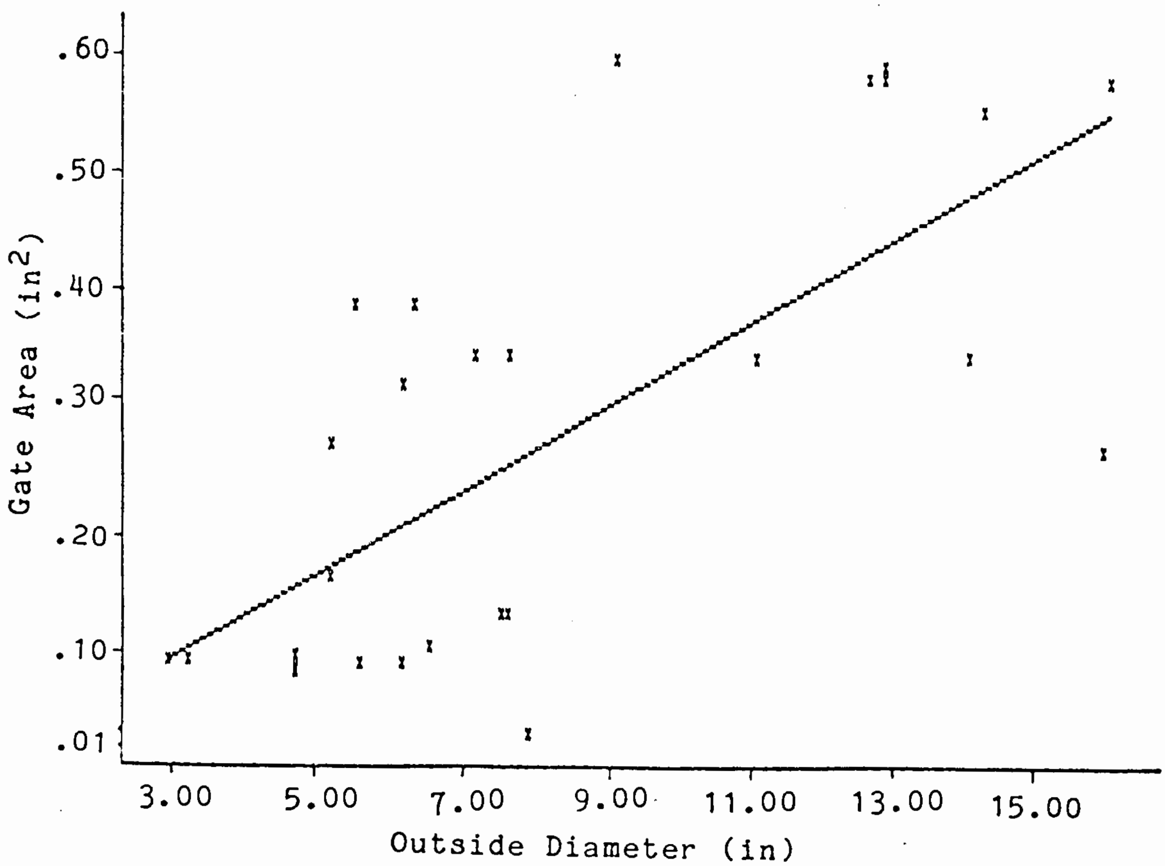
$$\text{Gate Area (in}^2\text{)} = .0092 + .0345 \times \text{Outside Diameter (in)}$$

This regression line indicates that an increase in one inch of outside diameter results in a .0345-square inch increase in gate area.

Table 11

<u>The Statistical Summary for the Relationship Between Gate Area and Outside Diameter</u>

| | | | |
|---|---|---|---|
| Correlation (r) | = .6744 | Intercept (A) | = .0092 |
| Significance | = .0001 | Slope (B) | = .0345 |
| Std Err of Est | = .1550 | Significance | = .0002 |




<u>Figure 9</u>. The scattergram and line of best fit for gate area and outside diameter.

## Question 15

What is the relationship between gate area and a combination of several aluminum die casting features?

### Findings

The 30 sets of gate area, casting weight, average thickness, surface area, and outside diameter were analyzed to answer question 15. The correlation matrix shows the high correlations of casting features in Table 12. After the stepwise selection, only casting thickness was accepted in the multiple regression model. The statistical summary is shown in Table 13.

### Discussion of Findings

1. The SPSS stepwise selection with the default criteria (pIN = .05, pOUT = .10, and tolerance = .01) were used to select the important casting feature variable(s) and determine the optimal number of casting feature variables for the regression equation. The casting feature with the largest partial correlation, outside diameter, was selected and tested first. Because outside diameter met the criterion for inclusion (pIN < .05), it was entered into the equation.

The casting feature with the next largest partial coefficient, average thickness, was selected next.

Table 12

The Correlation Matrix of Gate Area and Casting Features

N = 30

| | Gate | Weight | Thick | Surface | O.D. |
|---|---|---|---|---|---|
| Gate | | | | | |
| Weight | .6150<br>p = .0001 | | | | |
| Thick | .5157<br>p = .0035 | .6208<br>p = .0000 | | | |
| Surface | .6021<br>p = .0001 | .8257<br>p = .0000 | .4177<br>p = .0220 | | |
| O.D. | .6744<br>p = .0001 | .9082<br>p = .0000 | .5479<br>p = .0020 | .7931<br>p = .0000 | |

Note. Gate = gate area; Weight = casting weight; Thick = average thickness; Surface = surface area; O.D. = outside diameter; N = number of total sample upper value = correlation coefficient; lower value = significance level.

Table 13

The Statistical Summary of the Multiple Regression Analysis Between Gate Area and Casting Features

---

Dependent Variable: gate area
Variable Entered on Stepwise Selection: outside diameter

Multiple R = .6744
R Square = .4548, Standard Error = .1550

---

Analysis of Variance

Variable in the Equation

| Variable | B | T | Sig T |
|---|---|---|---|
| O.D. | .0345 | 4.8330 | .0000 |
| (constant) | .0092 | .1470 | .8844 |

Variables Not in the Equation

| Variable | Partial | T | Sig T |
|---|---|---|---|
| Weight | .0083 | .0430 | .9661 |
| Thickness | .2366 | 1.2660 | .2165 |
| Surface | .1495 | .7860 | .4390 |

Note. Weight = casting weight; Thick = average thickness; Surface = surface area; O.D. = outside diameter.

However, because average thickness did not meet the default criterion for inclusion, forward selection stopped. Therefore, only outside diameter was considered for predicting gate velocity from casting features (see Appendix M).

2. The multiple regression coefficient (R) may increase as casting weight, average thickness, and surface area are included. However, it does not necessarily mean that the equation with more variables better fits the population (Norusis, 1982). This is because each time a variable is added to the equation, one degree of freedom is lost from the residual sum of squares, and one is gained in the regression sum of squares.

3. The final multiple regression line between cavity fill time and casting thickness is

$$\text{Gate Area } (\text{in}^2) = .0092 + .0345 \times \text{Outside Diameter (in)}$$

This equation was the same as the simple regression line between gate area and outside diameter (see Figure 9, p. 62).

# CHAPTER V

# SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

## Summary

### Statement of the Problem

The purpose of this study was to investigate the relationships between casting features (including weight, average thickness, surface area, and outside diameter) and casting process variables (including cavity fill time, gate velocity, and gate area) for aluminum die casting. The literature review revealed that cavity fill time, gate velocity, and gate area are the three critical process variables for determining the quality of aluminum die castings. It also indicated that cavity fill time, gate velocity, and gate area are related to some casting features. However, there has been no systematic and detailed investigation into the precise relationships between these three process variables and casting features for aluminum die castings.

### Significance of the Study

The aluminum die casting industry commonly uses the trial-and-error method to determine the best cavity fill time, gate velocity, and gate area. This method is expensive and time-consuming. It was believed that an accurate determination of the relationships between casting features and casting process variables could be used to predict the best gate design and machine settings from the drawing of a casting. This would significantly reduce the number of trials and increase production efficiency.

## Methodology

The approach to obtain the relationships between casting features and casting process variables was to analyze the historical data from engineering records of the Kiowa Corporation in Marshalltown, Iowa. Good quality round castings were selected for computer analyses. The following correlation analyses were used:

1. the correlation of one casting process variable and one casting feature.

2. the multiple correlation of one casting process variable and a combination of several casting features.

## Findings

The following findings were based on results of statistical analyses of the sample data:

Cavity Fill Time and Casting Features

1. Two significant simple correlations were found:

   a. cavity fill time and average thickness

      When average thickness increased, cavity fill time was longer (see Figure 3, p. 40).

   b. cavity fill time and outside diameter

      When outside diameter increased, cavity fill time was longer (see Figure 4, p. 42).

2. The multiple correlation analysis showed that for predicting cavity fill time from casting features, the optimal casting feature variable is average thickness. The following linear regression equation was developed to predict cavity fill time from average thickness (see Table 4, p. 45):

$$\text{Cavity Fill Time (sec)} = 0.0059 + 0.3757 \times \text{Average Thickness (in)}$$

Gate Velocity and Casting Features

1. Only one significant simple correlation was found:

   a. gate velocity and average thickness

      When the average thickness increased, gate velocity decreased (see Figure 5, p. 49).

2. The multiple correlation analysis showed that for predicting gate velocity from casting features, the optimal casting feature variable is average thickness. The following linear regression equation was developed to predict gate velocity from average thickness (see Table 7, p. 53):

Gate Velocity (ft/sec)

= 133.5828 + (-152.2890) x Average Thickness (in)

<u>Gate Area and Casting Features</u>

1. Four significant simple correlations were found:

   a. gate area and casting weight

      When the casting weight increased, gate area was bigger (see Figure 6, p. 56).

   b. gate area and average thickness

      When the average thickness increased, gate area was bigger (see Figure 7, p. 58).

   c. gate area and surface area

      When the surface area increased, gate area was bigger (see Figure 8, p. 60).

   d. gate area and outside diameter

      When the outside diameter increased, gate area was bigger (see Figure 9, p. 62).

2. The multiple correlation analysis showed that for predicting the gate area from casting features, the optimal casting feature variable is outside diameter. The following linear regression equation was developed to predict casting gate area from outside diameter (see Table 13, p. 65):

$$\text{Gate Area (in}^2\text{)} = 0.0092 + 0.0345 \times \text{Outside Diameter (in)}$$

Die Design Aid for Aluminum Die Casting

By summarizing the range of cavity fill time, gate velocity, and gate area and by using the same technology as the Zinc Die Casting Die Design Aid (see Appendix A), the Die Design and Process Prediction Nomograph for Aluminum Die Casting (see Appendix N) was developed. This nomograph can provide an optimal choice of cavity fill time, gate velocity, and gate area to match the capability of the aluminum die casting machine.

## Conclusions

The following conclusions were based on the findings of data analyses in which the relationships between casting features and casting process variables were investigated. In applying these conclusions, the reader should be aware that they apply specifically to round aluminum die castings of alloy A380 with the metal temperature 1220° F, in size of 2.7 to 16 inches, made by a horizontal cold chamber machine with a die temperature of 350° F (see Limitations and Delimitation in Chapter I, pp. 10-11).

1. There are significant correlations between some casting features and casting process variables. Among casting weight, average thickness, surface area, and outside diameter, average thickness had the highest correlation with cavity fill time and gate velocity; outside diameter had the highest correlation with gate area.

2. Large coefficients in the correlation matrix between any two casting feature variables indicate the presence of intercorrelations. The results of the high correlation of casting weight, thickness, surface area, and outside diameter contribute to the result of linear combination. This interdependency among casting feature variables causes the following results: (a) one casting process variable could correlate with each of several casting features, and (b) the stepwise selection method only selects some of the casting feature variables in building a multiple regression model.

Therefore, in this study, the prediction of casting process variables from casting features only needed one specific casting feature. Using more than one casting feature variable does not result in a significant difference in prediction.

3. Casting cavity fill time can be predicted from the average thickness of a casting by using the following linear regression equation:

$$\text{Cavity Fill Time (sec)} = 0.0059 + 0.3757 \times \text{Average Thickness (in)}$$

Gate velocity can be predicted from average thickness by using the following linear regression equation:

$$\text{Gate Velocity (ft/sec)} = 133.5828 - 152.2890 \times \text{Average Thickness (in)}$$

Gate area can be predicted from outside diameter by using the following linear regression equation:

$$\text{Gate Area (in}^2\text{)} = 0.0092 + 0.0345 \times \text{Outside Diameter (in)}$$

4. Casting weight, average thickness, surface area, and outside diameter are commonly considered together to be the important factors in determining the gate area

design and the machine control of cavity fill time and gate velocity. However, this view was not supported by this study. According to the findings of this study, the design of gate area can be based on casting outside diameter alone, and the machine control of cavity fill time and gate velocity can be based on the casting average thickness alone.

## Recommendations

For aluminum die castings with similar features, a precise prediction of casting process variables from a specific casting's features can be calculated directly from the equations included in this study. In addition, a combination of the findings of this study and a casting machine P-Q (metal pressure-flow rate) Diagram could lead to the technological transfer of British Zinc Design Aid for that aluminum die casting machine (see Appendix N). This technology could help aluminum die casting engineers predict the best range of cavity fill time and gate velocity in casting machine control and determine the best gate area in the design of a die.

This research clearly demonstrated that there is a relationship between casting features and cavity fill time, gate velocity, and gate area for the selected aluminum die castings. For an aluminum die casting with similar casting features, average thickness is critical in determining cavity fill time and gate velocity; outside diameter is critical in determining gate area. In order that these correlations be better understood, the following studies are recommended:

1. An investigation of the solidification process of aluminum die casting:

Most casting engineers agree that average thickness affects the time of casting solidification. A further study investigating the solidification process may find that the solidification process could be the main source of the correlation between average thickness and machine control variables. If the solidification process is shown to be the explanation of the correlation, the control of the casting solidification process could more directly address quality problems of in the aluminum die casting industry. However, because the sophisticated casting solidification process is affected by the kinds of aluminum material used (Kaye & Street, 1982), the heat transfer between die temperature and metal temperature (Cocks, 1985), and the capacity of the hydraulic system, computerized simulation experiments may be needed (Walther, 1984).

2. An investigation of the metal flow in the filling process of aluminum die casting:

Obviously, outside diameter affects the distance which metal must travel in the casting die and thus affects the metal flow in the filling process. Therefore, a further study involving computer simulation of the metal filling process may show that the metal flow pattern could explain the relationship between outside diameter and gate area. If the metal flow in the filling process is shown to be the explanation of this correlation, designing the gate area by using the results of the analysis of the metal flow in the filling process could more directly address quality problems in the aluminum die casting industry (Cope & Siauw, 1985).

3. Further studies on aluminum die castings which differ from the castings in this study:

In order to compensate for the limitations of this study, this study can be repeated with castings which are not round and are not made of A380 alloy. In addition, further studies using different die and metal temperatures are also recommended (see Delimitation in Chapter I, p. 11).

# REFERENCES


American Die Casting Institute (ADCI), Inc. (1981). _Introduction to diecasting_. Des Plaines, IL: Author.

British Non-Ferrous (BNF) Metal Technology Center. (1980). Gate area, gate velocity and cavity fill time. In S. E. Booth & D. F. Allsop (Eds.), _BNF manual of pressure diecasting gating design_ (section 4). Oxfordshire, England: BNF.

Cocks, D. L. (1980). Technology transfer in the U.K. _Proceedings of the First South Pacific Diecasting Congress_. River Grove, IL: Society of Diecasting Engineers.

Cocks, D. L., & Wall, A. J. (1983). Technology transfer in the United Kingdom: Progress and prospects. (Paper No. G-T83-074). _SDCE 12th International Die Casting Congress and Exposition_. River Grove, IL: Society of Die Casting Engineers.

Cocks, D. L., & Wall, A. J. (1984). Modern technology ensures zinc die castings meet market needs. _81st Annual Conference of the Institute of British foundrymen_. River Grove, IL: Society of Die Casting Engineers.

Cocks, D. L., & Wall, A. J. (1985). Zinc die castings: Properties plus technology to meet designers' needs. (Paper No. G-T85-053). _SDCE 13th International Die Casting Congress and Exposition_. River Grove, IL: Society of Die Casting Engineers.

Cocks, D. L. (1985). New directions. _Die Casting Management_, _3_(4), 31-43.

Cope, M. A., & Siauw T. H. (1985). _Metlflow design concepts_. Melbourne, Australia: Colin Austin R & D.

Die Casting Research Foundation (DCRF). (1961). _DCRF gating work sheet for AL Alloy 380 (SC84)_. Des Plaines, IL.: DCRF.

Die Casting Research Foundation (DCRF). (1986). _Predicting cavity fill conditions--Worksheet_. Des Plaines, IL: DCRF.

Garber, L. W. (1979). Internal quality of aluminum die castings. Unpublished doctoral dissertation, Pennsylvania State University, PA.

Herman, E. A. (1973). Gating system design. Diecasting Engineer, 17(6), 22.

Herman, E. A. (1979). Die casting design: Designing. Detroit, MI: Society of Die Casting Engineers.

Kaye, A., & Street, A. (1982). Die casting metallurgy. Boston, MA: Butterworth Scientific.

Kolar, J. J. (1985). Die casting technology roundtable '85. Die Casting Management, 3(6), 24-30.

Kruszynski, E. A. (1986). Die casting defects: Causes and remedies. Diecasting Engineer, 30(1), 54-55.

LaRue, J. P., & Pershing, R. W. (1985). A device to sense the presence of metal at the gate orifice in a die casting die. Metal Sensing Device DCRF Project 06-10 Final Report. Des Plaines, IL: Die Casting Research Foundation.

Luis, L., & Draper, A. B. (1966). Effect of overflow wells, gating, and injection parameters on the porosity of a die casting. Transactions of American Foundrymen's Society, 74, 245-256.

Norusis, M. J. (1982). Multiple linear regression analysis. SPSS introductory guide: Basic statistics and operations (2nd ed.). New York: McGraw-Hill.

Pokorny, H. H., & Thukkaram, P. (1981). Gating: Die casting dies (4th ed.). Des Plaines, IL: Society of Die Casting Engineers.

Robinson, P. M. (1977). Assessing the performance of metal feed systems. (Paper No. G-T77-071). 9th SDEC International Die Casting Congress & Exposition. Milwaukee, Wisconsin: Society of Die Casting Engineers.

Stuhrke, W. F., & Wallace, J. F. (1965). Gating of die casting. American Foundrymen's Society Third Year Progress Report. Chicago, Illinois: American Foundrymen's Society.

Walther, M. K. (1984). Casting solidification analysis using CAST. Modern Casting, 24(3), 18-22.

Wall, A. J., & Cocks, D. L. (1980). Developments in zinc die casting technology. 77th Annual Conference of The Institute of British Foundrymen. London, England: British Non-Ferrous Metal Technology Center.

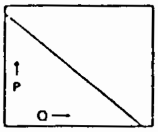
Zinc Development Association. (1980). Zinc die casting die design aid. London, England: Zinc Development Association.

# APPENDICES

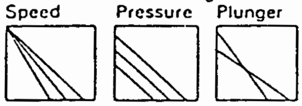
# Appendix A

## Zinc Die Casting Die Design Aid from the Zinc Development Association, London, U. K. (ZDA, 1980)

**Step 1**

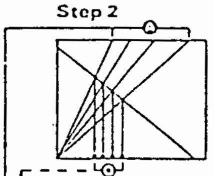



**Select PQ² diagram** for machine to be used.
**Note:** Remember that machine conditions can be changed:
Speed Pressure Plunger



| Machine make/model: | Locking force (tonnes): |
|---|---|
| HYDRAULIC | 60T |
| Hydraulic/pneumatic pressure (MPa): 10 | Plunger diameter (mm): 35mm |

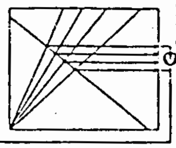
**Step 2**




**Add resistance lines** and read off the flow rate Q in litres/second for gate areas which look acceptable and enter below in arrowed table

**Note:** Three scales are available. Ensure the scales match

**Step 3**




**Add velocity scale** and read off the gate velocity V in metres/second for gate areas chosen or calculate:

$$\frac{Q\ (l/s)}{A\ (mm^2)} \times 1000 = V\ (m/s)$$

**Step 4**

**Calculate cavity fill time t** in milliseconds for the gate areas chosen

$$\frac{\text{Casting volume}\ (mm^3)}{1000 \times Q\ (l/s)} = t$$

Individual casting weights

1 500 g
2 g
3 g
4 g
Total 500 g

$$\frac{wt\ (g)}{0.0063} = \text{Casting Volume}\ (mm^3)$$

$$\frac{500}{0.0063} = 79{,}365\ mm^3$$

(0.0063 = Density of molten zinc alloy)

| Step 5 Combination* | A Area (mm²) | Q Flow rate (l/s) | V Velocity (m/s) | t Cavity fill time (millisecs) |
|---|---|---|---|---|
| •1 | 60 | 3·0 | 50 | 26·5 |
| •2 | 80 | 3·6 | 45 | 22·0 |
| •3 (circled) → | 100 | 4·1 | 41 | 19·4 |
| •4 | 120 | 4·4 | 37 OK | 18·0 |
| •5 | 140 | 4·7 | 34 | 16·9 |
| •6 | 160 | 4·9 | 31 | 16·2 OK |
| •7 | 180 | 5·1 | 28 | 15·6 |

These are the possible fill conditions which the machine can achieve. Read Step 6 and make your choice*

**Step 6**
**Select the gate area** using the following guide lines

**A** **Gate area:** Small gates ease runner removal.
Use the minimum, decide gate length and thickness and ensure it will fit on casting

**V** **Gate velocity:** High velocity gives good casting soundness.
30 m/s minimum velocity. 40 m/s preferred velocity. 60 m/s absolute maximum velocity

**t** **Cavity fill time:** Short times give good surface finish.
20 millisecs maximum for Cr work. 40 millisecs for functional castings.

**Note:** Compromises can be made, but if no condition is satisfactory: return to Step 1

# Appendix B

## DCRF Gating Work Sheet for AL Alloy 380 (DCRF, 1961) (side A)

### DCRF GATING WORK SHEET FOR AI ALLOY 380 (SC84)

CUSTOMER____________________ DATE__________ BY__________

PART NAME__________________ PART NO.________ MACHINE NO.________

A. Calculate the temp. of the metal ($T_{metal}$) when it reaches the gate.

1. When hand ladling,

   $T_{metal} = T_{pot} - 10t - 20 = (\quad) - 10(\quad) - 20 =$ ______ °F

   NOTE: t is time in sec. from beginning of pour until ram starts moving

2. When transferring metal by means other than hand ladling,

   $T_{metal} = T_{pot} - 10t - 10 - T_{drop} = (\quad) - 10(\quad) - 10 - (\quad) =$ ______ °F

   NOTE: $T_{drop}$ is the estimated or measured metal temp. drop between machine pot and shot sleeve.

B. Find cavity fill time

*METHOD*

1. Use $T_{metal}$ found above, calc. W/A ratio, find point on ref. line.

   NOTE: If a multiple cavity system is used, calc. W/A for each type of casting and use smallest ratio

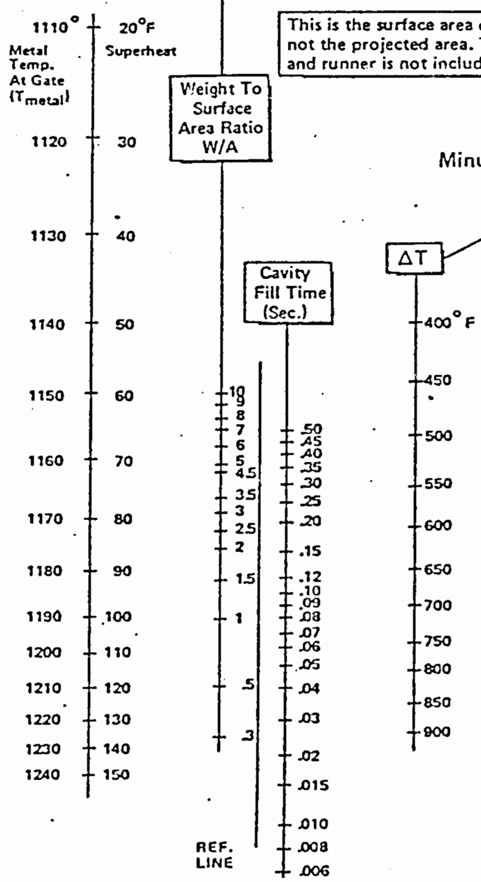
2. Determine ΔT, find cavity fill time.

Does not include biscuit and runner

[ ] = _____ = $\frac{W(lb)}{A(ft^2)}$ = $\frac{\text{Wt of casting}}{\text{Total surface area of casting}}$

This is the surface area of all sides of the casting and is not the projected area. The surface area of the biscuit and runner is not included.

*NOTES & SKETCHES*




$T_{metal}$ ______

Minus die temp ______

ΔT = ______

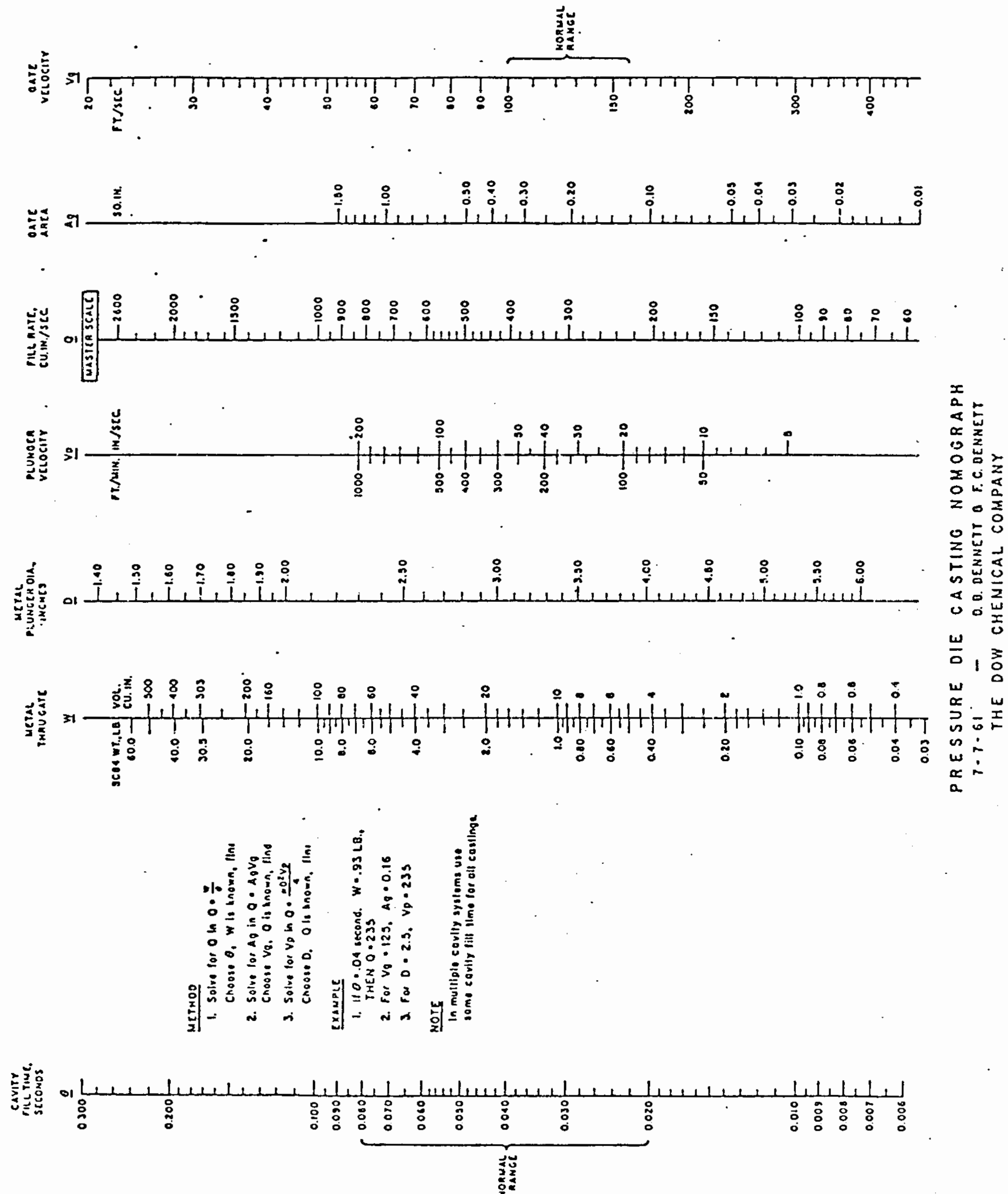
NOTE: Die temp. is avg. die surface temp.

| | |
|---|---|
| Cool Die | 350°F |
| Avg. Die | 500°F |
| Hot Die | 650°F |

PART NAME

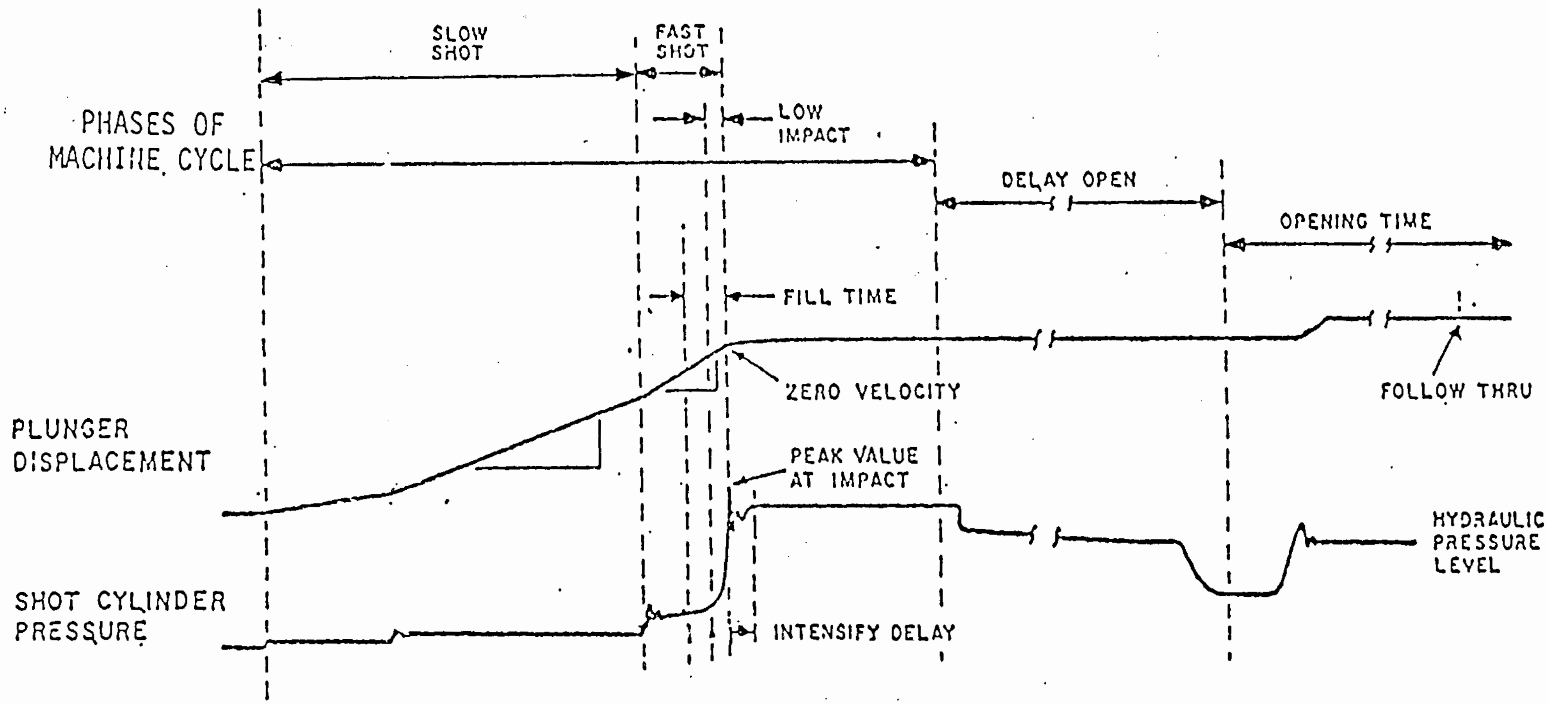
C. Turn page over and determine gate area and plunger velocity using above cavity fill time. Same information can also be found using die casting calculator.

# DCRF Gating Work Sheet for AL Alloy 380 (DCRF, 1961) (side B)



# Appendix C

## Diagram of a Die Casting Process Cycle



# Appendix D

## Data Collection Sheet

| Part No: | Scrap Rate: | Machine No: | Plu A. (in²) | Plu.V. (in/sec) | Gate (in²) | Velo (ft/sec) | Flow (in³/sec) | Volume (in³) | Weight (lb) | Time (sec) | Thick (in) | Surface (in²) | O.D. (in) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 325001 | .003 | 10335 | 2.948 | 14.000 | .090 | 38.215 | 41.272 | 11.112 | 1.009 | .269 | .382 | 106.161 | 6.400 |
| 327801 | .005 | 10334 | 3.976 | 16.000 | .540 | 9.817 | 63.616 | 12.079 | 1.184 | .190 | .429 | 205.883 | 6.930 |
| 328709 | .022 | 10335 | 2.948 | 32.000 | .104 | 75.590 | 94.336 | 7.806 | .765 | .083 | .157 | 74.644 | 5.600 |
| 329301 | .028 | 10362 | 3.976 | 23.000 | .594 | 12.829 | 91.448 | 33.157 | 3.249 | .363 | .540 | 191.700 | 12.800 |
| 329401 | .016 | 10335 | 3.142 | 38.000 | .011 | 90.452 | 119.396 | 14.265 | 1.398 | .119 | .220 | 61.756 | 7.800 |
| 333001 | .010 | 10332 | 3.976 | 48.000 | .119 | 133.647 | 190.848 | 8.204 | .804 | .043 | .156 | 101.613 | 7.500 |
| 333202 | .000 | 10332 | 3.142 | 23.000 | .065 | 92.649 | 72.266 | 5.857 | .574 | .081 | .362 | 47.713 | 4.500 |
| 335601 | .001 | 10381 | 6.777 | 78.000 | .563 | 78.242 | 528.626 | 43.459 | 4.259 | .082 | .175 | 338.664 | 14.200 |
| 336701 | .017 | 10371 | 4.664 | 64.000 | .344 | 72.341 | 298.624 | 39.479 | 3.869 | .132 | .488 | 254.214 | 14.000 |
| 337601 | .030 | 10332 | 2.405 | 14.000 | .120 | 23.385 | 33.674 | 13.559 | 1.329 | .403 | .449 | 114.284 | 7.400 |
| 339301 | .004 | 10362 | 3.976 | 35.000 | .345 | 33.614 | 139.164 | 21.060 | 2.064 | .151 | .570 | 192.306 | 11.000 |
| 340902 | .012 | 10362 | 3.976 | 28.000 | .605 | 15.334 | 111.328 | 32.153 | 3.151 | .209 | .520 | 178.499 | 12.800 |
| 342101 | .004 | 10372 | 6.777 | 70.000 | .509 | 67.118 | 474.390 | 71.428 | 7.000 | .151 | .740 | 329.860 | 16.000 |
| 342204 | .018 | 10361 | 3.341 | 32.000 | .612 | 14.558 | 106.912 | 27.745 | 2.719 | .260 | .282 | 182.212 | 9.000 |
| 346002 | .004 | 10332 | 3.976 | 64.000 | .078 | 271.863 | 254.464 | 2.583 | .253 | .010 | .257 | 18.464 | 2.700 |
| 346801 | .006 | 10332 | 2.405 | 72.000 | .072 | 200.442 | 173.182 | 4.420 | .433 | .026 | .125 | 74.204 | 5.410 |
| 347402 | .000 | 10362 | 3.976 | 18.000 | .594 | 10.030 | 71.570 | 36.939 | 3.620 | .516 | .600 | 266.503 | 12.750 |
| 350901 | .011 | 10335 | 2.948 | 32.000 | .350 | 22.463 | 94.346 | 12.851 | 1.260 | .136 | .425 | 113.747 | 7.500 |
| 351202 | .002 | 10335 | 2.948 | 13.000 | .272 | 11.741 | 38.324 | 6.673 | .650 | .226 | .533 | 58.905 | 5.000 |
| 351401 | .000 | 10373 | 6.777 | 68.000 | .262 | 146.800 | 460.843 | 71.428 | 7.000 | .155 | .740 | 339.860 | 15.900 |
| 351601 | .010 | 10335 | 2.948 | 28.000 | .074 | 92.964 | 82.552 | 8.393 | .823 | .102 | .265 | 121.542 | 6.000 |
| 352101 | .011 | 10332 | 3.976 | 28.000 | .118 | 78.621 | 111.328 | 8.194 | .803 | .074 | .155 | 101.611 | 7.500 |
| 352201 | .042 | 10332 | 3.141 | 44.000 | .080 | 144.008 | 138.248 | 6.826 | .669 | .049 | .312 | 65.738 | 4.500 |
| 352301 | .016 | 10332 | 3.142 | 52.000 | .070 | 194.505 | 163.384 | 5.388 | .528 | .033 | .369 | 39.761 | 4.500 |
| 352601 | .002 | 10335 | 3.140 | 60.000 | .350 | 44.880 | 188.496 | 12.659 | 1.241 | .067 | .354 | 73.650 | 7.000 |
| 352701 | .043 | 10335 | 3.140 | 40.000 | .394 | 26.579 | 125.664 | 11.748 | 1.152 | .094 | .346 | 88.620 | 6.160 |
| 352801 | .004 | 10334 | 2.948 | 20.000 | .394 | 12.472 | 58.966 | 13.007 | 1.283 | .222 | .581 | 55.794 | 5.300 |
| 353803 | .031 | 10335 | 2.405 | 46.000 | .078 | 118.194 | 110.630 | 2.316 | .227 | .021 | .091 | 21.206 | 3.000 |
| 355301 | .001 | 10334 | 3.976 | 40.000 | .150 | 88.356 | 159.040 | 9.316 | .913 | .059 | .481 | 58.905 | 5.000 |
| 356701 | .011 | 10335 | 2.948 | 38.000 | .324 | 28.816 | 112.036 | 11.697 | 1.146 | .104 | .441 | 85.577 | 6.000 |

Note: Plu. A. = Plunger Area, Plu. V. = Plunger Velocity,
Gate = Gate Area, Velo = Velocity, Flow = Flow Rate,
Volume = Casting Volume, Weight = Casting Weight,
Time = Cavity Fill Time, Thick = Average Thickness,
Surface = Surface Area, O.D. = Outside Diameter.

# Appendix E

## Computer Input Data File

| PART NO | CASTING WEIGHT (lb) | AVERAGE THICKNESS (in) | SURFACE AREA ($in^2$) | OUTSIDE DIM. (in) | CAVITY FILL TIME (sec) | GATE VEL. (ft/sec) | GATE AREA (in) |
|---|---|---|---|---|---|---|---|
| 1. 325001 | 1.089 | .382 | 106.161 | 6.400 | 0.269 | 38.215 | .090 |
| 2. 327801* | 1.184 | .429 | 285.883 | 6.930* | 0.190 | 9.817 | .540 |
| 3. 328709* | 0.765 | .157 | 74.644 | 5.600* | 0.083 | 75.590 | .104 |
| 4. 329301 | 3.250 | .540 | 191.700 | 12.800 | 0.363 | 12.829 | .594 |
| 5. 329401 | 1.398 | .220 | 61.765 | 7.800 | 0.119 | 90.452 | .011 |
| 6. 333001 | 0.804 | .156 | 101.613 | 7.500 | 0.043 | 133.647 | .119 |
| 7. 333201 | 0.574 | .362 | 47.713 | 4.500 | 0.081 | 92.649 | .065 |
| 8. 335601 | 4.259 | .175 | 338.664 | 14.200 | 0.082 | 78.242 | .563 |
| 9. 336701 | 3.869 | .480 | 254.214 | 14.000 | 0.132 | 72.341 | .344 |
| 10. 337601 | 1.329 | .449 | 114.284 | 7.400 | 0.403 | 23.385 | .120 |
| 11. 339301 | 2.064 | .570 | 192.306 | 11.000 | 0.151 | 33.614 | .345 |
| 12. 340902 | 3.151 | .520 | 178.499 | 12.800 | 0.289 | 15.334 | .605 |
| 13. 342101 | 7.000 | .740 | 329.860 | 16.000 | 0.151 | 67.118 | .589 |
| 14. 342204 | 2.719 | .282 | 182.212 | 9.000 | 0.260 | 14.558 | .612 |
| 15. 346002 | 0.253 | .257 | 18.464 | 2.700 | 0.010 | 271.863 | .078 |
| 16. 346801 | 0.433 | .125 | 74.204 | 5.410 | 0.026 | 200.442 | .072 |
| 17. 347402 | 3.620 | .600 | 66.503 | 12.570 | 0.516 | 10.030 | .594 |
| 18. 350901 | 1.260 | .425 | 113.747 | 7.500 | 0.136 | 22.463 | .350 |
| 19. 351202 | 0.850 | .533 | 58.905 | 5.000 | 0.226 | 11.741 | .272 |
| 20. 351401 | 7.000 | .740 | 339.860 | 15.900 | 0.155 | 146.800 | .262 |
| 21. 351601 | 0.823 | .265 | 121.542 | 6.000 | 0.102 | 92.964 | .074 |
| 22. 352101 | 0.803 | .155 | 101.611 | 7.500 | 0.074 | 78.621 | .118 |
| 23. 352201 | 0.669 | .312 | 65.738 | 4.500 | 0.049 | 144.008 | .080 |
| 24. 352301 | 0.528 | .369 | 39.761 | 4.500 | 0.033 | 194.505 | .070 |
| 25. 352601 | 1.141 | .354 | 73.651 | 7.000 | 0.067 | 44.880 | .350 |
| 26. 352701 | 1.152 | .346 | 88.620 | 6.160 | 0.094 | 26.579 | .394 |
| 27. 352801 | 1.283 | .581 | 55.734 | 5.300 | 0.222 | 12.472 | .394 |
| 28. 353803 | 0.227 | .091 | 21.206 | 3.000 | 0.021 | 118.194 | .078 |
| 29. 355301 | 0.313 | .481 | 58.905 | 5.000 | 0.059 | 88.356 | .150 |
| 30. 356701 | 1.146 | .441 | 85.577 | 6.000 | 0.104 | 28.816 | .324 |

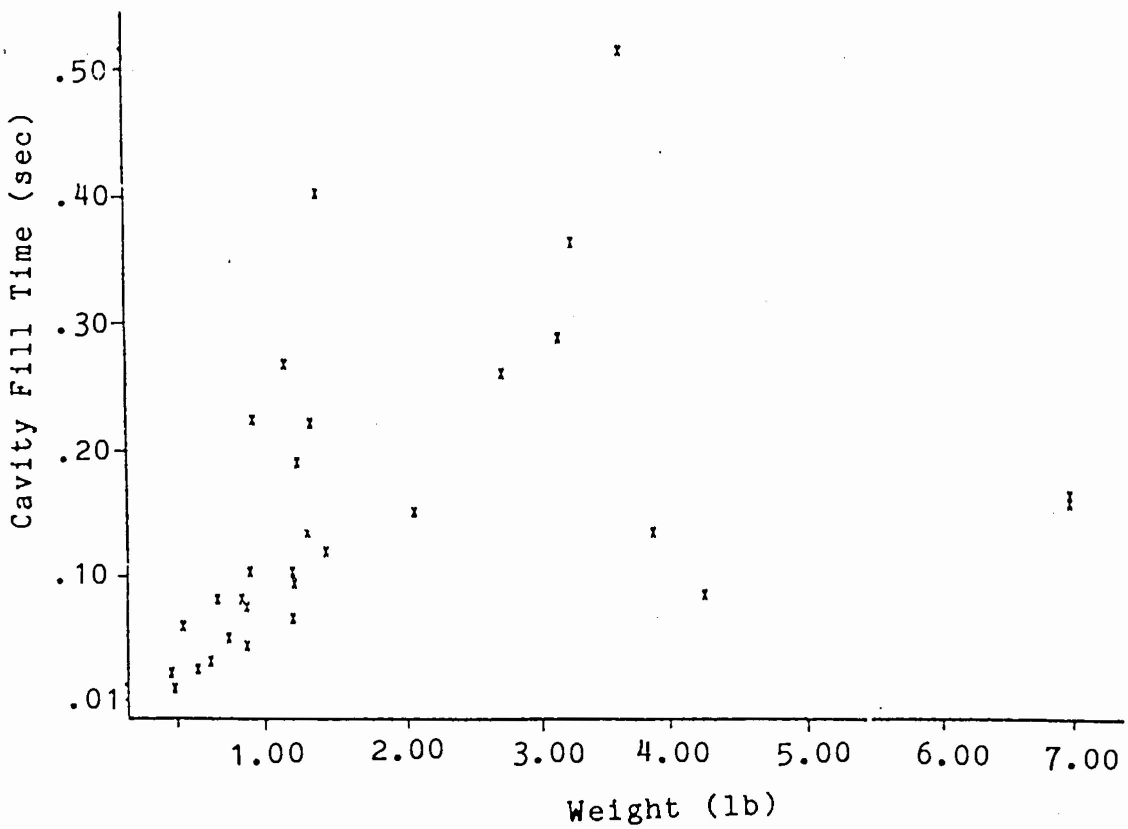
Appendix F

The Statistical Summary and the Scattergram for the Relationship Between Cavity Fill Time and Casting Weight

Statistical Summary

| | | | |
|---|---|---|---|
| Correlation (r) | = .3554 | Intercept (A) | = .1062 |
| Significance | = .0539 | Slope (B) | = .0241 |
| Std Err of Est | = .1162 | Significance | = .0270 |

Scattergram



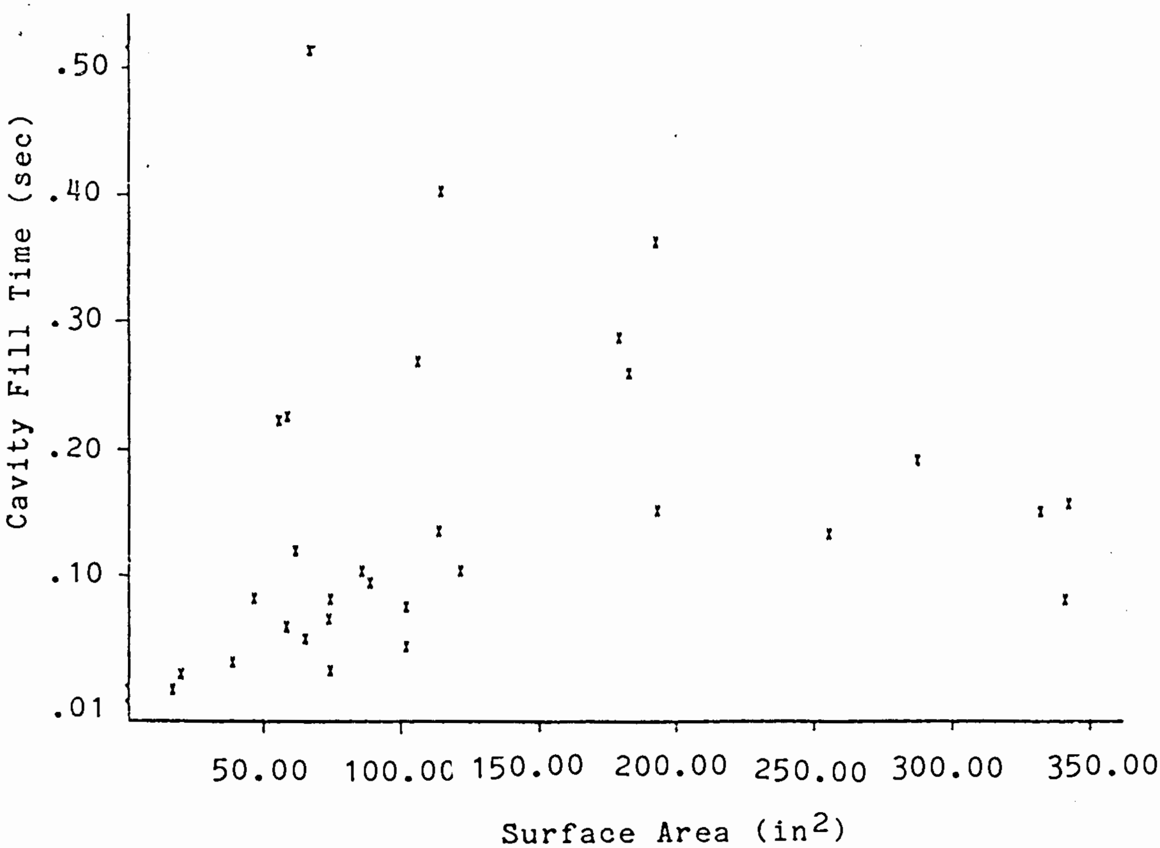
# Appendix G

## The Statistical Summary and the Scattergram for the Relationship Between Cavity Fill Time and Surface Area

### Statistical Summary

| | | | |
|---|---|---|---|
| Correlation (r) | = .1850 | Intercept (A) | = .1200 |
| Significance | = .3276 | Slope (B) | = .0002 |
| Std Err of Est | = .1221 | Significance | = .1639 |

### Scattergram



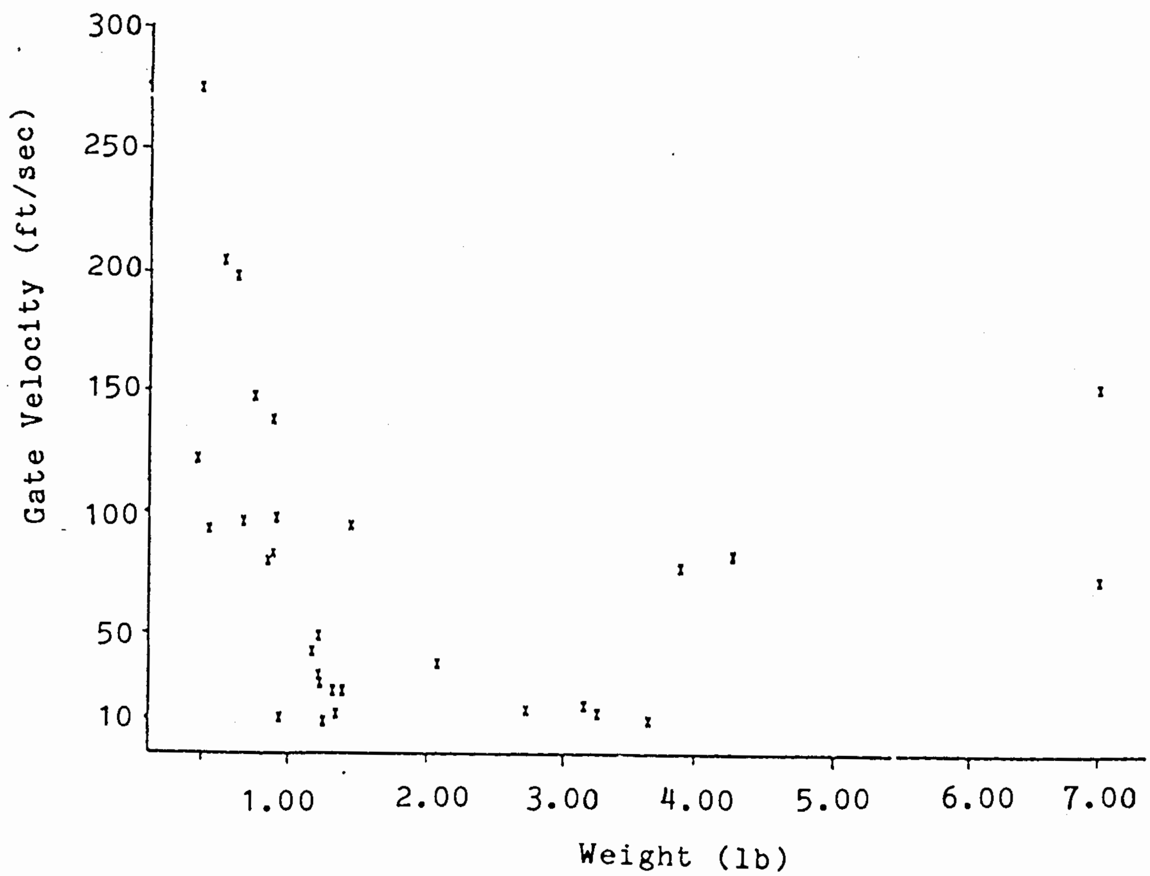
# Appendix H

## The Statistical Summary and the Scattergram for the Relationship Between Gate Velocity and Casting Weight

### Statistical Summary

| | | | |
|---|---|---|---|
| Correlation (r) | = -.1827 | Intercept (A) | = 87.3024 |
| Significance | = .3338 | Slope (B) | = -6.7062 |
| Std Err of Est | = 66.0765 | Significance | = .1669 |

### Scattergram



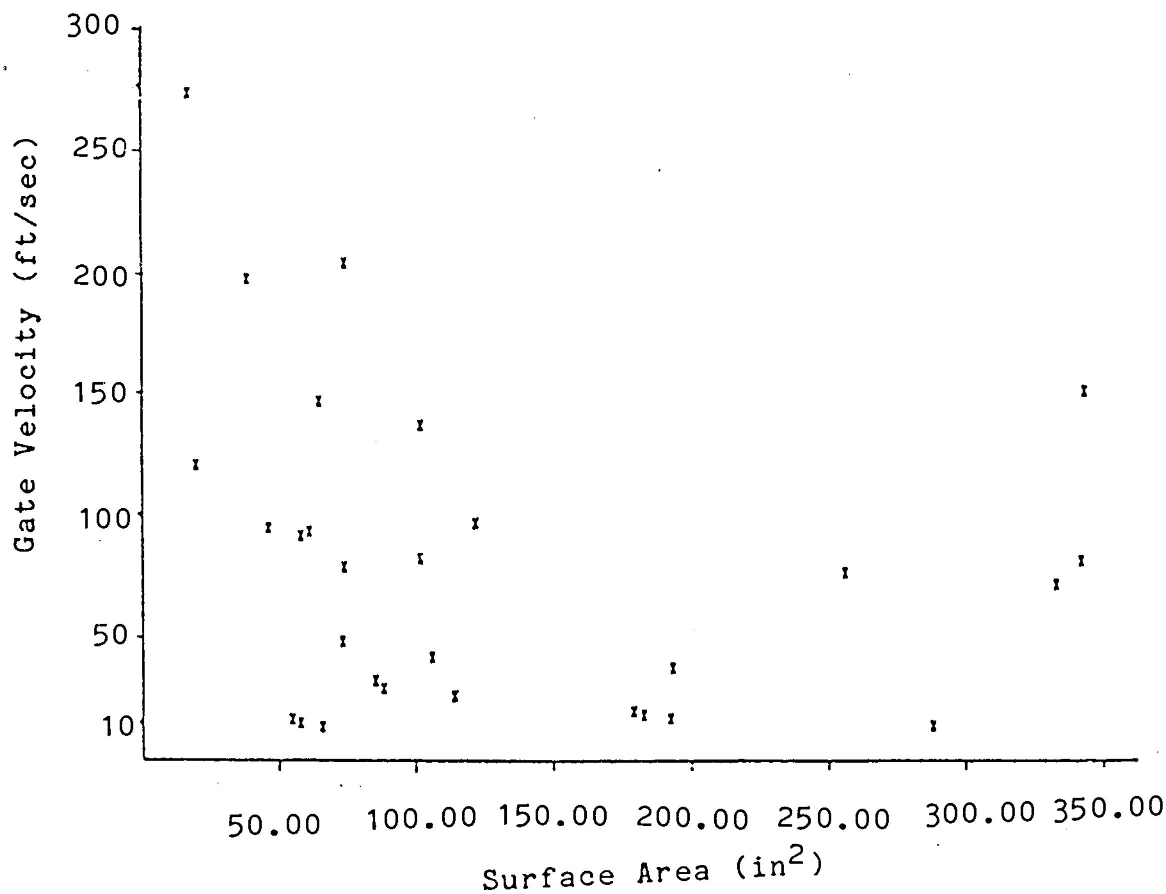
# Appendix I

## The Statistical Summary and the Scattergram for the Relationship Between Gate Velocity and Surface Area

### Statistical Summary

| | | | |
|---|---|---|---|
| Correlation (r) = | -.2274 | Intercept (A) = | 95.2104 |
| Significance = | .2268 | Slope (B) = | -.1576 |
| Std Err of Est = | 65.4469 | Significance = | .1134 |

### Scattergram



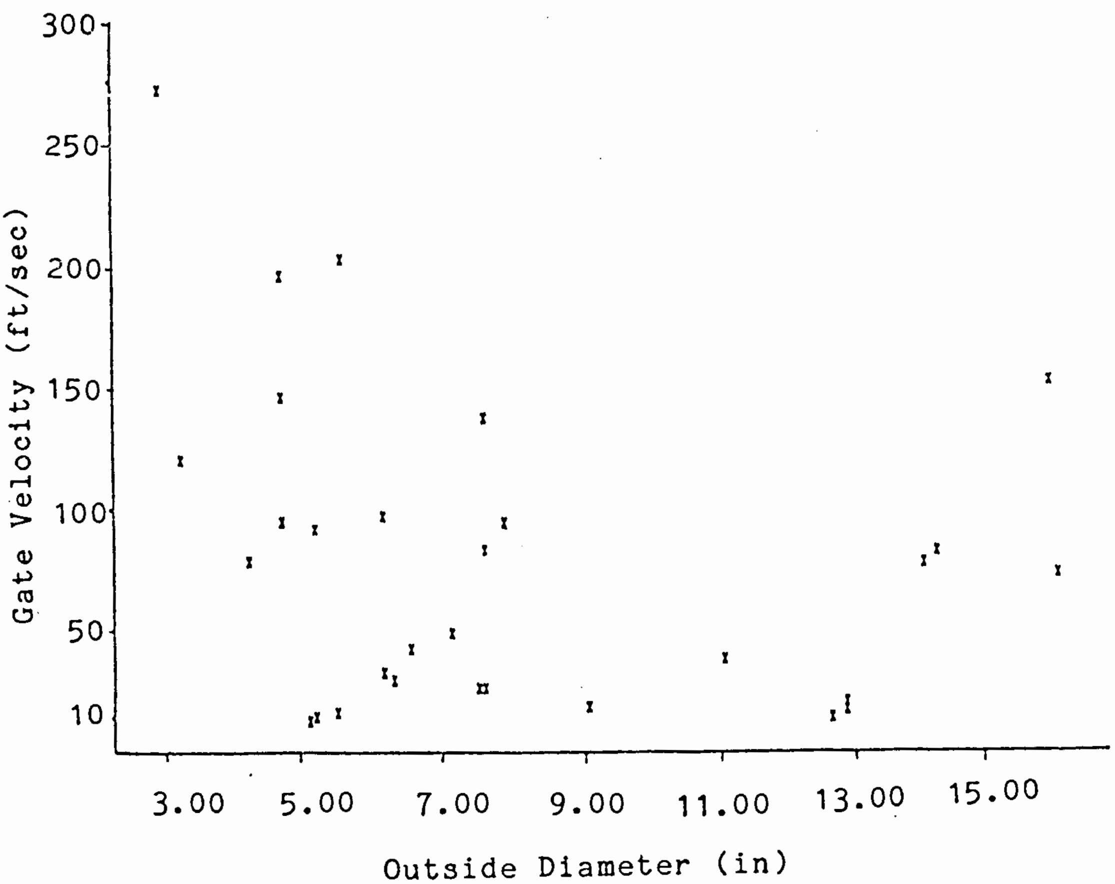
# Appendix J

## The Statistical Summary and the Scattergram for the Relationship Between Gate Velocity and Outside Diameter

### Statistical Summary

| | | | | | |
|---|---|---|---|---|---|
| Correlation (r) | = | -.2997 | Intercept (A) | = | 113.3544 |
| Significant | = | .1080 | Slope (B) | = | -4.9030 |
| Std Err of Est | = | 64.1196 | Significance | = | .0538 |

### Scattergram



# Appendix K

## Statistical Summary of Multiple Regression Between Cavity Fill Time and Casting Features

---

Variable list number: 1.
Equation number: 1.
Dependent variable: cavity fill time
Beginning block number 1. method: stepwise
Variable(s) entered on step number 1.. average thickness

Multiple R = .5411, R square = .2928, Std Err = .1045

Analysis of Variance

| | DF | Sum of Squares | Mean Square |
|---|---|---|---|
| Regression | 1 | .1266 | .1266 |
| Residual | 28 | .3057 | .0109 |

F = 11.5933 Sig F = .0020

Variable(s) in the Equation

| Variable | B | SE B | BETA | T | Sig T |
|---|---|---|---|---|---|
| Thick | .3757 | .1103 | .5411 | 3.405 | .0020 |
| (constant) | .0059 | .0465 | | .126 | .9009 |

For block number 1 Pin = .05 limits reached.

Variable(s) Not in the Equation

| Variable | BETA IN | Partial | MIN TOLER | T | Sig T |
|---|---|---|---|---|---|
| Weight | .0317 | .0295 | .6146 | .153 | .8792 |
| Surface | -.0497 | -.0537 | .8255 | -.279 | .7821 |
| OD | .1835 | .1825 | .6998 | .965 | .3433 |

---

# Appendix L

## Statistical Summary of Multiple Regression Between Gate Velocity and Casting Features

---

Variable list number: 1.
Equation number: 1.
Dependent variable: gate velocity
Beginning block number 1. method: stepwise
Variable(s) entered on step number 1.. average thickness

Multiple R = .4055, R square = .1644, Std Err = 61.4342

Analysis of Variance

| | DF | Sum of Squares | Mean Square |
|---|---|---|---|
| Regression | 1 | 20797.5438 | 20797.5438 |
| Residual | 28 | 105676.4983 | 3774.1607 |

F = 5.5105 Sig F = .0262

Variable(s) in the Equation

| Variable | B | SE B | BETA | T | Sig T |
|---|---|---|---|---|---|
| Thick | -152.2890 | 64.8743 | -.4055 | -2.347 | .0262 |
| (constant) | 133.5828 | 27.3538 | | 4.884 | .0000 |

For block number 1 Pin = .05 limits reached.

Variable(s) Not in the Equation

| Variable | BETA IN | Partial | MIN TOLER | T | Sig T |
|---|---|---|---|---|---|
| Weight | .1123 | .0963 | .6146 | .503 | .6192 |
| Surface | -.0703 | -.0699 | .8255 | -.364 | .7186 |
| OD | -.1107 | -.1013 | .6998 | -.529 | .6009 |

---

# Appendix M

## Statistical Summary of Multiple Regression Between Gate Area and Casting Features

---

Variable list number: 1.
Equation number: 1.
Dependent variable: gate area
Beginning block number 1.      method: stepwise
Variable(s) entered on step number 1..  outside diameter

Multiple R = .6744,  R square = .4548,  Std Err = .1550

Analysis of Variance

| | DF | Sum of Squares | Mean Square |
|---|---|---|---|
| Regression | 1 | .5613 | .5613 |
| Residual | 28 | .6730 | .0240 |

F = 23.3541          Sig F = .0000

Variable(s) in the Equation

| Variable | B | SE B | BETA | T | Sig T |
|---|---|---|---|---|---|
| O.D. | .0345 | .0071 | .6744 | 4.833 | .0000 |
| (constant) | .0092 | .0625 | | .147 | .8844 |

For block number 1 Pin = .05 limits reached.

Variable(s) Not in the Equation

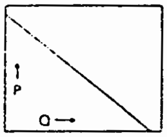
| Variable | BETA IN | Partial | MIN TOLER | T | Sig T |
|---|---|---|---|---|---|
| Weight | .0146 | .0083 | .1751 | .043 | .9661 |
| Thick | .2088 | .2366 | .6998 | 1.266 | .2165 |
| Surface | .1812 | .1495 | .3710 | .786 | .4390 |

---

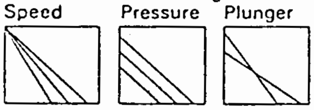
# Appendix N

## A Sample of Die Design and Process Prediction Nomograph for Aluminum Die Casting (side A)

**Step 1**

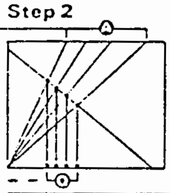



**Select PQ² diagram** for machine to be used.
**Note:** Remember that machine conditions can be changed:
Speed Pressure Plunger



| Machine make/model: | Locking force (tonnes): |
|---|---|
| Hydraulic/pneumatic pressure (psi): | Plunger diameter ($in^2$): |

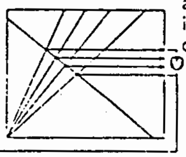
**Step 2**




**Add resistance lines** and read off the flow rate **Q** in litres/second for gate areas which look acceptable and enter below in arrowed table

**Note:** Three scales are available. Ensure the scales match

**Step 3**




**Add velocity scale** and read off the gate velocity **V** in metres/second for gate areas chosen **or** calculate:

$$\frac{Q\ (in^3/sec)}{A\ (in^2) \times 12} = V\ (ft/sec)$$

**Step 4**

**Calculate cavity fill time t** in milliseconds for the gate areas chosen

$$\frac{\text{Casting volume } (in^3)}{Q\ (in^3/sec)} = t$$

Individual casting weights

1
2
3
4 ______
Total ______ lb.

$$\frac{\text{wt lb.}}{0.093} = \text{Casting Volume } (in^3)$$

$$\frac{\quad}{0.093} = \underline{\qquad} \ in^3$$

10·0 = Density of molten alloy.

| Step 5 Combination* | A Area ($in^2$) | Q Flow rate ($in^3$/sec) | V Velocity (ft/sec) | t Cavity fill time (sec) |
|---|---|---|---|---|
| *1 | .10 | | | |
| *2 | .20 | | | |
| *3 | .30 | | | |
| *4 | .40 | | | |
| *5 | .50 | | | |
| *6 | .60 | | | |
| *7 | .70 | | | |

These are the possible fill conditions which the machine can achieve. Read **Step 6** and make your choice*

**Step 6**
**Select the gate area using the following guide lines**

**A** **Gate area:** Small gates ease runner removal (.10–.70 $in^2$)
**Use the minimum, decide gate length and thickness and ensure it will fit on casting**

**V** **Gate velocity:** High velocity gives good casting soundness. (ft/sec)
25 minimum velocity. 70 : preferred velocity. 120 absolute maximum velocity

**t** **Cavity fill time:** Short times give good surface finish.
.10 sec maximum for Cr work. .20 sec for functional castings. .30 sec maximum

**Note:** Compromises can be made, but if no condition is satisfactory: **return to Step 1**

# A Sample of Die Design and Process Prediction Nomograph for Aluminum Die Casting
(side B)