APPLICATION OF MODIFIED FMEA APPROACH FOR IRON FOUNDRY’S PRODUCT DEFECTS REDUCTION

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วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
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งานวิจัยนี้มีวัตถุประสงค์เพื่อลดของเสียในผลิตภัณฑ์เหล็กหล่อ และเพื่อคำนวณหาจุดคุ้มทุนจากการลงทุนเพื่อลดของเสียจากงานหล่อ ผลิตภัณฑ์ที่เลือกเพื่อเป็นแนวทางศึกษาคือชิ้นส่วนประกอบรถยนต์ Fly Wheel ZE1 เนื่องจากเป็นรุ่นที่มีการผลิตเป็นจำนวนมากรุ่นหนึ่งของบริษัทที่เป็นกรณีศึกษา อาการเสียที่พบมากเป็นอันดับต้นๆคือ ปัญหาตามด ซึ่งมีสาเหตุมาจากหลายปัจจัย ปัญหาตามดนี้ส่งผลเสียในเชิงประสิทธิภาพของสายการผลิต และชื่อเสียงของบริษัทกรณีศึกษา เนื่องจากปัญหาดังกล่าวสามารถพบได้หลังการส่งมอบให้ลูกค้า

ในเบื้องต้นทีมงานวิจัยได้เปรียบเทียบปัจจัยควบคุมเกี่ยวกับการผลิตผลิตภัณฑ์กับบริษัทลูกค้า ซึ่งมีกิจกรรมการผลิต Fly Wheel ZE1 เช่นเดียวกัน พบว่ามี 2 ปัจจัยที่ควบคุมแตกต่างกัน คือ ยี่ห้อ coal dust และการเติมแป้งข้าวโพดในแบบหล่อทราย โดยที่บริษัทกรณีศึกษาใช้ coal dust ยี่ห้อ A เติมแป้งข้าวโพดในอัตราส่วนกับทรายทำแบบ 1:8 ในขณะที่ทางบริษัทเปรียบเทียบใช้ coal dust ยี่ห้อ B และไม่ใช้แป้งข้าวโพดเติมในทรายทำแบบหล่อเลย ทีมงานได้ระดมความคิดถึงปัจจัยอื่นๆในสายการผลิตที่ส่งผลกับปัญหาตามด โดยใช้เทคนิค Cause and Effect Matrix Why-Why analysis และ FMEA ปัจจัยที่มีคะแนน RPN ตั้งแต่100 คะแนนขึ้นไปได้แก่ %ซัลเฟอร์และปริมาณขี้เถ้าที่ปนใน coal dust A ในปริมาณที่สูง ค่าความโป่งของแบบทรายต่ำเนื่องจากการดูดซับน้ำในปริมาณมากจากแป้งข้าวโพด ค่าความอัดแน่นของแบบทรายต่ำเนื่องจากความละเอียดแบบผงฝุ่นของแป้งข้าวโพด และ ทรายร้อนที่ติดกับกระสวน ทีมงานสนใจที่จะทำการทดลองว่าการเปลี่ยนยี่ห้อ coal dust จาก A เป็น B และการไม่ใช้แป้งข้าวโพดเป็นส่วนผสมในแบบทราย จะสามารถลดของเสียจากปัญหาตามดได้ โดยวิธีทดสอบทีละปัจจัยโดยหล่องานจำนวน 168 ตัว พบว่าการใช้ coal dust B และการไม่ใช้แป้งข้าวโพด ช่วยให้ปัญหาตามดลดลงอย่างมีนัยสำคัญด้วยความเชื่อมั่น 95% ทีมงานได้ทำการทดลองเพื่อยืนยันผลการหล่อโดยใช้ coal dust B และ ไม่ใช้แป้งข้าวโพด ด้วยจำนวนงานหล่อเพิ่มขึ้นเป็น 6,000 ตัว พบว่าปัญหาตามดลดลงอยู่ที่ 1.7% ซึ่งถือว่าเป็นที่อัตราส่วนที่ยอมรับได้ เมื่อคำนวณความคุ้มค่าพบว่า สามารถลดต้นทุนต่อตัวเนื่องจากการใช้ coal dust B ในปริมาณที่เพิ่มขึ้น และไม่ใช้แป้งข้าวโพดเป็นจำนวน 0.52 บาท และสามารถลดต้นทุนจากค่าความเสียหายของงานที่เป็นตามดได้เป็นจำนวนมากอย่างมีนัยสำคัญ จุดคุ้มทุนจากการลงทุนด้านคุณภาพนี้ได้จากการหล่อชิ้นงาน Fly Wheel ZE1 ตั้งแต่ 6,381 ตัวขึ้นไป

ผลการวิจัยนี้สามารถสรุปได้ว่า coal dust A และแป้งข้าวโพดส่งผลต่อปัญหาตามดในสายการผลิตชิ้นส่วนยานยนต์รุ่น Fly wheel ZE1 ของโรงงานตัวอย่าง ดังนั้นการปรับเปลี่ยนที่เหมาะสมคือ การใช้ coal dust B ในอัตราส่วนต่อ bentonite 1:4 และหยุดใช้แป้งข้าวโพดเป็นส่วนผสมของทรายทำแบบ

ศูนย์ระดับภูมิภาคทางวิศวกรรมระบบการผลิต
สาขาวิชา การจัดการทางวิศวกรรม
ปีการศึกษา 2547

ลายมือชื่อนิสิต :…………………………..
ลายมือชื่ออาจารย์ที่ปรึกษา :……..………...

457 16370 21 : MAJOR ENGINEERING MANAGEMENT
KEY WORD : DEFECTS IN IRON CAST / FMEA / COAL DUST / CORN STARCH

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The purpose of this study is to reduce defects in cast iron products and to evaluate the return on quality investment. The selected product is an automotive part, Fly wheel ZE1, which is the most volume production of the case study company. The defect symptom of interest is blowholes or pinholes defect (B111) which is the highest defect found in production. There are many possible causes of B111 defect. The defect is as high as to lower the production yield and also ruin the company's reputation from customer complain.

Primarily, the team benchmarks on the production control with the first tier company who is producing the Fly wheel ZE1. 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 compactability due to fine substance from present of corn starch, and hot sand stick to the pattern due to using up high temperature mould sand. Coal dust B and absent of 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 6,000 units. The B111 defect exists at 1.7% which is acceptable. Return on quality investment (ROQI) is defined based on the 6,000 cast units. The company can reduce the unit cost 0.52 baht 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 6,381 units Fly Wheel ZE1.

To draw the conclusion that coal dust A and corn starch are main effects to B111 defect on Fly Wheel ZE1 of the case company. Thus, the appropriate control is using coal dust B : bentonite at ratio 1 : 4 and stop using corn starch in sand moulding.

The Regional Centre for Manufacturing Systems Engineering Student's signature :……….……..

Field of study : Engineering Management Advisor's signature :……....…...

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CHAPTER I

Introduction

1.1 <u>Background</u>

The company was established in July 2003 manufacturing gray and ductile cast irons, FC and FCD. The products are classified into two product lines. The first is about automotive part; drum break, hup, and fly wheel. The second is mechanical part; pulley, valve and ring. The company supplies those automotive parts to an auto parts manufacturer who is the first tier supplier of car manufacturers such as Honda, Mitsubishi, etc. The first tier company is either running production line in iron casting. It employs the case study company to produce parts as a sub-contactor. The business activities are demonstrated in figure 1.1. After receiving parts from the case study company, the first tier company starts machining and supplies to the car manufacturers for assembly.

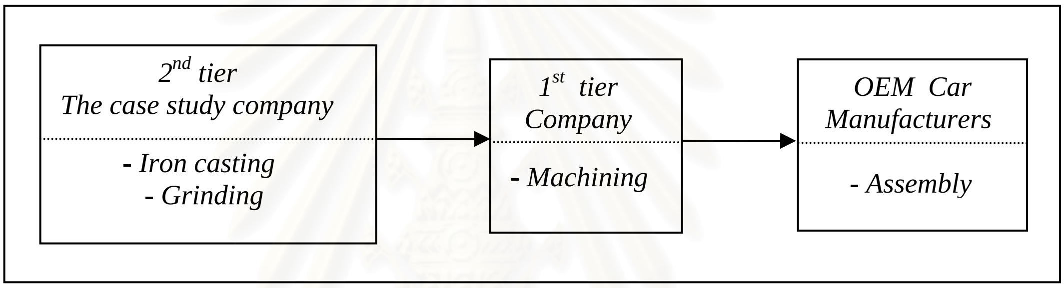


Figure 1.1 : Business chain of the case study company

This thesis is conducted to study cause of failure in iron casting manufacturing and to suggest area of improvement throughout the tools FMEA (Failure Modes and Effects Analysis) and DOE (Design of Experiment). By the way, the case study company, where production average yield at 86.4%, is benchmarked in term of operation with the leading company whose performance held at average 98.2%. Cause and effect matrix plays role on weighting for the major factors that cause defective. Finally, the quality cost concurring with the defectiveness will be verified in order to evaluate return on quality investment (ROQI).

FMEA is a disciplined method of product or process analysis that is conducted to identify potential failures that could affect customer's expectation of product quality or process performance. It is a bottom up technique in which study is made of how components or processes can fail. Implementing FMEA to processes will enable implementer to;

1 Identify key areas in which to control the process and, where appropriate, place inspection and manufacturing controls.
2 Provide a systematic and rigorous study of the process and its environment that will almost always improve understanding of how the process might fail.
3 Support the need for a standby or alternative process or improvement to current processes.

To develop FMEA, it is primary to study and understand the process flow as a first step to access the problems. Secondly, it is to make use of the basic analysis tools, cause and effect diagram, and brainstorming to classify problems into its categories ; man, machine, material, measurement and environment.

The design of experiment (DOE) is employed, herewith, as a tool to designate a type of plan to be used for the assignment of test units to experimental conditions (or treatments) for the purpose of statistical generating (versus collecting) data. The objective of the DOE is to understand the impact of specific changes to the inputs of a process and then to maximize or minimize the outcome by manipulating the inputs. An analysis of the inputs and recorded observation help determine the level of input needed to meet the desired output.

Successful implementation of FMEA and process development will be reflected in term of cost reduction. Detail of the thesis will cover studying cost of quality to give a management numeral perspective which is more concrete and convincible. Cost of quality is classified into 4 categories.

1. Internal failure costs which relate to in-house defective works, for example, rework, scrap, waste and re-inspection.
2. External failure costs which incur from return, repair, claim after delivering goods to customers.
3. Appraisal costs which are about quality activities, for example, inspection, assessment, measurement, calibration and maintenance.
4. Prevention costs which incur through the entire chain of activities regarding defective prevention.

1.1.1 Production

The iron casting is divided into four main processes as following. The flow chart of typical foundry operation is exhibited in figure 1.2.

1. Melting Process.
   Raw materials are conveyed to an one ton (900 KW.) induction furnace and melted at high temperature. Not only the raw materials to be melted in the furnace, but also are the steel scrap, return scrap with ingredient of chemicals.
2. Mould Making Process.
   2.1 Sand : In this process, new sand, reused sand, and additional ingredients, for example, corn starch, bentonite, water, sea coal, are mixed in the sand mixer and then milled. The milled sand is conveyed into automatic mould machine and stamped upon the pattern of product.
   2.2 Pattern : Metallic pattern is selected suitably to the case study iron casting production. The core is brought to finish the mould.
3. Casting Process.
   The melted metal from furnace is carried to the production line by the ladle and poured into sand mould manually. The melted metal cools down naturally at room temperature and becomes solid afterward.

4. Finishing Process.
   The cast iron is taken off from sand mould and gating, snagging are removed. Shot blasting is applied to the cast iron to clean up leavings sand on the surface. After having been cleaned, the cast iron is finished by grinding to remove seams, gating joints.

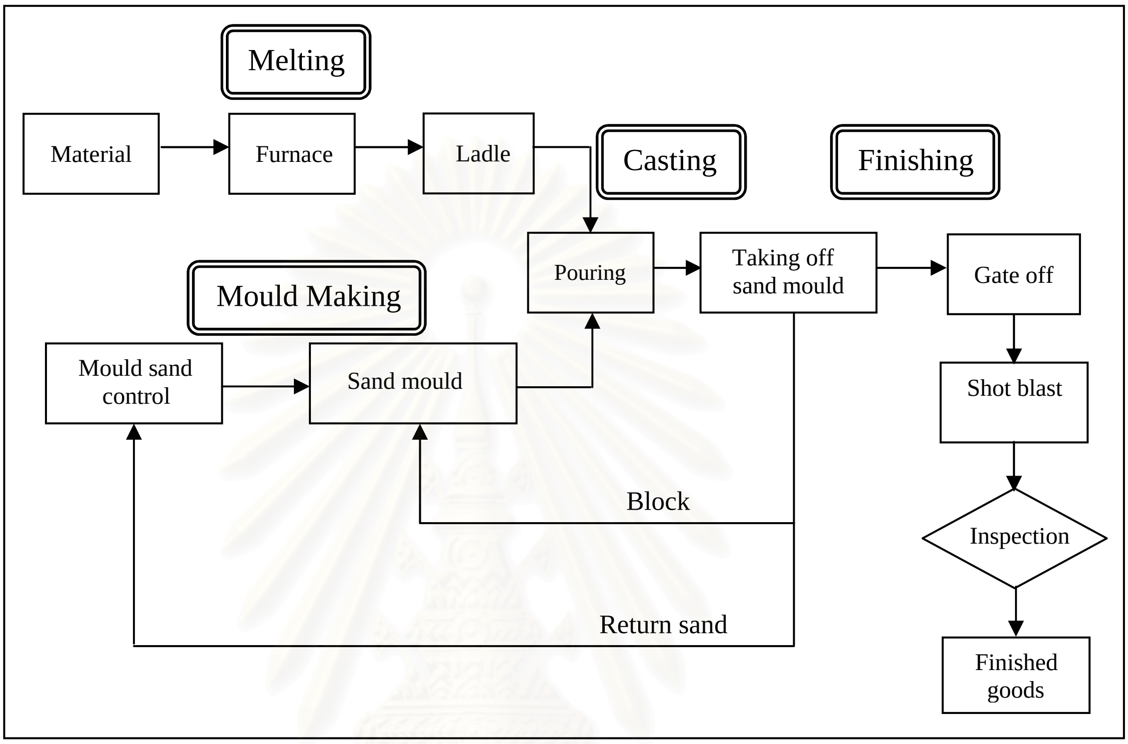


Figure 1.2 : Flow chart of typical foundry operation
[Source : Cast Iron : Physical and Engineering Properties, 1976]

1.1.2 Inspection

Inspections and controls are conducted in-house, as well as by third party. Procedure and inspection criteria are given in operation standard. Detail of inspections and controls are as described below.

1.1.2.1 In-House Inspection.

In-line inspection : The sampling of incoming steel scrap is analyzed for chemical composition by spectrometer. The new sand is quality guaranteed by the sand certificate which issued by sand supplier. Either are the others casting materials coming with data sheet. In casting process, the mixed sand is inspected for temperature, moisture level, compactability, compressive, shearability, and permeability. After having been stamped on the pattern, the sand mould is inspected again for strength and green hardness. The height of pouring from ladle to mould, temperature of melted metal in ladle, fading time are controlled factors.

Off-line inspection : After the shot blasting process, QC inspects for appearance defect and quantity. The good parts are sent to grinding while defected parts are returned to recycle. After machining, the finished goods are inspected for blowholes or pinholes, crack, dimension, hardness, micro structure, and quantity.

1.1.2.2 Third Party Sand Analysis.

Sample of the mixed sand is sent for property analysis by third party regarding sand grading, AFS No., %loss on ignition (L on I), %volatile, shatter index, %clay grade, and active clay. The analysis interprets the quality of the mould sand and efficiency of mould materials in the mixed sand.

1.2 Statement of problem

After having discussed with the company's shareholder, it was found that the case study company has been falling below customer's standard requirement. According to monthly report as shown in table 1-1, the defective rate in May and June was 15.53% and 19.31%, respectively. Performance of the case study company is considered low comparing to the first tier company who is producing iron casting under defect rate allowance at 5% only.

Table 1-1 : Monthly Performance on Cast Iron of May and Jun, 2004

Table 1-1a : Monthly Report on Cast Iron Performance of May 2004

Part Name	Inspection Q'ty (pcs)	Good (pcs)	NG (pcs)	In-house defect(pcs)	Claims (pcs)	%defect
DRUM MN	15,639	13,599	2,040	1,639	401	13.04
HUB KD	11,116	9,657	1,459	975	484	13.13
HUB NOK	1,834	1,480	354	209	145	19.30
FLY WHEEL FCC	2,571	1,991	580	372	208	22.56
FLY WHEEL ZE7	13,987	11,224	2,763	1,640	1,123	19.75
PULLEY PROTON	4,154	3,274	880	653	227	21.18
FLY WHEEL ZE1	17,886	14,716	3,170	1,929	1,241	17.72
FLY WHEEL ZE0	14,146	12,812	1,334	1,119	215	9.43
RING NOK	405	395	10	10	-	2.47
HUB-02	8,115	6,766	1,349	1,160	189	16.62
DRUM JT	-	-	-	-	-	-
RING NZ	10,407	9,240	1,167	534	633	11.21
RING KD	5,543	4,215	1,328	1,043	1,328	23.96
TOTAL	***105,803***	***89,369***	***16,434***	***11,283***	***6,194***	***15.53***

Table 1-1b : Monthly Report on Cast Iron Performance of June 2004

Part Name	Inspection Q'ty (pcs)	Good (pcs)	NG (pcs)	In-house defect(pcs)	Claims (pcs)	%defect
HUB KD	19,354	14,833	4,521	4,136	385	23.36
HUB NOK	4,731	3,792	939	939	0	19.85
FLY WHEEL ZE7	10,723	8,966	1,757	1,324	433	16.39
PULLEY PROTON	9,035	6,930	2,105	2,058	47	23.3
FLY WHEEL ZE1	28,161	24,376	3,785	2,900	885	13.44
FLY WHEEL ZE0	10,835	9,284	1,551	874	677	14.31
RING NOK	3,252	3,162	90	90	0	2.77
HUB-02	11,303	7,373	3,930	3,776	154	34.77
RING NZ	372	170	202	202	0	54.3
TOTAL	***97,766***	***78,886***	***18,880***	***16,299***	***2,581***	***19.31***

The details of defect symptoms of those two production months are described in table 1-2. The Pareto diagram in figure 1.3 and 1.4 exhibit the defect symptoms and amounts of iron casting of May and June 2004, respectively.

Table 1-2 : Defect Symptoms on Cast Iron of May and Jun, 2004

Table 1-2a) : Defect Symptoms on Cast Iron of May 2004

Part Name	Defect Symptom (pcs)																Total defect (pcs)
	B221	C311	B113	E122	G211	D141	B311	B111	A211	A123	G131	E123	B121	F221	E221	Machining error	
DRUM MN								821			412		597	210			2,040
HUB KD		12	9			10		290	128	97	150	87	356	266		54	1,459
HUB NOK		18	58							98	122	9		49			354
F/W FCC								126			63			195	189	7	580
F/W ZE7		168	15			21		943		84	817	5		127	577	6	2,763
PULLEY PROTON						93		596	145						46		880
F/W ZE1	3	413	95	6		25		2,014		74				133	386	21	3,170
F/W ZE0	8	79	63			86				35	412	37		602		12	1,334
RING NOK		2	1							2	5						10
HUB-02	21	32	75				14	404		93	231	43	321	57	47	11	1,349
DRUM JT																	-
RING NZ							38	194	83	387	98		367				1,167
RING KD				9			217	868				66	164			4	1,328
TOTAL	32	724	316	15	-	235	269	6,256	356	870	2,310	247	1,805	1,639	1,245	115	16,434

Table 1-2b) : Defective Symptoms of iron casting of June 2004

Part Name	Defect Symptoms (pcs)																Total defect (pcs)
	B221	C311	B113	E122	G211	D141	B311	B111	A211	A123	G131	E123	B121	F221	E221	Machining error	
HUB KD		21	12			7		2,198			693	157	965	468			4,521
HUB NOK		21	43		40					34	52	11		734	4		939
F/W ZE7		142	12		13	16		542		46	704	21	35		223	3	1,757
PULLEY PROTON						312		753	467				248		321	4	2,105
F/W ZE1	35	412	87	3		9		2,476		125	75	43		213	299	8	3,785
F/W ZE0	4	59	62			33		365	48	73	263	195	64	325	57	3	1,551
RING NOK		1	1								67	4	9			8	90
HUB 02		15	66	21			72	1,886		56	143	18	803	753	91	6	3,930
RING NZ											2		200				202
TOTAL	39	671	283	24	53	377	72	8,220	515	334	1,999	449	2,324	2,493	995	32	18,880

From the Pareto Diagram as shown in figure 1.4, the most three defective products during production period May and June, 2004 are F/W ZE1, HUB KD, and HUB 02. F/W ZE1, which is the most frequently produced each month in a considerable amount, is selected as a model to the study defect reduction in cast iron by modified FMEA approach.

From the Pareto Diagram as shown in figure 1.5, it is obvious that the top four defective symptoms during production period May and June, 2004 are :

1. B111 : Blowholes or pinholes in cast iron below or near the surface appeared when machining as exhibited in figure 1.3.
2. B121 : Surface blowholes or cavities that expose to the surface of cast iron and may sometimes appear as shinny spots at shake out.
3. G131 : Sand inclusions of irregular shape, usually compact, in the vicinity of the cope surface of the casting. The cavities are about two to six mm thick which are more or less exposed and with sand inclusions adjacent to them.
4. F221 : Shift caused by pattern mismatch, poor machining or loose fit.

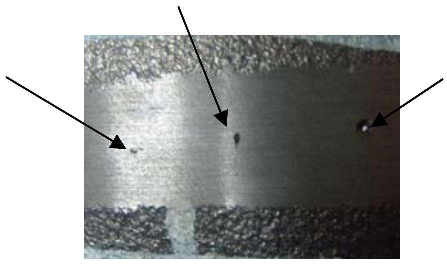


Figure 1.3 Blowholes or pinholes defect

It is considered that the defective B111 is frequently occurred in various models, especially F/W ZE1. The defective B121, which is classified as the same defective phenomenon as B111, also plays a significant role to production performance. Therefore, it is worth to study the blowholes or pinholes defect reduction base on F/W ZE1 and to apply what studied on this model to others.

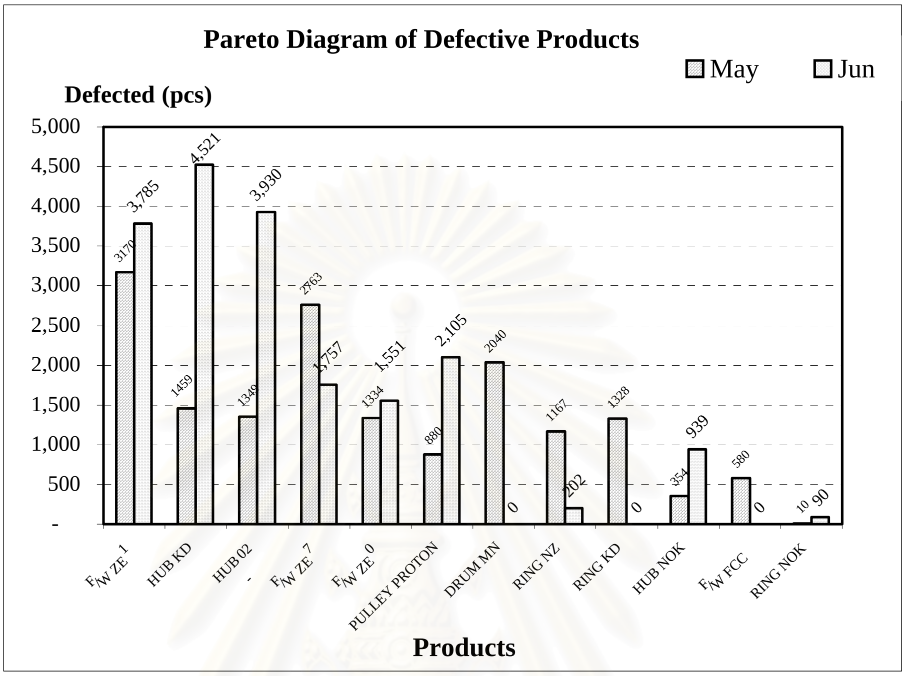


Figure 1.4 : Pareto Diagram of Defective Products of May and Jun, 2004

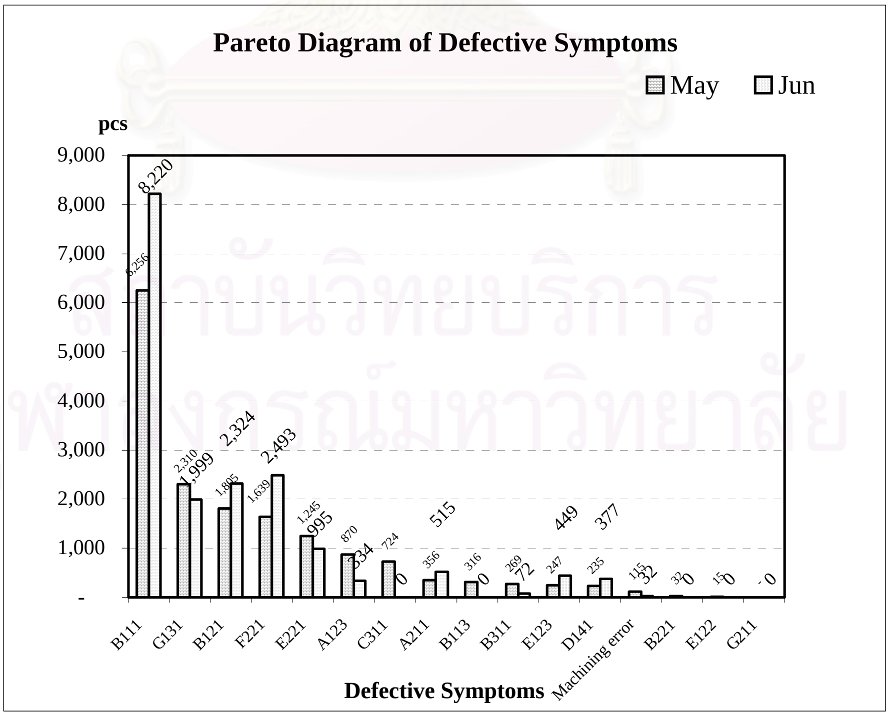


Figure 1.5 : Pareto Diagram of Defective Symptoms of May and Jun, 2004

1.3 Objective of the Thesis

1. To reduce defect rate in iron casting process.
2. To evaluate return on quality investment.

1.4 Scope and Limitation

1. The study will be conducted base on automatic production line for part fly wheel ZE1 in which supplied to automotive manufacturer only.
2. The quality cost is scoped to the actual cost concurred in manufacturing and customer claim only, administrative is excluded.

1.5 Organisation of the Thesis

First of all this project is initialized from looking at the existing problems in the case company production. The most frequent and serious problems are verified using pareto diagram for data arrangement. The blowholes or pinholes defect (B111) in cast iron is selected as the current major problem and the product fly wheel ZE1 is a model for studying as the highest production volume. Studying the relevant literatures and academic researches, they are denoted in chapter 2. The essential cast iron technology is briefed in chapter 3. Regarding the acquired knowledge base and tools, the factors related to the B111 problem are verified in chapter 4. Chapter 5 is talking about the Design of Experiment in order to confirm the findings from chapter 4 and determine the optimum level for the case production. Since any change comes with cost more or less, therefore, the ROQI is verified in chapter 6 as a value data to the management for further decision making. Conclusion, recommendation to the case company and hinge for further study are summarized in the last chapter.

1.6 Thesis Schedule

1. Study Benchmarking, C&E matrix, FMECA, DOE, Poka-Yoke, and ROQI from literature and relevant research of these tools.
2. Study iron casting technique from academic sources.
3. Benchmark the case study company with SBM in term of operation standard.
4. Apply C&E matrix to weight the major factors that lead to defective
5. Study the current problem of the case study foundry to identify the potential failures and their root causes analysis on part fly wheel ZE1.
6. Gather statistic data and relevant information to conduct the design of experiment to test whether the hypothesis of the problem statement is right.
7. Design the experiment and trial by employing Poka-Yoke technique to fool proof and controlled factors.
8. Study cost of quality improvement before implementation and ROQI evaluation.
9. Summarize and propose development plan.
10. Complete the thesis and submit as in time manner as shown in table 1-3.

Table 1-3 : Gantt chart of thesis schedule during Jul 2004 – Apr 2005

Task description	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
1. Study Benchmarking, C&E matrix, FMEA, DOE, Poka-Yoke and ROQI.										
2. Study cast iron techniques from academic sources										
3. Benchmark the case study company with the first tier company										
4. Apply C&E matrix to weight the major factors that lead to defective										
5. Study the current problem to identify the potential failures and their root causes analysis.										
6. Gather statistic data and relevant information to conduct the DOE										
7. Design the experiment and implement the plan										
8. Study cost of quality improvement before implementation and ROQI evaluation.										
9. Summarize and propose development plan.										
10. Complete the thesis and submit										

1.7 Expected Benefits

1. To increase productivity by reducing defects.
2. To evaluate cost saving versus implementation cost.
3. To be a guidance for defect reduction to other models.

CHAPTER II

Theory and Literature Surveys

Theories and literatures described in this chapter are as imperative background of the thesis completion. Theories are regarding benchmarking definition, Failure Mode and Effect Analysis (FMEA) technique, fool proof technique as so called "Poka-Yoke", and Design of Experiment (DOE) which applied to study the defect reduction in cast iron production. The literature surveys are those academic from master thesis works and researches.

2.1 <u>Benchmarking</u>

Benchmarking is a method in which an organization uses to measure itself against the best- in-class industry practices or across the industries in order to achieve competitiveness. The primary three types of benchmarking are internal, competitive, and process. Process benchmarking is based on the idea that many processes are common across industry boundaries, and innovations from other types of organizations can be applied across industries [Total Quality Management, p.275]. The essential step of benchmarking is thoroughly understanding and documenting the current process through several techniques, for instance, flow diagrams, cause-effect diagrams. The benchmarking process contains with six basic steps as following.

1. Decide what to benchmark
1. Get understanding current situation
2. Make a plan
3. Study others whom to benchmark with
4. Learn from the collected data
5. Digest the findings.

However, to initiate the benchmarking, it is necessary to adjust the procedure to best fit with own needs and organization. Table 2-1 exhibits how AT&T and Xerox adapt their benchmarking procedures.

Table 2-1 : Comparison between AT&T's and Xerox's benchmarking procedure.
[Source : Total Quality Management]

AT&T's 12-Step Process	Xerox's 10-Step Process
1. Determine who the clients are – who will use the information to improve their processes.	1. Identify what is to be benchmarked.
2. Advance the clients from the literacy stage to the champion stage.	2. Identify comparative organizations.

(continued)

AT&T's 12-Step Process	Xerox's 10-Step Process
3. Test the environment. Make sure the clients can and will follow through with benchmarking findings.	3. Determine data-collection method and collect data.
4. Determine urgency. Panic or disinterest indicate little chance for success.	4. Determine current performance gap.
5. Determine scope and type of benchmarking needed.	5. Project future performance levels.
6. Select and prepare the team.	6. Communicate benchmark findings and gain acceptance.
7. Overlay the benchmarking process onto the business planning process.	7. Establish functional goals.
8. Develop the benchmarking plan.	8. Develop action plans.
9. Analyze the data.	9. Implement specific actions and monitor progress.
10. Integrate the recommended actions.	10. Recalibrate benchmarks.
11. Take action.	
12. Continue improvement.	

After having implemented the plan, the organization has to verify critical success factor as a measurement of success. The numerical measurement is an obvious information of improvement, for instance, Cpk, PPM, per-cent yield, etc.

2.2 Failure Mode and Effective Analysis (FMEA)

FMEA was first developed in the 1960s by the aerospace industry during the Apollo program and later adopted by the automotive industry as a required component of the advanced quality planning process. In the automotive industry, FMEA has been applied to vehicle systems, subassemblies, and components.

2.2.1 *Definition of FMEA*

FMEA is a systematical method to identify and prioritize foreseeable failures of product or process based on the quantitative assessment by mean of risk priority number (RPN). Prioritization of the potential failures or RPN regards the severity, occurrence, and detection relatively impacted on the product or process. Severity (S) is a rating corresponding to the seriousness of an effect of a potential failure mode. Occurrence (O) is a rating corresponding to the rate at which a first level cause and its resultant failure mode will occur over the design life of product or process, or before any additional process controls are applied. Detection (D) is a rating corresponding to the likelihood that the detection methods or current controls will detect the potential failure mode before the designed product released for production, or for process before it leaves the production facility.

2.2.2 *RPN Rating Scale and Criteria*

RPN is calculated by the multiplication of S, O, D as in equation 2-1 where scaled 1-10 for each.

$$RPN = S \times O \times D \qquad \text{(equation 2-1)}$$

Therefore the highest possible risk of each failure mode is 1,000 and the lowest is 1. According to the automotive standard 16949, the RPN score 75 is considered acceptable. The criteria of ranking the scale for severity, occurrence and detection are described in table 2-2, table 2-3, and table 2-4, respectively.

Table 2-2 : Ranking scale for severity of potential failure mode.

Ranking	Description	Criteria
1	None	Slight inconvenience to operation or operator or no effect.
2	Very Minor	A portion (less than 100%) of the product may have to be reworked, with no scrap, on-line but in-station.
3	Minor	A portion (less than 100%) of the product may have to be reworked, with no scrap, on-line but out-of-station.
4	Very Low	The product may have to be sorted, with no scrap, an a portion (less than 100%) reworked
5	Low	100% of product may have to be reworked, or vehicle/ item repaired offline but does not go to repair department.
6	Moderate	A portion (less than 100%) of the product may have to be scrapped with no sorting, or vehicle/item repaired in repair department with repair time less than half an hour.
7	High	Product may have to be sorted an a portion (less than 100%) scrapped, or vehicle/item repaired in repair department with repair time between half an hour and an hour.
8	Very High	100% of product may have to be scrapped, or vehicle/item repaired in repair department with repair time more than 1hr.
9	Hazardous with warning	May endanger operator (machine or assembly) with warning.
10	Hazardous without warning	May endanger operator (machine or assembly) without warning.

Table 2-3 : Ranking scale for probability and frequency of occurrence.

Ranking	Description	Criteria
1	Remote : Failure is unlikely	<= 0.01 per thousand pieces; Ppk => 1.67.
2	Low : Relatively few failures	0.1 per thousand pieces; Ppk => 1.30.
3	Low : Relatively few failures	0.5 per thousand pieces; Ppk => 1.20.
4	Moderate : Occasional failures	1 per thousand pieces; Ppk => 1.10.
5	Moderate : Occasional failures	2 per thousand pieces; Ppk => 1.00.
6	Moderate : Occasional failures	5 per thousand pieces; Ppk => 0.94.
7	High : Frequent failures	10 per thousand pieces; Ppk => 0.86.
8	High : Frequent failures	20 per thousand pieces; Ppk => 0.78.
9	Very High : Persistent failures	50 per thousand pieces; Ppk => 0.55.
10	Very High : Persistent failures	=> 100 per thousand pieces; Ppk => 0.55.

Table 2-4 : Ranking scale for detection.

Ranking	Description	Criteria
1	Very High	Discrepant parts cannot be made because item has been error proofed by process/product design.
2	Very High	Error Proofed or Gauging Inspection. Error detection in-station (automatic gauging with automatic stop feature). Cannot pass discrepant part.
3	High	Error Proofed or Gauging Inspection. Error detection in-station, OR in subsequent operations by multiple layers of acceptance: supply, select, install, verify. Cannot accept discrepant part.
4	Moderately High	Error Proofed or Gauging Inspection. Error detection in subsequent operations, OR gauging performed on setup and first-piece check (for setup causes only).
5	Moderate	Gauging Inspection. Control is based on variable gauging after parts have left the station, OR Go/No Go gauging performed on 100% of the parts after parts have left the station.
6	Low Gauging or Manual Inspection	Control is achieved with charting methods, such as SPC (Statistical Process Control)

7	Very Low Manual Inspection	Control is achieved with double visual inspection only.
8	Remote Manual Inspection	Control is achieved with visual inspection only.
9	Very Remote	Manual Inspection. Control is achieved with indirect or random checks only.
10	Almost Impossible Manual Inspection	Cannot detect or is not checked.

2.2.3 *FMEA Classification*

FMEA falls into four types which are System FMEA, Design FMEA, Process FMEA, and Service FMEA. The diagram in figure 2.1 exhibits type of FMEA with their focuses and objectives.

1. System FMEA.

   System FMEA aids in analyzing the potential failure occurred in the systems and subsystems during conceptual design process and concerning about safety issues in order to forestall the system-based failures. It provides an optimum system design alternative and the basis for system level diagnostic procedures. Therefore, the redundancy of system design could be eliminated.

2. Design FMEA.

   Design FMEA (DFMEA) aids in identifying and ranking the potential failure modes in the design process. The action plan will help eliminate the failures effected to operation of the process by specifying the appropriate tests to prove the design. Consequently, development time and cost of manufacturing could be minimized.

3. Process FMEA.

   Process FMEA (PFMEA) are based on manufacturing or assembly processes used to make a component, subsystem, or main system. The potential failures that might occur in the manufacturing and assembly processes, inspection points, and processes for handling non-conforming material are identified beforehand. Risk assessment helps determine and prioritize high risk parts of the process. The control plan and corrective action are developed and documented to manage the process away from potential failures.

4. Service FMEA.

   Service FMEA aids in monitoring service process or system that might be failed before the service reaching to customers. This is to improve service timing and efficiency.

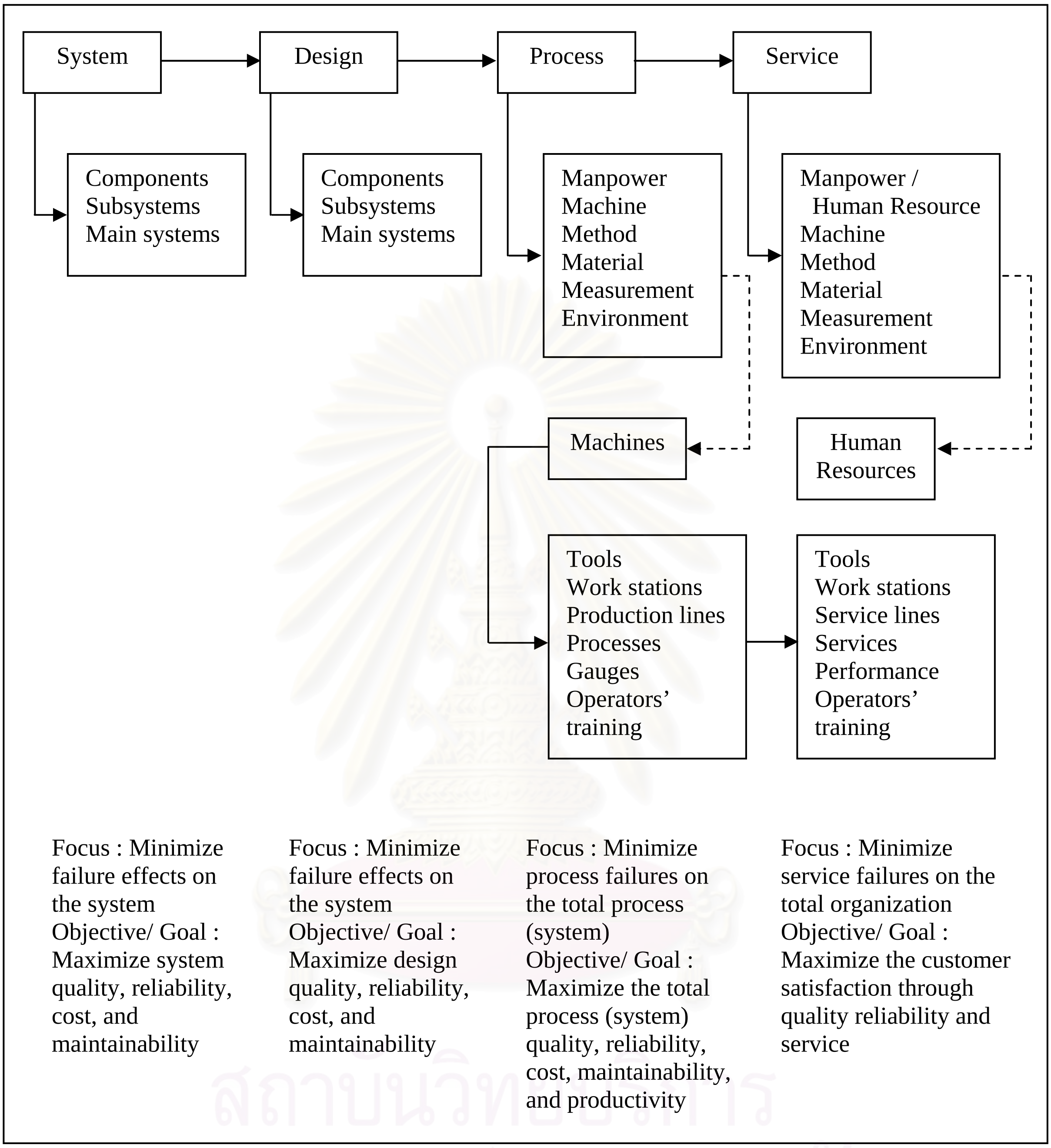


Figure 2.1 : Type of FMEA
[Source : Failure Mode and Effect Analysis, p. 47]

2.2.4 FMEA Implementation

FMEA is a proactive process of continuous improvement that involves team effort. FMEA team essentially requires experienced members from multifunctional areas - design, materials, manufacturing, assembly, packaging, shipping, service, recycling, quality, reliability, vendors, and customers - to brainstorm and identify the potential failures that effect quality of product or process and plan for actions that could eliminate or reduce the chance of occurring. The documentation is generated from conducting FMEA as to control the process. The effective document should be kept updating regularly. The FMEA roadmap is as expressed in figure 2.2.

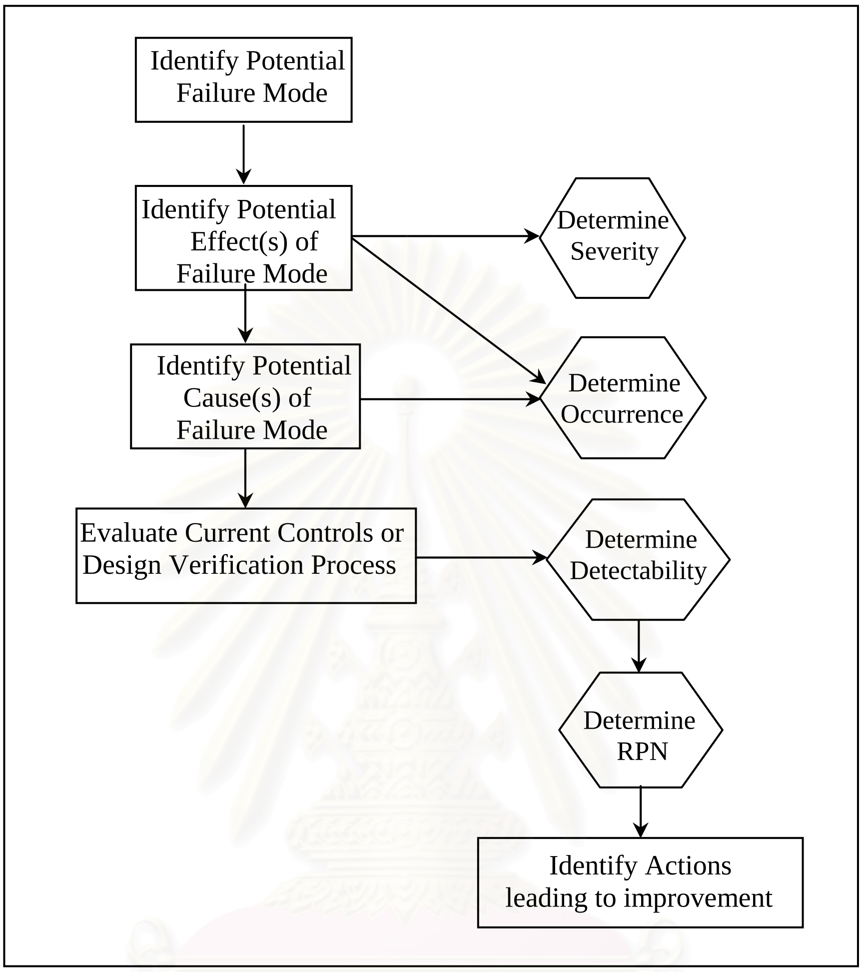


Figure 2.2 FMEA Roadmap
[Source : Total Quality Management, University of Michigan]

The following step-by-step guides to FMEA initiation. *[Source : www.oahhs.org]*

Step 1 Define the FMEA : Describe the process and its boundaries and define individual and team responsibilities.

Step 2 Assemble the FMEA : Assign team leader and ensure adequate team members qualification.

Step 3 Review the Process : A clear and specific description of the process undergoing FMEA must first be articulated and then number process and sub-process steps in column 1 of the FMEA table as shown in appendix B.

Step 4 Brainstorm all potential failure modes associated with the product or process : Define all the possible ways that each process / sub-process step could fail and put them into column 2.

Step 5 List potential effects : The corresponding effect (s) of each potential failure mode in column 2 must be identified and described in column 3. A failure effect is what the customer will experience or perceive once the failure occurs. A customer may either be internal or external, so effects to both must be included. Examples of effects include inoperability or performance degradation of the product or process, injury to the user, damage to equipment, etc.

Step 6 Assess the severity of each of potential effects : The severity is rated to each effect in column 4 upon the seriousness to the customers. The level of severity is as described in table 2-2.

Step 7 Identify the potential cause(s) of each failure mode : At this point provides some insight into probability throughout why-why analysis. The related causes must be identified in column 5 down to each failure mode.

Step 8 Assess the likelihood of each of potential causes occurring : Team will quantify the frequency of occurrence of potential causes – in column 6- based on the statistical data or the participants' experiences. The rating of frequency is as ranked in table 2-3.

Step 9 Identify the control plans contributed to prevention of each of failure cause : Present controls that prevent the causes of each failure mode must be identified in column 7

Step 10 Assess the detectability of each control plan : The detectability must be evaluated in numerical whether the current control plans are effective to prevent the process from each failure mode. The quantification of ability of each control plan must be noted in column 8.

Step 11 Calculate priority risk number : After assigning components of RPN to each potential failure mode, then the RPN of each of them will be determined by multiplying the components -severity, occurrence, and detectability - together and put down the number in column 9.

Step 12 Recommend countermeasures : Team proposes the feasible actions to reduce or eliminate the risk associated with the failure mode. A high RPN needs the immediate attention since it indicates extreme negative effect addressed to its failure mode. The feasible actions included but should not be limited to the following; inspection, testing, monitoring, redesign, re-rating, conduct of preventative maintenance, redundancy, process evaluation, etc. The recommended actions must be described in column 10.

Step 13 Assign responsibility for actions : The person in charge of each task and completion date must be put in column 11.

Step 14 Re-assign RPN : Regarding each recommended action, what tasks to be implemented must be identified in column 12. Determination the new RPN (this is so called the "residual risk") would become after implementation. The new RPN indicates whether the countermeasures are effective in reducing risk. The re-assigned scores of RPN components must be written in column 13, 14, 15 and 16, respectively.

Step 15 Keep FMEA table updated. The FMEA table should be updated regularly or every time the product design or process changes.

2.3 Poka-Yoke Fool Proof Technique

Poka-Yoke was developed by Shigeo Shingo where "*poka*" means an inadvertent mistake and "*yoke*" means prevention. Therefore, Poka-Yoke is a technique to eliminate unaware mistake or discover and correct incorrect action. Poka-Yoke is broadly used in manufacturing. It could be simple or complex method. The effective one is to make possible error impossible. The common techniques are, for instance, applying guide pins to differentiate sizes, alarm/ warning lamp for indicating machine operation status, applying limit switches to level control, installing counters and checklists.

2.4 Design of Experiment

A Design of Experiment (DOE) is a structured, organized method for determining the relationship between variable factors (Xs) affecting a process and the output or response of that process (Y). Statistically based experimental design is a gadget in Engineering works for improving the manufacturing performance, design or product development, etc. In the reality, any experiment is complex with many controllable and uncontrollable variables as shown in figure 2.3. Each variable has at least two levels or so called treatments. Therefore, it is crucial to screen for critical variables that influence to improve the process or response. In the end, the optimized level of those variables will be determined result in the best process performance. Experiment methodology, generally, involves a sequence of activities as following.

1. Conjecture - the original hypothesis that motivates the experiment.
2. Experiment - the test performed to investigate the conjecture.
3. Analysis - the statistical analysis of the data from the experiment.
4. Conclusion - what has been learned about the original conjecture from the experiment. Often the experiment will lead to a revised conjecture, and a new experiment, and so forth.

Conducting an experiment the variables and their treatments are verified and the observed data or so called replicates are collected. Randomization is a technique employed to rearrange the order of runs unfashionably resulting in any nuisance variable or bias that may influence to the response.

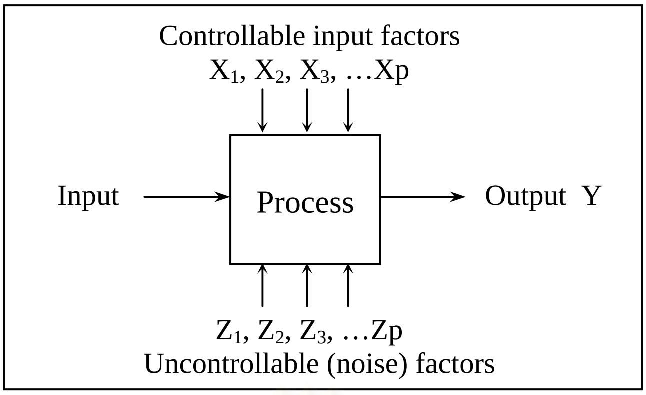


Figure 2.3 General Model of a Process

[Source : Applied Statistics and Probability for Engineers, p.688]

2.4.1 Type of Experimental Design

According to the number of variables, the experiment could be classified into 3 types; Single-Factor, and Factorial experiment.

2.4.1.1 Single-Factor experiment concerns a single factor with at least two levels that effect to the response. The linear statistical model could be expressed as in equation 2-2.

$$Y_{ij} = \mu + \tau_i + \varepsilon_{ij} \qquad \text{(equation 2-2)}$$

where $i = 1,2,3,\ldots a$; $j = 1,2,3,\ldots,n$; Y_{ij} is a random variable denoting the (ij)th observation; μ is a parameter common to all treatments or so called overall mean; τ_i is a parameter associated with the ith treatment or so called ith treatment effect; and ε_{ij} is a random error component.

The hypothesis testing is $\quad H_o : \tau_1 = \tau_2 = \ldots = \tau_a = 0$

$H_1 : \tau_1 \neq 0 \quad$ for at least one i

The sum of squares computing formulas for the analysis of variance with equal sample sizes in each treatment are :

$$SS_T = \sum_{i=1}^{a} \sum_{j=1}^{n} y^2_{ij} - (y^2_{..}/N) \qquad \text{(equation 2-3)}$$

and

$$SS_{Treatments} = \sum_{i=1}^{a} (y^2_{i}/n) - (y^2_{..}/N) \qquad \text{(equation 2-4)}$$

The error sum of squares is obtained by subtraction as

$$SS_E = SS_T - SS_{Treatments} \qquad \text{(equation 2-5)}$$

The ratio of Mean Square for Treatments is

$$MS_{Treatments} = SS_{Treatments} / (a-1) \qquad \text{(equation 2-6)}$$

The Error Mean Square is

$$MS_E = SS_E / a(n-1) \qquad \text{(equation 2-7)}$$

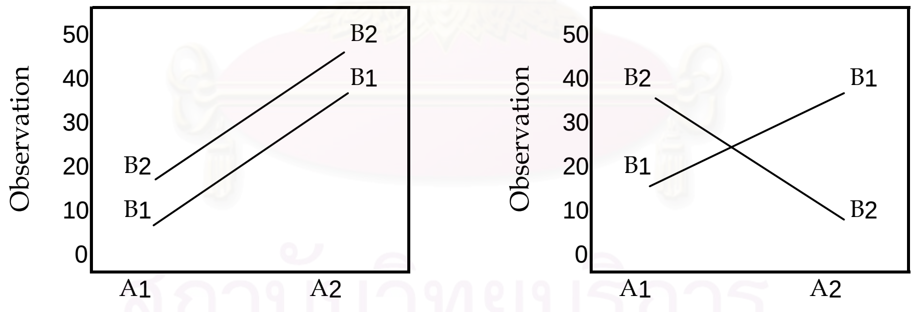
Therefore analysis of variance for a Single-Factor Experiment is as shown in table 2-5.

Table 2-5: Aanalysis of variance for a Single-Factor Experiment, Fixed-Effects model

Source of variation	Sum of Squares	Degree of Freedom	Mean Square	F_o
Treatments	$SS_{Treatments}$	a-1	$MS_{Treatments}$	$MS_{Treatments}$ / MS_E
Error	SS_E	$a(n$-1)	MS_E	
Total	SS_T	an-1		

[Source : Applied Statistics and Probability for Engineers, p.635]

2.4.1.2 Factorial Experiment (2^k) is used when several factors are of interest in an experiment. By definition, each complete trial or replicate of the experiment all possible combinations of the levels of the factors are investigated. The experiment can be conducted in full or fractional factorial depending upon the purpose and the volume of input factors and the level of each variable factor. The simplest factorial experiment is two factors (2^2). Given that each replicate will contain all *ab* treatments combinations if the factors A has *a* levels and factor B has *b* levels as variable inputs of the experiment. The effect of a factor is defined as the change in response produced by a change in the level of factor which is called main effect. In some experiments, the difference in response between the levels of one factor is not the same at all levels of the other factors. This is due to an interaction between the factors. These relation are as expressed in graphical diagram in figure 2.4.



a) no interaction b) with interaction

Figure 2.4 : Graphical Diagram of Factorial Experiment
[Source : Applied Statistics and Probability for Engineers, p.693]

The linear statistical model is as expressed in equation 2-8.

$$Y_{ijk} = \mu + \tau_i + \beta_j + \varepsilon_{ijk} \qquad \text{(equation 2-8)}$$

where i = 1,2,…,a ; j = 1,2,…b ; k = 1,2,…,n ; μ is the overall effect; τ_i is the effect of the ith level of factor A; β_j is the effect of the jth level of factor B; $(\tau\beta)_{ij}$ is the effect of the interaction between A and B; and ε_{ijk} is a random error component having a normal distribution with mean zero and variance σ^2. The graphical expression of levels of two factors is as in figure 2.5.

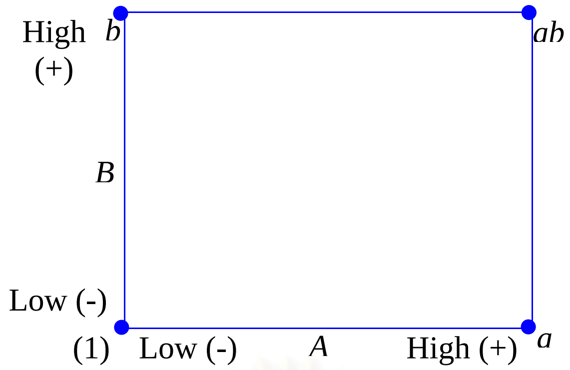


Figure 2.5 : The 2^2 factorial design
[Source :Applied Statistics and Probability for Engineers, p.721]

where

Treatment	A	B
(1)	-	-
a	+	-
b	-	+
ab	+	+

The analysis of variance can be used to test hypothesis about the main effects of A and B and the interaction AB .

1. H_o : $\tau_1 = \tau_2 = \ldots = \tau_a = 0$ (no main effect of factor A)
   H_1 : at least one $\tau_i \neq 0$
2. H_o : $\beta_1 = \beta_2 = \ldots = \beta_b = 0$ (no main effect of factor B)
   H_1 : at least one $\beta_i \neq 0$
3. H_o : $(\tau\beta)_{11} = (\tau\beta)_{12} = \ldots = (\tau\beta)_{ab} = 0$ (no interaction)
   H_1 : at least one $(\tau\beta)_{ij} \neq 0$

The computing formulas for the sum of squares in a two-factor analysis of variance are:

$$SS_T = \sum_{i=1}^{a} \sum_{j=1}^{b} \sum_{k=1}^{n} y^2_{ijk} - (y^2_{..}/abn) \qquad \text{(equation 2-9)}$$

$$SS_A = \sum_{i=1}^{a} (y^2_{i}/bn) - (y^2_{..}/abn) \qquad \text{(equation 2-10)}$$

$$SS_B = \sum_{j=1}^{b} (y^2_{j}/an) - (y^2_{..}/abn) \qquad \text{(equation 2-11)}$$

$$SS_{AB} = \sum_{i=1}^{a} \sum_{j=1}^{b} (y^2_{ij}/n) - (y^2_{..}/abn) - SS_A - SS_B \qquad \text{(equation 2-12)}$$

$$SS_E = SS_T - SS_{AB} - SS_A - SS_B \qquad \text{(equation 2-13)}$$

An analysis of variance for a Two-Factor Factorial is as expressed in table 2-6.

Table 2-6 : Analysis of Variance for a Two-Factor Factorial, Fixed-Effects Model

Source of Variation	Sum of Square	Degree of Freedom (ν)	Mean Square	F_o
A Treatments	SS_A	a-1	$MS_A = SS_A /(a-1)$	MS_A /MS_E
B Treatments	SS_A	b-1	$MS_B = SS_B /(b-1)$	MS_B / MS_E
Interaction	SS_{AB}	$(a-1)(b-1)$	$MS_{AB} = SS_{AB} /(a-1)(b-1)$	MS_{AB}/ MS_E
Error	SS_E	$ab(n-1)$	$MS_E = SS_E / ab(n-1)$	
Total	SS_T	abn-1		

[Source :Applied Statistics and Probability for Engineers, p.702]

$F_{\alpha, \nu 1, \nu 2}$ is obtained from the table of F distribution, where α is level of significance, ν_1, ν_2 are degrees of freedom. The null hypothesis, H_o, will be rejected if F_o of A treatment is greater than $F_{\alpha, a-1, ab(n-1)}$. A conclusion is drawn that factor A has significant effect to the response. The null hypothesis, H_o, will be rejected if F_o of B treatment is greater than $F_{\alpha, b-1, ab(n-1)}$. To draw a conclusion that factor B has significant effect to the response. And the null hypothesis, H_o, will be rejected if F_o of interaction is greater than $F_{\alpha, (a-1)(b-1), ab(n-1)}$. To draw a conclusion that interaction between A and B has significant effect to the response.

2.4.2 Model Adequacy Check

The role of residuals from the experiment is to check whether the model is adequate. Term residuals are the difference between observation and corresponding cell average. The residuals from a two-factor factorial are expressed by equation 2-14.

$$e_{ijk} = y_{ijk} - y_{ij} \qquad \text{(equation 2-14)}$$

The graphical expression of normality assumption is constructed by plotting the residuals versus their cumulative probability points. The residuals are analyzed by the spread of the graph.

2.5 Literature Survey

1. Theerayuth Madjupa suggested six sigma as a tool to reduce defective in printed circuit board manufacturing. The author implemented 5 steps of six sigma; define phase, analyze phase, improve phase and control phase, to define the influencers and suggest solution.

In define phase, the author defined that the Cpk of PCB production line in Jul 2003 was 0.72 leading to loss of money 1.5 million baht because of the copper-in-hole thickness parameters out of customers' specification.

In analyze phase, it was found that there were a number of factors which have significant impact to customers' quality perception. Pareto chart was used as a tool to rank from the highest score to the lowest one. The author selected the first 27 KPIVs in which the score were about 53% of the total. Besides, the author had used statistic tool, anova, to guarantee the precision of measurement system. FMEA was employed to analyze those 27 KPIVs in term of severity, causes and frequency to occur and protection ability. They were rated by RPN (risk priority number) in which calculated by multiplication of severity level to customer's perception, frequency of occurrence, and level of detection. Consequently, the first 7 KPIVs came up with RPN 46% of the total score that were as follows:

- Time consumption in dipping PBC in acid copper plating in pattern plating process
- Current level in acid copper plating in pattern plating process
- Temperature of solvent in acid copper plating in pattern plating process
- Concentration of solvent in electroless copper 85 in electroless plating process
- Temperature of solvent in electroless copper 85 in electroless plating process
- Concentration of H_2SO_4 acid in acid copper plating in pattern plating process
- Time consumption in dipping PCB in electroless copper 85 in electroless plating process.

Those 7 factors were verified by hypothesis testing whether significant affected to the copper-in-hole thickness. The author concluded that there were only 5 factors that had significant affect to the average thickness of copper-in-hole in PCB processing at 95% confidence which were as follows:

- Time consumption in dipping PBC in acid copper plating in pattern plating process
- Current level in acid copper plating in pattern plating process
- Temperature of solvent in acid copper plating in pattern plating process
- Concentration of chloride ion in acid copper plating in pattern plating process
- Concentration of H_2SO_4 acid in acid copper plating in pattern plating process.

In improve phase, the Design of Experiment, 2^k full factorial design and additional of the center point, was implemented through Minitab software. By linear model, it was not able to testify due to an error in the experiment. However, the author changed analysis by quadratic model and concluded that those 5 factors had significant affect to the average thickness of copper-in-hole after plating process. Having done the experiment, the author found that to meet the average thickness of copper-in-hole at 1.50 mils it was necessarily to control those 5 factors as the followings;

- Time consumption in dipping PBC in acid copper plating = 59.65 minute,
- Current level in acid copper plating = 29 A/ft^2 ,
- Temperature of solvent in acid copper = 25^oc,
- Concentration of chloride ion in acid copper plating = 52 ppm, and
- Concentration of H_2SO_4 acid in acid copper plating = 255 g/lt.

Consequently, the Cpk was improved to 1.34.

In control phase, the author had designed check sheet for periodical control those 5 factors in pattern plating process and defined process control flow charts.

2. Settasart Rugmai applied benchmarking technique to compare and analyze performance of the case study iron foundry company with the outstanding ones. The benchmarking fell into 4 steps of implementation.

- Planning : To select the business processes of the case study company that fell in productivity problem and affected to company's competitiveness and establish performance measures for the processes.

- Searching : To seek competitive companies, who were performing better in any particular area than the case study company did, to be benchmarked.

- Observing : To access information, select method and tool for collecting those information which made possible to achieve the performance levels.

- Analyzing : To analyze and conclude the business processes that the company were doing different from the benchmarked companies and finally suggest for solution to improve performance.

The author selected CSF as a performance indicator (PI) concerning customer and employee satisfaction. The CSF in term of customer satisfaction were about quality, cost and delivery. And those of employee satisfaction were morale and safety. After having been collecting data, the author evaluated PI of each process of the case study company. Questionnaires related to production performance assessment were sent to 35 iron foundries. There were only 7 plants sending the questionnaires in return. The author benchmarked the company with those candidates and the result of analysis were as follow.

- The company's best performances had been gone to employee turnover, OEE and %on-time delivery.
- The company's performances in material yield, inventory turnover were lower than those of the 7 candidates but not significant different.
- The company's performances in %claim and defect were considered the worst due to significant difference performance comparing to the others.

Conclusively, the author select %claim category, which was high PI, to benchmark with one of the cooperative candidates and study how to improve the process of the case study company accordingly.

3. J.A. Ghani and et. al. applied the Taguchi optimization methodology to optimize cutting parameters in end milling when machining hardened steel AISI H13 with TiN coated P10 carbide insert tool under semi-finishing and finishing conditions of high speed cutting. The main objective was to find a combination of milling parameters to achieve low cutting force and surface roughness.

The evaluated milling parameters were cutting speed, feed rate and depth of cut. The uncontrollable factors which caused the functional characteristics of a product to deviate from their target values were called noise factors, which could be classified as external factors (e.g. temperatures and human errors), manufacturing imperfections (e.g. unit to unit variation in product parameters) and product deterioration. The most important stage in the design of an experiment lies in the selection of control factors. As many factors as possible should be included, so that it would be possible to identify non-significant variables at the earliest opportunity. Taguchi created a standard orthogonal array to accommodate this requirement. Signal-to-noise (S/N) ratio was used as a measurable value instead of standard deviation due to the fact that as the mean decreased, the standard deviation also decreased and vice versa.

The two techniques, an orthogonal array, S/N ratio and Pareto analysis of variance (ANOVA), were employed to analyze the effect of these milling parameters. Using Taguchi method for design of experiment (DOE), other significant effects such as the interaction among milling parameters were also investigated. The study showed that the Taguchi method was suitable to solve the stated problem with minimum number of trials as compared with a full factorial design.

From the analysis of result in end milling using conceptual S/N ratio approach and Pareto ANOVA, the study could be concluded as followings:

1. Taguchi's robust design method was suitable to analyze the metal cutting problem as described in this paper.
2. Conceptual S/N ratio and Pareto ANOVA approached for data analysis draw similar conclusion.
3. In end milling, use of high cutting speed (355 m/min), low feed rate (0.1 mm per tooth) and low depth of cut (0.5 mm) were recommended to obtain better surface finish for the specific test range.
1. Low feed rate (0.1 mm per tooth) and low depth of cut (0.3 mm) led to smaller value of resultant cutting force the specific test range.
2. Generally, the use of high cutting speed, low feed rate and low depth of cut led to better surface finish and low cutting force.

4. Gunilla W. and et. al. applied DOE technique to compare two different production methods in which eradicated pathogenic microorganisms and to prolong shelf life of the dairy heat treated milk and milk-based products. There were differences of opinion about which process was the most gentle towards milk and milk-based products when the product was heat treated at high temperatures. It was found that the more intense the heat treatment, the more off-flavors became in the milk and milk-based products and the more changes occurred in the milk's nutritional value, e.g., protein denaturation at high temperature. Variable factors comprised the processes (A and B), fat content of the milk and temperature.

The experiments were planned according to DOE as a full factorial design with three factors; fat content of the milk, processes A and B, and temperature, including three centre points for each process. Holding time was kept constant throughout the experiments. The experiments were evaluated using Partial Least Squares/Projection to Latent Structures (PLS) and Multiple Linear Regression (MLR) using the MODDE 6.0 software package.

It was concluded that the two processes for milk tested during these experiments had no significant different to sensory attributes. These process did not influence the off-flavors of milk. It was possible to make an investment decision based on other criteria such as price, maintenance costs, service agreement and so forth. Design of Experiment and sensory analysis were useful tools for investigating the processes prior to the investment and provided a good basis for the decision making process.

5. Anker Nielsen employed FMEA to define failure mode and risks involved in the failure of moisture problems in buildings. Two types of analysis were approached. The first one was the design FMEA where an evaluation was done at the design stage. At this stage possible failures and priorities based on severity and uncover oversight, and errors were identified before the house was built. The second type was the "as build" FMEA where any possible failure modes of finished building were identified. The research referred that around 80% of all investigated building failures was related to water and moisture. 70% of moisture failures were related to water leakage and moisture transport, 20% was condensation and 10% was moisture from building phase.

Using systematic approach, FMEA, the author gained better understanding of building failures, their effects and remediation method. The risk of serious damage from water leakage can be reduced by using the right solution in the constructions. As a result from combination of research and practice, FMEA analysis on buildings was a method for better quality of the building. The solution of keeping moisture-proof constructions were also important for preventing health problems in buildings.

CHAPTER III

Cast Iron Technology

This chapter contains basic cast iron technology, technique and thorough the international cast defect classification.

3.1 Cast Iron Technology

Cast iron is a Fe-C-Si alloy containing minor (<0.1%) and often alloying (>0.1%) elements and is used in the as-cast condition or after heat treatment. The property of cast irons depend on the form of C precipitation and the matrix structure. Since the mechanical properties of cast iron are derived mainly from the matrix, they are described in terms of their matrix structure. The major matrix structures are ferrite, pearlite, ferrite-pearlite, bainite, and austenite.

- Ferrite (Fe-C). It is relatively soft, ductile, of low strength and with poor wear resistance, good fracture toughness, relatively good thermal conductivity, and good machinability.
- Pearlite (Fe_3C). It is relatively hard, moderate toughness, reduced thermal conductivity, and good machinability. The C content of pearlite is variable in cast iron depending on the iron composition and cooling rate.
- Ferrite-pearlite. This mixed structure is used to obtain properties intermediate between the extremes described above.
- Bainite. It is produced, as-cast, in alloyed (Ni and Mo) irons when it is known as acicular iron or by an austemper heat treatment. The advantages of austempered spheroidal irons are;

    1. high tensile strength coupled with toughness, ductility and good fatigue resistance,
    2. good resistance to wear and scuffing which is retained under poor lubrication,
    3. high noise damping capacity giving quiet operation,
    4. good casting characteristics,
    5. near net shape formability even with highly complex shapes,
    6. good machinability as-cast, and
    7. a 10% weight saving against steel.

- Austenite. It requires a high alloy content to retain this phase during cooling. High alloy flake and spheroidal iron have excellent heat, corrosion and non-magnetic properties. This matrix shows good toughness, creep resistance and stress rupture properties up to 800^{o}C and a wide range of thermal expansivity depending on the Si content.

3.2 Type of cast iron

Cast iron is divided into two main groups; firstly, general purpose alloys which are used for majority of engineering application, and secondly, white and alloy cast irons which are used for applications involving extremes of heat, corrosion or abrasion.

3.2.1 General purpose cast irons are classified according to the graphite morphology into flake, malleable, spheroidal and compacted/vermicular types.

3.2.1.1. Grey flake iron: It is named from the characteristic grey colour of the fracture surface and the graphite morphology. It is relatively inexpensive and easy to produce due to wide tolerances and few foundry problems from feeding and shrinkage. It is high machinability, resistant to sliding wear, thermal conductivity, low modulus of elasticity, and able to withstand thermal shock. The weak points are section sensitivity and low strength in heavy section. The properties of flake iron depend on size, amount and distribution of the graphite flakes and the matrix structure. In turn, these also depend on C.E.V. (carbon equivalent value = %C + 1/3%Si + 1/3%P), minor and alloying additions and processing, for instance, melting method, inoculation practice, and cooling rate. Flake morphologies are classified into five classes by ASTM (The American Society for Testing and Materials) specification A247 as shown in figure 3.1.

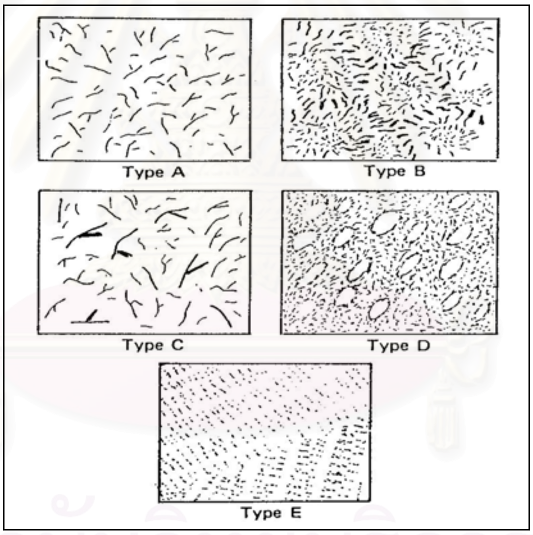


Figure 3.1: Types of flake graphite defined by ASTM A247
A) uniform distribution, random orientation ; B) rosette grouping, random orientation; C) superimposed flake size, random orientation; D) interdendritic, random orientation; E) interdendritic, preferred orientation
[Source:, Cast Iron Technology, 1998]

Type A : It is random distribution of uniform size flakes. A high degree of nucleation promoting eutectic solidification close to the equilibrium graphite eutectic is necessary for the formation of A-type graphite.

Type B : It forms in rosette pattern. A low degree of nucleation enlarges eutectic cell size. Recalescence raises the eutectic growth temperature resulting in a coarse, radially growing flake structure.

Type C : It occurs in hypereutectic irons and forms with coarse primary Kish graphite. It may influence the size of the eutectic cell and distribution of eutectic graphite and also reduce the tensile properties and cause pitting on machined surfaced. However, it will be beneficial subjected to thermal conductivity.

Type D : It forms when solidification occurs at a large under cooling. This structure forms in the presence of Ti and in rapidly cooled irons that contain sufficient Si to ensure a graphitizing potential that is high enough to avoid chill formation at the high cooling rate.

Type E : The graphite forms in strong hypoeutectic irons of low C.E.V. resulting in strong primary austenite dendrite structure before undergoing eutectic solidification.

Flake iron can be influenced by its structure formation and mechanical properties on cooling rate which makes it particularly section sensitive. Cooling rate can be related to section thickness only for simple casting. In complex casting, the following factors can also influence cooling rate.

- Location of sections that may become a heat source (heavy sections) or a heat sink (thin sections);
- Location of section regarding thermal centre of the casting or heavily cored sections;
- Pouring temperature, gating, feeder and runner design, and thermal capacity of the mould.

Either can be graphite or matrix influenced by these factors.

3.2.1.2. Malleable cast iron : Being cast white when its structure consists of metastable carbide in a pearlitic matrix makes malleable cast iron differ from other irons. The final structure of graphite aggregates in a matrix, which can be ferritic or pearlitic depending on the composition and heat treatment, are result of high temperature annealing followed by suitable heat treatment. The traditional malleabilizing processes introduced by Roaumur and Seth Boyden are European Whiteheart and American Blackheart, respectively.

The Whiteheart process is a combination of decarburization and graphitization process performed in an oxidizing atmosphere. The original process was done by packing casting into iron ore mixtures. Recently, it is carried out in continuous gas ovens which operate at higher temperature about 1070^{o}C to be used with shorter annealing times. These two reactions produce C gradient in the casting. The outer layer normally displays a ferritic structure without graphite and the centre temper C clusters in a pearlitic matrix. Small casting may be fully decarburized and are referred to as weldable malleable irons.

The Blackheart process has only graphitization occur in neutral atmosphere annealing. Final uniform structure of temper C clusters in a ferritic matrix is a result of slow cooling after the annealing process. The higher strength pearlitic grades are produced by

1. increasing the Mn content to about 1%,
2. arrested annealing, quenching and tempering, and
3. annealing, reheating and quenching with or without subsequent tempering.

The Blackheart process provides the austenite that exists after the graphitizing process can transform into pearlite, bainite or martensite to give the wide range of properties specified for pearlitic malleable irons.

3.2.1.3. Spheroidal cast iron: It is known as ductile nodular. A typical spheroidal base iron composes of 3.7%C, 2.5%Si, 0.3%Mn, 0.01%S, 0.01%P and 0.04%Mg [13]. The more adaptable and economical spheroidal graphite can be produced varied on content of Mg or Ce. The molten iron must be inoculated simultaneously with or subsequent to the Mg addition. Mg is a deoxidizer and a desulphurizer only modifying the graphite morphology when the concentration of O and S become low. Deoxidizers such as C, Si, and Al present in the liquid iron ensure a low content of O but a desulphurizations process is often necessary to reduce the content of S. Too low level of Si the base iron can decrease the spheroid count by removing potential nuclei for graphite formation while too high the level results in excessive Mg usage and dross formation. Composition effects are influenced by the various steps in the production sequence, for instance, pouring temperature , time and sequence used at each stage, cooling rate and section size. Type of mould, sand or permanent mould, is one of factors to be modified appropriated to the casting. The other two factors should be taken in consideration for large casting. Firstly, it is freedom form carbides in the as-cast state. If fail, it will extremely impact hardness which impair mechanical properties and prohibit machining. The necessitate heat treatment can cause distortion unless performed correctly. The risk of chill carbine formation can be reduced by a high liquid graphitization potential and effective inoculation. A carbide-free structure and good spheroid quality is kept at minimum C.E.V. of at least 4.3. The lower C.E.V, the lesser graphitizing potential. However, if over 4.65, it will lead to spheroid flotation and degeneracy, especially in heavy sections. Secondly, it is the choice of C and Si levels for the chosen C.E.V. regarding the effect of Si on properties. Si can increase the graphitization potential and refine the graphite distribution. On the other hand, it causes ferrite-reducing strength, thus increasing impact transition temperature and decreasing thermal conductivity.

3.2.1.4. Compacted/ vermicular cast iron : It is also referred to as quasi-flake, pseudo nodular, upgraded chunk and semi-ductile. It was originally considered as a degenerate form of spheroidal iron. Recently it has been accepted commercially and used to fill the mechanical and physical properties void between flake and spheroidal iron. A compacted iron has superior tensile strength, stiffness and ductility, fatigue life, impact resistance, and elevated temperature properties compared to a flake iron with a similar matrix structure and better resistance to distortion than spheroidal iron. Because of such physical and mechanical properties make compacted iron suitable for ingot mould.

3.2.2 Special purpose white and alloy cast iron : The greater alloy content (>3%) and inability to be produced by making ladle additions to irons of a standard base composition derive this alloyed iron differ from the others described above. It can be divided into graphite-free and graphite-bearing alloys and noted for its corrosion, elevated temperature, and wear and abrasion resistance properties.

3.3 <u>Introduction to the casting processes</u>

Foundry activity generally composes of mould, core making, melting, cleaning, and control laboratory department. The typical foundry operation is exhibited in figure 3.2.

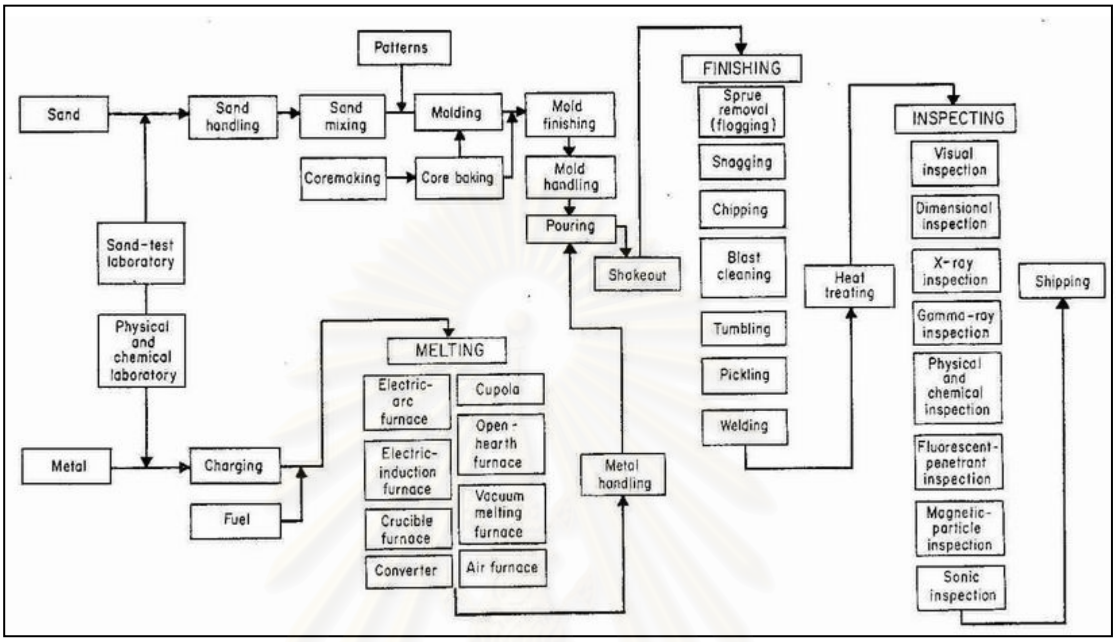


Figure 3.2 : Flow chart of a typical foundry operation.
[Source : Introduction to Foundry Technology]

3.4 <u>Related casting materials</u>

3.4.1 Sand Mould and Core

A sand mould functions as a sand container into which molten metal is poured and allowed to solidify in complex shapes. Sand is used largely due to the fact that it provides several major characteristics that may not be provided with other materials. Green sand mould is broadly used for making small steel castings up to about 100 Kg in weight. Various kinds of green sand are used more extensively than any other type of molding sand. So is it because of the least expensive type to construct, non-baking necessity, cheap, less time-consuming, and ability to lend itself to the use of dry-sand and cores. However, there still are disadvantages in some areas. Firstly, it is not strong enough and damaged easily during handling or by metal erosion. Secondly, moisture that required in preparing green-sand mould may cause certain defects in the casting. Lastly, it does not lend itself to storage for any appreciable length of time.

The major characteristics of sand are as following.

1. *Permeability* : It is a condition of porosity and thus is related to the passage of gaseous materials through the sand. Degree of permeability relates to granular particles of various sizes and shapes, compactness or density of the sand, moisture content, and bond content.

2. *Cohesiveness* : It can be defined as the holding together of sand grains or strength of the mould sand. Bond and moisture content are key factors in strength of sand. Different kinds of bond require variable amount of moisture, could be proportional or inverse proportional, to create optimum strengths. Ramming is a simple method to promote strength in molding sand. The cohesiveness can be measured in many ways, for instant, compression, shear, transverse load, and tension.
3. *Refractoriness* : It relates to ability of silica sand to withstand high heat without breaking down or fusing.

The term core refers to a performed mass of sand positioned in a mould to help shape that part of a casting not readily shaped by the mould proper. Cores are classified by the materials that are formed or by position that they are used. Types of cores are exhibited in figure 3.3.

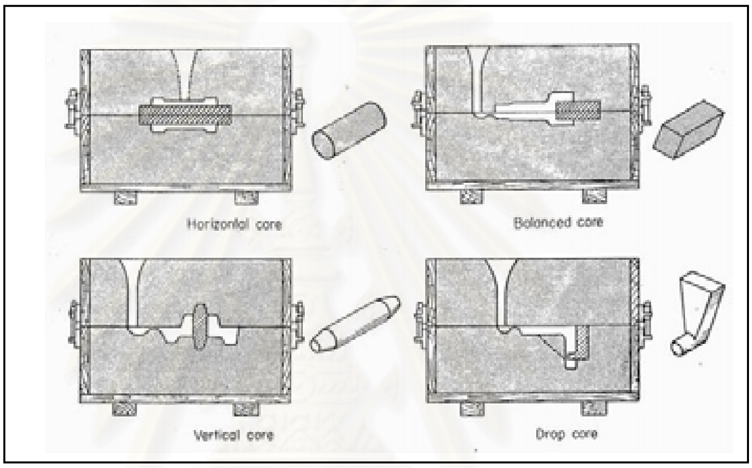


Figure 3.3 : Type of cores and their applications
[Sources : Introduction to Foundry Technology]

<u>Binder</u>

Binder is any materials that added to the sand to imparts cohesiveness. There are a number of types of binders, for example, clay-type, organic-type, inorganic-type, resins and gums, proteins, pitch, and drying oils. In this thesis, only clay-type binder will be focused as being used in the case study company.

Clay is a natural earthy material which becomes plastic when moistened. The major subdivisions of clay family are bentonites, fireclays, and others. In mould sand application bentonites are more commonly used. In normal green sand purposes, a satisfactory unit sand should contain 4 to 6 per cent live bentonite and not exceed 5 per cent dead clay. An addition of 1 per cent bentonite at each cycle is adequate to bond the additional new sand plus core sand and replenish losses without excessive build-up of live and dead clay. The per cent of bentonite can be adjusted properly to a high clay content in high pressure mould process as said 1.5 per cent with 10 per cent of new sand addition.

<u>Sand Additives</u>

It can refer to any material, apart from binder, that is added to the heap sand by purpose of improving some special features and does not promote cohesion. Wood flour, silica flour, and sea coal are all the main ingredients of proprietary additives.

Wood flour is pulverized softwood aiding to improve finish, prevent burning in, cleaning and collapsibility. The amount of wood flour used in mixing with sand is about ½ to one per cent. Silica flour is derived from grinding silica sand to be less than 54 microns. The use of silica flour is for reducing metal penetration, increasing toughness of sand. Silica flour content from five to ten per cent usually mixed with the facing sand. Sea coal is used for surface finish improvement, cleaning of casting aid and burnt-on sand prevention. It composed of a various chemical components. Coal test is made by means of the proximate and ultimate analysis. The proximate analysis aims to determine moisture(M), ash(A), and volatile matter(V) and calculate of the fixed carbon value(FC). The moisture content is evaluated by the weight lost of a sample heated to 105^{o}C. The ash content is verified by the residue after combustion. The volatile matter is the loss in weight of a sample heated in the absence of air for a fixed time under prescribed condition. In effect the volatile content is a measure of the amount of gas, particularly carbon dioxide and hydrocarbon gases, in the coal. The FC is not a chemical entity and determined by equation 3-1.

$$\%FC = 100 - (\%M + \%A + \%V) \qquad \text{(equation 3-1)}$$

The ultimate analysis is to determine the principle elements, carbon, hydrogen, oxygen, nitrogen, and sulphur, in coal in the sense of tracability of most elements in the periodic table as shown in table 3-1 below.

Table 3-1 Ultimate composition (%) of various coals as related to rank.

Coal Type	Raw Moisture	Dry, ash free basis				Rank
		C	H	O	N	
Peat	70	45-60	5-7	20-45	3.0	Low
Brown	30-50	60-75	5-7	15-35	2.0	Medium
Bituminous	2-15	75-90	4-6	3-15	1.5	High
Anthracite	1-5	90	3-4	2-3	1.0	Highest

[Source : The James Durrans Group, Coal Dust in Greensand, UK.]

3.5 Testing of mould materials

Testing is performed randomly from taking three 1-quart samples: one each from the front, middle and rear of the mixed sand heap, at a depth of more than six inches. Aid of testing is mainly to determine moisture content, clay content, fineness, grain-size distribution, permeability, strength of mould sand, and green harness.

3.5.1 Determination of moisture content

Moisture is essential in green sand to plasticise the bonds, bentonite and cereals, and so provide the desired mould properties. The sand mould will be brittle and will not lift from the pattern if the moisture in it is too low. On the other hand, too much water will generate excessive steam evolution which contributes to blowholes and pinholes defect. Moisture content is represented in per cent by weight and is the loss of weight after evaporation of dried sand. In the other hand, moisture content is also determined by mean of a chemical reaction. Moisture content is proportional to measurable amount of acetylene gas which is as a by-product of reaction between sand and powdered calcium carbide. However, there are some sand-testing equipment that can read the moisture content on the scale by utilizing the electrical conductivity to the moist sand.

3.5.2 Determination of clay content

Clay content can be represented by the loss of weight after washing of previously dried sand. The previously dried sand is weighted and treated with a standard sodium hydroxide solution under controlled conditions. After completely washing, residue is dried and reweighed. The clay substance is a measurement of the lost weight by mean of per cent by weight.

3.5.3 Determination of fineness and grain-size distribution

The residue from the clay test is used to determine fineness and grain-size distribution. Fineness is expressed by per cent of different sizes of sand, silt, and clay. The range of sand-grain particles are from 53 to 3,360 microns. Pan-size particles (silt) range from 20 to 53 microns and the rests, less than 20 microns, are clay particles. These residue sand is put in a stack of sieves in a shaker device which provide a continuum of decreasing mesh sizes from top to bottom. The mesh numbers are ranging from 6, 12, 20, 30, 40, 50, 70, 100, 140, 200, and 270. Smaller than 270 particles will pass the mesh and be caught in a pan at the bottom of the stack. Per cent of material retained on each sieve is taken into account.

3.5.4 Determination of permeability

The volume of air in cubic centimeters that will pass per minute under a pressure of one gram per square centimeter through specimen of sand one square centimeter in cross-sectional area and one centimeter in height expresses permeability of the sand. The permeability is classified, upon how the measurement is conducted to, into four categories.

1. Base permeability is measured with a specimen of packed dry sharp sand.
2. Green permeability is measured with a specimen made of moist mould sand.
3. Dry permeability is measured with a specimen made of mould sand and dried at 220^{o}F to 230^{o}F.
4. Baked permeability is measured with a specimen made of sand with thermosetting binders and baked at some temperature above 230^{o}F.

The tested specimen is usually in a 2-by-2 inch tube. An amount of air is forced through the specimen that placed in the instrument cup which provides a mercury seal under controlled conditions. Time of flow rate of the air is measured to calculate a permeability number. The mathematical relationship of the variables can be expressed as in equation 3-2.

$$P = \frac{vh}{pat} \qquad \text{(equation 3-2)}$$

where P represents permeability number

v represents volume of air passing through test specimen (in unit cubic centimeter)

h represents height of specimen (in unit centimeters)
p represents pressure of air (in unit grams per square centimeter)
a represents cross sectional area of specimen (in unit square centimeters)
t represents time that taken for air to pass the specimen (in unit minutes)

3.5.5 Determination of strength of mould sand

Strength of mould sand can be measured in various methods under controlled conditions.

1. Compression strength is amount of uniformly increasing force that applied to break the 2-by-2 inch sand specimen. The unit of measurement is pounds per square inch.
2. Shear strength is measured by applying shearing load that to break the 2-by-2 inch sand specimen.
3. Tensile strength is measured by applying tension forces that to break the baked- sand or “dog-bone” specimen.
4. Transverse strength is measured by applying bending load that to break the baked-sand specimen.

Green sand is evaluated by means of compression and shear strengths.

3.6 Pattern

Pattern is used to pack the mould material to create mould cavity.

3.6.1 Pattern Classification

1. Classified by utilization. This group of patterns are loose, gated, and match plate patterns as shown in figure 3.4. Loose pattern is complete in itself and not dependent on any rigging or mounting. It may be single, split or loose-piece in construction. Gated pattern is added detail designed to form the gate and runner. Match-plate pattern is a pattern which has been fastened to a plate and equipped to fit a given flask size and type. There still are other miscellaneous pattern types used for special job, such as, sweep pattern, skeleton pattern.

2. Classified by material. Patterns can be made of wood, aluminum, steel or plastic dependent upon production criteria.

3.6.2 Pattern allowances and factors

It is necessary to add some allowance to compensate for metal contraction that occurs during cooling after solidification. The amount of contraction varies upon the composition of the metallic alloy and proportionally to the drop of temperature while the alloy is in molten state. For instance, Gray iron commonly contracts 1/8 inch per foot of dimension whilst steel ¼ inch per foot. Distortion allowance is set to compensate for possible distortion while casting. Shake allowance is for enlargement compensation of the casting cavity due to the excessive rapping.

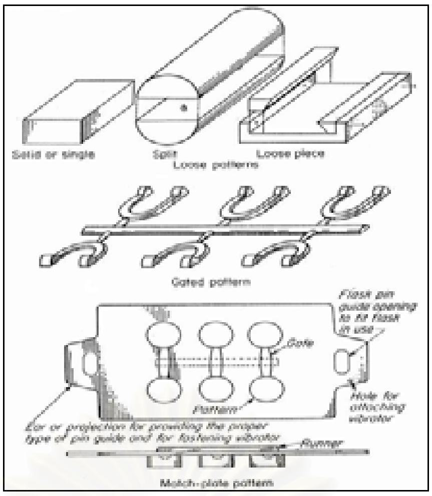


Figure 3.4 : Type of Patterns

3.7 Induction Furnace

There are various types of furnaces used in metal melting process, for example, cupola furnace, open-heart furnace, air furnace, electric-arc furnace, induction furnace, and crucible furnace. Only is the induction furnace focused in this chapter as being used in the case study. The component of induction furnace is as exhibited in figure 3.5. The induction furnace is suitable to small quantity of special alloys of any type with a minimum of contamination. Its capacity ranges from 10 to 1,000 pounds of steel per batch. The advantages of induction furnace are as followings.

- Easy to control chemical ingredients and temperature
- Less loss of molten metal
- Low quality of molten steel allowable
- Not a few operators require
- Easy to operate

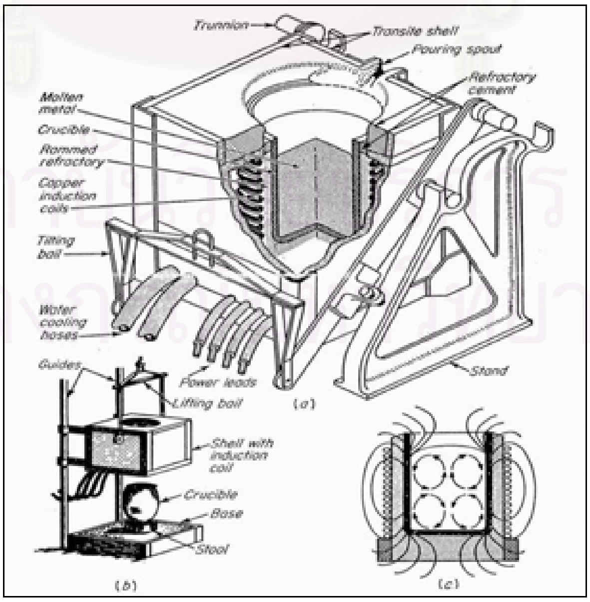


Figure 3.5 : Induction Furnace

a) Tiling furnace; b) lift coil furnace; c) lines of magnetic force and stirring action on the molten-metal bath.

3.8 The Influence of Alloying Elements and Nonferrous Alloys

I. Common alloying elements in ferrous alloys.

a) Carbon as symbolic "C". It broadly effects on the physical properties of ferrous alloys. It can be in the form of graphite or cementite which are free carbon and combined carbon, respectively. The amount of carbon, form of carbon and size, and distribution of particles have influence to the structure of cast iron. Carbon has a direct bearing on the fluidity of cast iron as softening the iron and aiding machinability. The presence of carbon also reduces shrinkage in casting.

b) Silicon as symbolic "Si". Silicon is a main element in the metallurgy of gray iron because it is to promote the formation of graphite. The concentration of silicon is at least three per cent that drives the basic action. Silicon will promote corrosion-resistant, hard, unmachinable irons when the amount over three per cent, particularly ranging between 13 to 17 per cent.

c) Manganese as symbolic "Mn". Manganese usually exists in cast iron 0.5 to 0.75 per cent. It is a deoxidizing and purifying agent which promotes fluidity and strength.

d) Phosphorous as symbolic "P". Phosphorous commonly exists in cast iron 0.1 to 1 per cent. It promotes castability at any given temperature.

e) Sulfur as symbolic "S". Sulfur should not be amounted above 0.1 per cent in cast iron since it decreases fluidity and strength of cast iron.

f) Magnesium as symbolic "Mg". Magnesium is used as an inoculant to form spheroidal graphite in ductile cast iron in controlled amount 0.03 to 0.2 per cent.

g) Nickel as symbolic "Ni". Ni is an important element obtained in cast iron and steel. In cast iron, Nickel is a graphitizer and does not form carbine. It is used in small amount ranging 0.1 to 1 per cent to refine the grain and size of graphite flake. In steel, Nickel enhances strength and hardness when used in higher percentages.

h) Chromium as symbolic "Cr". The small amount of chromium promotes strength, hardness, depth of chill, and thermal and wear resistance of the alloy. It is normally used in cast iron ranging from 0.2 to 2 per cent. Chromium is a carbide-forming element which impacts machinability and ductility.

i) Copper as symbolic "Cu". Copper is used in ranges from 0.25 to 2.5 per cent. It increases formability of graphite and strengthens cast iron. An iron may be hardened or softened depending upon the basic structure of the copper alloy.

j) Molybdenum as symbolic "Mo". Amount of molybdenum used in cast iron is between 0.25 to 1.25 per cent. With relation to its carbide-stabilizing tendencies, molybdenum enhances strength and depth of chill.

k) Titanium as symbolic "Ti". Titanium is seldom used in cast iron in ranges 0.5 to 1.5 per cent. Under interaction with other alloying elements, titanium enhances fluidity and strength characteristics.

l) Vanadium as symbolic “V”. Vanadium is a powerful carbide former as small used as 0.1 to 0.5 per cent to increase tensile, transverse strengths and hardness.

m) Tungsten as symbolic “W”. Tungsten is a rare metallic used in cast iron works. In amount between 0.5 to 20 per cent, it enhances hardness and strength at high temperature.

II. Common Nonferrous Alloys

The base or major metallic elements presented in the alloy are factors of nonferrous alloys classification. Those elements are, for example, aluminum, copper, magnesium, zinc, lead, tin, and nickel.

a) Alloys of aluminum. They are generally light in weight , possess good thermal and electrical conductivity. The primary alloying elements used with aluminum are copper, silicon, magnesium, zinc, manganese, and chromium. Tensile strengths in aluminum alloys may range from 19,000 to 42,000 psi. and elongation from 1.8 to 9 per cent upon the alloy and heat treatment.

b) Alloys of copper. There are various copper alloys that are generally dense metallic alloys with good corrosion resistance, high electrical conductivity. The principal alloying elements used with copper are zinc, tin, aluminum, silicon, and manganese. Tensile strengths in copper alloys may range from 20,000 to 40,000 psi. and elongation from 10 to 35 per cent.

c) Alloys of manganese. Manganese is the lightest of the structural metals, and its alloys have moderate-to-good strength properties and excellent machinability. The main secondary elements in manganese alloys as silicon, copper, aluminum, and zinc. Aluminum and zinc will increase hardness and also as same as silicon which decrease ductility.

d) Alloys of zinc. Zinc can be alloyed with aluminum, copper, or magnesium. Copper increases strength but reduces ductility of zinc alloys. Aluminum increases strength but reduces tendency of the alloy to attack iron in the dies.

e) Alloys of lead. Lead is a dense, heavy metal with relatively low strength and poor impact resistance. Antimony and tin are secondary element alloys with lead that promote hardness alloys of lead.

f) Alloys of tin. Tin, when alloyed with antimony and copper, will produce the true babbitts for bearing application. Copper and antimony help promote hardness.

g) Alloys of nickel. Nickel has properties as high corrosion resistance to water solutions, mineral and organic acids, alkalis, good mechanical strength, wear resistance, etc. Nickel can be alloyed with copper, molybdenum, and chromium. Silicon may also be alloyed with nickel to increase fluidity and hardness; manganese increases toughness; sulfur and phosphorus embrittle nickel alloys.

3.9 Cleaning of Casting

After solidity the molten metal to become, some particles adhered on the surface and other protuberances not part of the casting are removed. Cleaning can be classified into four levels as follows.

1. Rough cleaning is to apply mechanic forces to the casting to remove gates and risers. It could be done by flogging with hammer, mechanic cut-off machines, burning or torch cutting, and powder cutting.
2. Surface cleaning is applied to remove sand, scale or other adhering material on the casting surface. There are several methods of surface cleaning, such as tumbling with abrasives; sand, grit, tumbling with a caustic water solution, blasting with stream of sand or grit, wire brushing, etc.
3. Trimming is a method to remove fins, gate pads, chaplets, flash, and other exceeding parts. Trimming can be done by grinding or chipping.
4. Finishing is the final stage of cleaning including chemical treatment, machining, painting, etc.

3.10 Inspection

There are several methods of inspection which are generally divided as destructive and nondestructive method. Destructive method necessitates to destroy sample casting for mechanical properties testing, such as tensile strength, per cent of elongation. Nondestructive method performed without destroying the sample, such as visual check, dimensional inspection, X-ray and gamma-techniques, magnetic-particle inspection, fluorescent penetrant, and supersonic inspection.

3.11 Casting Defects

According to the International Committee of Foundry Technical Associations (ICFTA), the casting defects classification has been identified by letters in seven categories as following.

A - Metallic Projections
B - Cavities
C - Discontinuities
D - Defective Surface
E - Incomplete Casting
F - Incorrect Dimensions or Shape
G - Inclusions or Structure Anomalies

Each category is divided into groups and sub-groups subjected to numerals. Three numerals are assigned to specify each particular defect following a letter. The third numeral identifies the defect within each subgroup. Detail of the casting defect classification is defined in appendix A.

CHAPTER IV

Methodology

As stated in chapter one how the problem defined, this chapter is about methodology to study the present iron casting processes of the case study company and to identify the potential causes of blowholes or pinholes, which are significantly to the production performance and quality cost by the analysis tools; Brainstorming, Cause and Effect diagram, Why-Why analysis, and FMEA. Screening the prioritized high RPN factors will be conducted through the OFAT experiment technique. The experiment observation description is obtained in the last section.

4.1 Process Boundary Definition

In this thesis, the process boundary, as shown in figure 4.1, is the automatic line cast iron for an automotive part, Fly Wheel ZE1. The process starts from incoming material and ends at the finished goods delivery.

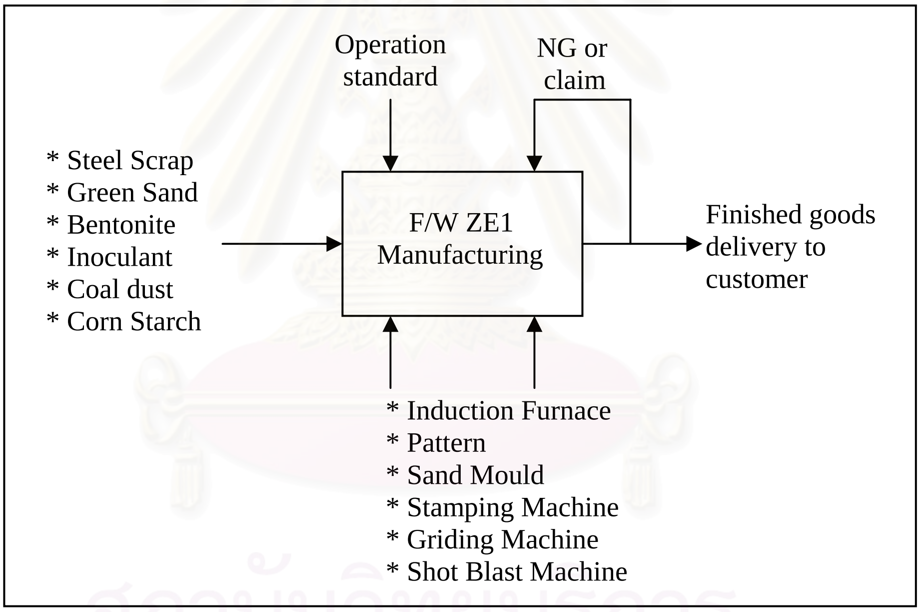


Figure 4.1 : Process Boundary of iron cast F/W ZE1

4.2 Team Set Up

The team is formed by gathering members from multifunctional sections. There are six participants, including the author, selected from Engineering, Manufacturing, Process Engineering, and QC and two consultants. Here below is detail of the participants.

1. Team Chief — The author
2. Special Consultant — Specialist from James Durrans, UK.

3. Team Consultant	Plant Manager – Bachelor and Master degree in Industrial Engineer, working experience 9 years.
4. Team Co-ordinator	Assistant Manager – Bachelor degree in Power Control Engineering, working on Master degree in Engineering Business Management, working experience 3 years.
5. Product Engineer	Bachelor in Chemical Engineering – working experience 5 years.
6. Process Engineer	Undergraduate in Chemical Science – working experience 3 years.
7. Manufacturing	Working experience 8 years.
8. Quality Control	Undergraduate in Chemical Science – working experience 5 years.

Working as a team the common goal is as a hinge that drives the team step forward in the same direction. After grouping up and considering for the participant's qualification, the objective and goal are contributed to the team members.

4.3 <u>Benchmarking</u>

In this thesis the first tier supplier in the business chain as shown in figure 1.1 was referred to for benchmarking as a stable high yield production of the product F/W ZE1. Benchmarking will be conducted in manufacturing aspects as well as criteria on the B111 defect of the product F/W ZE1.

Table 4-1 : Manufacturing process benchmarking on F/W ZE1 between the first tier and the case study company.

Manufacturing Processes F/W ZE1	Benchmarked Items	The first tier	The case study company
Incoming Materials	Steel scrap	Fe	Fe
	Green sand	*	*
	Inoculant	*	*
	Coal dust	Brand "B"	Brand "A"
	Bentonite	*	*
	Corn starch	Absent	Present

(continued)

Manufacturing Processes F/W ZE1	Benchmarked Items	The first tier	The case study company
Furnace Control	Furnace capacity	2 tons	1 ton
	Furnace type	Induction	Induction
	Range of melting temp	1,510°C~1,530°C	1,510°C~1,530°C
	Chemical addition	Ref Spec ES-W24114	Ref Spec ES-W24114
Design	Pattern	*	*
	Core quantity	0	0
Sand Inspection	Inspection equipment	Brand "E"	Brand "F"
	Permeability	100 ~ 140	80 ~ 120
	Compactabiltiy	20% ~ 35%	15% ~ 25%
	Temp. of moulding sand	35°C ~ 40°C	35°C ~ 40°C
	Moist. of moulding sand	2.8 % ~ 3.5%	3.0% ~ 4.2%
Sand Milling	Milling machine	Brand "G"	Brand "H"
	Milling time	10 min	12 min
	New sand addition	1% per batch	1% per batch
	Bentonite addition	1% per batch	1% per batch
	Inoculant : Sand	3 kg / 250 kg	3 kg / 250 kg
	Coal dust : bentonite	1 kg : 4 kg	1 kg : 4 kg
	Corn starch : Sand	No	0.2% per batch
Moulding	Moulding machine	Model "I"	Model "J"
	Pressure setting	100 ~ 110 Kg/cm^2	90 ~ 100 Kg/cm^2
Casting	Temp. of pouring	1380°C ~ 1430°C	1380°C ~ 1430°C
	Height of pouring	10 cm	10 cm
	Fading time per ladle	≤ 12 min	≤ 12 min
	Pouring time/ mould	5.5 ~ 7.5 sec	5.5 ~ 7.5 sec
	Mould per ladle	≤ 30	≤ 30
	Taping Weight	600 ± 20 Kg	600 ± 20 Kg
Gate Off Shot Blast	Gate off equipment	hammer	hammer
	Quantity / minute	15 pcs	18 pcs.
	Steel shot diameter	0.85 ~ 2.00 mm.	0.85 ~ 2.00 mm.
	Shot blast machine	Model "K"	Model "L"

(continued)

Manufacturing Processes F/W ZE1	**Benchmarked Items**	**The first tier**	**The case study company**
Blowholes or pinholes criteria	Good	free from blowholes / pinholes on casting surface after machining	
	Minor defect	max. dia.1mm and < 5 blowholes/ pinholes around casting surface	
	Major defect	bigger than dia. 1mm or >5 blowholes/ pinholes around casting surface	
Performance	Yield (avg Oct - Dec, 04)	98.20%	86%

*** : same material**

The major process control is standardized by the first tier company throughout the operation standard. After benchmarking, it is found that the obvious different level of control in the casting process between two companies are brand of coal dust and present of corn starch. The basic coal dust quality is per cent of ash contained in it. Regarding the sand certificate, coal dust A contain 6% of ash while B only 3%. The coal dust B is medium 145 grade. Detail of coal dust grading is as referred in table 4-2.

Table 4-2 : Coal dust grading available from a UK supplier

Size μm	% retained						
	Coarse 75	Medium 100	Medium 145	Super fine 190	Super fine 210	Super fine 250	Super fine 300
+1000	-	-	-	-	-	-	-
+500	10	10	3	1	1	-	-
+210	40	30	17	6	4	2	-
+150	15	12	12	8	7	3	1
+75	25	23	23	25	20	15	9
-75	10	25	45	60	68	80	90

[Source : James Durrans & Sons Ltd, UK, A. Moore]

The other factors are about permeability, compactability, temperature and moisture content of mould sand which depend on the level of inputs. The difference in machine brands and models are considered as less effect to the production performance.

4.4 Problem analysis

The team brainstorms the possible factors that impact the blowholes or pinholes defective on the F/W ZE1. There are various ideas come up which based on either iron cast theoretical or practical experiences. Every idea is short noted in the paper and classified into the 4Ms and 1E categories of fishbone diagram – man, material, method, machine, and environment as exhibited in figure 4.2. These factors, process inputs, are obtained in Cause and Effect matrix as shown in table 4-3. The arrangement bases on the process they are in. The team assigns the weight to them in accordance with the significance to customer in following fashion.

- Highest score 4 to the most significant factor;
- Score 3 to significant factor;
- Score 2 to partly affected factor;
- Score 1 to rare factor;
- and score 0 to unrelated factor.

Since the blowholes or pinholes defective is unacceptable in customer's perspective, therefore, its criticalness weighted 10. The process inputs that expected to affect the blowholes or pinholes (B111) defect in cast iron are totally 43 items. By weighting regarding the significance to customer there are 36 factors that relate to the B111 defect and the rests are considered as unrelated. Using Pareto diagram to present these factors, they are arranged from the most significance to customer to unrelated factors as shown in figure 4.3. Ascending order according to the total weights of those factors is in table 4-4. According to Pareto principle 20 : 80, the main problems that affect to quality issue in production come from vital few causes or 20% only whilst the minor problems from trivial many causes or 80%. The vital few causes will be taken into account. The 20% of those 36 factors are the first 8 items. By the way, the next 10 factors, which weighted 40 as same as those first 8 items, will be obtained to further study FMEA. The selected process inputs are conclusively 18 factors in which their weight summation are majority, 720, of the total weight, 1140. With the weighting accounted for 63.2%, the selected factors will sufficiently cover the main causes of the B111 defect. They are listed out below.

1. % Al in steel scrap
2. % N in steel scrap
3. % Mn in steel scrap
4. % Mg in steel scrap
5. % S in steel scrap
6. % Al in inoculant
7. % S in coal dust
8. Rust substance
9. Purity of new green sand
10. Furnace temperature
11. Gating system
12. Coarse and magnetic material separation
13. Ash content in mould sand
14. Corn starch addition
15. Temperature of mould sand
16. Moisture in mould sand
17. Pouring temperature
18. Height of pouring

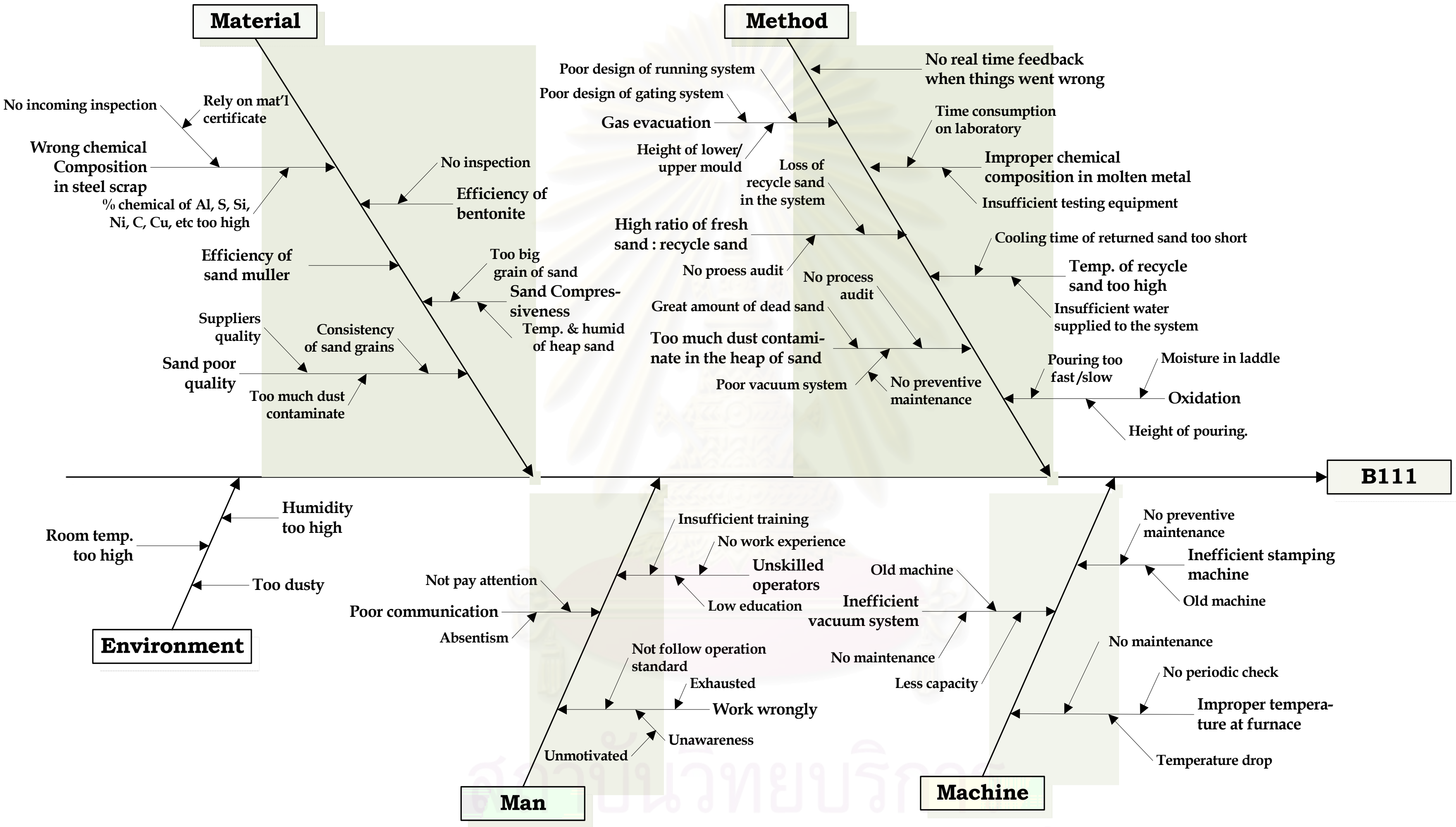


Figure 4.2 Fish Bone Diagram : Cause and Effect to B111 defect in cast iron

Table 4-3 : Cause and Effect Matrix to B111 defect in cast iron

Cause & Effect Matrix

F/W ZE1 Manufacturing: Factors relate to blowholes, pinholes defect(B111 | Importance to customer = 10

Items	Process	Subprocess	Related Factors	Weight	Total Weight
1	Incoming		% Al in steel scrap	4	40
2			% N in steel scrap	4	40
3			% Mn in steel scrap	4	40
4			% Mg in steel scrap	4	40
5			% S in steel scrap	4	40
6			% Al in inoculant	4	40
7			% S in coal dust	4	40
8			% Si in green sand	3	30
9			% Si in inoculant	3	30
10			Rusty substance on steel scrap	4	40
11			Purity of new green sand	4	40
12	Furnace	Chemical addition	% C in molten metal	3	30
13			% P in molten metal	1	10
14			% Cu in molten metal	0	0
15			% Sn in molten metal	0	0
16			% Cr in molten metal	0	0
17			% Ni in molten metal	3	30
18		Set up	Furnace temperature	4	40
19	Design	Pattern design	Running system	3	30
20			Gating system	4	40
21			Height of upper mould	0	0
22			Height of lower mould	0	0
23	Manufacturing	Sand mixing	Temperature of returned sand	3	30
24			Coarse and magnetic material separatio	4	40
25			Ash content in moulding sand	4	40
26			Corn starch addition	4	40
27		Sand milling	Milling time	3	30
28			Efficiency of milling machine	3	30
29		Moulding	Green hardness of sand mould	2	20
30			Pressure at stamping machine	1	10
31			Temperature of moulding sand	4	40
32			Moisture content in moulding sand	4	40
33			Dust contaminated in moulding surface	3	30

(continued)

Cause & Effect Matrix

F/W ZE1 Manufacturing : Factors relate to blowholes, pinholes defect(B111) | Importance to customer = 10

Items	Process	Subprocess	Related Factors	Weight	Total Weight
34	Manufacturing	Moulding	Time of stamping	0	0
35			Efficiency of stamping machine	1	10
36		Pouring	Pouring temperature	4	40
37			Environment temperature	1	10
38			Environment humidity	1	10
39			Height of pouring	4	40
40			Pouring time	3	30
41			Fading time / ladle	3	30
42			Strainer size	0	0
43			Temp. of ladle before carry the molten metal	2	20
			total	114	1140

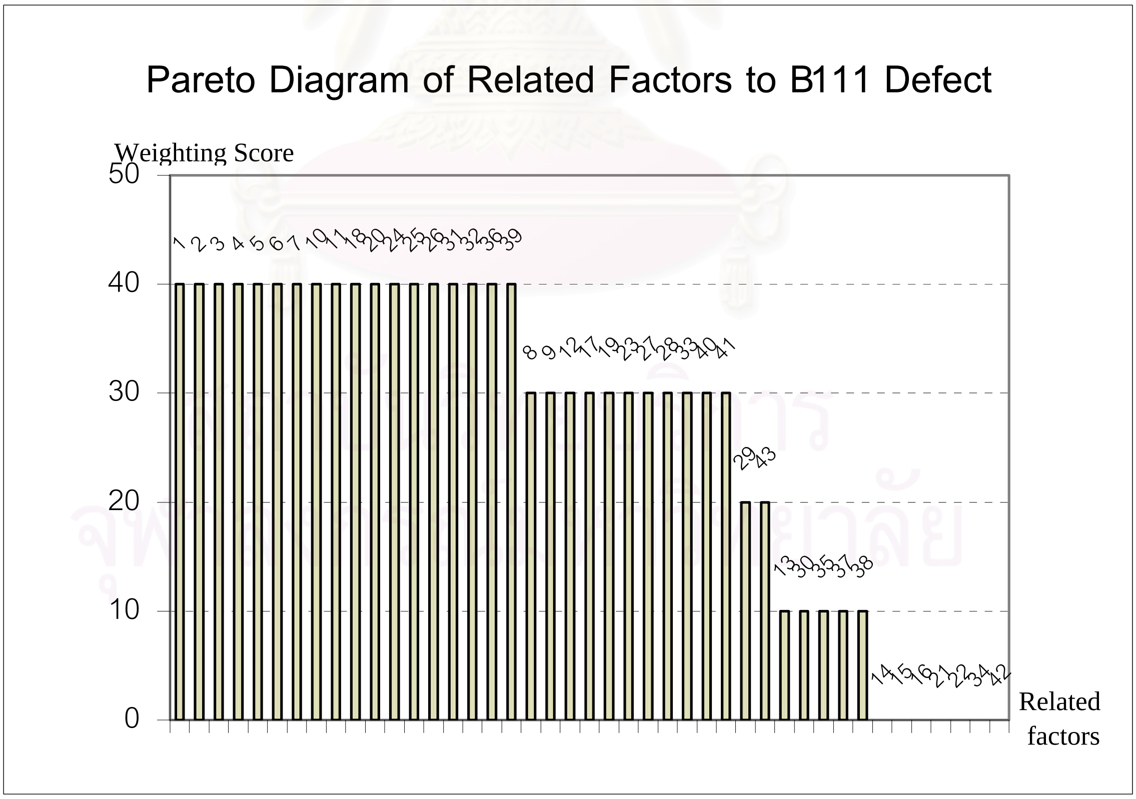


Figure 4.3 Pareto diagram of related factors to B111 defect

Table 4-4 : Ascendant factors affected to B111 defect in cast iron

No.	Items	Related Factors	Weighting	Total Weight
1	1	% Al in steel scrap	4	40
2	2	% N in steel scrap	4	40
3	3	% Mn in steel scrap	4	40
4	4	% Mg in steel scrap	4	40
5	5	% S in steel scrap	4	40
6	6	% Al in inoculant	4	40
7	7	% S in coal dust	4	40
8	10	Rusty substance on steel scrap	4	40
9	11	Purity of new green sand	4	40
10	18	Furnace temperature	4	40
11	20	Gating system	4	40
12	24	Coarse and magnetic material separation	4	40
13	25	Ash content in mould sand	4	40
14	26	Corn starch addition	4	40
15	31	Temperature of mould sand	4	40
16	32	Moisture content in mould sand	4	40
17	36	Pouring temperature	4	40
18	39	Height of pouring	4	40
19	8	% Si in green sand	3	30
20	9	% Si in inoculant	3	30
21	12	% C in molten metal	3	30
22	17	% Ni in molten metal	3	30
23	19	Running system	3	30
24	23	Temperature of returned sand	3	30
25	27	Milling time	3	30
26	28	Efficiency of milling machine	3	30
27	33	Dust contaminated in mould surface	3	30
28	40	Pouring time	3	30
29	41	Fading time / ladle	3	30
30	29	Green hardness of sand mould	2	20
31	43	Temp. of ladle before carry the molten metal	2	20
32	13	% P in molten metal	1	10
33	30	Pressure at stamping machine	1	10
34	35	Efficiency of stamping machine	1	10
35	37	Environment temperature	1	10
36	38	Environment humidity	1	10
37	14	% Cu in molten metal	0	0
38	15	% Sn in molten metal	0	0
39	16	% Cr in molten metal	0	0
40	21	Height of upper mould	0	0
41	22	Height of lower mould	0	0
42	34	Time of stamping	0	0
43	42	Strainer size	0	0

Using why-why analysis technique helps approach the root causes of blowholes or pinholes (B111) defect by classifying the possible causes and asking why the problems occur according to the findings from Cause and Effect matrix and so on until the root causes are found. The main causes and their roots of the defect classified as following.

- Inadequate provision of gas and air.
  - The second thermometer located 50 cm away from the spray fuzzer where the distance may be too near to capture the cooling temperature of the sand after being wetted.
  - Addition of new sand sometimes less than 1%.
- Gas generation by chemical reaction.
  - Operator lift up the ladle higher than 10 cm at the last few moulds due to less than ¼ of melt left in the ladle and limited area to move the ladle backward instead.
  - Operator draws up the melt when furnace temperature less than 1,500^{o}C.
  - Change inoculant supplier in order to reduce cost.
  - Poor quality of coal dust "A".
- Hot sand stick to pattern.
  - Waste of sand due to poor knockout condition, thus the sand in the system reduces. And that shortens the cooling time of the recycle sand.
- Poor sand distribution.
  - The O-ring deteriorates which may cause a big gap that a cake of sand can pass through without milled.
- Dirty sand
  - There is only one workstation for fractional metal separation which may be insufficient.

Hot sand tick to pattern can either defect the sand inclusion as illustrated in figure 4.4.

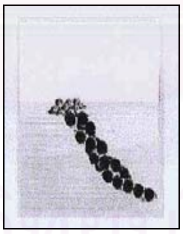


Figure 4.4 Sand inclusion defect

In table 4-5, the root causes of the above causes are defined based on the case production. According to the findings, immediate actions for improvement could be taken place as scheduled in table 4-6.

- Relocate the second thermometer from 50 cm to 100 cm away from the spray fuzzer in order to get the actual temperature of cooling sand.
- Set an accurate control over the ratio of new sand addition and make a record.
- Set the preventive maintenance to the milling and stamping machine.
- Increase capacity of coarse and magnetic material filter from the returned sand by adding another workstation as the second filter.
- Install tower light to alarm when furnace temperature reaches the set point.

Table 4-5 Why-Why analysis of B111 defect in cast iron.

Problem	Why 1	Why 2	Why 3	Why 4	Why 5	Why 6
Blowholes or pinholes	Inadequate provision for evacuation of air and gas	Inproper Pattern Design	Running system // OK			
			Gating system // OK			
		Sand permeability low (<80)	Moisture content of mould sand too high (>3.5%)	Too much water sprayed to the returned sand in cooling system	Temp. of returned sand higher than 40^{o}C	The second thermometer located 50 cm away from the spray fruzzer where considered as too near and may cause error reading from the actual temp of the sand after cooling
				Too much water required in milling process	Addition of corn starch which is a well water absorbent substance.	
					Excess of dead clay or dust that contaminated in the returned sand will absorb water much more than active sand	Addition of new sand less than 1%
			High content of ash	Poor quality coal dust "A"		

Remark : OK means that the identified causes are controllable.

(continued)

Problem	Why 1	Why 2	Why 3	Why 4	Why 5	Why 6
Blowholes or pinholes	Gas generation by chemical reaction	Introduction of hydrogen from chemical reaction	Introduction of oxygen in the air to the molten metal	The higher pouring distance, oxygen introduced to the molten metal	Operator lifts up the ladle higher than 10cm at the last few moulds	Little molten metal left in the ladle
						Limited area to move the ladle backward
		Pouring temperature drops <1,380^{o}C or higher than 1,430^{o}C	Operator draws up the molten metal when temp in furnace not yet reach 1,500^{o}C or higher 1,560^{o}C			
		Al in steel scrap >0.1%	Uncertainty incoming part control // OK			
		Al in inoculant >0.05%	Change inoculant supplier	Reduce cost		
		N in steel scrap>0.004%	Uncertainty incoming part control // OK			
		Mg in steel scrap >0.5%	Uncertainty incoming part control // OK			
		Mn in steel scrap >0.7%	Uncertainty incoming part control // OK			
		S in steel scrap >0.2%	Uncertainty incoming part control // OK			
		S in coal dust >0.1%	Poor quality coal dust "A"			
		Rusty substance in molten metal	Rust generated on steel scrap	Uncertainty incoming part control // OK		

(continued)

Problem	Why 1	Why 2	Why 3	Why 4	Why 5	Why 6
Blowholes or sand inclusion	Hot sand stick to pattern	Temp. of mould sand running in the range 41°C ~ 45°C	Insufficient cooling time, the mould sand is reused faster	Amount of sand decreases by 0.5% in every lot	Poor knockout condition wastes of sand	
Blowholes or pinholes	Poor sand distribution	Caking of mixed sand	Mixed sand get moist	Too much water sprayed in mixing		
				Milling efficiency drops	The O-ring deteriorates which causes a big gap that a cake of sand can pass through without milled	
		Fractional metal contaminated in returned sand	Insufficient process of fractional metal separation			
	Dirty sand	Impurity of new green sand	Sand Inspection Report// OK			
		Coarse and magnetic material contaminated in returned sand	There is only one workstation to separate the unwanted material which maybe insufficient			

Table 4-6 : Immediate actions for B111 defect protection

Topic	Start date	Dept. in charge	Audit date	Remark
1. Relocate the second thermometer from 50 cm to 100 cm away from the spray fuzzer				
1.1 Make record on the second thermometer every hour	18/1/05	Mfg.	25/1/05	Comparison between recorded temp. at 50 and 100 cm found the average 2°C difference.
2. Set an accurate control over the ratio of new sand addition				
2.1 Line out at the level that 2,000kgs of sand will be heaped up in the sand tank.	20/1/05	Mfg.	22/1/05	
2.2 Add new sand 20kgs only when the returned sand is full up to the line and make record	24/1/05	Mfg.	every week	
3. Set preventive maintenance to the milling and stamping machine				
3.1 Study detail of deterioratable parts of the machines and schedule for maintenance and exprie date of each parts	20/1/05	P.E	25/1/05	
3.2 Get approval from the plant manager then start the schedule	31/1/05	P.E	every two weeks	
4. Increase capacity of coarse and magnetic material filter				
4.1 Assign another operator to be in charge of this job as the second filter from the existing workstation	24/1/05	Mfg.		
5. Install tower light at the furnace oven for temperature alert				
5.1 Propose the purchase request	19/1/05	Mfg.		
5.2 Installation	27/1/05	P.E	28/1/05	

Next step is to bring the major 18 related factors as identified in cause and effect matrix and the root causes of each B111 defective factor as defined in the why-why analysis into FMEA study. Those related factors will be worked out in order of functions or processes they are in. The level of severity, occurrence, and detection to each cause are rated to evaluate the risk priority. The rating criteria of the severity, occurrence and detection regards to detail described in table 2-2, 2-3, and 2-4, respectively. Some problems that are solved effectively according to the actions in table 4-6 will be defined as good detection and less occurrence. The significant high RPN will be taken into consideration of further solution and improvement.

Table 4-7 : Process FMEA to B111 defect in cast iron

Process FMEA (Failure Mode and Effect Analysis)

Process Name : Incoming Material
Documented by : Areerat
FMEA No : WFD-M41112
Product Name : F/W ZE1
Responsibility : VQA
FMEA Date (Org.) : 24 / 11 / 04
Core Team : Team chief, team co-ordinator, product engineer, process engineer, manufacturing, QC
(Rev.) : ___________
Page : 1 of 6

Process Function and Requirement	Related factors	Potential Failure Mode	Potential Effect (s) of Failure	S	Potential Cause (s) / Mechanism (s) of Failure	O	Current Process Controls	D	RPN	Ranking	Recom-mended Action(s)	Responsibility & Target completion date	Expected			
													S	O	D	RPN
Incoming Material Inspection	% Alumineum in steel scrap	Al >0.1%	Al will introduce hydrogen which causes oxidation	8	- Unreliable supplier quality	3	Mat'l data certificate/ Spectrometer	3	72	**10**						
	% Nitrogen in steel scrap	N>0.004%	Gas generated by chemical reaction	8	- Unreliable supplier quality	3	Mat'l data certificate/ Spectrometer	3	72	**10**						
	% Magnesium in steel scrap	Mg>0.03%	Gas generated by chemical reaction	8	- Unreliable supplier quality	3	Mat'l data certificate/ Spectrometer	3	72	**10**						
	% Manganese in steel scrap	Mn>0.75%	Gas generated by chemical reaction	8	- Unreliable supplier quality	3	Mat'l data certificate/ Spectrometer	3	72	**10**						
	% Sulphur in steel scrap	S >0.1%	Gas generated by chemical reaction	8	- Unreliable supplier quality	3	Mat'l data certificate/ Spectrometer	3	72	**10**						
	Rusty substance on steel scrap	Steel scrap got rust	Oxidation	8	- Unreliable supplier quality	3	100% visual check	2	48	**12**						

(continued)

Process FMEA (Failure Mode and Effect Analysis)

Process Name : Incoming Material　　Documented by Areerat　　FMEA No : WFD-M41112

Product Name : F/W ZE1　　Responsibility : VQA　　FMEA Date (Org.) : 24 / 11 / 04

Core Team : Team chief, team co-ordinator, product engineer, process engineer, manufacturing, QC　　(Rev.) : ___________

Page : 2 of 6

Process Function and Requirement	Related factors	Potential Failure Mode	Potential Effect (s) of Failure	S	Potential Cause(s) / Mechanism(s) of Failure	O	Current Process Controls	D	RPN	Ranking	Recom-mended Action(s)	Responsibility & Target completion date	Expected S	Expected O	Expected D	Expected RPN
Incoming Material Inspection	%Aluminium in inoculant	Al >0.05%	Al will introduce hydrogen which causes oxidation	8	- Change inoculant from new supplier in order to reduce cost	2	Mat'l data certificate	4	64	**11**						
	%Sulphur in coal dust	S >0.01%	Gas generated by chemical reaction	8	- Present coal dust "A" contains a lot of sulfur	6	Mat'l data certificate	4	192	**6**	- Try coal dust "B"	Mfg. & Eng Dept Jan,05	8	2	2	**32**
	Purity of new green sand	Dirty sand	Sand properties fail	7	- Impurity of new green sand	3	Sand Inspection Report	4	84	**8**						

(continued)

Process FMEA (Failure Mode and Effect Analysis)

Process Name : Furnace
Product Name : F/W ZE1
Core Team : Team chief, team co-ordinator, product engineer, process engineer, manufacturing, QC

Documented by: Areerat
Responsibility : Mfg and Engineerin

FMEA No : WFD-M41112
FMEA Date (Org.) : 24 / 11 / 04
(Rev.) : ___________
Page : 3 of 6

Process Function and Requirement	Related factors	Potential Failure Mode	Potential Effect (s) of Failure	S	Potential Cause (s) / Mechanism (s) of Failure	O	Current Process Controls	D	RPN	Rank ing	Recom-mended Action(s)	Responsibility & Target completion date	Expected			
													S	O	D	RPN
Furnace	Furnace temp	Inaccurate temperature	Temp. of molten metal out of spec	6	-Poor maintenance	3	Temp. check every shift	4	72	**10**						
Pattern Design	Gating system	Inproper gatin system	blowholes or pinholes	8	- Inadequate provision for evacuation of air and gas	3	Customer design approved	2	48	**12**						

(continued)

Process FMEA (Failure Mode and Effect Analysis)

Process Name : Sand Mixing | Documented by : Areerat | FMEA No. : WFD-M41112

Product Name : F/W ZE1 | Responsibility : Mfg | FMEA Date (Org.) : 24 / 11 / 04

Core Team : Team chief, team co-ordinator, product engineer, process engineer, manufacturing, QC | (Rev.) : ___________

Page : 4 of 6

Process Function and Requirement	Related factors	Potential Failure Mode	Potential Effect(s) of Failure	S	Potential Cause(s) / Mechanism(s) of Failure	O	Current Process Controls	D	RPN	Rank ing	Recom-mended Action(s)	Responsibility & Target completion date	Expected S	Expected O	Expected D	Expected RPN
Returned sand	Coarse and magnetic material separation	Contanimated coarse and metal in the returned sand	chemical reaction with the metl	8	Insufficient workforces of fractional metal separation	2	2 workstations in charge of coarse and magnetic separation	4	64	**11**						
Sand mixing	Ash content in moulding sand	High % Loss on Ignition	blowholes or pinholes	8	Present coal dust "A" contains a lot of ash	7	Mat'l data sheet	6	336	**5**	Trial coal dust B	VQA & Mfg. Jan,05	8	4	3	**96**
	Corn starch addition	Permeability low < 80	blowholes or pinholes	8	Addition of corn starch, a well water absorbent substance, keep much moisture	9	No control	10	720	**1**	Stop using corn starch	Mfg & QC. Jan,05	8	4	2	**64**
		Compactability low < 15%	blowholes or pinholes	8	Corn starch addition could become dust in the mould sand	7	No control	10	560	**2**	Stop using corn starch	Mfg & QC. Jan,05	8	4	2	**64**

(continued)

Process FMEA (Failure Mode and Effect Analysis)

Process Name : Sand Moulding
Documented by Areerat
FMEA No : WFD-M41112
Product Name : F/W ZE1
Responsibility : Mfg and QC
FMEA Date (Org.) : 24 / 11 / 04
Core Team : Team chief, team co-ordinator, product engineer, process engineer, manufacturing, QC
(Rev.) : ___________
Page : 5 of 6

Process Function and Requirement	Related factors	Potential Failure Mode	Potential Effect(s) of Failure	S	Potential Cause(s) / Mechanism(s) of Failure	O	Current Process Controls	D	RPN	Rank ing	Recom-mended Action (s)	Responsibility & Target completion date	Expected S	Expected O	Expected D	Expected RPN
Sand moulding	Temp of mould sand	Hot sand sticks to the pattern	Blowholes and sand inclusion	8	Waste of sand due to poor knockout condition thus sand in the system is reused faster	6	Extra addition of new sand 0.5% per lot	8	384	**4**	Good quality coal dust helps improve knock-out condition	Mfg Jan,05	8	2	1	**16**
	Moisture content in mould sand	Low permea bility<80	blowholes or pinholes	8	Spray too much water due to error measure the actual temp of return sand after cooling	5	Relocate 2nd thermometer 100cm away from the spray fuzzer	2	80	**9**						
			blowholes or pinholes	8	Extra water required due to the addition of corn starch	#	Ratio of corn starch	6	480	**3**	Stop using corn starch	Mfg & QC Jan,05	8	3	2	**48**

(continued)

Process FMEA (Failure Mode and Effect Analysis)

Process Name : Casting
Documented by Areerat
FMEA No : WFD-M41112
Product Name : F/W ZE1
Responsibility : Mfg
FMEA Date (Org.) : 24 / 11 / 04
Core Team : Team chief, team co-ordinator, product engineer, process engineer, manufacturing, QC
(Rev.) : ___________
Page : 6 of 6

Process Function and Requirement	Related factors	Potential Failure Mode	Potential Effect (s) of Failure	S	Potential Cause(s) / Mechanism(s) of Failure	O	Current Process Controls	D	RPN	Ranking	Recommended Action(s)	Responsibility & Target completion date	Expected			
													S	O	D	RPN
Pouring	Pouring temp	Temp too low <1380°C	Chemical reaction	8	pouring time longer than 10 min	3	measure and record before pouring the last 5 moulds	3	72	**10**						
					The melt was drawn up when temp less than 1,500°C or greater than 1,560°C	2	Install alarm light when temp reach the set point	2	32	**13**						
	Height of pouring	Pouring height >10cm	Introduction of oxygen leads to oxidation	8	Operator lifts up the ladle higher when the melt left 1/4 of ladle at the last few moulds	2	Visual check not lower min level as marked in the ladle	4	64	**11**						
			blowholes or pinholes	8	Excess of dead clay or dust contaminated in the returned sand	6	Control new sand addition at 1%	2	96	**7**						

According to the RPN ranking from FMEA table 4-7, there are five outstanding failure modes that impact to the blowholes or pinholes defect 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 compactability due to fine substance from present of corn starch.
- Hot sand stick to the pattern due to insufficient cooling of returned sand.

Conclusively, the coal dust brand “A” and present of corn starch are suspected to be key factors of the blowholes or pinholes problem. As benchmarking with the first tier company, the coal dust brand “B” is of interest whether to switch to use it in order to reduce the problem. By the way, corn starch is considered as an extraneous ingredient. The reason that the case study company keeps using corn starch is to improve the efficiency of bentonite. However, there is no scientific paper to confirm this attitude. Therefore, the team will conduct experimental study whether using coal dust brand “B” and stop using corn starch will significantly improve the performance of the case study company.

4.5 Factor Screening

The suspected factors of blowholes or pinholes defect are using coal dust brand “A” and present corn starch in mould sand. The alternative coal dust as of interest is brand “B” which is being used in the first tier’s production. And the corn starch factor which is considered as an extraneous factor in casting works. The response is amount of defective parts. In this section the one factor at a time (OFAT) technique is employed to confirm the significant impact of these two variables to the blowholes or pinholes defect.

4.5.1 Parameters Agreement

Since the measure of success of the case study is the improvement of yield and the response is amount of B111 defective part, therefore, the two-proportion test is applied to test for significant impact of the variables to the response. The level of setting throughout the experiment are as below.

Level of Confidence = 95%
Level of significance (α) = 0.05

The present B111 defect yields at 15% while the team is expecting to diminish the defect to 5%. To be precise, the power of test is set at 90%. Employing MiniTab to calculate the sample size, 188 units of specimens are required. Due to the capacity of a furnace at one time casting the F/W ZE1, 168 units are produced. In order to lessen the chance of any errors from furnacing process, the team agrees to put these 168 units as samples size at the power of test 86.7%.

Hypothesis Testing : This is to test the difference between two proportions of successes when using coal dust brand, “A” and “B”, and between present and absent corn starch. The null hypothesis is the proportions of two variables are not different and the alternative hypothesis is the proportions of two variables are different. The mathematic signs are as following.

$$H_o \ : \ p_1 - p_2 = 0$$
$$H_a \ : \ p_1 - p_2 \neq 0$$

Decision Making : If the p-value is larger than commonly chosen α levels, the data are consistent with the null hypothesis. On the other hand, if the p-value is lesser than α levels, the data are consistent with the alternative hypothesis.

4.5.2 Experiment Procedure.

The flow of casting procedure is as shown in figure 4.5. The controlled factors about chemical composition, furnace temperature, sand mixing ratio, height of pouring, fading time per ladle, and so on are set as specified in the case company column in the table 4-1. Operator will record number of blowholes or pinholes on the observed units after machining. The variable factors are coal dust brand and present of corn starch in which will be experimented in next section.

4.5.3 One-factor at a time testing

4.5.3.1 Test for difference of proportions between coal dust A and B to the blowholes or pinholes defect of F/W ZE1.

$$H_o \ : \ p_1 - p_2 = 0$$
$$H_a \ : \ p_1 - p_2 \neq 0$$

where p_1 and p_2 are proportions of the blowholes or pinholes defect when using coal dust “A” and “B”, respectively.

The experiments are conducted by keeping controllable factors at the level of control as shown in table 4-1 but using coal dust “A” and “B” in the first and second experiment, respectively. After machining, all 168 specimens of each experiment are inspected and recorded for the amount of blowholes or pinholes defect as shown in appendix C. Employing MiniTab to help verify the difference of two-proportion , p-value is computed as expressed in figure 4.6.

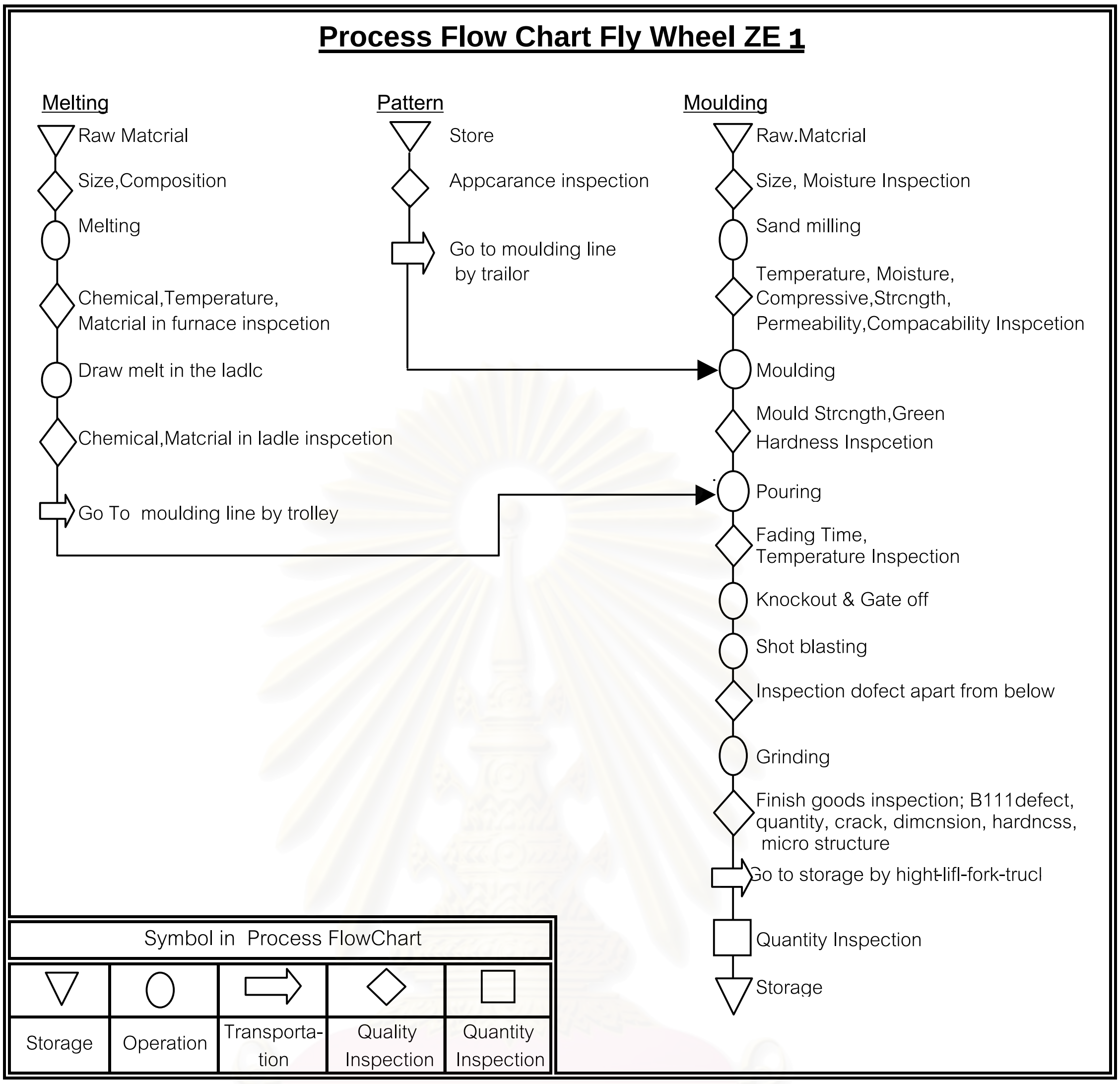
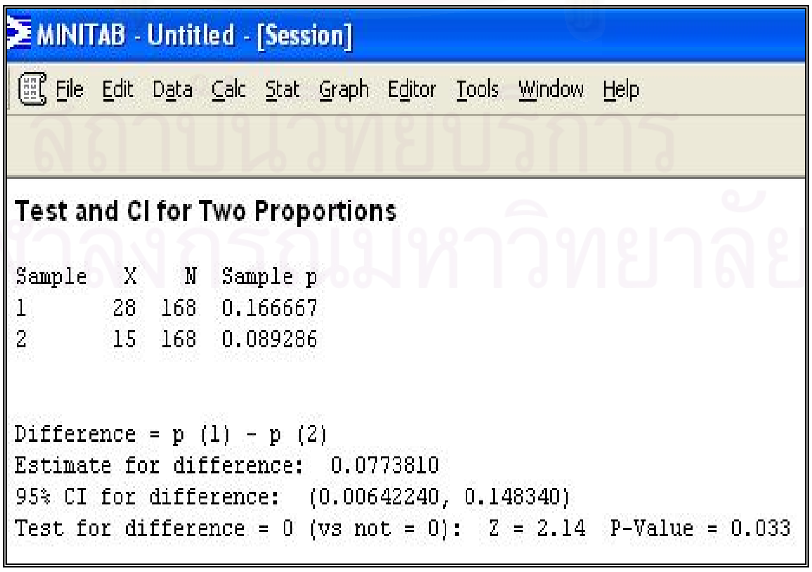


Figure 4.5 Process flow chart



Test and CI for Two Proportions

```
Sample    X    N  Sample p
1        28  168  0.166667
2        15  168  0.089286


Difference = p (1) - p (2)
Estimate for difference:  0.0773810
95% CI for difference:  (0.00642240, 0.148340)
Test for difference = 0 (vs not = 0):  Z = 2.14  P-Value = 0.033
```

Figure 4.6 : Test and calculation for two-proportion using coal dust A and B

Result Interpretation: Since the p-value 0.033 is lesser than 0.05, the null hypothesis is rejected at the confidence 95%. That is the proportion of blowholes or pinholes defect by using coal dust A is different from that of using coal dust B with 95% confidence.

4.5.3.2 Test for difference of proportions between present and absent corn starch to the blowholes or pinholes defect of F/W ZE1.

$$H_o \ : \ p_1 - p_2 = 0$$
$$H_a \ : \ p_1 - p_2 \neq 0$$

where p_1 and p_2 are proportions of the blowholes or pinholes defect when corn starch is presented and absented in mould sand, respectively.

Rule of conducting experiment is as same as previous experiment using coal dust A but present and absent corn starch are of interest variables. Only will except the amount of water sprayed into the sand mixing process be reduced by 1/4 in the experiment that corn starch absented. After machining, all 168 specimens of each experiment are inspected and recorded for the amount of blowholes or pinholes defect as shown in appendix C. Employing MiniTab to help verify the difference of two-proportion of interest as result shown in figure 4.7.

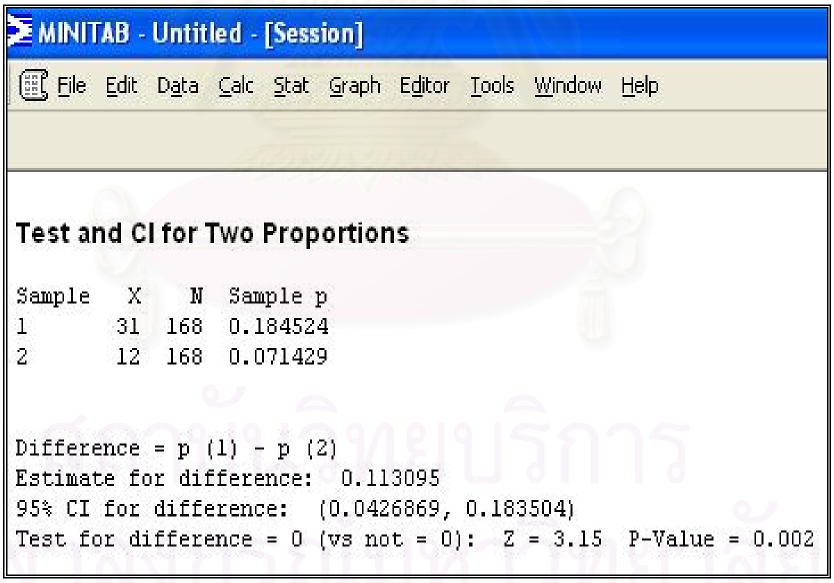


Figure 4.7 : Test and calculation for two-proportion of present and absent corn starch

Result Interpretation : Since the p-value 0.002 is lesser than 0.05, the null hypothesis is rejected at the confidence 95%. That is the proportion of blowholes or pinholes defect by presenting corn starch differs from that of absenting corn starch with 95% confidence.

4.6 Experiment Observation

Switching to coal dust B, the outcome of knockout condition seems to be better. It is obviously found that less sand is carried over with the cast unit. This will benefit in not unnecessarily wasting of sand in the system. This is explained according to the consultant – specialist from James Durrans, that gas generated by the coal dust during casting will act as shield on the mould surface, thus the grain sand does not addict to the metal surface. Consequently, knockout condition improves. In the past, when sand amount reduced, the operator added more new sand to fill up the sand tank. If the ratio of new sand in the system is much inappropriate (>>1%), this will effect to casting quality. Hence, the casting quality is more stable regarding the stability of returned sand properties.

From OFAT experiment, it is concluded that coal dust A and present of corn starch play role in blowholes or pinholes defect in cast iron model F/E ZE1. Changing coal dust and absenting the corn starch, the B111 defect obviously reduces to satisfaction rate. However, the appearance on the cast surface seems to be unsatisfied yet. The surface of casting units by coal dust B look more rough than using coal dust A. The comparison is as illustrated in figure 4.8a) and 4.8b).

4.8a) Smooth surface using coal dust A

4.8b) Rough surface using coal dust B

Figure 4.8 Casting surface

According to the specialist, the coal dust B may affect the efficiency of bentonite. He suggests that adjust ratio of coal dust : bentonite from 1:4 to 1:3 instead and extend resting time for 5 minutes before feeding the milled sand into the stamping process so that the bentonite can swell completely. The better swell of bentonite, the better surface finished. However, the roughness appearance on the surface is not as serious as to be rejected in customer's perspective. Therefore, the team decides to start the experiment based on the suggestion once the interaction between coal dust and corn starch defined in full factorial experiment in the next chapter.

CHAPTER V

Design of Experiment

Problem analysis from chapter 4, the significant factors of blowholes or pinholes defect are using coal dust brand "A" and the present of corn starch in mould sand. As benchmarking with the first tier, using coal dust B and absenting corn starch ingredient in mould sand are of interests for alternatives. Therefore, this chapter will conduct the experiment to verify the interaction of these two factors. Since the coal dust and corn starch may influence the level of secondary sand inspection which are temperature, moisture content, permeability, and compactability of mould sand, thus, during run the experiment these data will be recorded to investigate the trend of changes. Another trial will be conducted, hereafter, to define whether the recommended ratio of bentonite and coal dust can improve the quality of surface finish. The findings will be confirmed by implementing the new setting to the mass production of the product under study. Finally, cost that associated with change will be verified whether the company earns the benefits from implementation.

5.1 Experimental Factors

The input variables are coal dust "A" and "B", and present and absent of corn starch in mould sand. The response(Y) is amount of blowholes and pinholes defective parts. Mathematic equation of response Y is as expressed in equation 5-1.

$$Y = f(x_1, x_2, x_3, \ldots x_n) \qquad \text{(equation 5-1)}$$

Since the input variables are in text, so the level setting of each variable will be transferred in numeric as low (-1) and high (+1) as expressed in table 5-1.

Table 5-1 : Factors and factor level setting

Variable Factors	Level Setting	
	Low (-1)	High (+1)
Coal dust brand	"A"	"B"
Corn starch addition	Present	Absent

Procedure setting follows the flow chart as exhibited in figure 4.4. The process inputs are classified as controllable and uncontrollable. The controllable factors and level of control are listed out in Table 5-2. The uncontrollable factors are about environment temperature and humidity. In order to avoid from human error, the responsible participants will be fixed to his duty throughout the experiment. Before initiating the experiment, the meeting is set aims for consensus among the participants.

Table 5-2:Controllable Factors and Level of Control in cast iron process for F/W ZE1

Process	Controllable Factors	Level of control
Incoming Material	All the steel scrap used in the experiment	100% Chemical composition analysis by spectrometer and visual check rusty substance.
Sand Mixing	New sand addition	1% of total sand in the tank
	Inoculant : sand	3 Kg : 250 Kg
	Coal dust : bentonite	1 : 4
Sand Milling	Pressure setting	90 – 100 Kg/ cm^2
	Milling time	12 minutes
Moulding	Temp. of mould sand	35 ^{o}c ~ 40 ^{o}c
	Humid. of mould sand	3.0% ~ 4.2%
Pouring	Temp. of pouring	1,380^{o}c ~ 1,430^{o}c
	Height of pouring	10 cm
	Fading time / ladle	$\leq$ 12 min.
	Pouring time / mould	5.5 ~ 7.5 sec

5.2 <u>Two-factor Factorial Experiment</u>

Since there are only two factors with two levels each under consideration, therefore, screening design is omitted and full factorial experiment required – totally four runs in a single experiment. To reduce error from furnace process and to have sufficient analysis data, the 168 units, cast at one time furnace capacity, are observed as a set of one replicate, that is n = 168. Due to the costly experiment and time consumption, the team agrees to conduct the experiment at two replicates. Therefore, there are 8 runs concerned in the experiment. The raw data from the experiments are recorded as shown in appendix D. Creating experimental design by MiniTab, the responses (Y) from the experiments are brought to the table 5-3.

Table 5-3 : The response Y of each testing combination.

StdOrder	RunOrder	CenterPt	Blocks	coal dust	corn starch	Y
6	1	1	1	1	-1	11
2	2	1	1	1	-1	13
8	3	1	1	1	1	27
4	4	1	1	1	1	25
5	5	1	1	-1	-1	2
1	6	1	1	-1	-1	3
7	7	1	1	-1	1	15
3	8	1	1	-1	1	11

In the proportional test, it is often to stabilize the variance by transformation. The function of transformation is as in equation 5-2 *[Statistics for Experimenters , p.234]*.

$$\sin x = \sqrt{y/n}$$

$$x = \sin^{-1}\sqrt{y/n} \qquad \text{(equation 5-2)}$$

The transformed value of response Y is expressed in table 5-4.

Table 5-4 : The response Y in transformed term of x.

StdOrder	RunOrder	CenterPt	Blocks	coal dust	corn starch	Y	*x*
6	1	1	1	1	-1	11	14.83
2	2	1	1	1	-1	13	16.15
8	3	1	1	1	1	27	23.63
4	4	1	1	1	1	25	22.69
5	5	1	1	-1	-1	2	6.26
1	6	1	1	-1	-1	3	7.68
7	7	1	1	-1	1	15	17.39
3	8	1	1	-1	1	11	14.83

5.3 <u>Data Analysis</u>

According to the data analyzed by MiniTab, the main effects to the response Y in term of *x* are significant as the P-value less than 0.05. That is the coal dust and corn starch have significant effect to the blowholes or pinholes defect with 95% confidence. On the other hand, the interaction between two of them has no effect to the response with 95% confidence due to the P-value = 0.429 which is greater than 0.05.

Factorial Fit: x versus coal dust, corn starch

```
Estimated Effects and Coefficients for x (coded units)

Term                       Effect     Coef  SE Coef      T      P
Constant                          15.4325   0.4183  36.90  0.000
coal dust                  7.7850   3.8925   0.4183   9.31  0.001
corn starch                8.4050   4.2025   0.4183  10.05  0.001
coal dust*corn starch     -0.7350  -0.3675   0.4183  -0.88  0.429


S = 1.18300   R-Sq = 97.92%   R-Sq(adj) = 96.36%


Analysis of Variance for x (coded units)

Source              DF   Seq SS   Adj SS   Adj MS      F      P
Main Effects         2  262.501  262.501  131.250  93.78  0.000
2-Way Interactions   1    1.080    1.080    1.080   0.77  0.429
Residual Error       4    5.598    5.598    1.399
  Pure Error         4    5.598    5.598    1.399
Total                7  269.179
```

This analysis is confirmed by Normal Probability Plot of the standardized effects and Pareto Chart as shown in figure 5.1 and 5.2, respectively.

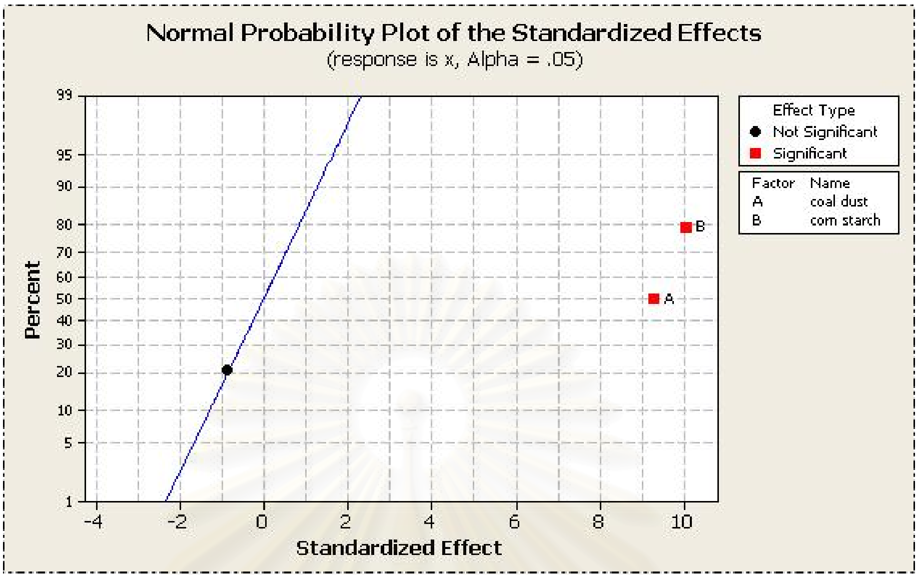


Figure 5.1 : Normal Probability Plot of the Standardized Effects

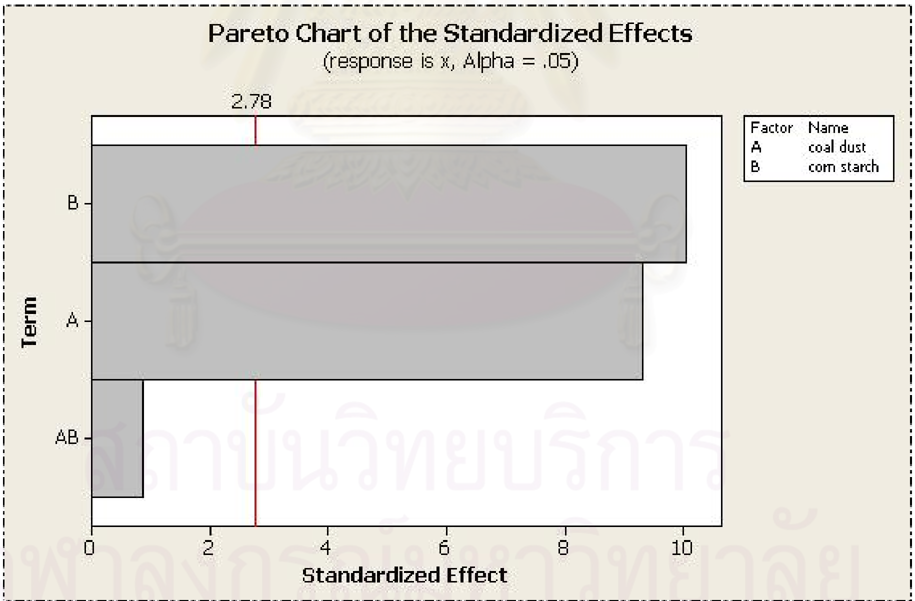


Figure 5.2 : Pareto Chart of the Standardized Effects

The normal probability plot of residual, as expressed in figure 5.3, implies the reasonably analysis. There are only 8 points on the residuals versus fitted value, as plotted in figure 5.4, which are not sufficient to an analysis. However, they both look normal.

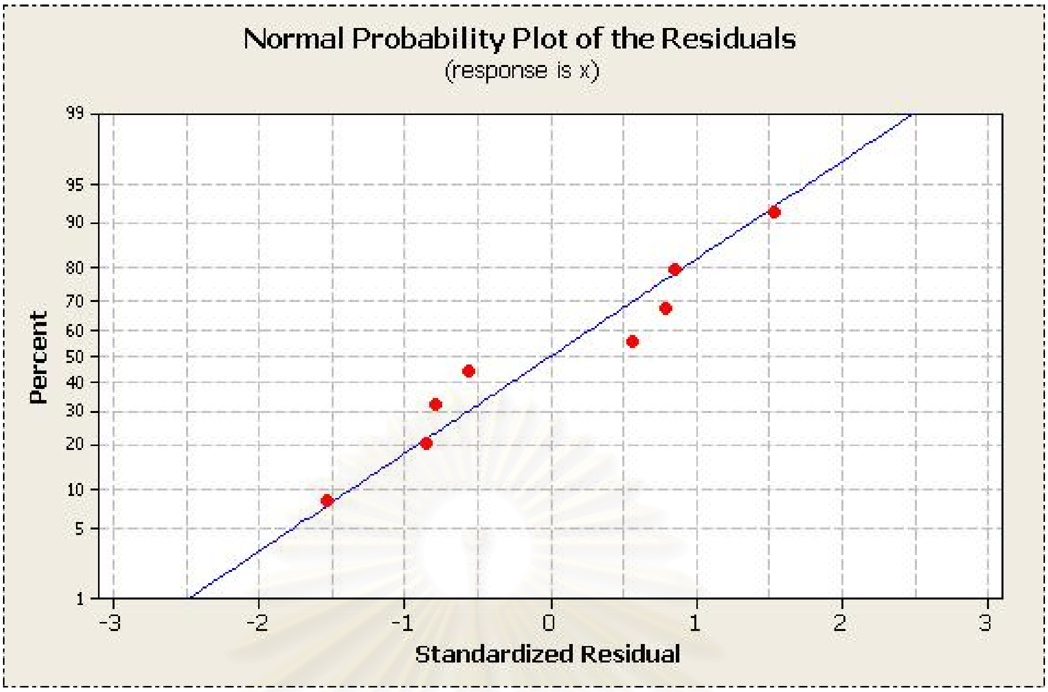


Figure 5.3 : Normality Probability Plot of residuals of response x

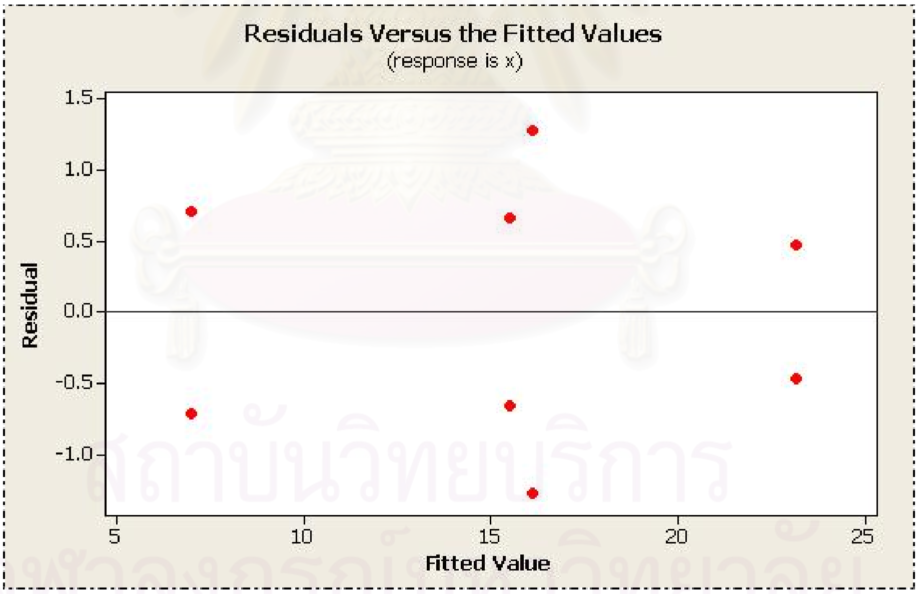


Figure 5.4 : Dispersion of Residuals VS Fitted values

5.4 Secondary Sand Inspection

During the experiments, the mould sand properties of both two replicates in each testing combination are inspected and kept record as frequent as every half an hour. The properties of interest are temperature (T), moisture (M), permeability (P), compactability (C). The recorded data of each testing combination and the averages are exhibited in table 5-4 which will be benefit in further adjustment level of control due to the change of variables. The procedures of inspections are as following.

Specimens preparation :

1. Weight the amount of sand for 150g
2. Place the cylindrical tube, and using Ridsdale-Dietest apparatus as shown in figure 5.4a), ram the specimens three times. Adjust amount of sand for exactly 2" in height.

Temperature (T) :

Record the temperature of mould sand as displayed on the control panel.

Permeability (P) :

Using permeability meter (permmeter), as shown in figure 5.5b), to test a sample of mould sand which is prepared in cylinder 2", the permeability value is read out from the dial scale.

1. Place the specimen tube over the center post of the permmeter.
2. Rotate the knurled ring of the center post anti-clockwise to seal the specimen tube.
3. Place the lever on the left-hand side of the permmeter forward.
4. Adjust the gauge at "0".
5. Move the lever to the test position and read the permeability from the scale.

Compactability (C):

Using the apparatus, Force-gen, to measure the decrease in height of a riddled mass of sand under the influence of a standard compacting force.

1. Crush the specimen sand on the mesh , as in figure 5.5c), and put the cylindrical tube to carry the crumby sand.
2. Strickle the sand level with the top of the tube with a straight edge as figure5.5d)
3. Place the tube in position on the sand rammer.
4. Lower the plunger gently onto the sand and ram with 3 blows.
5. Take out the rigid sand specimen from the cylinder tube.
6. Position the specimen in the squeezing arms of the Force-gen as in figure 5.5e).
7. Rotate the shaft until the sand specimen starts deformation as shown in figure 5.5f) and read out the percentage compactability on the dial.

Moisture (M) :

1. Take 150g of sand specimen to dry in an oven at temperature 130^{o}c for half an hour.
2. After baking for half an hour, reweight the sand specimen.
3. Do calculation for the percentage of weight lost as the evaporated moisture.

5.5a) Ridsdale-Dietest apparatus

5.5b) Permmeter

5.5c) Sand crushing by hand

5.5d) Strickling sand for straight edge.

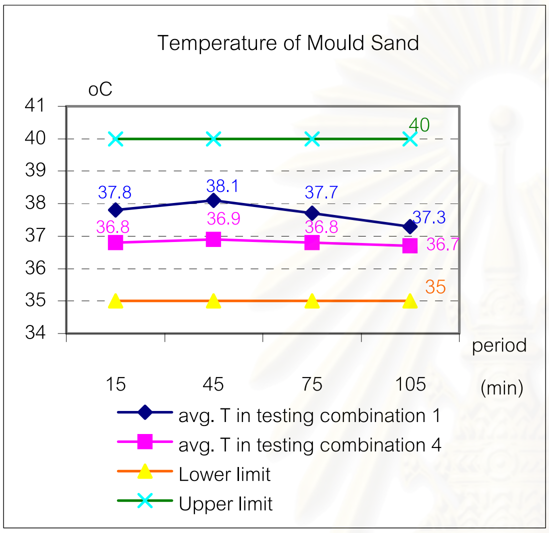
5.5e) Positioning the specimen on the Force-gen

5.5f) Rotating the shaft to squeeze the specimen

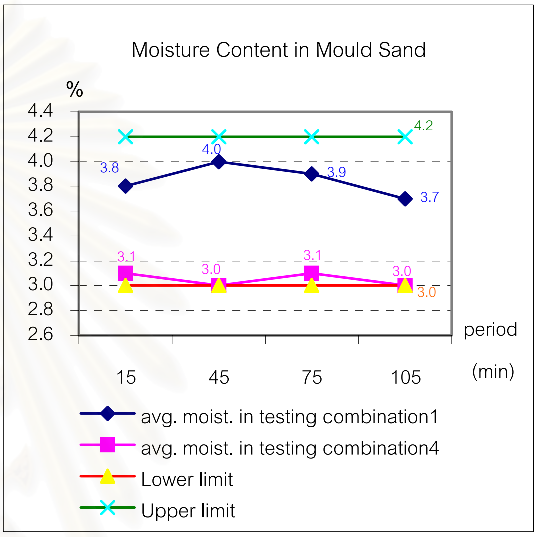
Figure 5.5 : Sand inspection apparatus and method

5.4.1 Sand Properties Analysis

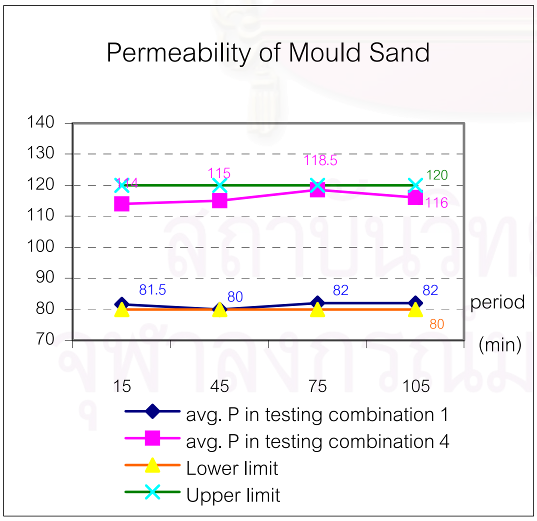
Obviously seen that properties of specimens sand in testing combination 1 are different from those in testing combination 4. Graphical plots are visual illustration on the trend of change expressed in figure 5.6. The plotted data is an average of data in replicate 1 and 2. Temperature is running within the controlled range. On account of reducing water by half in mixing sand process, the moisture content in the mould sand has declined comparing to the range in testing combination 1. It is running around the lower limit. The permeability of mould sand in testing combination 4 – staying around the upper level - is dramatically different from that in testing combination 1- staying around the lower level. The higher permeability the mould sand, the better evaporation of gas or air. It is noted that permeability of mould sand in testing combination 4 is better than that in testing combination 1. However, the permeability is limited as not exceeding 140, otherwise will impact to the strength of sand mould. According to the specialist, the permeability of sand mould generally is as the best at 100 ~ 120. The trend of compactability is either improving due to small per cent of ash content in coal dust B (3%) – compare to coal dust A (6%)- and absent of fine from corn starch addition. Since there are four points of each data plotted in the graph which are not sufficient to make concrete conclusion. What could be seen is trend of change.



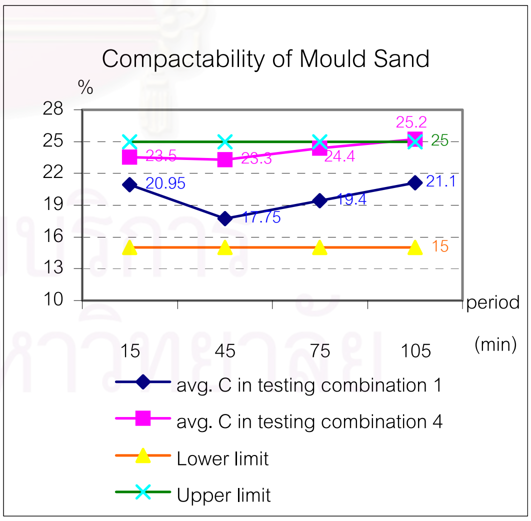
5.6a) Comparison between temperature of mould sand



5.6b) Comparison between moisture content of mould sand



5.6c) Comparison between permeability of mould sand



5.6d) Comparison between compactability of mould sand

Figure 5.6 : Comparison between specimen sand properties in testing combination 1 and 4

Table 5-5 : Specimen Sand Properties at each Testing Combination

Table 5-5a) Coal Dust A VS Present Corn Starch

Period (min)	Properites of Specimen Sand								AVG			
	Testing combination 1 / Replication 1				Testing combination 1 / Replication 2				Testing combination 1			
	T (^oC)	M (%)	P	C (%)	T (^oC)	M (%)	P	C (%)	T (^oC)	M (%)	P	C (%)
15	37.8	3.7	82	20.7	37.2	3.9	81	21.2	37.5	3.80	81.5	20.95
45	38.1	4.1	77	15.8	36.8	3.9	83	19.7	37.45	4.00	80	17.75
75	37.7	3.9	79	18.3	36.8	3.8	85	20.5	37.3	3.85	82	19.4
105	37.3	4.1	83	21.4	36.9	3.7	80	20.8	37.1	3.90	82	21.1

Table 5-5b) Coal Dust B VS Present Corn Starch

Period (min)	Properites of Specimen Sand								AVG			
	Testing combination 2 / Replication 1				Testing combination 2 / Replication 2				Testing combination 2			
	T (^oC)	M (%)	P	C (%)	T (^oC)	M (%)	P	C (%)	T (^oC)	M (%)	P	C (%)
15	37.0	3.9	82	22.0	38.3	4.0	79	24.4	37.7	3.95	81	23.2
45	37.5	3.8	81	22.5	38.2	3.8	84	21.5	37.9	3.80	83	22.0
75	37.2	3.9	84	23.4	38.8	3.9	81	21.7	38.0	3.90	83	22.6
105	36.8	4.0	85	21.8	39.3	3.8	80	23.2	38.1	3.90	83	22.5

Table 5-5c) Coal Dust A VS Absent Corn Starch

Period (min)	Properites of Specimen Sand								AVG			
	Testing combination 3 / Replication 1				Testing combination 3 / Replication 2				Testing combination 3			
	T (^oC)	M (%)	P	C (%)	T (^oC)	M (%)	P	C (%)	T (^oC)	M (%)	P	C (%)
15	39.8	3.5	98	16.8	37.5	3.0	105	15.2	38.65	3.25	102	16.0
45	39.2	3.2	105	17.4	38.1	3.1	102	16.3	38.7	3.15	104	16.9
75	38.5	3.0	106	18.3	37.8	3.1	108	15.8	38.15	3.05	107	17.1
105	37.9	3.6	104	16.7	37.5	3.8	110	14.2	37.7	3.7	107	15.5

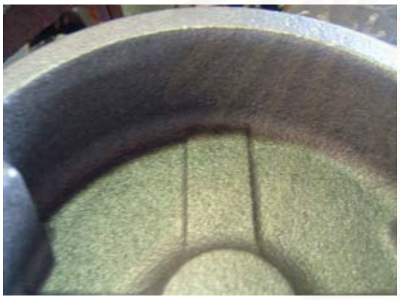
Table 5-5d) Coal Dust B VS Absent Corn Starch

Period (min)	Properites of Specimen Sand								AVG			
	Testing combination 4 / Replication 1				Testing combination 4 / Replication 2				Testing combination 4			
	T (^oC)	M (%)	P	C (%)	T (^oC)	M (%)	P	C (%)	T (^oC)	M (%)	P	C (%)
15	36.8	3.2	115	23.5	37.1	2.9	112	23.4	36.95	3.05	114	23.5
45	36.9	2.9	119	23.7	36.9	3.1	111	22.8	36.9	3	115	23.3
75	36.8	2.9	121	24.2	36.6	3.2	116	24.6	36.7	3.05	118.5	24.4
105	36.7	3.1	118	25.5	36.5	3.2	114	24.9	36.6	3.15	116	25.2

5.5 <u>Experiment Observation</u>

During the full factorial experiment, the team has observed any matters that possibly go wrong due to the changing variables. Again that the rough surface found on the cast units from the testing combination 2 and 4 that coal dust B were used. To confirm with the consultant's suggestion on increasing coal dust ratio in accordance with bentonite as 1 : 3 and leaving the mixed sand in the tank for 5 minutes rest, another trial is conducted based on the setting of control level regarding table 5-2 but the bentonite and coal dust ratio. Because of costly experiment and time consumption, the team agrees that confidence in good surface finish could be made through 50 specimens. It is unnecessarily to run the full capacity upto 168 specimens. Since the testing combination 4 seems to be positive outcome in solving blowholes or pinholes defect, thus, the trial will be conducted based on the set condition.

Result : The surface finish of the specimens reflect good appearance and free from blowholes or pinholes as compared in figure 5.7 The knockout condition is better as compared in figure 5.8.



5.7a) Using coal dust B : bentonite
1 : 4

5.7b) Using coal dust B : bentonite
1 : 3

Figure 5.7 : Surface finish comparison

5.8a) Before

5.8b) After

Figure 5.8 : Comparison knockout condition before and after improvement

5.6 Confirm the Optimum Setting

This is to confirm the outcome from DoE whether setting both variables at high level -use of coal dust “B” and absent of corn starch -are applicable in the mass production. Procedure and level of control are set according to the previous experiment in testing combination 4. Only except three of these.

- Ratio of coal dust B : bentonite = 1 : 3;
- Leaving the milled sand in the rest tank for better swelling of betonite; and
- Increasing the casting units to 6,000 pieces.

Regarding the inspection criteria, free from blowholes or pinholes casting unit considered as good - otherwise defect (NG). Hence, QC staff will mark NG on the F/W ZE1 once a hole appeared on the surface regardless size. After delivery the investigated lot to customer, the team has collected the data from in-house quality report and claim report from customer in order to summarize the performance as exhibited in table 5-6.

Table 5-6 : Production performance of F/W ZE1

Defect / Product	Inspection Q'ty (pcs)	In-House Defect (pcs)					Claim Defect (pcs)	Total (pcs)	Yield (%)
		B111	C311	E221	F221	A123			
F/W ZE1	6,000	102	67	18	59	23	-	269	95.52

The B111 defect is dramatically reduced and, consequently, the production yield improved to 95.5%. The B111 defect remains as low as 1.7%. and none claimed by customer. According to the plant manager, such a defect rate is acceptable. The other defect symptoms are ordinary amount in casting.

5.7 Return on Quality Investment

It is proved that using coal dust brand B, instead of brand A, with proportion 1:3 of bentonite and stop using corn starch can reduce blowholes or pinholes as well as keep quality of surface finish. Hence, along this research completion, the company has invested in tooling, equipment, workforces, and so on in quality improvement. Quality investment and cost associated with change in brand and ratio of coal dust will be verified. The return on quality investment on this research and for the consistent production will be also determined. Table 5-7 illustrates total expenses spent during the research.

Table 5-7 : Expenses during the research period from Sep, 2004 – Apr, 2005.

No.	Description	Unit cost (baht)	x Amount (unit)		Expenses (baht)
1	Tower Light	1,500.00	1	unit	1,500.00
2	Avg. production cost per hour	1,275.38	18	hrs	22,956.84
3	Inspection = 10% of production	187.50	8	hrs	1,500.00
4	Cost of defects during the experime	57.91	193	pcs.	11,176.63
5	Avg. labor cost per hour of four of team members	256	32	hrs	8,192.00
6	Avg. labor cost per hour of officers	185	25	hrs	4,625.00
			sub-total		**49,950.47**
7	Miscellaneous expense= 5% of sub-total				2,497.52
			Grand total		**52,447.99**

Amount of coal dust and corn starch per batch of mould sand are identified in table 5-8. The other factors are kept the same control as original. Unit cost of the casting F/W ZE1 will be changed according to the new setting as evaluated in table 5-9. The actual unit cost excluding coal dust and corn starch is represented by Q.

Table 5-8 : Comparison between amount of coal dust and corn starch in original control and new control based on a batch of mould sand

Description	Original control	New control
Mould sand capacity per batch	800 kg	800 kg
Bentonite 1%	8 kg	8 kg
Coal Dust	2 kg (1 coal A : 4 bentonite)	2.6 kg (1 coal B : 3 bentonite)
Corn starch	1.6 kg (0.2% per batch)	- (absent)
Casting unit	30	30

Table 5-9 : Material Cost Evaluation per Unit

Factor	Price (baht / kg)	Usage per batch	Amount (baht)
Original setting			
Coal dust A	16.00	2 kg	32.00
corn starch	16.50	1.6 kg	26.40
			58.40
		amount per unit	1.95
New setting			
Coal dust B	16.50	2.6 kg	42.90
		amount per unit	1.43

The original unit cost of F/W ZE1 is Q+1.95 baht. From the cost working in table 5-9, the case company can reduce cost to Q+1.43 baht per unit or 0.52 baht less. Refer to the trial lot- 6,000 cast units - the company can save non-metal material cost up to 3,120 baht. Moreover, the company can also gain the advantage from saving sand that drops out from knockout process. In the old day, the carryover sand was taken out from the cast unit by shot blasting and could not be recycled any more. The less sand carried over, the less metal bullet used up in shot blasting process. Due to time constrain, the return on quality investment will be estimably calculated based on the saving proportion from the trial lot 6,000 units and the average casting amount per mount 30,000 units. The estimated cost saving from the study is expressed in table 5-10.

Table 5-10 : Estimated cost saving regards the new setting on F/W ZE1.

Casting Units	B111 defect (pcs.)	Unit price (baht)	Amount (baht)
Casting at 6,000 units			
Actual defect (1.7%)	102	57.91	5,906.82
Prior defect before improvement (15%)	900	57.91	52,119.00
Saving amount from defective parts			46,212.18
Saving amount from non-metal material			3,120.00
Total saving			49,332.18

(continued)

Casting Units	B111 defect (pcs.)	Unit price (baht)	Amount (baht)
Average production volume on F/W ZE1 @ 30,000 units/month			
Estimate defect from new setting (1.7%)	510	57.91	29,534.10
Estimate defect from original setting (15%)	4500	57.91	260,595.00
Saving amount from defective parts			231,060.90
Saving amount from non-metal material			15,600.00
Total saving			246,660.90

Information from table 5-10 implies that the company saves up to 8.22 baht per casting unit (246,660 / 30,000). Thus, the breakeven point of the investment is at casting the first 6,381 units F/W ZE1.

Return on quality investment regarding benefits and cost ratio within a month will be as following.

$$ROQI = \frac{\text{Benefits per month}}{\text{Cost per month}} \qquad \text{(equation 5-3)}$$

The amount of investment is expected to last advantage for two years because the tooling should need to be maintained or replaced and the cost of expenses might be altered.

$$ROQI = \frac{246,661}{(52,448 / 24)}$$

$$\simeq 113 \text{ times}$$

CHAPTER VI

Conclusion and Recommendations

The purpose of this research is to improve the case company productivity by reducing defect rate in casting activity. Blowholes or pinholes defect is an outstanding concern to the company performance as pulling the yield down to 85%. The team consents to conduct the study over the mass model, automotive disc break-Fly Wheel ZE1. Improvement in quality will be, hereafter, computed for the return on investment.

6.1 <u>Conclusion</u>

Benchmarking with the first tier company it is found that the case study company has level of control in some factors different from the benchmarked company, which are brand of coal dust, present of corn starch, permeability, compactability, temperature and moisture content of mould sand. The last four factors are secondary control effected by the input variables. The team, firstly, brainstorms for the possible causes of blowholes or pinholes defect in product F/W ZE1 based on the 4Ms and 1E categories and plots in fish bone diagram as shown in figure 4.2. Secondly, these factors are determined based on importance to customer by weighting from 0 to 4 as from unrelated to the most important in the cause and effect matrix. Since the blowholes or pinholes defect is serious to customer, therefore, its weight is 10. The defined possible causes, counting for 43 items, are listed due to the process they are in. Weighting according to the importance to customer, the outstanding 18 factors out of 43 are determined as below.

1. % Al in steel scrap
2. % N in steel scrap
3. % Mn in steel scrap
4. % Mg in steel scrap
5. % S in steel scrap
6. % Al in inoculant
7. % S in coal dust
8. Rusty substance
9. Purity of new green sand
10. Furnace temperature
11. Gating system
12. Coarse and magnetic material separation
13. Ash content in mould sand
14. Corn starch addition
15. Temperature of mould sand
16. Moisture in mould sand
17. Pouring temperature
18. Height of pouring

Refer to the text and research, the causes of blowholes or pinholes defect are contained in the why-why analysis as a tool to define the root causes based on the case production where the five main causes are determined as followings.

- Inadequate provision of gas and air
- Gas generation by chemical reaction
- Hot sand stick t pattern
- Poor sand distribution
- Dirty sand

From why-why analysis, the team defines solutions to improve the production line in the following matters.

- Relocate the second thermometer form 50 cm to 100 cm away from the spray fuzzer in order to get the actual temperature of cooling sand.
- Set an accurate control over the ratio of new sand addition and make a record.
- Set the preventive maintenance to the milling and stamping machine.
- Increase capacity of coarse and magnetic material filter from the returned sand by adding another workstation as the second filter.
- Install tower light to alarm when furnace temperature reaches the set point.

The findings from why-why table are brought to further improvement as described in recommended action in the FMEA table. From FMEA study, those 18 factors are ranked based on the level of severity, occurrence, and detection. The first five highest RPNs, which are consequence of using coal dust “A” and presenting corn starch in the mould sand, are as followings.

- ✓ High sulphur in coal dust “A”,
- ✓ High ash content in coal dust “A”,
- ✓ Sand low permeability due to too much water absorption by presenting corn starch,
- ✓ Sand low compactability due to fine substance from corn starch, and
- ✓ Hot sand stick to the pattern due to insufficient cooling of returned sand.

To verify significant effect of the suspected factors to the blowholes or pinholes defect, the OFAT experiments are conducted. Interpreting result from the experiment, it is concluded that brand of coal dust and present of corn starch have significant effects to the blowholes or pinholes defect with 95% confidence. Implementing DOE, it is inferred that the coal dust B and absent of corn starch have influence to the defect without interaction to each other with 95% confidence. The secondary relevant factors to the B111 defect are also observed. Conclusively, temperature is running in the controlled range while moisture, permeability, and compactability are improved as consequences of using coal dust “B” and absenting corn starch. Confirmation is done throughout the mass production of F/W ZE1. The input variables are set according to the control level as in testing combination 4. The B111 defective parts counted as 1.7% of the total cast unit – 6,000 pieces. The amount of other defects are considered as ordinary to the production. By the way, the company can reduce cost 0.52 baht per unit. Furthermore, the company also benefits from casting non-defective parts up to 49,330 baht. The breakeven point is at the first 6,381 cast units and the return on quality investment is approximately 113 times within two years.

6.2 Further recommendation

Since there are many pitfalls during casting production, for example, chemical addition, temperature control in pouring, sand recycle, sand properties inspection, and so on, and these will possibly effect the defectives afterwards and also distort the response. Besides, unskilled and lack of discipline operators will either cause low production performance. Recommendation will go to process control for continuous improvement. The sand properties as verified in prior chapter are basic data but not applicable to make the standard of control. The trends of mositure, permeability, and compactability of mould sand in testing combination 4 are all running in the upper level rather the lower level as of mould sand in testing combination 1. Therefore, study in resetting these control levels will be a part of continuous improvement plan. One of the blowholes or pinholes defect comes from core part of the mould pattern. If the company obtains products including core part in production line, study on the effect from core part should be concerned. The implementation team should set the experiment referring to tools and techniques involved in this thesis as a guidance to study other models. The result from the study will be valuable to set the operation standard that fits to the individual model. Lastly, the operation standard should be revised and announced for common acknowledgement.

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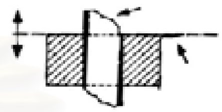
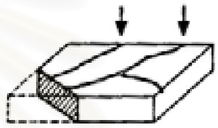
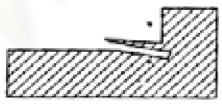
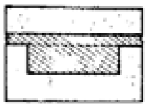
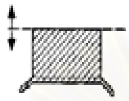
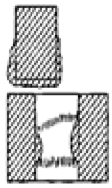
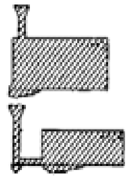
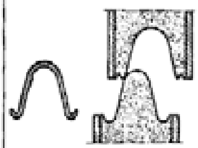
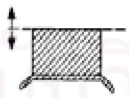
APPENDICES

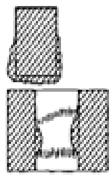
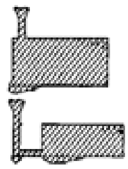
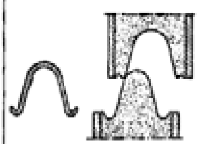
APPENDIX A : International Atlas of Casting Defects Classification

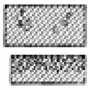
No.	Description	Common Name	Sketch
A 100	**Metallic projections in the form of fins or flash**		
A 110	**Metallic projections in the form of fins (or flash) without change in principal casting dimensions.**		
A 111	Thin fins (or flash) at the parting line or at core prints.	Joint flash or fins	
A 112	Projections in the form of veins on the casting surface.	Veining or finning	
A 113	Network of projections on the surface of diecastings.	Heat checked die	
A 114	Thin projection parallel to a casting surface, in re-entrant angles.	Fillet scab	
A 115	Thin metallic projection located at a re-entrant angle and dividing the angle in two parts.	Fillet vein	

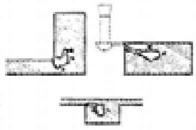
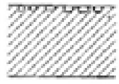
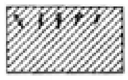
No.	Description	Common Name	Sketch
A 120	**Metallic projections in the form of fins with changes in principal casting dimensions.**		
A 121	Thick fin attached to the casting at the parting line.	Cope raise, raised mold	
A 122	Thick fin at other casting locations	Sag or strain	
A 123	Formation of fins in planes related to direction of mold assembly (precision casting with waste pattern).	Cracked or broken mold	

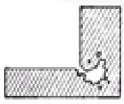
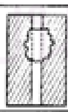
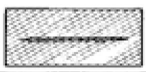
No.	Description	Common Name	Sketch
A 200	**Massive projections.**		
A 210	**Swells.**		
A 211	Excess metal on the external or internal surfaces of the casting.	External or internal swells	
A 212	Excess metal in the vicinity of the gate or beneath the sprue.	Erosion, cut or wash	
A 213	Metal projections in the form of elongated areas in the direction of mold assembly.	Crush	

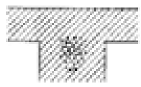
No.	Description	Common Name	Sketch
A 120	**Metallic projections in the form of fins with changes in principal casting dimensions.**		
A 121	Thick fin attached to the casting at the parting line.	Cope raise, raised mold	
A 122	Thick fin at other casting locations	Sag or strain	
A 123	Formation of fins in planes related to direction of mold assembly (precision casting with waste pattern).	Cracked or broken mold	

No.	Description	Common Name	Sketch
A 200	**Massive projections.**		
A 210	**Swells.**		
A 211	Excess metal on the external or internal surfaces of the casting.	External or internal swells	
A 212	Excess metal in the vicinity of the gate or beneath the sprue.	Erosion, cut or wash	
A 213	Metal projections in the form of elongated areas in the direction of mold assembly.	Crush	

No.	Description	Common Name	Sketch
B 100	**Cavities with generally rounded, smooth walls detectable to the naked eye (blowholes, pinholes).**		
B 110	**Class B 100 cavities internal to the casting, not extending to the surface, discernible only by special methods, machining, or fracture of the casting.**		
B 111	Rounded cavities, usually smooth-walled, of varied size, isolated or grouped irregularly in all areas of the casting.	Blowholes, pinholes	
B 112	As above, but limited to the vicinity of metallic pieces placed in the mold (chills, inserts, chaplets, etc.)	Blowholes, adjacent to inserts, chills, chaplets, etc.	
B 113	Like B 111, but accompanied by slag inclusions (G 122).	Slag blowholes	

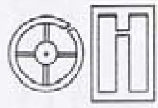
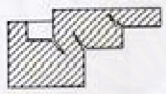
No.	Description	Common Name	Sketch
B 120	**Class B 100 cavities located at or near the casting surface, largely exposed or at least connected with the exterior.**		
B 121	Class B 120 cavities of various sizes, isolated or grouped, usually at or near the surface, with shiny walls.	Surface or subsurface blowholes	
B 122	Class B 120 cavities, in re-entrant angles of the casting, often extending deeply within.	Corner blowholes, draws	
B 123	Fine porosity (cavities) at the casting surface, appearing over more or less extended areas.	Surface pinholes	
B 124	Small, narrow cavities in the form of cracks, appearing on the faces or along edges, generally only after machining.	Dispersed shrinkage	

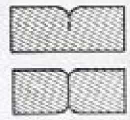
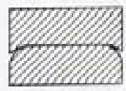
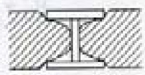
No.	Description	Common Name	Sketch
B 200	**Cavities with generally rough walls, shrinkage.**		
B 210	**Open cavity of Class B 200, sometimes penetrating deeply into the casting.**		
B 211	Funnel-shaped cavity. Wall usually covered with dendrites.	Open or external shrinkage	
B 212	Sharp-edged cavity in fillets of thick castings or at gate locations.	Corner or fillet shrinkage	
B 213	Cavity extending from a core.	Core shrinkage	
B 220	**Class B 200 cavity located completely internal to the casting.**		
B 221	Irregular-shaped cavity. Wall often dendritic.	Internal or blind shrinkage	
B 222	Cavity or porous area along central axis.	Center-line or axial shrinkage	

No.	Description	Common Name	Sketch
B 300	**Porous structures caused by numerous small cavities.**		
B 310	**Cavities according to B 300, scarcely perceptible to the naked eye.**		
B 311	Dispersed, spongy dendritic shrinkage within walls of casting.	Macro- or micro-shrinkage, shrinkage porosity, leakers	

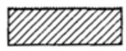
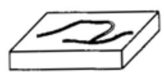
C. Discontinuities

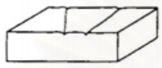
No.	Description	Common Name	Sketch
C 100	**Discontinuities caused by mechanical effects. (Rupture)** **Discontinuities, generally at intersections. According to casting shape and fracture appearance the latter does not seem to be the result of internal tension.**		
C 110	**Normal cracking.**		
C 111	Normal fracture appearance, sometimes with adjacent indentation marks.	Breakage (cold)	
C 120	**Cracking with oxidation.**		
C 121	Fracture surface oxidized completely around edges.	Hot cracking	

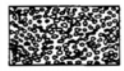
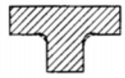
No.	Description	Common Name	Sketch
C200	**Discontinuities caused by internal tension and restraints to contraction (cracks and tears).**		
C 210	**Cold cracking or tearing.**		
C 211	Discontinuities with squared edges in areas susceptible to tensile stresses during cooling. Surface not oxidized.	Cold tearing	
C220	**Hot cracking and tearing.**		
C 221	Irregularly shaped discontinuities in areas susceptible to tension; oxidized fracture surface showing dendritic pattern.	Hot tearing	
C 222	Rupture after complete solidification, either during cooling or heat treatment.	Quench cracking	

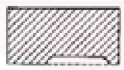
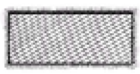
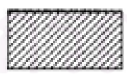
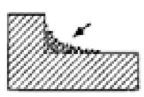
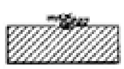
No.	Description	Name	Sketch
C 300	**Discontinuities caused by lack of fusion (cold shuts); edges generally rounded, indicating poor contact between various metal streams during filling of the mold.**		
C 310	**Lack of complete fusion in the last portion of the casting to fill.**		
C 311	Complete or partial separation of casting wall, often in a vertical plane.	Cold shut or cold lap	
C 320	**Lack of fusion between two parts of casting.**		
C 321	Separation of the casting in a horizontal plane.	Interrupted pour	
C 330	**Lack of fusion around chaplets, internal chills and inserts.**		
C 331	Local discontinuity in vicinity of metallic insert.	Chaplet or insert cold shut, unfused chaplet	

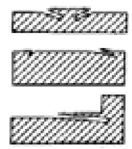
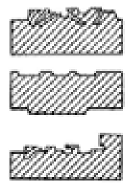
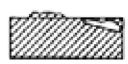
No.	Description	Common Name	Sketch
C 400	**Discontinuities caused by metallurgical defects.**		
C 410	**Separation along grain boundaries.**		
C 411	Separation along grain boundaries of primary crystallization.	Conchoidal or "rock candy" fracture	
C 412	Network of cracks over entire cross-section (zinc die-casting defect).	Intergranular corrosion	

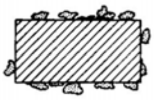
No.	Description	Common Name	Sketch
D 100	**Casting surface irregularities.**		
D 110	**Fold markings on the skin of the casting.**		
D 111	Fold markings over rather large areas of the casting.	Surface folds, gas runs	
D 112	Surface shows a network of jagged folds or wrinkles (ductile iron).	Cope defect, elephant skin, laps	
D 113	Wavy fold markings without discontinuities; edges of folds at same level, casting surface is smooth.	Seams or scars	
D 114	Casting surface markings showing direction of liquid metal flow (light alloys).	Flow marks	

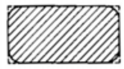
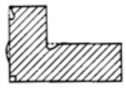
No.	Description	Common Name	Sketch
D 120	**Surface roughness.**		
D 121	Depth of surface roughness is approximately that of the dimensions of the sand grains.	Rough casting surface	
D 122	Depth of surface roughness is greater than that of the sand grain dimensions.	Severe roughness, high pressure molding defect	
D 130	**Grooves on the casting surface.**		
D 131	Grooves of various lengths, often branched, with smooth bottoms and edges.	Buckle	
D 132	Grooves up to 0.2 inches depth, one edge forming a fold which more or less completely covers the groove.	Rat tail	
D 133	Irregularly distributed depressions of various dimensions extending over the casting surface, usually along the path of metal flow (cast steel).	Flow marks, crow's feet	

No.	Description	Common Name	Sketch
D 130	**Grooves on the casting surface. (continued)**		
D 134	Casting surface entirely pitted or pock-marked.	Orange peel, metal-mold reaction, alligator skin	
D 135	Grooves and roughness in the vicinity of re-entrant angles on die castings.	Soldering, die erosion	
D 140	**Depressions in the casting surface.**		
D 141	Casting surface depressions in the vicinity of a hot spot.	Sink marks, draw or suck-in	
D 142	Small, superficial cavities in the form of droplets or shallow spots, generally gray-green in color (investment cast chrome-carbon steels).	Slag inclusions	

No.	Description	Common Name	Sketch
D 200	**Serious surface defects.**		
D 210	**Deep indentation of the casting surface.**		
D 211	Deep indentation, often over large area of drag half of casting.	Push-up, clamp-off	
D 220	**Adherence of sand, more or less vitrified.**		
D 221	Sand layer strongly adhering to the casting surface.	Burn on	
D 222	Very adherent layer of partially fused sand.	Burn in	
D 223	Conglomeration of strongly adhering sand and metal at the hottest points of the casting (re-entrant angles and cores).	Metal penetration	
D 224	Fragment of mold material embedded in casting surface (lost wax investment casting).	Dip coat spall, scab	

No.	Description	Common Name	Sketch
D 230	**Plate-like metallic projections with rough surfaces, usually parallel to casting surface.**		
D 231	Plate-like metallic projections with rough surfaces parallel to casting surface; removable by burr or chisel.	Scabs, expansion scabs	
D 232	As above, but impossible to eliminate except by machining or grinding.	Cope spall, boil scab, erosion scab	
D 233	Flat, metallic projections on the casting where mold or core washes or dressings are used.	Blacking scab	

No.	Description	Name	Sketch
D 240	**Oxides adhering after heat treatment (annealing, tempering, malleablizing) by decarburization.**		
D 241	Adherence of oxide after annealing.	Oxide scale	
D 242	Adherence of ore after malleablizing (white heart malleable).	Adherent packing material	
D 243	Scaling after malleablizing anneal.	Scaling	

No.	Description	Common Name	Sketch
E 100	**Missing portion of casting (no fracture).**		
E 110	**Superficial variations from pattern shape.**		
E 111	Casting is essentially complete except for more or less rounded edges and corners.	Misrun	
E 112	Deformed edges or contours due to poor mold repair or careless application of wash coatings.	Defective coating (tear-dropping) or poor mold repair	

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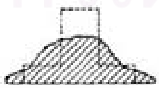
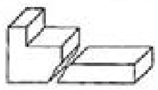
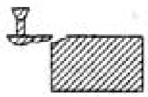
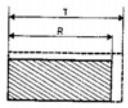
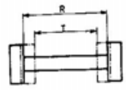
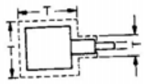
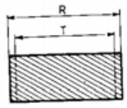
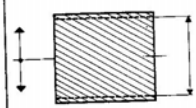
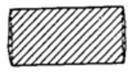
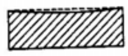
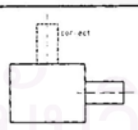
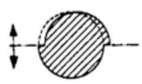
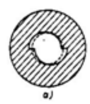
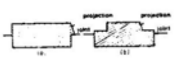
No.	Description	Common Name	Sketch
E 120	**Serious variations from pattern shape.**		
E 121	Casting incomplete due to premature solidification.	Misrun	
E 122	Casting incomplete due to insufficient metal poured.	Poured short	
E 123	Casting incomplete due to loss of metal from mold after pouring.	Runout	
E 124	Significant lack of material due to excessive shot-blasting.	Excessive cleaning	
E 125	Casting partially melted or seriously deformed during annealing.	Fusion or melting during heat treatment	

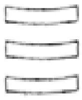
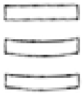
No.	Description	Common Name	Sketch
E 200	**Missing portion of casting (with fracture).**		
E 210	**Fractured casting.**		
E 211	Casting broken, large piece missing; fracture surface not oxidized.	Fractured casting	
E 220	**Piece broken from casting.**		
E 221	Fracture dimensions correspond to those of gates, vents, etc.	Broken casting (at gate, riser or vent)	
E 230	**Fractured casting with oxidized fracture.**		
E 231	Fracture appearance indicates exposure to oxidation while hot.	Early shakeout	

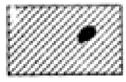
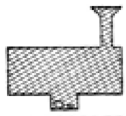
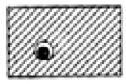
No.	Description	Common Name	Sketch
F 100	**Incorrect dimensions; correct shape.**		
F 110	**All casting dimensions incorrect.**		
F 111	All casting dimensions incorrect in the same proportion.	Improper shrinkage allowance	

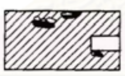
No.	Description	Name	Sketch
F 120	**Certain casting dimensions incorrect.**		
F 121	Distance too great between extended projections.	Hindered contraction	
F 122	Certain dimensions inexact.	Irregular contraction	
F 123	Dimensions too great in the direction of rapping of pattern.	Excess rapping of pattern	
F 124	Dimensions too great in direction perpendicular to parting line.	Mold expansion during baking	
F 125	Excessive metal thickness at irregular locations on casting exterior (same as A 211; Swells).	Soft or insufficient ramming, mold-wall movement	
F 126	Thin casting walls over general area, especially on horizontal surfaces.	Distorted casting	

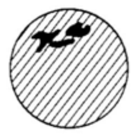
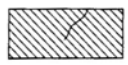
No.	Description	Common Name	Sketch
F 200	**Casting shape incorrect overall or in certain locations.**		
F 210	**Pattern incorrect.**		
F 211	Casting does not conform to the drawing shape in some or many respects; same is true of pattern.	Pattern error	
F 212	Casting shape is different from drawing in a particular area; pattern is correct.	Pattern mounting error	

No.	Description	Common Name	Sketch
F 220	**Shift or Mismatch.**		
F 221	Casting appears to have been subjected to a shearling action in the plane of the parting line.	Shift	
F 222	Variation in shape of an internal casting cavity along the parting line of the core.	Shifted core	
F 223	Irregular projections on vertical surfaces, generally on one side only in the vicinity of the parting line.	Ramoff, ramaway	

No.	Description	Name	Sketch
F 230	**Deformations from correct shape.**		
F 231	Deformation with respect to drawing proportional for casting, mold and pattern.	Deformed pattern	
F 232	Deformation with respect to drawing proportional for casting and mold. Pattern conforms to drawing.	Deformed mold, mold creep, spring-back	
F 233	Casting deformed with respect to drawing. Pattern and mold conform to drawing.	Casting distortion	
F 234	Casting deformed with respect to drawing after storage, annealing, machining.	Warped casting	

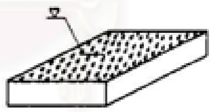
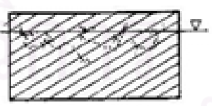
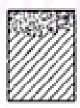
No.	Description	Common Name	Sketch
G 100	**Inclusions.**		
G 110	**Metallic inclusions.**		
G 111	Inclusions whose appearance, chemical analysis or structural examination show to be caused by an element foreign to the alloy.	Metallic inclusions	
G 112	Inclusions of the same chemical composition as the base metal; generally spherical and often coated with oxide.	Cold shot	
G 113 A 311	Spherical metallic inclusions inside blowholes or other cavities or in surface depressions (see A 311). Composition approximates that of the alloy cast but nearer to that of a eutectic.	Internal sweating, phosphide sweat	

No.	Description	Common Name	Sketch
G 120	**Non-metallic inclusions; slag, dross, flux.**		
G 121	Non-metallic inclusions whose appearance or analysis shows they arise from melting slags, products of metal treatment or fluxes.	Slag, dross or flux inclusions, ceroxides	
G 122	Non-metallic inclusions generally impregnated with gas and accompanied by blowholes (B 113).	Slag blowhole defect	
G 130	**Non-metallic inclusions; mold or core materials.**		
G 131	Sand inclusions, generally very close to the surface of the casting.	Sand inclusions	
G 132	Inclusions of mold blacking or dressing, generally very close to the casting surface.	Blacking or refractory coating inclusions	

No.	Description	Common Name	Sketch
G 140	**Non-metallic inclusions; oxides and reaction products.**		
G 141	Clearly defined, irregular black spots on the fractured surface of ductile cast iron.	Black spots	
G 142	Inclusions in the form of oxide skins, most often causing a localized seam.	Oxide inclusion or skins, seams	
G 143	Folded films of graphitic luster in the wall of the casting	Lustrous carbon films, or kish tracks	
G 144	Hard inclusions in permanent molded and die cast aluminum alloys.	Hard spots	

No.	Description	Name	Sketch
G 200	**Structural anomalies visible by macroscopic observation.**		
G 210	**Abnormal structures in gray cast iron.**		
G 211	Structure partially or totally white, particularly in thin walls, projecting corners and edges, showing gradual transition to a normal structure.	Chill spots, hard edges, primary chill	
G 212	Like G 211, but without any transition to a normal structure.	Unmottled chill, clear chill	
G 213	White zones clearly outlined in the last sections of the casting to solidify. Structure at surface is gray.	Inverse chill	

No.	Description	Common Name	Sketch
G 220	**Abnormal malleable iron structures.**		
G 221	Dark spots in the as-cast structure; gray-black fracture with coarse grain size after heat treatment.	Primary graphite	
G 222	Black-heart malleable; fracture after annealing shows a distinct shiny layer over 0.5 mm thick at surface with dark interior.	Excessive pearlite layer	
G 223	Shallow, hard surface layer whose structure contains phases due to quenching.	Localized hard spots or chilled areas	

No.	Description	Common Name	Sketch
G 260	**Abnormal graphite formation.**		
G 261	Regularly-distributed, coarse graphite.	Kish graphite spots, open grain	
G 262	Local accumulations of coarse graphite in the structure. Precipitation of graphite in shrinkage cavities.	Kish graphite inclusions	
G 263	Concentrations of graphite nodules on the upper surfaces of castings (ductile iron).	Carbon flotation	
G 264	Fracture shows randomly oriented flat facets (ductile iron, eutectic Al-Si alloy).	Facetted (dendritic) structure	

APPENDIX B : FMEA TABLE

Process FMEA (Failure Mode and Effect Analysis)

Process Name : ___________ Documented by : _______________________ FMEA No. : _____________

Product Name : ___________ Responsibility : ______________ FMEA Date (Org.) : ______ (Rev.) : ____

Core Team : ____ Page : __ of __

Column 1	Column 2	Column 3	4	Column 5	6	Column 7	8	9	Column 10	Column 11	12	13	14	15	16
Process Function and Requirement	Potential Failure Mode	Potential Effect(s) of Failure	S	Potential Cause(s) / Mechanism(s) of Failure	O	Current Process Controls	D	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Action Result				
											Action	S	O	D	RPN

APPENDIX C: OFAT RECORD

No.	OFAT				No.	OFAT			
	Coal dust "A"	Coal dust "B"	Present corn starch	Absent corn starch		Coal dust "A"	Coal dust "B"	Present corn starch	Absent corn starch
1	0	0	0	0	43	0	0	0	0
2	0	0	0	0	44	0	0	0	0
3	0	0	0	0	45	0	0	0	0
4	0	0	1	0	46	0	0	0	0
5	4	0	0	0	47	0	0	0	0
6	0	0	0	0	48	2	0	1	0
7	0	1	0	0	49	0	0	0	0
8	0	0	0	0	50	0	0	0	0
9	0	0	0	1	51	0	0	0	0
10	0	0	2	0	52	0	1	0	0
11	0	0	0	0	53	0	0	0	0
12	3	2	0	0	54	0	0	0	0
13	0	0	0	0	55	0	0	0	0
14	0	0	0	2	56	1	0	3	0
15	2	0	0	0	57	0	0	0	0
16	0	0	2	0	58	0	0	0	0
17	0	0	0	0	59	1	0	0	1
18	0	0	0	0	60	0	0	0	0
19	0	1	0	0	61	0	0	0	0
20	5	0	0	0	62	0	2	0	0
21	2	0	3	0	63	0	0	4	0
22	0	0	2	0	64	0	0	0	0
23	0	0	1	0	65	0	0	0	0
24	1	0	0	0	66	0	0	0	1
25	0	0	0	0	67	6	0	0	0
26	0	0	0	0	68	2	0	0	0
27	0	0	0	0	69	0	0	0	0
28	0	0	0	0	70	0	0	2	0
29	0	0	0	0	71	0	0	0	0
30	0	2	0	0	72	0	0	0	0
31	0	0	4	0	73	0	0	0	0
32	3	0	0	3	74	0	0	0	0
33	4	0	0	0	75	0	0	0	0
34	0	0	0	0	76	0	4	0	0
35	0	0	0	0	77	2	0	3	1
36	6	0	6	0	78	0	0	0	0
37	0	1	0	0	79	0	0	0	0
38	0	0	0	0	80	0	0	0	0
39	0	0	0	0	81	0	0	0	0
40	4	0	0	0	82	0	0	0	0
41	0	0	0	0	83	1	0	1	0
42	0	0	2	0	84	0	0	0	0

(continued)

No.	OFAT			
	Coal dust "A"	Coal dust "B"	Present corn starch	Absent corn starch
85	0	3	1	0
86	0	0	0	0
87	0	0	0	2
88	0	0	0	0
89	0	0	0	0
90	0	0	2	0
91	0	0	0	0
92	0	0	0	0
93	4	0	0	0
94	0	0	0	0
95	0	0	2	0
96	0	0	0	0
97	0	0	0	0
98	0	0	0	0
99	0	1	1	0
100	0	0	0	0
101	2	0	0	0
102	0	0	0	0
103	0	0	0	2
104	0	0	1	0
105	0	0	0	0
106	0	0	0	0
107	2	0	0	0
108	0	2	2	0
109	0	0	2	0
110	0	0	0	0
111	0	0	0	0
112	0	0	0	0
113	0	0	0	0
114	3	0	3	1
115	0	0	0	0
116	0	0	0	0
117	0	0	0	0
118	0	0	0	0
119	2	2	4	0
120	0	0	0	0
121	0	0	0	0
122	0	0	0	0
123	0	0	0	0
124	0	0	0	1
125	0	0	0	0
126	0	0	0	0
127	4	0	1	0
128	0	0	0	0
129	0	0	0	0
130	0	0	0	0
131	0	0	0	0
132	0	0	0	0
133	0	0	0	0
134	0	0	0	0
135	1	1	3	0
136	0	0	0	0
137	0	0	0	0
138	0	0	0	0
139	0	0	0	1
140	0	0	0	0
141	0	0	0	0
142	0	0	0	0
143	0	0	5	0
144	0	0	0	0
145	0	0	0	0
146	0	0	0	0
147	0	2	0	0
148	0	0	0	0
149	0	0	0	0
150	2	0	0	0
151	0	0	2	0
152	0	0	0	2
153	0	0	0	0
154	3	0	0	0
155	0	0	0	0
156	0	0	0	0
157	0	0	0	0
158	0	1	0	0
159	0	0	1	0
160	0	0	0	0
161	0	0	0	0
162	0	0	0	0
163	0	0	2	0
164	3	0	0	0
165	0	0	0	0
166	0	0	0	0
167	1	0	2	0
168	0	0	0	0
Total defects (pcs)	**28**	**15**	**31**	**12**

APPENDIX D : 2^2 Experiment Record

Rep.1 No.	Coal A vs present of corn starch	Coal B vs present of corn starch	Coal A vs absent of corn starch	Coal B vs absent of corn starch
1	0	0	0	0
2	0	0	0	0
3	3	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	1	2	0
10	1	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	2	0	0	0
16	0	0	0	0
17	0	0	1	0
18	0	0	0	0
19	0	3	0	0
20	0	0	0	0
21	0	0	0	0
22	0	0	0	1
23	0	0	0	0
24	0	0	1	0
25	0	0	0	0
26	0	0	0	0
27	0	4	0	0
28	2	0	0	0
29	0	0	0	0
30	0	0	1	0
31	0	0	0	0
32	0	0	0	0
33	0	0	0	0
34	0	0	0	0
35	0	0	0	0
36	0	0	1	0
37	0	0	0	0
38	6	0	0	0
39	0	2	0	0
40	0	0	0	0
41	0	0	0	0
42	0	0	0	0
43	0	0	0	0
44	0	0	0	0
45	0	0	0	0
46	0	0	0	0
47	2	0	0	0
48	0	0	0	0
49	0	0	0	0
50	0	0	0	0
51	0	0	0	0
52	0	0	2	0
53	0	0	0	2
54	0	0	0	0
55	0	0	0	0
56	1	0	0	0
57	0	0	0	0
58	0	1	0	0
59	0	0	0	0
60	0	0	0	0
61	0	0	0	0
62	0	0	0	0
63	1	0	0	0
64	0	0	2	0
65	0	0	0	0
66	0	0	0	0
67	0	0	0	0
68	0	0	0	0
69	0	0	0	0
70	0	0	0	0
71	3	0	2	0
72	0	0	0	0
73	0	0	0	0
74	0	0	0	0
75	0	2	0	0
76	4	0	0	0
77	0	0	0	0
78	0	0	0	0
79	0	0	0	0
80	0	0	0	0
81	0	0	0	0
82	0	0	0	0
83	0	0	1	0
84	0	0	0	0

(continued)

Rep1 No.	Coal A vs present of corn starch	Coal B vs present of corn starch	Coal A vs absent of corn starch	Coal B vs absent of corn starch	Rep1 No.	Coal A vs present of corn starch	Coal B vs present of corn starch	Coal A vs absent of corn starch	Coal B vs absent of corn starch
85	1	0	0	0	127	0	0	1	0
86	2	0	0	0	128	0	0	0	0
87	1	0	0	0	129	0	0	0	0
88	0	0	0	0	130	0	0	0	0
89	0	1	1	0	131	0	0	0	0
90	0	0	0	0	132	5	0	0	0
91	0	0	0	0	133	0	0	0	0
92	0	0	0	0	134	0	0	0	0
93	0	0	0	1	135	0	0	0	0
94	0	0	0	0	136	0	0	1	0
95	0	0	0	0	137	0	0	0	0
96	0	0	0	0	138	0	0	0	0
97	0	0	0	0	139	0	0	0	0
98	4	0	3	0	140	0	0	0	0
99	0	0	1	0	141	2	0	0	0
100	0	0	0	0	142	0	0	0	2
101	0	0	2	0	143	0	0	0	0
102	0	0	0	0	144	0	0	0	0
103	0	0	0	0	145	0	1	0	0
104	0	0	0	0	146	2	0	0	0
105	0	2	0	0	147	0	0	0	0
106	0	0	0	0	148	0	0	1	0
107	0	0	0	0	149	0	0	0	0
108	0	0	0	0	150	0	0	0	0
109	1	0	1	0	151	0	0	0	0
110	0	0	0	0	152	0	0	0	0
111	0	0	1	0	153	3	0	0	0
112	0	0	0	0	154	0	0	0	0
113	0	0	0	0	155	0	0	0	0
114	3	0	0	0	156	0	0	0	0
115	0	0	0	0	157	0	0	0	1
116	0	0	0	0	158	0	0	0	0
117	0	0	0	0	159	0	0	0	0
118	0	0	0	1	160	0	0	1	0
119	2	0	0	0	161	4	0	0	0
120	0	0	0	0	162	0	0	0	0
121	0	0	0	0	163	2	0	0	0
122	0	3	0	0	164	3	0	0	0
123	0	0	0	0	165	0	0	0	0
124	0	0	0	0	166	0	0	0	0
125	0	0	0	0	167	0	0	0	0
126	0	0	0	0	168	0	0	0	0
					Total Defect	25	11	13	3

(continued)

Rep.2 No.	Coal A vs present of corn starch	Coal B vs present of corn starch	Coal A vs absent of corn starch	Coal B vs absent of corn starch	Rep.2 No.	Coal A vs present of corn starch	Coal B vs present of corn starch	Coal A vs absent of corn starch	Coal B vs absent of corn starch
1	0	0	0	0	43	0	0	0	0
2	0	0	0	0	44	0	0	0	2
3	0	0	0	0	45	1	0	0	0
4	0	0	0	0	46	0	0	0	0
5	0	0	0	0	47	0	0	0	0
6	0	0	0	0	48	4	0	0	0
7	1	0	0	0	49	0	0	0	0
8	0	0	0	0	50	0	3	0	0
9	0	0	0	0	51	0	0	0	0
10	0	0	0	0	52	0	0	0	0
11	0	1	0	0	53	0	0	0	0
12	0	0	0	0	54	0	0	0	0
13	0	0	0	0	55	0	0	0	0
14	0	0	0	0	56	0	0	3	0
15	0	0	0	0	57	0	0	0	0
16	2	0	0	0	58	0	0	0	0
17	0	0	1	0	59	0	0	0	0
18	0	0	0	0	60	3	0	0	0
19	0	1	0	0	61	0	2	0	0
20	0	0	0	0	62	0	0	0	0
21	0	0	0	0	63	0	0	0	0
22	1	0	0	0	64	0	0	2	0
23	0	0	0	0	65	0	0	0	0
24	0	0	0	0	66	1	0	0	0
25	0	0	0	0	67	0	0	0	0
26	0	0	0	0	68	0	0	0	0
27	0	0	0	0	69	0	1	0	0
28	2	0	0	0	70	0	0	0	0
29	0	2	1	0	71	0	0	0	0
30	0	0	0	0	72	0	0	0	0
31	0	0	0	0	73	2	1	0	0
32	0	0	0	0	74	0	0	0	0
33	0	0	0	0	75	0	0	0	0
34	0	0	0	0	76	0	0	0	0
35	0	0	0	0	77	0	0	0	0
36	0	0	0	0	78	2	0	1	0
37	1	0	0	0	79	0	0	0	0
38	0	0	0	0	80	0	0	0	0
39	0	0	0	0	81	0	0	0	0
40	0	2	0	0	82	0	0	0	0
41	0	0	1	0	83	2	0	0	0
42	0	0	0	0	84	2	1	0	0

(continued)

Rep.2 No.	Coal A vs present of corn starch	Coal B vs present of corn starch	Coal A vs absent of corn starch	Coal B vs absent of corn starch	Rep.2 No.	Coal A vs present of corn starch	Coal B vs present of corn starch	Coal A vs absent of corn starch	Coal B vs absent of corn starch
85	0	0	0	0	127	0	0	0	0
86	0	0	0	0	128	0	0	0	0
87	0	0	0	0	129	0	0	0	0
88	0	0	0	0	130	2	0	0	0
89	0	0	0	0	131	0	0	0	0
90	2	0	0	0	132	0	0	0	0
91	0	0	1	0	133	0	1	0	0
92	0	0	0	0	134	1	0	0	0
93	0	0	0	0	135	0	0	2	0
94	0	0	0	0	136	0	0	0	0
95	1	0	0	0	137	0	0	0	0
96	0	0	0	0	138	3	0	0	0
97	0	0	0	0	139	0	0	0	0
98	0	2	0	0	140	0	0	0	0
99	0	0	0	0	141	0	0	0	0
100	1	0	0	0	142	0	0	0	0
101	0	0	0	0	143	0	0	1	0
102	0	0	0	0	144	0	0	0	0
103	0	0	0	0	145	1	0	0	0
104	0	0	0	0	146	0	0	0	0
105	0	0	0	0	147	0	0	0	0
106	0	0	1	0	148	0	0	0	0
107	0	0	0	0	149	0	0	0	0
108	1	0	0	0	150	0	0	0	0
109	0	0	0	0	151	0	1	0	0
110	0	0	0	0	152	0	0	0	0
111	0	0	0	0	153	0	0	0	0
112	0	0	0	0	154	0	0	0	0
113	0	1	0	0	155	0	0	0	0
114	0	0	0	1	156	0	1	0	0
115	0	0	0	0	157	0	0	0	0
116	0	0	0	0	158	0	0	0	0
117	2	0	0	0	159	2	0	0	0
118	0	0	0	0	160	0	0	0	0
119	0	0	0	0	161	1	0	0	0
120	0	0	0	0	162	0	0	0	0
121	3	0	0	0	163	0	0	0	0
122	0	0	0	0	164	0	0	0	0
123	0	0	0	0	165	0	0	0	0
124	0	1	0	0	166	0	0	0	0
125	0	0	0	0	167	2	0	0	0
126	3	0	1	0	168	0	0	0	0
					Total Defect	27	15	11	2

BIOGRAPHY

Intira Laosrimongkol was born in Bangkok, 1976. She graduated from Assumption University in 1998 with a Bachelor Degree in Electronics Engineering. After graduated, she had involved in new project team in charging of product and process quality control for two and a half year at Cal-Comp Electronics (Thailand) Plc., Ltd. She engaged her second career as an Assistant Sales Manager (Technical sales support) for WKK (Thailand) Ltd. for three years. She, presently, works for her family business regarding automotive spare parts manufacture. She continues her study in Engineering Business Management for Master Degree at Regional Centre for Manufacturing Systems Engineering, Chulalongkorn University (TH) and University of Warwick (UK).