CHAPTER II

THEORY AND LITERATURE SURVEYS

Theories and Literature Surveys that described in this chapter are the background and the guideline for completion of this thesis. Theories and Literature Surveys that included in this chapter are Design of Experiments, Split Plot design, Data transformation, and causes of defects in a casting process.

2.1 Design of Experiments (DOE)

A Design of Experiment (DOE) was first developed in the 1920s and 1930, by *Sir Ronald A. Fisher*. Design of Experiment is a structured, organized method for determining the relationship between factors (Xs) affecting a process and the output of that process (Y).

2.1.1 Guidelines for Design of Experiments

1. **Recognition of and statement of the problem**, it is necessary to have a clear and accepted statement of the problem. All the ideals about the objective of the experiment have to be developed. It is important to input the entire ideal from concerned parties, such as: engineering, quality assurance, manufacturing, marketing, management, the customer, and operating personnel. Therefore the *team approach* is recommended for the DOE.

2. **Selection of the response variable**, it is very important to select the response variables that provide useful information about the process understudy.

3. **Choice of factor, levels, and range**, the factors that may influence the performance of a process or system are called *potential design factors.* These potential design factors are the factors that the experimenter may wish to vary in the experiment, which helpful potential design factors will classify as *design factors*. After selected design factors the experimenter must choose the ranges over which these factors will be varied and the specific levels at which run will be made.

   However, if there a lot of potential design factors, the cause-and-effect diagram or fishbone diagram can be useful technique to organize the factors. The response variable is drawn along the spine of the diagram and the potential causes or design factors are organized in a series of ribs. The causes will be used in diagram are Measurement, material, people, Environment, methods, and machines.

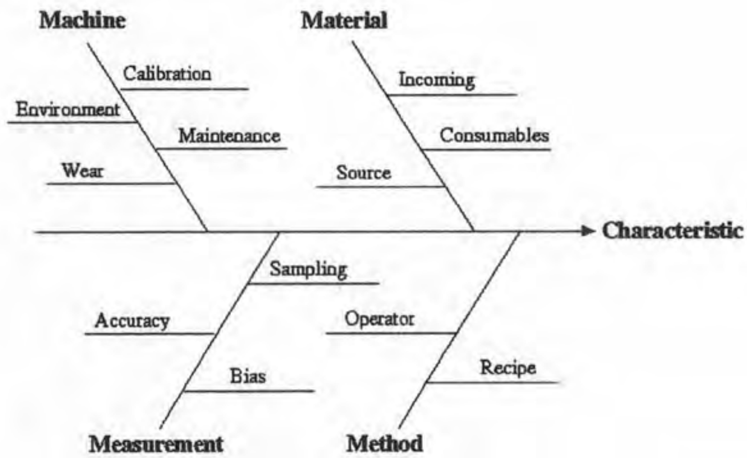

Figure 2.1 Fishbone Diagram

4. **Choice of design types**, Choice of experimental design involves consideration of sample size (number of replicates), and selection of a suitable run order for the experimental trial.

5. **Performing the experiment,** the experiment has to be done following the plan otherwise error in this stage will destroy experimental validity. Conduct a few trial runs or pilot run are often helpful.

6. **Statistical analysis of the data,** Statistical methods is used to analyze the data, and provide guidelines as to the reliability and validity of results.

7. **Conclusion and recommendations,** after the data have been analyzed, the experimenter must conclude the results and recommend a course of action. Follow-up run and confirmation testing should also be performed to confirm the conclusion from the experiment.

2.1.2 The Factorial Design

Factorial designs are widely used in experiments involving several factors because factorial designs are most efficient for this type of experiment. Each complete trial or replication of the experiment all possible combinations of the levels of the factors are investigated.

The effect of a factor defined by changing of response that produced by changing in level of the factor, which this effect is called *main effect.* Main effect in the 2-level factorial design can be defined as follow,

Main Effect of a factor	=	Average of responses at High level of factor	–	Average of response at low level of factor

$$MainEffects = \bar{y}_{factor=1} - \bar{y}_{factor=-1}$$

In some experiment the difference in response between the level of one factor is not the same as all levels of other factors when this happen, there is an *interaction* between the factors. Interaction effect can be defined as follow,

For 2 factors, x1 and x2, the interaction effect is	=	$\frac{1}{2}$	(Effect of factor 1 on response at high level of factor 2	- Effect of factor 1 on response at low level of factor 2)

In a 2^k factorial design, main effect and 2-factor interaction also can be estimated by fitting the Regression model. The Regression model is

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \varepsilon$$

Where y is the response, the β's are parameters whose values are to be determined x_1 is a variable that represents factor A, x_2 is a variable that represents factor B, ε is a random error term, and $x_1 x_2$ represents the interaction between x_1 and x_2.

In general:

Main effect of factor "i" = $2\hat{\beta}_i$

Interaction effect between factors "i", "j" = $2\hat{\beta}_{ij}$

In order to determine which factors are likely to be significant, the magnitude and direction of the factor effects have to be examined. The analysis of variance (ANOVA) can be used to examine whether the magnitude of factor effects are statistical significant.

Table 2.1 The Analysis of Variance Table for the Two-Factor Factorial, Fixed Effects model

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_0
***A* treatments**	SS_A	$a-1$	$MS_A = \frac{SS_A}{a-1}$	$F_0 = \frac{MS_A}{MS_E}$
***B* treatments**	SS_B	$b-1$	$MS_B = \frac{SS_B}{b-1}$	$F_0 = \frac{MS_B}{MS_E}$
Interaction	SS_{AB}	$(a-1)(b-1)$	$MS_{AB} = \frac{SS_{AB}}{(a-1)(b-1)}$	$F_0 = \frac{MS_{AB}}{MS_E}$
Error	SS_E	$ab(n-1)$	$MS_E = \frac{SS_E}{ab(n-1)}$	
Total	SS_T	$abn-1$		

The total sum of squares is computed by

$$SS_T = \sum_{i=1}^{a} \sum_{j=1}^{b} \sum_{k=1}^{n} y_{ijk}^2 - \frac{y^2 ...}{abn}$$

The sums of squares for the main effects are

$$SS_A = \frac{1}{bn}\sum_{i=1}^{a} y_{i..}^2 - \frac{y_{...}^2}{abn}$$

And

$$SS_B = \frac{1}{an}\sum_{j=1}^{b} y_{.j.} - \frac{y_{...}^2}{abn}$$

The sums of squares for the subtotals

$$SS_{Subtotals} = \frac{1}{n}\sum_{i=1}^{a}\sum_{j=1}^{b} y_{ij.}^2 - \frac{y_{...}^2}{abn}$$

The sums of squares for interaction is computed by

$$SS_{AB} = SS_{Subtotals} - SS_A - SS_B$$

The sums of squares for Error is

$$SS_E = SS_T - SS_{AB} - SS_A - SS_B$$

Or

$$SS_E = SS_T - SS_{Subtotals}$$

2.1.3.1 Model Adequacy Checking

Before conclude the result from ANOVA, the adequacy of the model should be checked. The primary diagnostic tool is residual analysis. The residual analysis is the difference between actual value and fitted value. The residuals for a two-factor factorial model are

$$e_{ijk} = y_{ijk} - \hat{y}_{ijk}$$

2.1.3 Split-plot Design

Split-plot design is the design that level one or more factors are difficult to change, complete, and randomization. Split-plot design divides into two groups of factor. The first group is classification factors or whole-plot factors. These factors are included in the experiment to see if they modify the action of the other factors or indicate how the other factors work. Normally these types of factor the main effect are assumed not to be major interest or in other word it is environment factor. The second group is subplots factors or split-plots factors. There types of factors are the factors that divided from whole plot factor. These types of factors are the major interest or it is product design factors.

Arrangement for Split-plot Factors

$$Y_{ijk} = \mu + \rho_k + \alpha_i + \delta_{ik} + \beta_j + (\alpha\beta)_{ij} + (\alpha\beta)_{ij} + \varepsilon_{ijk}$$

where:

Y_{ijk} is the response value for the k^{th} replicate of the i^{th} level of factor A and the j^{th} level of factor B (where i = 1 to a, j = 1 to b and k = 1 to r).

μ is the overall mean.

ρ_k is the block effect for the k^{th} block; the block effect may be either fixed or random.

α_i is the effect of the i^{th} level of factor A; the effect may be either fixed or random.

δ_{ik} is the whole plot random error effect, for the i^{th} , k^{th} combination of block and factor A.

β_j is the effect for the j^{th} level of factor B; the effect may be either fixed or random.

$\alpha\beta_{ij}$ is the interaction effect of the i^{th} level of factor A with the j^{th} level of factor B; the interaction effect may be either fixed or random

ε_{ijk} is the subplot random error effect associated with the Y_{ijk} subplot unit.

Table 2.2 ANOVA Table for arrangement

Source of Variation	Degrees of Freedom	Mean Square
Whole plot analysis		
Blk	$r-1$	$\sigma_\varepsilon^2 + b\sigma_\delta^2 + ab_{Blk}^2$
A	$a-1$	$\sigma_\varepsilon^2 + b\sigma_\delta^2 + rb\theta_A^2$
Error a	$(r-1)(a-1)$	$\sigma_\varepsilon^2 + b\sigma_\delta^2$
Sub-plot analysis		
B	$b-1$	$\sigma_\varepsilon^2 + ra\theta_B^2$
A*B	$(a-1)(b-1)$	$\sigma_\varepsilon^2 + r\theta_{AB}^2$
Error b	$(r-1)a(b-1)$	σ_ε^2
Total	$rab-1$	

2.1.4 Data Transformation

Data transformation is a technique to help experimenter to convert the data that does not meet the assumptions of parametric statistical test: the data is not normally distributed. The transformation the data will make it fit the assumptions.

There are an infinite number of transformations that can be used. In order to define the transformation that suite the data there are some condition that have to be considered. The following lists are some transformation techniques that are commonly used.

Square root transformation, this technique is commonly used when the variable count of something or the variable follow the Poisson distribution.

$$y_{ij}^{*} = \sqrt{y_{ij}} \text{ or } y_{ij}^{*} = \sqrt{1 + y_{ij}}$$

Logarithmic transformation, this technique commonly used for the size variables or the data follows the lognormal distribution.

$$y_{ij}^{*} = \log y_{ij}$$

Arcsine transformation, this is commonly used for proportions or binomial data expressed as fractions.

$$y_{ij}^{*} = \arcsin \sqrt{y_{ij}}$$

2.2 Alloy Casting

2.2.1 Casting

Casting is a process by which a material is introduced into a mold while it is liquid form. When the material cools off and return to its solid stage, it would then be removed from the mold.

2.2.2 Type of Alloy

Alloy can be divided into two categories, the first category is Ferrous alloys and the second category is Non-Ferrous Alloys.

Ferrous alloys are iron-based materials that widely uses in industrial applications. The examples of the steels in this category are Alloy steels, Carbon steels, Stainless Steels, and Tool Steels.

Carbon steels are the steel that alloy element does not exceed the following limits: 1% carbon, 0.6% copper, 1.65% manganese, 0.4% phosphorus, 0.6% silicon, and 0.05% sulfur.

Alloy steel is the steel that exceed the element limits for carbon steels.

Stainless Steels are high-alloy steels that have corrosion resistance more than other steels Stainless Steels can be divided into three basic group which it bases on their crystalline structure: austenitic, ferritic, and martensitic.

Tool Steels are the steels that primarily use in making tools used in manufacturing processes. Tool Steels are ingot-cast wrought products which it can stand high specific loads.

Non-Ferrous Alloys are the alloys contain no iron. The examples of the Non-Ferrous Alloys are Aluminum Alloys, Copper Alloys, Magnesium Alloys, and Titanium Alloys.

Aluminum Alloys are a mixture of aluminum base metal with one or more alloying elements. Aluminum alloys is very light compared to metals such as steel.

Copper Alloys are alloys with copper as a main component. They have high resistance to corrosion.

Magnesium Alloys are the lightest of all the metals and have high resistance to corrosion.

Titanium Alloys are metallic materials which contain a mixture of titanium and other chemical element. Titanium alloys have very high tensile strength and toughness, light weight, and extraordinary corrosion resistance. It popularly uses in the aerospace industry.

2.2.3 Alloy Casting Method

Alloy casting method is divided into three methods, each method has it own specific character and some method is only suitable with some materials. The following are the description of each method.

1. **Sand Casting,** for hundreds of years sand casting was the most popular method of all casting methods, and it stills play an important role in today's casting business.

   Methodology: A wood or metal pattern is placed into the tempered sand. After the tempered sand packed the pattern will be removed. The cores can be assembled with or without. Then the liquid metal is poured into resultant cavities. After the metal cools down, the mold will be broken in order to remove the casting.

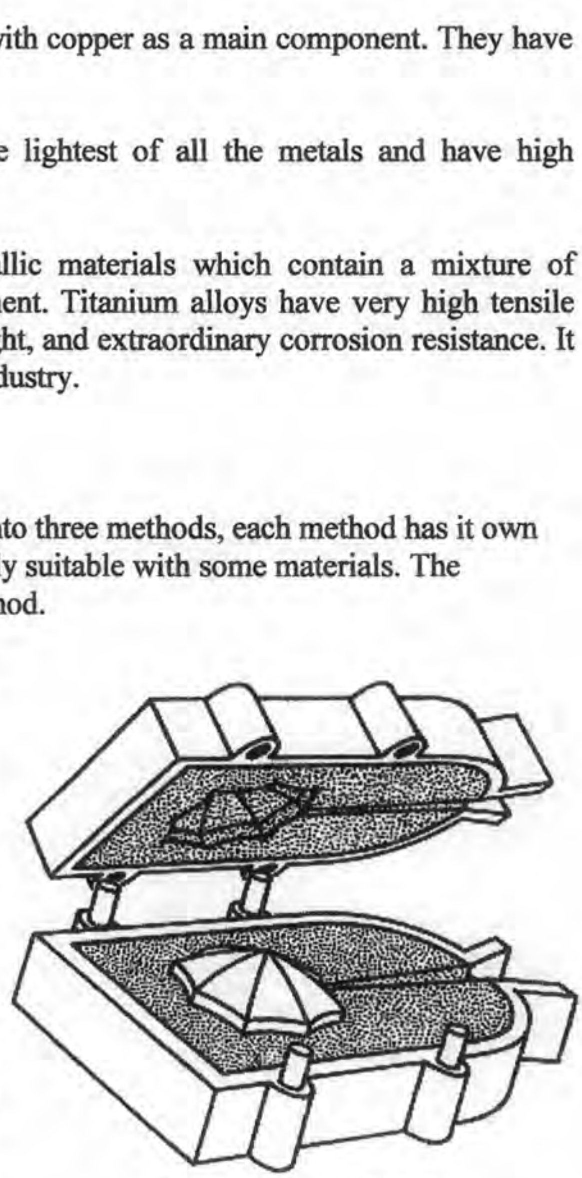

Figure 2.2: Sand Mold

   Metals: Suitable for most castable metals.

Size Range: depends on the capability of the foundry.

2. **Investment Casting**, or also known as lost-wax process. It was first used in the period of 4000-3500 B.C. The pattern is made from plastic or wax.

    Methodology: A wax or thermoplastic is used as a pattern in this method. The pattern is invested (surrounded) by refractory slurry. After the mold is dry, the pattern is melted or burned out of the mold cavity. Then, molten metal is poured into the resulting cavity. Molds are broken to remover the castings.

    Metals: Suitable for most castable metals.

    Size Range: from an ounce to 150 lbs.

3. **Die Casting**, is the most famous casting technique in the casting business today. Die casting is fast, cost-effective manufacturing process for production of high volume, net-shaped, tight tolerance metal components.

    Methodology: Die casting can be done by using a cold chamber or hot chamber process.

    In Cold Chamber process, the molten metal is injected into the cold chamber for each shot. There is less time exposure of the melt to the plunger walls or the plunger. This is particularly useful for metals such as aluminum, and copper.

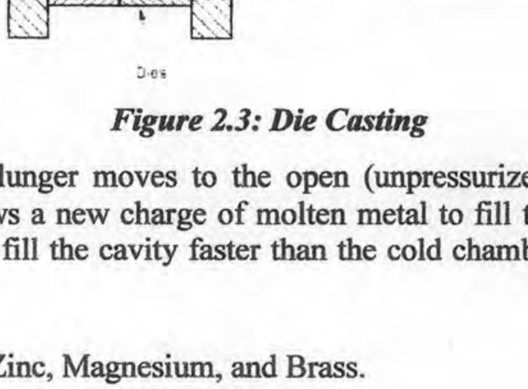

Figure 2.3: Die Casting

In Hot Chamber process, the pressure chamber is connected to the die cavity is immersed permanently in the molten metal. The inlet port of the pressurizing cylinder is uncovered as the plunger moves to the open (unpressurized) position. Thus allows a new charge of molten metal to fill the cavity and thus can fill the cavity faster than the cold chamber process.

Metal: Aluminum, Zinc, Magnesium, and Brass.

Size Range: normally not over 2 feet square, but some foundry is capable of larger size.

2.2.4 Casting Defects

Most of the casters try to make each product as perfect as possible, however only few cast products are completely free from the defects. Casting Defects can occur in various forms, which it can be categorized into seven categories as follow.

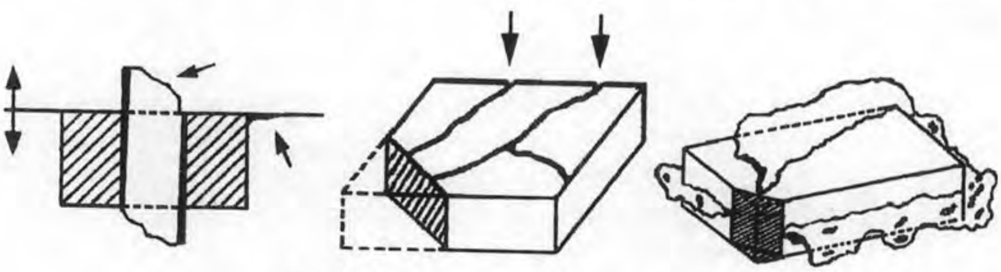

Figure 2.4: Metallic Projections

1. ***Metallic Projections***, the appearance of metallic projections are the projections of the irregular thickness as the *Figure 2.4*. They occur at the joint or parting line of the mold or wherever two elements of the mold intersect.

   Possible Causes: Mold Fractured, Improperly dried mold, too high temperature, poorly fit mold joint.

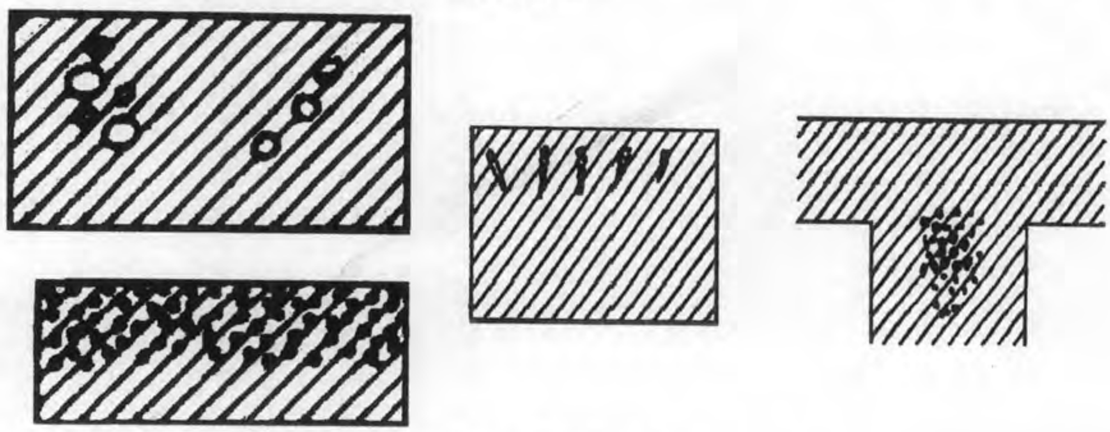

Figure 2.5: Cavities

2. ***Cavities***, Smooth-walled cavities, it is essentially spherical in shape and often does not contacting the external casting surface. Small cavities are appeared in group. Large cavities are appeared in isolation. The defect can appear all over the regions of the casting

   Possible Causes: Dissolved gases release during the solidification, too much moisture in molds or cores.

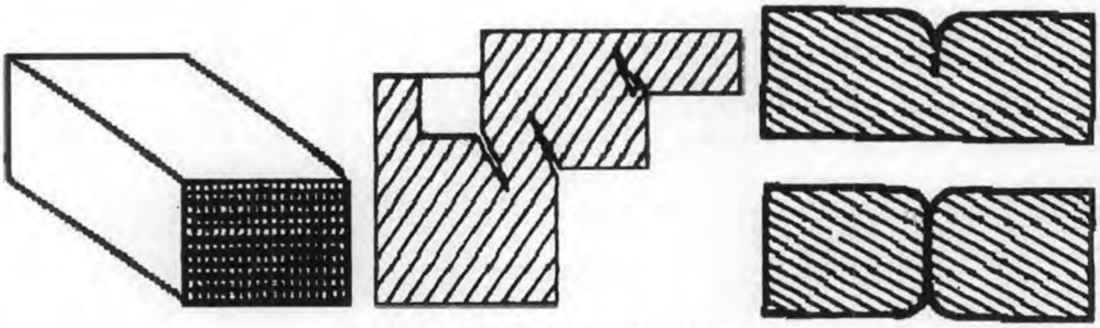

Figure 2.6: Discontinuities

3. ***Discontinuities***, these defects do not often occur in the casting but, when it occurred, it is very difficult to detect since the casting piece has not separated into fragments.

   Possible Causes: Damage to the casting while it still hot, careless heating treatment, and improper casting parameters.

Figure 2.7: Defective Surface

4. ***Defective Surface,*** the defect appears as lines. It occurs from the flow marks of the streams of liquid metal distributed across a surface of the casting. Defect normally occurs where thin sections are.

   Possible Causes: Improper casting parameters.

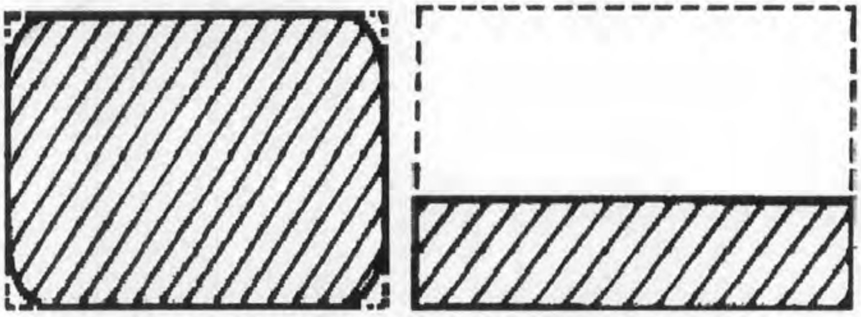

Figure 2.8: Incomplete Casting

5. ***Incomplete Casting***, the defect is where a portion of the casting is missing or some areas of casting are not filled.

   Possible Causes: the temperature of the liquid metal is too cold, insufficient quantity of the liquid metal.

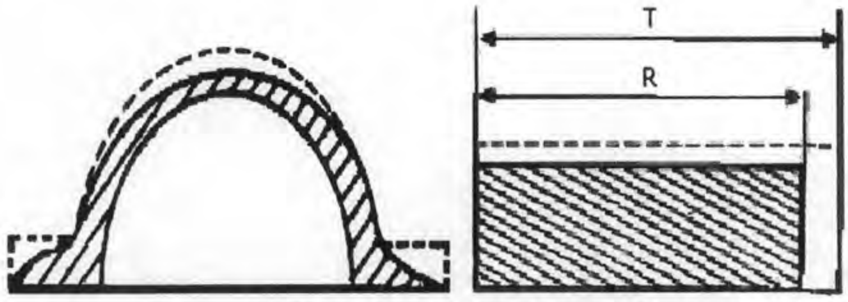

Figure 2.9: Incorrect Dimensions or Shape

6. ***Incorrect Dimensions or Shape,*** the measurement of the cast product is larger or smaller than the original pattern. Some areas of the cast product are thinner than the original pattern.

   Possible Causes: the shrinkage of the alloy, insufficient placing pressure when applied to the sand, the excessive cleaning or grinding of the pattern during finishing.

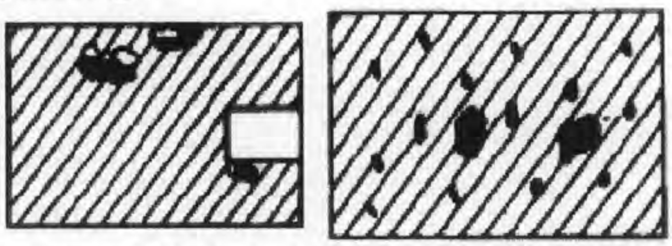

Figure 2.10: Inclusion or Structural Anomalies

7. ***Inclusions or Structural Anomalies,*** metallic inclusions of various sizes which are distinctly different in structure and color from the base material.

   Possible Causes: the contamination in the metal source.

2.2.5 Type of Inspection methods

1. Use polishers & microscopes to look at microscopic structures
2. Use metal analyzer such as to determine chemical composition
3. Use X-rays are used to examine hidden cracks and blowholes
4. Use ultrasonic inspection is used to detect sub-surface defects in aluminum die-casting parts.
5. Use magnetic particle is inspection method to locate surface and neat subsurface discontinuities in ferromagnetic materials.
6. Use liquid penetrate is a nondestructive method to expose discontinuities that are open to the surfaces of solid and essentially nonporous materials.

2.3 Literature Survey

Laosrimongkol (2004), apply the modified FMEA approach for iron foundry's product defects reduction. The author uses the team benchmarks on the production control with the first tier company, which it is found that there are two different controlled factors which are brand of coal dust and present of corn starch in mould sand. The case company is using coal dust brand A and corn starch addition with ratio per sand 1:8 while the benchmarked company using coal dust brand B and not using corn starch any more. Brainstorming other related factors to B111 defect and applying cause and effect matrix, why-why analysis, and FMEA, relevant factors with more than 100 RPN in FMEA table found which are high % sulphur in coal dust due to the present coal dust brand "A", ash content in mould sand due to the present coal dust brand "A", sand low permeability due to too much water absorption by present of corn starch, sand low compatibility due to fine substance from present of corn starch, and hot sand stick to corn starch are factors of interest in B111 defect reduction . Factors screening is done by one-factor-at a-time (OFAT) to the 168 specimens. It is found that using coal dust B and absent of corn starch can significantly reduce the B111 defect with 95% confidence. The findings are confirmed by casting the F/W ZE1 for 6000 unit. The B111 defect exists at 1.7 % which is acceptable. Return on quality investment (ROQI) is defined based on the 6000 cast units. The company can reduce the unit cost 0.52 baths from switching to coal dust B and stop using corn starch. Apart from that, the company can significantly save the damage cost due to the B111 defect. The company can gain the advantages of ROQI from casting the first 6381 units Fly wheel ZE1.

Witthawaskul (2003), has done the project about the reduction of defective products for a plastic injection process, which she starts the project by using cause and effect diagrams to explore all the potential influence factors affect on the defect product. Then, she used FMEA to analyse the factors and shown the risk priority number. In the end she used Why-Why analysis and the decision tree diagrams to define the root cause of the highest risk priority number and find the solutions before do the implementations. After the project is completed the defected product reduce from 6.68% to 1.94% in term of money it reduces 277,270 Bath within six weeks.

Anuraksakul (2002), applied the FMEA technique to analyse and reduce the defect for automotive body press part. The research begins with the collection, which the author found out that the defects are from DRAW, TRIM/PIERCE and SEPERATE processes. The defect can define into 5 defect types. First defect type is shrink defect. Shrink defect is caused by the low pressure cushion, part shift out the location and the height of the die is not standard. The second type is the sharp fin defect. The cause of the sharp fin is the die breakdown and unsuitability machine. The third type is swell defect. The swell defect is occurred from the dirtiness in the die and from the wrong removing part method. The forth type, part crack defect, the root cause of the problem is the pressure of the cushion is too high. The last type is the part deform. The cause of the problem is the die got damaged. After used FMEA technique for three months defects is reduced as follow. The defect rate in the Drawing process is reduced from 2.02% to 0.22%, the defect rate in TRIM/Pierce process is reduced from 2.2% to 0.22%, and the defect rate in Separate process is reduced from 2.25% to 0.18%.

Crow (2002), has describe the FMEA as the follow: Failure Modes and Effects Analysis (FMEA) is methodology for analyzing potential reliability problems early in the development cycle where it is easier to take actions to overcome these issues, thereby enhancing reliability through design. FMEA is used to identify potential failure modes, determine their effect on the operation of the product, and identify actions to mitigate the failures. A crucial step is anticipating what might go wrong with a product. While anticipating every failure mode is not possible, the development team should formulate as extensive a list of potential failure modes as possible.

Chawanaprenee (2000), has used FMEA to appoint and control the fire resistance cable design and production system. The research started with the Brain Storming, Relation Diagram, and Matrix Diagram to conclude all the problems that make the customer's dissatisfy. After problem is concluded, the FMEA is come up to analyse the problem. After the problem has been analysed the work standard has the new setting and the some of the document has re-written. The result of the action is the RPN is decreased; all of the RPN are lower than 100 points (before the actions the RPN are higher than 100 points). And the other advantage that the factory gains from this research is that the factory has the product prototype. This prototype has the properties corresponding to customer requirement, and the cost of the prototype is lower than one before.

Nawalamlert (1999), has done the research about quality assurance system for project management of water treatment plant in order to create the confidence of the provided project on the customer. He has included the way to reduce the frequent failure occurred during the project and the improvement of the machine during the operation. The research started by analysis the current management. The problems that he found in the process were the poor quality of work, delay of project completion, and customer dissatisfaction. He recorded the problems in term of reworking hours, financial loss, and the number of delay period. Then he applied FMEA in to the project by study the potential failures, potential effects, and the recommended actions. He has added the inspection procedure and the document establishment for assisting in inspection and for remaining during the operation. After the project is completed the reworking hours occurred in design and installation phase has decreased and the financial loss decreased 71% and the delay periods decreased from 2 weeks to 3 days.