DEFECT REDUCTION IN MANUFACTURING PROCESS OF IN-MOLD DECORATION OF INJECTION MOLDED COMPONENTS

Miss Jintra Supapan

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering in Industrial Engineering
Department of Industrial Engineering
Faculty of Engineering
Chulalongkorn University
Academic Year 2018

การลดของเสียในกระบวนการผลิตชิ้นส่วนฉีดตกแต่งในแม่พิมพ์

น.ส.จินตรา สุภาพันธ์

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชาวิศวกรรมอุตสาหการ ภาควิชาวิศวกรรมอุตสาหการ
คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2561

Thesis Title	DEFECT REDUCTION IN MANUFACTURING PROCESS O F IN- MOLD DECORATION OF INJECTION MOLDED COMPON ENTS
By	Miss Jintra Supapan
Field of Study	Industrial Engineering
Thesis Advisor	Professor PARAMES CHUTIMA, Ph.D.

Accepted by the Faculty of Engineering, Chulalongkorn University in Partial Fulfillment of the Requirement for the Master of Engineering

.... Dean of the Faculty of Engineering

(Associate Professor SUPOT TEACHAVORASINSKUN, Ph.D.)

THESIS COMMITTEE

.... Chairman

(Associate Professor JEERAPAT NGAOPRASERTWONG)

.... Thesis Advisor

(Professor PARAMES CHUTIMA, Ph.D.)

.... Examiner

(Assistant Professor Somchai Puajindanetr, Ph.D.)

.... External Examiner

(Associate Professor Vanchai Rijiravanich, Ph.D.)

จินตรา สุภาพันธ์ : การลดของเสียในกระบวนการผลิตชิ้นส่วนฉีดตกแต่งในแม่พิมพ์. (DEFECT REDUCTION IN MANUFACTURING PROCESS OF IN-MOLD DECORATION OF INJECTION MOLDED COMPONENTS) อ.ที่ปรึกษาหลัก : ศ. ดร.ปารเมศ ชุติมา

วิทยานิพนธ์ฉบับนี้มีวัตถุประสงค์เพื่อลดของเสียจากกระบวนการผลิตชิ้นส่วนฉีดตกแต่งในมาพิมพ์ ซึ่งเป็นกระบวนที่รวมเอาชิ้นส่วนตกแต่งไว้บน PET film จากนั้นทำการฉีดพลาสติกชนิด ABS เข้าไปในด้านหลังของ PET film เพื่อให้ได้ชิ้นงานที่มีผิวทนทานและสวยงาม และยังเป็นการลดกระบวนการในการเพิ่มการพิมพ์ชิ้นส่วนตกแต่งหลังการฉีดชิ้นงาน

จากการศึกษาข้อมูลจากโรงงานกรณีศึกษาจะพบว่า มีของเสียที่เกิดจากกระบวนการผลิตชิ้นส่วนตกแต่งในแม่พิมพ์คิดเป็น 11.43% ซึ่งปัญหาหลักๆเกิดจาก PET Film ไม่ยึดเกาะในระหว่างชั้นของการพิมพ์และชิ้นงานเสียรูปที่ส่งผลต่อการประกอบชิ้นงาน เพื่อทำการลดของเสียที่เกิดขึ้นดังกล่าว โดยใช้หลักการของ Six Sigma ซึ่งมีทั้งหมด 5 ขั้นตอน ได้แก่ การนิยามปัญหา การวัดเพื่อระบุสาเหตุของปัญหา การวิเคราะห์สาเหตุของปัญหา การปรับปรุงแก้ไขกระบวนการ และ การควบคุมกระบวนการ โดยการดำเนินการจะเริ่มจากการศึกษาลำดับขั้นตอนและรายละเอียดของกระบวนการ จากนั้นระบุปัญหา กำหนดวิธีการวัดเพื่อระบุสาเหตุของปัญหา โดยใช้แผนภาพแสดงเหตุและผล และคัดเลือกตัวแปรที่จะนำมาทำการศึกษาโดยใช้เทคนิคการวิเคราะห์ข้อบกพร่องและผลกระทบ (FMEA) จากนั้นนำเอาปัจจัยที่คาดว่าจะมีผลต่อสาเหตุของปัญหามาทำการประยุกต์การออกแบบการทดลอง โดยใช้ DOE จากนั้นทำการหาพารามิเตอร์ที่เหมาะสมเพื่อทำการควบคุมกระบวนการต่อไป

หลังจากทำการปรับปรุงการบวนการแล้วพบว่าสัดส่วนของเสียที่เกิดจากชิ้นส่วนตกแต่งในแม่พิมพ์ลดลงจาก 11.43% เหลือ 1.25% ซึ่งสามารถทำการปรับปรุงเพื่อลดของเสียทั้งหมดได้ 89% หลังจากทำการปรับปรุงกระบวนการสามารถลดของเสียประเภท PET Film ไม่ยึดเกาะในระหว่างชั้นของการพิมพ์ได้ 86.6% และสามารถลดของเสียประเภทชิ้นส่วนเสียรูปได้ 97.8%

สาขาวิชา	วิศวกรรมอุตสาหการ	ลายมือชื่อนิสิต ....
ปีการศึกษา	2561	ลายมือชื่อ อ.ที่ปรึกษาหลัก ....

6070915421 : MAJOR INDUSTRIAL ENGINEERING

KEYWORD: In-mold decoration, Injection molding, PET film, Six sigma

Jintra Supapan : DEFECT REDUCTION IN MANUFACTURING PROCESS OF IN-MOLD DECORATION OF INJECTION MOLDED COMPONENTS. Advisor: Prof. PARAMES CHUTIMA, Ph.D.

The purpose of this research is to reduce the defect rate from manufacturing process of in-mould decoration (IMD), a process combining PET film with decorative patterns are moulded together with ABS resins, which has been developed to reduce the secondary process of decorative screen printing.

Recently, the case study company has produced components with a high defect rate average 11.43% in Feb-Jun 2018, which increased sharply to 22.3% in June 2018. The major causes of the defect resulting from PET film peeled off and difficult to assembly. In order to reduce the defect rate, the five steps of the DMAIC Six Sigma methodology are implemented. The detail of the IMD manufacturing process was studied to identify appropriate measurement methods and factors affecting PET film peeled off by using the cause and effect diagram and its scoring matrix. Then the prioritized factors were analyzed and selected from FMEA to conduct the design of experiment (DOE) to find significant factors and optimal parameter settings for improvement and control process to prevent reoccurrence.

After improvement of PET film peeled off by setting appropriate parameter as well as implementing control plans and Standard Operation Procedure (SOP) to eliminate other defects from in-mould decoration process, the result shows that the defect rate of in-mould decoration process decreased from11.43% average in Feb-June 2018 to1.25% after improvement in July-Oct 2018. It is found that IMD peeled off defect is reduce 86.6% and warpage defect is reduce 97.8% of defect before improvement.

Field of Study:	Industrial Engineering	Student's Signature ....
Academic Year:	2018	Advisor's Signature ....

ACKNOWLEDGEMENTS

The author gratefully acknowledges the thesis advisor: Professor Parames Chutima, Ph.D. who give all suggestions and direction to fulfill the accomplishment of this thesis. I really appreciate all grate supports from him. Moreover, I would like to thank the laboratory team as well as my colleagues in China for supporting all related data and supplementary to do the experiment. This research was also supported by the factory manager of the case study company who provide all materials, equipment and facility for supporting the experiments and manufacturing trials in this research.

Jintra Supapan

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

CHAPTER I

INTRODUCTION

Several grades of plastic have been developed to use in wide range of applications in manufacturing industries. The polymer can be produced by different fabrication process which depend on their applications such as compression moulding, injection moulding, extrusion and blow moulding. Injection moulding is the most useful process which are widely used to produce the plastic products especially, when large quantities and cost effective are required in recently competitive business.

The appearance of plastic products is becoming an important characteristic, especially in decorative components because of the diversification of products design in the market which requires aesthetic patterns such as high gloss and brilliant colours of graphic, texture effects, and surface decorations (Chen, Li et al. 2010). For these reasons, the in-mould decoration injection process, the process whereby a film with decorative elements are being moulded together with plastic resin, has been developed as new technology to combine several steps of decorated and moulded parts to reduce secondary process of creation the aesthetic patterns of components or products such as screen printing, spraying, surface plating and coating which can relatively save both production cycle times and manufacturing costs (Lin, Chen et al. 2015). In addition, the In-mould decoration (IMD) product can provide not only the high quality of appearance but also good durability against friction, scratches, chemical resistance and environmental effects(Chen, Li et al. 2010).

According to advantages of in-mould decoration (IMD), it has been typically, employed for applications of moulded part in various industry such as automotive interior, cellular applications, phone case and household appliances. In addition, In-mould decoration (IMD) will rapidly trend to become the priority choice for manufacturing of moulded parts and more application in the future.

1.1 Company Profile

The case study company of this research is one of electronics company who produces and supplies various type of products not only IMD parts but also membrane switch, Glass assembly, ITO touch film, screw and HSD components. The case study company was founded in 1997, located in China. This company has production and assembly capacity of 12 million quantities per year for IMD components and also experienced to produce IMD component since 2006 (more than 10 years). They have 9 sets of injection machine, 14 sets of forming machine, 8 set of automatic printing machine, 10 sets of semi-automatic printing machine and 2 painting system for supporting production capacity of IMD components. Although this company has more than 10 years' experience about IMD components, they are not a specialist in this field that can be observed by IMD production capacity is small portion when compare to overall products. Some production process of this company still using the traditional methods and insufficient technology to support production. For these reason, the improvement activities are required to support this company to get better capability and achieve quality level.

1.2 In-Mould Decoration Components

In-mould Decoration (IMD) is a process to produce the aesthetic moulded components whereby a film with decorative elements is being moulded together with the plastic to create decorative patterns and reduce the secondary process of graphics and screen printing (Wong A.C-Y 1997). The IMD fabrication process follows four main steps, i.e., screen printing, thermal forming, trimming and moulded to be some parts by injection moulding as presents in Figure 1 and Figure 2.

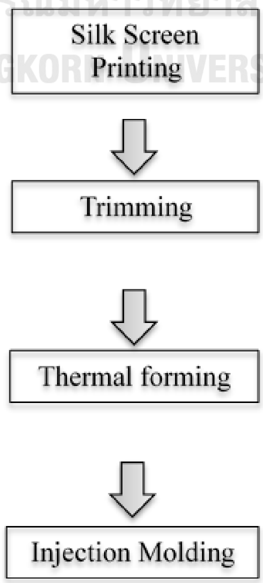


Figure 1 the main IMD process step

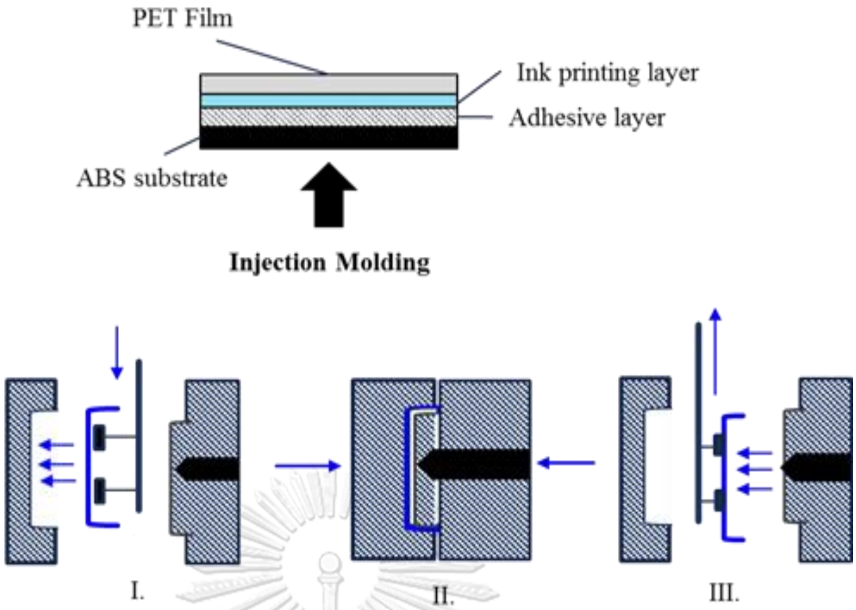


Figure 2 the in-mould decoration injection moulding process

The classification of In Mould Decoration (IMD) in Figure 3 is separated by two type following

1) In Mould Lay (IML) which involves laying of individual film into the tool during the moulding process.

2) In Mould Roll (IMR) which involves the film in a roll format that is moulded together with the plastic part.

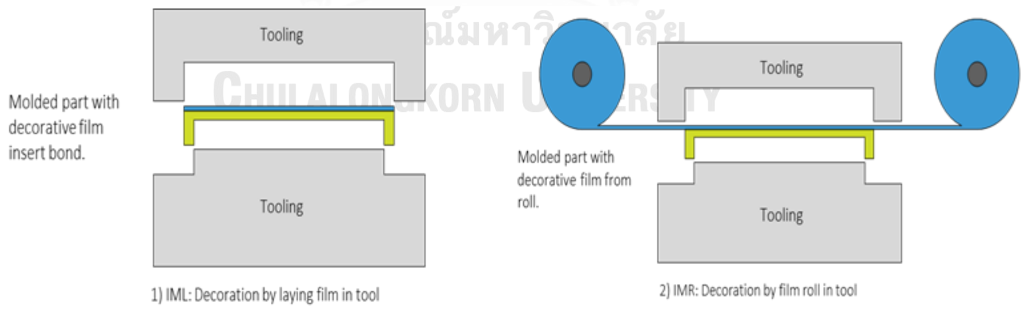


Figure 3 classification of In Mould Decoration (IMD)

The in-mould decoration components, which can be abbreviation as “IMD”, then will be shortly mentioned as “the IMD”. The In-Mould Decoration (IMD) in this research is belong to a part of the aesthetic component in screen cover panel of the washing machine product. There are 4 steps of IMD fabrication process represent following;

1.2.1 Screen printing

This is a first step of IMD fabrication process by creation of graphics in the PET film based on artwork provided the graphic and colour. The printing process is done layer by layer on an underside of the film using the corrected screen printing mesh. After finished this process, the printed films must be fully cured before going to conduct screen printing in the next layer. The number of Ink printing layers of PET film with silk screen printing depends on the complicated design and number of colours of artwork graphic including layer of transparent PET film and agglutinant layer as presents in Figure 4.

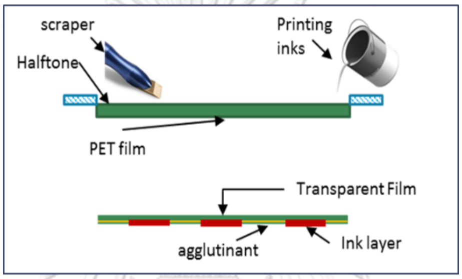


Figure 4 IMD Screen printing process

1.2.2 Thermal forming

This process is carried out after screen printing by forming of the shape to fit the position and alignment of components that required to assembly with another part. This is done through a thermal forming process (Chen, Huang et al. 2008) with positive (lower die) and negative (Upper die) tools. In the first step, PET films are inserted to forming palette, then the films are tempered to the appropriate level of temperature. This temperature equates to the glass transition temperature of PET, which provides a smooth forming with a low distortion and positioning tolerances.

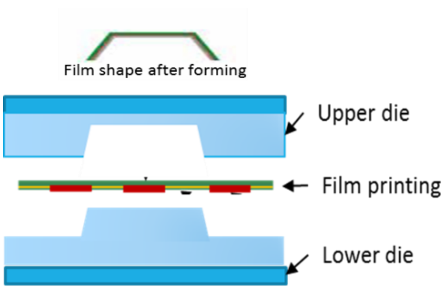


Figure 5 IMD Thermal forming

1.2.3 Trimming

Trimming is a process of cutting the final printed films usually by means of punching after thermal forming to be the specified shape and ready for moulding to be the completed parts. The films are placed in the corrected position before trimming by two stages. A first stage is vertical trimming around the film, followed by a second stage is horizontal punching to be the final 3D-shape of parts, represented in Figure 6.

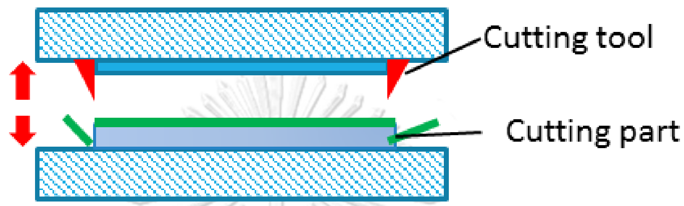


Figure 6 IMD Thermal forming

1.2.4 Injection Moulding

The final process of IMD is injection moulding by moulded ABS plastic to the back side of the completed forming PET with completed graphic printing to be the final decorated part, shown in Figure 7.

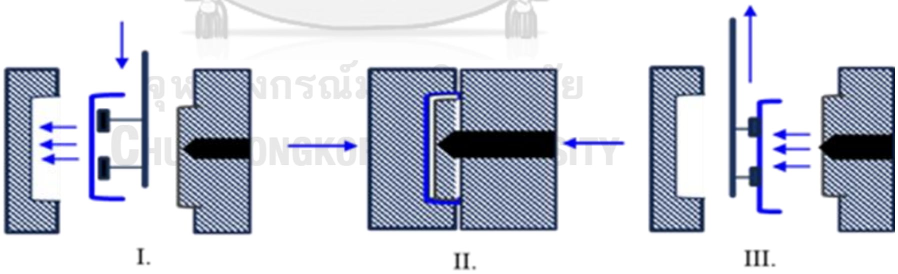


Figure 7 IMD Injection Moulding

1.3 Statement of Problem

The overall defect rate (SDPPM) of front load Fabric care product has continually increased since quarter 4 of Y2017 until recently quarter 2 of Y2018. Recently, top one of parts individual defect rate in Jun, 2018 was increased sharply from IMD component which is a new technology implementing as new product introduction of Front load fabric care. The case study company has just selected to be the new outsource, the second source of IMD components instead of current outsource who is not a specialist in this field. This can be observed by high defect rate and IMD production capacity is small portion when compare to overall products. Some production process of this company still using the traditional methods and insufficient process control system to meet required supplier performance.

In addition, the cost reduction project is done by developing this case study company who able to provide lower cost with same performance level comparing with current outsource who produces IMD components. In this case, can be also reduced the direct material cost. For these reason, the quality improvement activities are required to support this case study company to get better capability and achieve quality level.

1.4 Objective of Thesis

The objective of this study is to reduce defect rate of in-mould decoration components focusing on TC3 model process to meet quality target and reduce process variation by implementing five steps of six sigma DMAIC.

1.5 Scope of Thesis

The scope of this thesis is to study overall manufacturing process of In-mould decoration (IMD) components at the IMD process of the case study company consist of 4 main steps including screen printing, thermal forming, trimming and injection process in order improve quality level by reduction defective rate of IMD inlay panel components TC3 model by focusing on mainly two problems as follows;

1. PET film peel off
2. Difficult to assembly

Aspect of IMD difficult to assembly issue will point to improve dimension out of spec and part warpage of IMD panel by focusing on Process Capability (Cpk) of dimension to meet target as 1.33 implemented by adjusting mean and reduce variation to maintain quality level and prevent reoccurrence issue from manufacturing process.

However, this research is carried out quality improvement to cover only the IMD components of washing machine which are assembled with control panel. As aspect of other concerned assembly components such as LED display, knob, PCB and other connected parts with IMD are not included.

1.6 Expected benefit

The direct benefit required from this quality improvement project is defect reduction to achieve high quality level and minimize customer complains rate from IMD components. Regarding other benefit obtained from this research is following;

- Cost reduction by decreasing number of defects from the IMD components
- Cost reduction by developing the new outsource of IMD components (Develop this case study company to replace the current outsource)
- Increase yield rate and productivity
- Reduce cost of poor quality from rework and recheck
- Increase customer satisfaction level

1.7 Research Methodology

The research methodology of this thesis is based on 5 steps of six sigma methodology (DMAIC) which can be explained with quality control and statistical tools (Pugna, Negrea et al. 2016) following below table. Regarding description of individual step are following;

1) Review the literatures and related theory
2) Clarify Problem background and impact of business case
3) Define problem description and brainstorming to find high risk of potential causes to set up goal and project scope
4) Design the measurement methods appropriate with case study
5) Data collection and measure current situation
6) Identify potential root cause and select concern factors to do experiment
7) Do the experiment following selected factors and interpret data
8) Find the optimal solution then perform improvement and verify effectiveness
9) Set up control plan, control chart and standardization work
10) Summarize all result and suggestion for improvement in the future

DMAIC Step	Descriptions	Tools selection	
		Problem I. (Peeled off)	Problem II. (Dimension & Deformation)
Define (D)	• Clarify problem statement • Impact of business case • Benefits after improvement • Define project scope & objective • Complete Project charter	Project Charter / Team Brainstorming FMEA (Main Process) Process Flow Chart Pareto/Run Chart	Project Charter / Team Brainstorming FMEA (Main Process) Process Flow Chart Pareto/Run Chart
Measure (M)	• Measure current situation • Measurement methods • Calculate appropriate Sampling size • Data collection plan • Verify measurement system	Adhesive strength test (Peel test) Control Chart Process Capability (Cpk) Measurement System Analysis (Attribute GR&R)	Dimension measurement Control Chart Process Capability (Cpk) Sample size estimation Measurement System Analysis (MSA)
Analysis (A)	• Brainstorming to find potential causes • Verify potential root cause • Select concern factors to do experiment and find optimal solution	Cause & Effect Diagram FMEA (All sub process) >>Pareto (RPN prioritize) Design of Experiment (DOE)	Cause & Effect Diagram FMEA (All sub process) >>Pareto (RPN prioritize) Design of Experiment (DOE)
Improve (I)	• Perform improvement and verify effectiveness • Compare result before/ After improvement • Calculate project benefits (expense & saving)	Design of Experiment (DOE) Response Surface Methodology Process Capability (Compare before/after)	Design of Experiment (DOE) Response Surface Methodology Process Capability (Compare before/after)
Control (C)	• Set up control limit • Set up standardization to maintain quality level	Control chart, Control Plan, Inspection Standard, Working Instruction	Control chart, Control Plan, Inspection Standard, Working Instruction

Figure 8 DMAIC methodology

1.8 Research schedule

The time plan of this research is conducted in April - October 2018. The project has started in April 2018 and expect to finish in October 2018 to support mass production of another new model using IMD component supplied by this case study company which is the main project provided high production volume. For this reason, the quality level of IMD process should be improve before mass production of the new IMD project.

CHAPTER II

LITERATURE REVIEW

In this chapter consists of all theory, method and journal which involve and relate in this research are described. The five steps of six sigma including Define (D), Measure (M), Analyse (A), Improve (I) and Control (C) are employed in this research to reduce defect rate from in-mould decoration process. By studying the details of IMD manufacturing to verify measurement methods, identify factors affecting PET film peeled off and part warpage using the cause-and-effect diagram. Then the prioritized factors are analysed and selected from FMEA to conduct the design of experiment (DOE) to find significant factors and optimal parameter setting for improvement.

2.1 Quality Tools

2.1.1 Six Sigma Methodology (DMAIC)

A Six Sigma is a system of statistical tools and techniques focused on eliminating defects and reducing process variability. The Six Sigma methodology associated with five steps of DMAIC; define, measure, analyse, improve and control (Kevin Linderman 2006). The following is a list of the project DMAIC phases, along with a brief description accordingly:

2.1.1.1 Define Phase

The Define phase, should complete by the tasks the following activities then summarize as the project charter:

1) Define problem statement: The problem statement should contain the clarify problem description of the issue that the project will address (Pugna, Negrea et al. 2016).
2) Identify impact of business and benefit after improvement: the project should include information concerning business impact such as cost impact, customer impact, critical to customer quality requirements (both internal and external), in this research, will perform preliminary FMEA of main process to identify impact business case then set up goals and benefits expected through completion of the project (Roger G. Schroeder 2008).

3) Define the project scope: The project scope sets the project boundaries. It is essential that the beginning and ending process steps are clearly identified then agreed with team to the moving forward.
4) Identify project resources: Identify the champion, process owner and members of the team along with other resources that may be required to make project success.
5) Develop a project time plan: The project plan should identified of person in charge, how and when the tasks are to be completed. (Jonny and Christyanti 2012)
6) Develop a process flow chart: In this research, the process flowchart described manufacturing steps by steps of IMD process including related control factors were clearly identified.

2.1.1.2 Measure Phase

The Measure phase of the project, should include the measurement of current situation in IMD process by using statistical tools such as process capability analysis (Cpk) and control chart. The measurement methods should clearly identified and verified by Measurement System Analysis (MSA) to observe the current situation of system (Simanová and Gejdoš 2015). Overall main activities are including:

1) Clarify detailed process maps or process flow chart: to identify critical point of the process which will be selected to identify measurement methods (Roger G. Schroeder 2008). The process flow chart of IMD process should also identify data collection method appropriately with the project time plan.
2) Design data collection plan: Define the measurement methods and the data collection method for IMD process. Identify what will be measured, the tools or equipment required to measure, design how to measure by referring to international or related standard. Moreover, the document format to record the measurement data should be established.

3) Preliminary measure the current situation: In order to observe the current situation, the data collection plan to perform preliminary process capability analysis (Cpk), control chart, defect rate are implement in this research (Roger G. Schroeder 2008).
4) Validate the measurement system: A Measurement System Analysis (MSA) is required to ensure that the data collection is accurate enough to take decision and do further analysis in this research. In this research, if Gage Repeatability and Reproducibility (GR&R) is greater than 10-30%. It needs to make improvements to the measurement system.
5) Collect the data for measurement: The data collection should be done by gathering data in further defining the problem. In addition, the data should provide information aspect of possible factors that provide indications of how, when or where the problems occurred. In this research, it will be necessary to define a period of time to gather data. Statistical tools applied for collecting that data is the control chart and process capability analysis (Cpk) (Kevin Linderman 2006). The control chart can help identify any trends or outlier of measurements data.

2.1.1.3 Analyse Phase

In the Analyse phase is to identify all possible causes of problem then determine the root cause of the problem by using cause and effect diagram, scoring matrix and FMEA then finalized by selecting concerned factors to conduct the design of experiment (DOE). Overall main activities are including:

1) Brainstorming: This activity is aim to identify potential causes which is accomplished using various tools by process specialist or project member who have well-experience about the IMD process. There is a widely method applied for gathering all possible potential factors is the Cause and Effect or Ishikawa diagram. The diagram can also be called “Fishbone Diagram”, which is often used during brainstorming tools. The main branches of this diagram are usually identified with the 5M1E including; Man, Machine, Material, Method,

Measurement and Environment. The possible potential factors of individual main branches are listed under each category likes a fishbone.

2) Verify potential root cause: This activity is to determine root cause of problem after possible causes is identify by brainstorming from Fishbone or Ishikawa diagram. Then implement appropriate activity to verify whether are possible potential factors(Jonny and Christyanti 2012) to be investigated or not. 5Why is widely effective method for examining the potential root cause. The 5Why method is a simply asking the question “Why” until obtaining the final symptoms of a problem which is down to nearly the root cause of problem. Then the highlight possible causes derived from the 5Why are marked on cause and effect diagram then focused to do further analysis. In this research, the activity to verify potential causes from brainstorming activity is applied the cause and effect matrix. This method is done by evaluating scores for possible potential cause which have been done by brainstorming from specialists of IMD process. Then focused to investigate only very high concerned causes that prioritized by the Pareto Chart.

3) Analyse failure modes of proposed solutions: After all potential causes have been verified and focused to do further investigated. Then consider reviewing potential improvements for their risk and possible impact on other processes. A Failure Modes and Effects Analysis (FMEA) is applied in this prior to implementation of any changes. In addition, the FMEA is used to identify and address potential problems and potential risks along with their severity and likelihood of occurrence(Wessiani and Sarwoko 2015). Then critical issue and high risks of processes are identified to develop a plan to minimize all risk.

4) Select factors to do further investigate by DOE: Prioritize RPN from FMEA to generate factors list by using the Pareto chart to select concerned factors prior to cumulative percentage as 80% to do further by using Design of Experiment (DOE). Then go on to perform the optimal solution by using Response Surface Methodology (RSM).

2.1.1.4 Improve Phase

In the Improve phase, the identified possible root causes of the problem have been verify significant by performing the design of experiment (DOE) Response Surface Methodology (RSM). The improvement activity should be implemented and validated corrective actions to resolve any quality issues and improve its performance.

1) Identify potential solutions: The possible process improvements that would improve quality and increase process efficiency should identify after the root causes have been investigated. In these case the Design of Experiment (DOE) and Response Surface Methodology (RSM) is commonly used to analyse and find optimal solutions for process improvement. Regarding remain factors from FMEA list are also required to do improvement by brainstorming for potential solutions such as establish standardized work to control then validate by using statistical methods.
2) Validate efficiency of improvements: After all improvement activity have been implemented, any activities should be validated by using statistical methods such as process capability(Cpk) (Kevin Linderman 2006) to compare result of before and after implement the improvement activities. After implement all activities must be verified that the improvement can be resolved all issues to prevent reoccurrence in the future. The data collection plan must be stated for a future process control to ensure effectiveness of improvement activities.

2.1.1.5 Control Phase

The objective of the Control phase is to maintain the effectiveness of improvement which have been done during the Improve phase (Kevin Linderman 2006). Appropriate corrective actions must be taken to assure the process are in place of control and prevent reoccurrences. In order to achieve this goal, the following steps is need to be done:

1) Update Quality control plan, FMEA and related documentation: To ensure that all process documentation is updated with the changes to the process due to the

improvements implemented. The documents that should be updated include Standard Operation Procedure (SOP), FMEA Review, Work Instructions, Control Plans, Critical Process Map, Visual Control, etc.

2) Perform Associate Training: To assure that all related members are trained on the process and understand the improvement activity. The purposed improvement were introduced and how it affects their responsibilities. The associated person such as the inspector, worker or related person should be trained of the purpose of the changes and the benefits of making these changes.
3) Implement Statistical Process Control (SPC): The SPC or control chart must be in place to monitor the performance of the process that relate to the Critical to Quality (CTQs), identified during the Define phase (Simanová and Gejdoš 2015). The control chart should be updated on a regular basis. The process owner should review the control chart if any evidence of shifts or trends is occurred in the process.
4) Create a process monitoring: The purpose of this process is to address how the performance of the process will be monitored over a period of time like a project milestone management. The plan should include the metrics that will be monitored, the method of documentation, and frequency of measurement including sample size. In addition, the process monitoring plan should specify who will be in charged, the method and timing of the communication, what response is required and who is responsible for executing the response.

2.1.2 Cause & Effect Diagram

The Cause & Effect or Ishikawa diagram is applied to identify potential factors causing an overall effect of issue. Each cause or reason for imperfection is a source of variation (Pugna, Negrea et al. 2016). All p potential causes are usually grouped into major categories to identify and classify these sources of variation. The concept of 5M1E is one of the most common frameworks for root-cause analysis (Hassan, Siadat et al. 2010):

1) Machine (equipment, technology)
2) Method (process)

3) Material (includes raw material, consumables, and information)

4) Man / mind power (physical or knowledge work, suggestions)

5) Measurement / medium (inspection, testing)

6) Environment (Temperature, light, humidity…etc.)

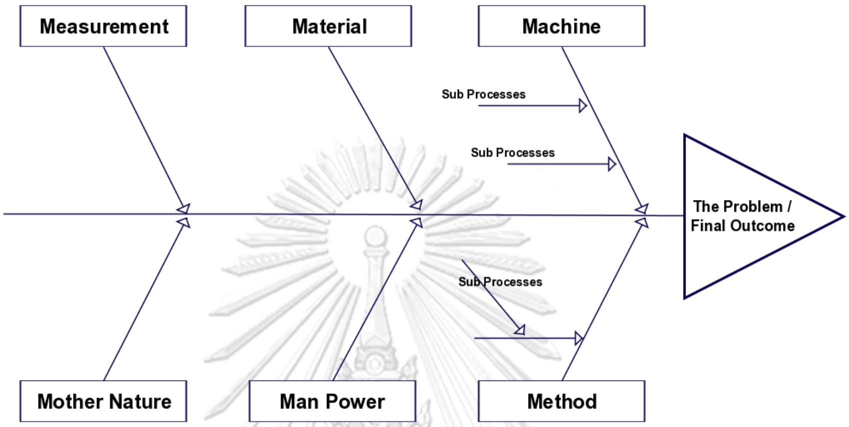


Figure 9 Cause & Effect Diagram

2.1.3 Failure and Effect Mode Analysis (FMEA)

Failure mode and effects analysis (FMEA) is one of the first highly structured, systematic techniques for failure analysis. The FMEA is often the first step of a system reliability study (Wessiani and Sarwoko 2015). It involves reviewing as many components, assemblies, and subsystems as possible to identify failure modes, and their causes and effects (Simanová and Gejdoš 2015). The FMEA activity also helps to identify potential failure modes based on experience with similar products and processes (Hassan, Siadat et al. 2010). It is widely used in both product and process development in manufacturing industries. The risk must be quantified and classified, and high risk prevented where after the failure risks are updated.

The FMEA includes information on causes of failure to reduce the possibility of occurrence by eliminating identified root causes (Renu, Visotsky et al. 2016). There are two mainly type of FMEA analysis including Design (DFMEA) and Process (PFMEA).

- Design FMEA: Design FMEA (DFMEA) explores the possibility of product malfunctions, reduced product life, safety and regulatory concerns derived from Material Properties, tolerances, interfaces with other components.
- Process FMEA: Process FMEA (PFMEA) is an analysis of potential failure risks in the manufacturing process which discovers failure that impacts product quality, reduced reliability of the process, customer dissatisfaction, and concerned safety. The whole process shall be analysed by means of FMEA techniques, to detect potential failure risks and weaknesses in the process. The risks must be quantified and classified so that adequate controls and safeguards are in place to prevent failure in the future.

The Failure Modes in a FMEA are equivalent to the Problem Statement or problem description in problem Solving (Renu, Visotsky et al. 2016). Causes in a FMEA are equivalent to potential root causes in problem solving. Effects of failure in a FMEA are problem symptoms in problem Solving. The FMEA and Problem Solving reconcile each failure and cause by cross documenting failure modes, problem statements and possible causes.

Example of FMEA for problem solving has one item with a progression through multiple recommended actions. With the below instance in Figure 10, the revised RPN has improved. The final RPN of 10 indicates the issue has been mitigated successfully. The new state should be captured as Standard Operation Procedure. The examples and structure of FMEA table is presented in Figure 10 including the definition following;

Failure Modes and Effects Analysis (FMEA)

FMEA is essentially a risk ID and abatement plan. Instructions below:

Process or Product Name:		Prepared by:	Page ___ of ___
Responsible:		FMEA Date (Orig) __________ (Rev) __________	

Process Step/Part Number	Potential Failure Mode	Potential Failure Effects	SEV	Potential Causes	OCC	Current Controls	DET	RPN	Actions Recommended	Resp.	Actions Taken	SEV	OCC	DET	RPN
What are the process steps?	In what ways can the process step go wrong?	What is the impact of the Failure Mode on the customer?	How severe is the effect on th customer?	What are the causes of the Failure Mode?	How often does the Cause or Failure Mode occur?	What are the existing controls and procedures that prevent this Cause of Failure Mode?	How well can you detect the Caus or Failure Mode?	Calculated	What are the actions for reducing the occurrence, decreasing severity or improving detection?	Who is responsible for the recommended action?	What are the completed actions?	Rate each and recalculate the RPN after action has been taken.			
								0							0
								0							0
								0							0
								0							0
								0							0

Figure 10 Example of FMEA

- Risk Priority Number (RPN)

The calculation formula of Risk Priority Number (RPN) is Severity (of the event) * Probability (of the event occurring) * Detection (Probability that the event would not be detected before the user was aware of it)

- Severity (S)

The consequences of a failure mode, Severity considers the worst potential consequence of a failure, determined by the degree of injury, property damage, system damage and/or time lost to repair the failure. The scale of severity is represented as FMEA scale in Figure 11.

- Occurrence (C)

It is necessary to look at the cause of a failure mode and the likelihood of occurrence. A failure cause is looked upon as a design weakness. All the potential causes for a failure mode should be identified and documented. This should be in technical terms. A failure mode is given a Probability Ranking shown likelihood of occurrence as below Figure 11.

- Detection (D)

The means or method by which a failure is detected. This is important for control or availability of the system and it is especially important for multiple failure scenarios. It should be made it cleared how the failure mode or cause can be discovered by an operator under normal system operation or if it can be discovered by the maintenance crew by some diagnostic action or automatic built in system test. The ability of detection scale are following below as Figure 11.

FMEA Scale

RATING	DEGREE OF SEVERITY	LIKELIHOOD OF OCCURRENCE	ABILITY TO DETECT
1	Customer will not notice the adverse effect or it is insignificant	Likelihood of occurrence is remote < 1 in 1,500,000	Sure that the potential failure will be found or prevented before reaching the next customer
2	Customer will probably experience slight annoyance	Low failure rate with supporting documentation Up to 1 in 150,000	Almost certain that the potential failure will be found or prevented before reaching the next customer
3	Customer will experience annoyance due to the slight degradation of performance	Low failure rate without supporting documentation up to 1 in 15,000	Low likelihood that the potential failure will reach the next customer undetected
4	Customer dissatisfaction due to reduced performance	Occasional failures up to 1 in 2,000	Controls may detect or prevent the potential failure from reaching the next customer
5	Customer is made uncomfortable or their productivity is reduced by the continued degradation of the effect	Relatively moderate failure rate with supporting documentation up to 1 in 400	Moderate likelihood that the potential failure will reach the next customer
6	Warranty repair or significant manufacturing or assembly complaint	Moderate failure rate without supporting documentation up to 1 in 80	Controls are unlikely to detect or prevent the potential failure from reaching the next customer
7	High degree of customer dissatisfaction due to component failure without complete loss of function. Productivity impacted by high scrap or rework levels.	Relatively high failure rate with supporting documentation up to 1 in 20	Poor likelihood that the potential failure will be detected or prevented before reaching the next customer
8	Very high degree of dissatisfaction due to the loss of function without a negative impact on safety or governmental regulations	High failure rate without supporting documentation up to1 in 8	Very poor likelihood that the potential failure will be detected or prevented before reaching the next customer
9	Customer endangered due to the adverse effect on safe system performance with warning before failure or violation of governmental regulations	Failure is almost certain based on warranty data or significant DV testing >1 in 3	Current controls probably will not even detect the potential failure
10	Customer endangered due to the adverse effect on safe system performance without warning before failure or violation of governmental regulations	Assured of failure based on warranty data or significant DV testing >1 in 2	Absolute certainty that the current controls will not detect the potential failure

Figure 11 FMEA Scale

2.1.4 Measurement System Analysis (MSA)

Measurement System Analysis (MSA) is defined as an experimental and mathematical method of determining the amount of variation that exists within a measurement process. Variation in the measurement process can directly contribute to our overall process variability (Kevin Linderman 2006). The Gage R&R Study is activity to ensure the adequacy of measurement will be defined, documented and quantified and then must be part of a comprehensive calibration system. Repeatability and Reproducibility (R&R) is used to determine the extent of measuring error which is a combination of equipment and operator.

Gage Repeatability and Reproducibility (Gage R&R) can be performed to evaluate the level of uncertainty within a measurement system. The Gage R&R is separated by two type as Variable Gage R&R and Attribute Gage R&R.

1) Variable Gage R&R

The variable Gage R&R is used to collect variable continuous data. To perform a Gage R&R, first select the gage to be evaluated. Then perform the following steps:

a. Obtain at least 10 random samples of parts manufactured during a regular production run
b. Choose three operators that regularly perform the particular inspection
c. Have each of the operators measure the sample parts and record the data
d. Repeat the measurement process three times with each operator using the same parts
e. Calculate the average (mean) readings and the range of the trial averages for each of the operators
f. Calculate the difference of averages by each operators, average range and the range of measurements for each sample part used in the study
g. Calculate repeatability to determine the amount of equipment variation
h. Calculate reproducibility to determine the amount of variation introduced by the operators
i. Calculate the total variation in the parts and total variation percentages

When interpreting the results of a Gage R&R. The percentage is used as a judgment criteria for evaluating the measurement method. In this research, the following percentages define the target for R&R study

<10%	Gage R&R is acceptable
10%-30%	Gage R&R requires for approval
>30%	Gage R&R is acceptable (Need to improve)

- The measurement system is acceptable if the Gage R&R score falls below 10%
- The measurement system may be determined acceptable depending upon the relative importance of the application or other factors if the Gage R & R falls between 10% to 20%
- Any measurement system with Gage R & R greater than 30% requires action to improve by performing any actions to improve the measurement system should be evaluated for effectiveness

3) Attribute Gage R&R

Attribute measurement systems can be analysed using a similar method. Measurement uncertainty of attribute gages shall be calculated using below method:

a. Determine the gage to be studied
b. Obtain 10 random samples
c. Select 2 operators who regularly perform the particular inspection
d. The selected operators perform the inspection two times for each of the sample parts and record the data
e. Calculate the kappa value by using Minitab software.
f. When the kappa value is greater than 0.6, the gage is acceptable if not, the gage is need to be improved

When interpreting the results of Gage R&R, performing a comparison study of the repeatability and reproducibility values. If the repeatability value is large in comparison to the reproducibility value, it would indicate a possible issue with the equipment used for the study. The equipment may need to be replaced or re-calibrated. Adversely, if the reproducibility value is large in comparison with the repeatability value, it would lead to demonstrate the variation is operator related. The operator may need additional training on the proper use of the equipment or design a jig and fixture to assist the operator when using the gage.

2.1.5 Design of Experiment (DOE)

Design of experiments (DOE) is a systematic method to determine the relationship between factors affecting a process and the output of that process (Montgomery 2015). In other words, it is a disciplined plan for collecting data of the experiment by changing input values to investigate the effect on output values. It is widely used to find cause-and-effect relationships supporting improvement of product and process design.

1) The Basic Principles of the design of experiment (DOE)

There are three basic principles of the design of experiment (Montgomery 2015) are randomization, replication and blocking represented following;

- Randomization - this is an essential part of any experiment. It means the experimental material and the order in which individual runs of the experiment are to be performed randomly.
- Replication – replication is the basic issue that will use to obtain an estimate of experimental error. It means an independent repeat run of each factor combination to obtain a more precise estimate of the parameter if samples mean are applied.
- Blocking – blocking is a design technique used to improve precision that comparison along with the factors of interest are made. There are various blocking techniques used to control sources of variation that will reduce error variance. Source of variation may cause by factors that may influence the experimental response but it is not interested directly.

2) Introduction to 2^k Factorial Designs

The 2^k designs are a major set of creating blocks for many experimental designs. These designs are usually referred to as screening designs. The 2^k refers to the designs with k factors where each factor has only two levels. These designs are created to explore a large number of factors, with each factor having the minimal number of two levels. A factorial experiment is an experiment in which factors are varied together at same time. This experiment is conducted at every combination of high and low values applied for all factors. There are two major information provided by a designed experiment to estimate the factors effect which is very importance for analyzing the result including main effect and interaction.

- Main effect – the main effect of factor is the average influence of a change in level of the single factor on the response. In case of 2-level factorial design, main effect is difference of the average of response at high level and low level of factor.
- Interaction – extent to which influence of one factor on response depends on level of another factor. In other word, it is called an interaction between factors if main effect between the levels of factor is not the same for different levels of the other factors.

2.1.6 Response Surface Methodology

Response Surface Methodology (RSM) is optimization and finding the best set of factor levels to achieve goal (Montgomery 2015). In many applications, the RSM is an applicable to achieve goal. However, in some cases the RSM can be implemented to achieve some given specifications.

1) The Sequential Process of RSM

In order to locate the optimum point. It is necessary to perform the experiment like a factorial experiment. The result of the initial factorial experiment can be observe at the corner of cubic which indicate the path of improvement direction in Figure 12. Therefore, the additional runs would be performed in this direction (Center point of cubic or current operating condition) to find the optimal point that lead to the region of the optimum. Once the optimum point has been founded, a second experiment would be performed to develop the model of process to obtain more precise estimation of the optimum operating condition.

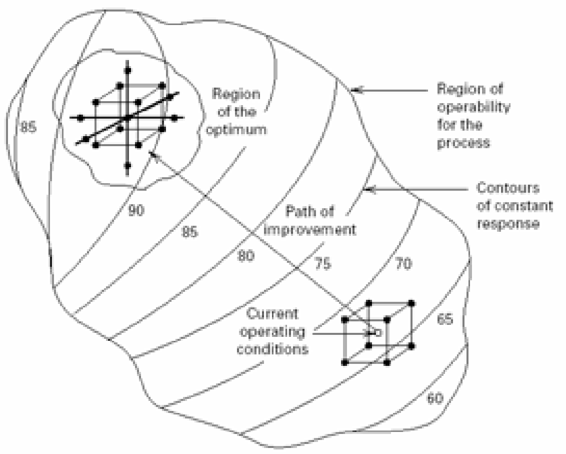


Figure 12 the Sequential nature of RSM

By considering in Figure 12 represented the sequential process approach to conduct the process optimization is called "Response Surface Methodology (RSM)". Regarding the second design of experiment in the region of the optimum in Figure 12 is called "A Central Composite Design" (Montgomery 2015).

After the optimum point have been founded, it is necessary to characterize the response surface by determining whether the optimum point is a point of maximum or minimum response or a saddle point. It is also necessary to study the relative sensitivity of the response to the variables. The most straightforward way is to do the contour plot of the fitted model. If there are relatively few variable such as only two process variable x_1 and x_2, a more formal analysis for this case should be the canonical analysis.

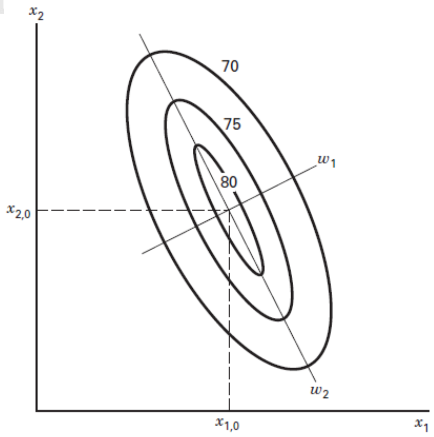


Figure 13 the canonical form of the second order model

By transforming the model into a new coordinate system with the origin at the optimum point and then to rotate the axes of this system until they are parallel to the principal axes of the fitted response surface which is call the canonical form of model represented in Figure 13.

2) The Central Composite Designs

The Central Composite Design is the most popular design for fitting the second order model. The CCD consists of a 2^k factorial with n_F factorial runs, 2*k star points and n_c center point. This design can be made rotatable which is important characteristic for the second order model to provide good prediction the region of interest (Montgomery 2015).

There are two types of central composite designs including the general composite design and the spherical central composite design.

a. The general central composite design

The general central composite design, for $k = 2$ which is a 2^2 design with center points n_c then $2*k$ star points were added. The star or axial points are normally at some value α and -α on each axis represented in Figure 14. However, this design is suitable for first order model which assume that the low and high levels of the k factors are coded to be ±1 levels.

b. The spherical central composite design

The spherical central composite design is the rotatable central composite design, suggested for the second order model where all the star points are the same distance from the center that means the variance of predicted response is constant on spheres. This design is made rotatable by the choices of α. The value of α for the rotatability depends on the number of points in the factorial design. If $\alpha = 1$, the star points would be right on the boundary, so it is a 3^2 design. Thus, $\alpha = 1$ is a special case. In this case, need to consider in the 3^k designs. A common choice of α is $\alpha = \sqrt{k} = k$ which gives a spherical design as shown in Figure 15.

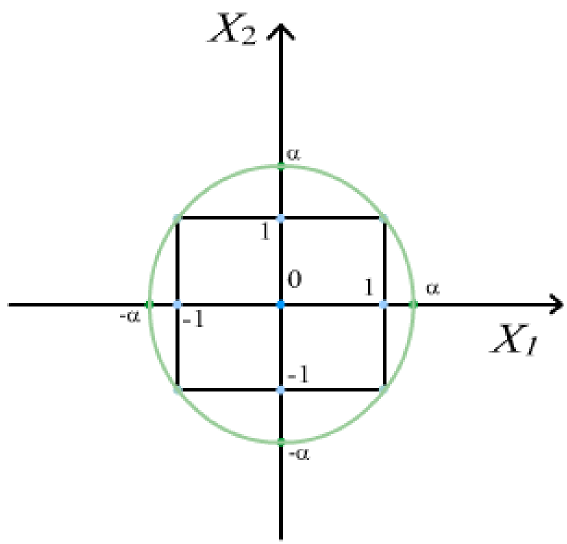


Figure 14 the general central composite design

The Figure 15 shown the spherical central composite design. The 2^2 design is given by adding the axial points (in green) on surface of the sphere (green points on sphere area). These can also give a spherical design where $\alpha = \sqrt{k} = k$. The corner points and the axial points at α, are all points on the surface of a sphere in three dimensions.

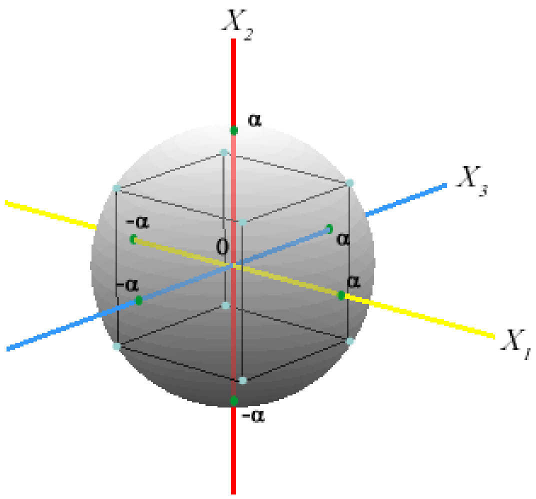


Figure 15 the spherical central composite design

For a spherical region of interest, the best choice of α from a prediction variance for the central composite design is $\alpha = \sqrt{k}$. This Spherical CCD puts all factorial and axial design points on surface of a sphere of radius$\sqrt{k}$. Regarding design in $k = 3, 4, 5$ dimensions can also be a central composite design with is a spherical CCD. Overall details of this detail is given in below Table 1. As previous mentioned, the choice of α in the CCD is dictated by the region of interest. If this region is a sphere, the design shall include center runs to provide a constant variance of the predicted response. Generally, there are three to five centers are recommended. As below Table 1 summarizes these designs and compares them to 3^k designs. If there are k factors, then we have, 2^k factorial points, 2*k axial points and n_c center points.

Table 1 Summary of central composite designs

Design	**Factor (k)**	$k = 2$	$k = 3$	$k = 4$	$k = 5$
Central Composite Designs	Factorial points 2^k	4	8	16	32
	Star points 2^k	4	6	8	10
	Center points n_c	5	5	6	6
2^k Designs	Total	13	19	30	48
3^k Designs	Total	9	27	81	243

By comparing the total number of observations required in the central composite designs versus the 3^k designs. The rotatable refers to the variance of the response. This design exists when it is an equal prediction variance for all points a fixed distance from the center, 0. This is a reasonable basis of model. If the center of design space and run experiments, all points that are equal distance from the center in any direction, having equal variance of prediction (Montgomery 2015).

However, the region of interest can be cuboidal rather the spherical in many situation. In this case, another useful type of central composite design is the face-centered central composite design (CCF) or face-center cube (Montgomery 2015) is recommended, with α=1. This design gives the star or axial points on the centers of the faces of the cube. In case of k=3, the variation of the face-centers central composite design is also be applied because it required only 3 levels of each factors which is difficult to change the factor levels. However, the face-centered central composite design (CCF) is not rotatable. The face-center cube does not require as many center points as the spherical CCD (Montgomery 2015). Only 2-3 center points are sufficient to provide good variance of prediction. It can be noted that more center runs will give a reasonable estimate of experimental error. Regarding the face-centered central composite design (CCF) represented that the standard deviation of predicted response is reasonably uniform over a relatively large portion of the design space (Montgomery 2015). These can be concluded that the face-centered central composite design (CCF) is a useful optional design in case of is difficult to change the factor levels with using a few center runs. But this design is limited to estimate of experimental error and provides low precision when compare with the spherical CCD.

2.2 In-Mould Decoration Manufacturing

In-mould decoration (IMD) process is now widely used in manufacturer graphical, textured and personalized products. For all manufacturing process, IMD is the most promising technology to produce diversified products.

The graphic design on demand could quickly alter the appearance and texture on the identical product shape (Hsieh and Chang 2013). For these reason, the in-mould decoration (IMD) injection moulding is recently- evolved process (Wong A.C-Y 1997) which combines several machining techniques and mould fabrication technology. During the IMD process, a pre-painted film is placed in the mould cavity prior to injection. The injection is then execute after the mould is closed. Compared to conventional injection moulding without the film, IMD can save post processing costs from secondary process such as printing, spraying, coating or plating. Because of it advantage, it has been used to produce many current products such as cell phone case, mouse shell, household appliance panel, automobile dashboards which demand good feel in the hand and precision appearance. This technique has two major categories; In-mould lay (IML) and In-mould roll (IMR)(Lin, Chen et al. 2015). The difference between IML and IMR lie in whether the In-mould lay (IML) has process of ink carrier the film is left on the final product as the protection of underneath ink then the film has complete trimmed before moulding process. In case of the In-Mould roll (IMR) process, the pre-painted film transfer ink to the product surface through the roller and the feeder presented in Figure 16. As the ink and films are separated, the next cycle of injection moulding process begins again. According to this technique, the film is attached is attached to the cavity wall, the heat transfer along the flow path causes different temperature boundaries for the cavity surface with film and core surface without film(Phillips, Bould et al. 2009, Puentes, Okoli et al. 2009). The non-uniform heat transfer in the cavity induce a non-uniform temperature distribution across the gap wise direction during the filling and cooling stage. As a result of the asymmetric temperature distribution in the cavity wall. Unbalance flow front advancement, serve warpage and stress and other impact may impact the part's properties (Lin, Chen et al. 2015)

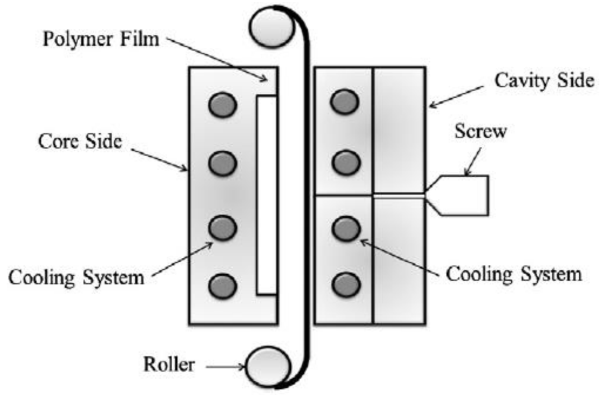


Figure 16 the In-Mold roll (IMR) process (Lin, Chen et al. 2015)

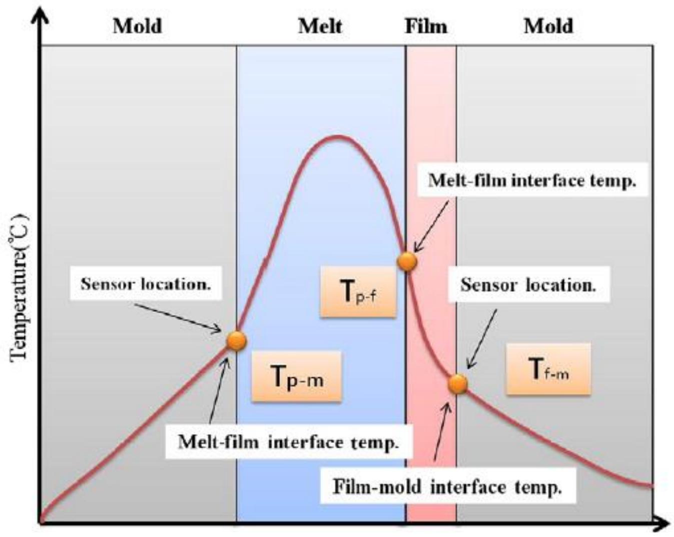


Figure 17 Melt temperature and mold temperature profile

2.3 In-Mould Decoration injection Moulding

In-mould decoration process (IMD) are used in injection moulding to manufacture parts with particular surface properties such as high gloss or printed surfaces (F.Woyan, 2015). In-Mould Decoration (IMD) injection moulding is the process of over-moulding on decorated thermoplastic film or applying on overlay of melted thermoplastic material(Shih-Po Sun 2017). There are 4 steps of IMD fabrication process consists of silk screen printing, thermal forming, trimming and injection moulding respectively. The first step is the film bearing the desired decoration pattern by silk screen printing or other techniques then go on to process of thermal forming to make the desired shape. After trimming, the film is placed in an open mould the hold into desired position of cavity(Lee D. 2013). The mould then closed, and molten polymer is injected into the cavity to perform the desired shape of the components. Once the object is injected from mould, the graphic on film cannot be removed, as the cooled object and film are formed as a single unit (Chen, Chen et al. 2013, Hsieh and Chang 2013, Lee D. 2013, Woyan F. 2014) The IMD can achieve difference colours, aesthetic patterns, effects and textures when the part comes out of the mould. It also provides many advantages including(Lee D. 2013);

- High durable graphic surface
- Adding back lighting behind a text or logo in one operation
- Creating different design without costly re-tooling
- Eliminate the tactility of convectional label on part surface and secondary printing
- Moulding recycled materials under the decorative film for more cost-effective mass production

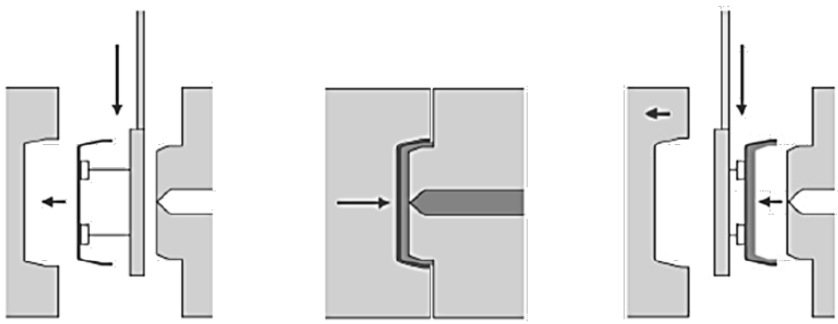


Figure 18 In-Mold Decoration injection Molding (Lee D. 2013)

2.4 Mechanical property of IMD

According to many advantage of in-mould decoration (IMD), this technique are widely used in many application. A challenge for a high quality consistent IMD process is to obtain a sufficient bond between substrate and over moulded thermoplastic material. This is due to thickness and surface pattern of the film, different material combination and process parameter. The relation equation of bonding strength between film and substrate material is defined (Woyan F. 2014)

$$\sigma = \frac{F}{A} \quad \text{……………..} \; (2.1)$$

An external force F is release to the nominal cross-section. The bonding strength is determined by the physical effect of adhesion, cohesion and diffusion (Woyan, Bruchmüller et al. 2016). The adhesion theories are divided into mechanical adhesion and specific adhesion. The mechanical adhesion describes the penetration of one component into pores and micro fissures of the others. The specific adhesion describes the bonding of two flat surface due to chemical and electrostatic process (Woyan, Bruchmüller et al. 2016)

2.5 Journal & related literature

The related articles and journal which involve and relate in this research are reviewed and studied. The summary of individual details are described as following;

1) Process parameter affecting the bonding of In-mould decoration of injection moulded component

(F. Woyan, M Bruchmuller and M. Koch, 2015)

This paper studies the fundamental parameters affecting bonding strength of injection moulded parts by an in-mould decoration process (IMD). In order to investigate the influence of materials in variety used of process conditions were created for experiment. The impact of each factor was examine by a full factorial design of experiment (DOE). Result shown that temperature in boundary layer are in range of 210 °C to 240 °C and depend on the melt and mould temperature. High temperature and low injection pressure increase molecular movement and boundary strength. The packing pressure has a small effect on the bonding strength(Woyan, Bruchmüller et al. 2016).

2) Factor influence the warpage in In-Mould Decoration Injection moulded composites

(D. Lee, W.-A. Chen, T.-W. Huang, S. –J. Liu, 2013)

This paper studies the factor effecting the warpage In-Mould Decoration (IMD) parts. This experiment are varies the PET with 30% fibre glass resin and U-shape plate with different draft angles (90º, 135º, and 150º) and also varies with various injection parameter. The result has been shown that the warpage of IMD injection moulded parts is mainly caused by the unbalanced temperature distribution during cooling, part geometry and the decoration film.

CHAPTER III
PROBLEM DESCRIPTION

In the first stage of six sigma is define phase that contains problem descriptions, the impact of business case and benefits after improvement in order to identify scope that project will be addressed to comply with required objectives by studying details of its process flowchart and historical data. The team members and process owner who have experience are required to determine with assigned task then finalized by creating a project charter.

3.1 Background of problem

The overall defect rate (SDPPM) of home appliance product has continually increased since quarter 4 of Y2017 (trial phase) until recently in quarter 2 of Y2018. The top one of parts individual defect rate quarter 1 and quarter 2 of 2018 from in-mould decoration components. The in-mould decoration (IMD) which is the new technology of injection moulding technique for decorative components. The IMD process is sensitive process to make high defect rate if quality control system is insufficient. The case study company is not a specialist in this field so they are considered to do improvement in this research.

The case study company of this research is one of the an electronics company located in China who produces and supplies various type of products, not only IMD products but also membrane switch, Glass assembly, ITO touch film, screw and HSD components. However, this company is not a specialist in the in-mould decoration (IMD) products observed by high defect rate affecting the quality level of product and IMD production capability is only a small portion when compared to overall products. The traditional methods and insufficient technology have been used in some manufacturing processes to support production and quality control system. The case study company has produced IMD with a high defect rate increased sharply in June 2018.

The table 2 and Figure 19 represented the historical data of overall IMD defect rate since quarter 4 of Y2017 (Oct –Dec 2018) to quarter 2 of Y2018 (Jan-June 2018). The defect rate of IMD components is slightly high in the beginning of part in manufacturing trial phase in Oct 2017 represented 22.9% then the defect rate has significantly decreased to 0.44% and 0.19%, after improvement of quality issues from previous trial stage which have been done in December 2017-January 2018 respectively. After that the defect rate from IMD components has gradually increased in February-April 2018 and increased sharply to be 22.3% in June 2018.

Table 2 Production and defect from IMD components

Month	SDPPM	Production Q'ty	Defect Q'ty	Defect Rate (%)	Phase
Oct-17	229,435	2480	569	22.94%	Trial
Nov-17	142,119	774	110	14.21%	Pre- pilot
Dec-17	4,448	1124	5	0.44%	Mass production
Jan-18	1,898	1581	3	0.19%	
Feb-18	83,370	8984	749	8.34%	
Mar-18	124,613	18,104	2256	12.46%	
Apr-18	89,965	9,726	875	9.00%	
May-18	50,148	19,582	982	5.01%	
Jun-18	223,449	23,992	5361	22.34%	

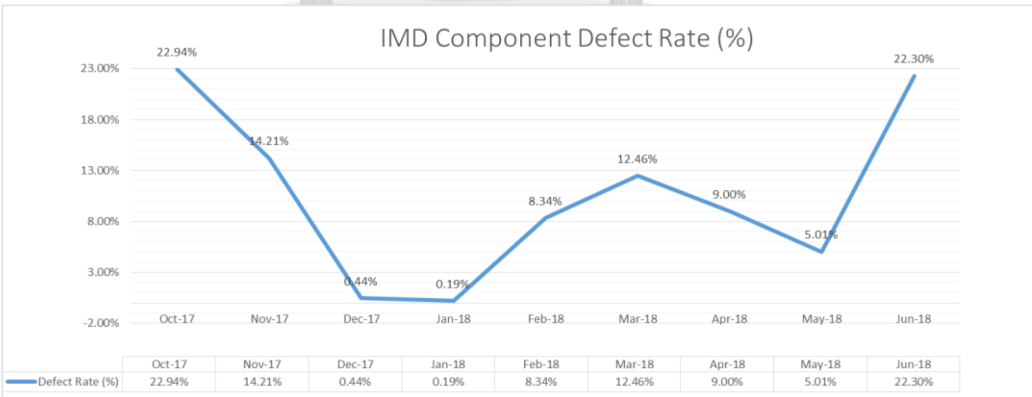


Figure 19 IMD components defect rate in October 2017-Jun 2018

In order to clarify the history of defect rate from overall IMD components represented likes a fluctuated trend in Table 2 and Figure 19, the defect rate was classified by defect symptoms that occurred since the beginning of trial stage in October 2017 until current mass production in June

2018. By classifying defect type of IMD component in Table 3 and Figure 20, represented high defect rate of trial stage in October-November 2017 has mainly caused by dimension out of specification and misalignment. After that containment and corrective actions have been implemented to solve all trial issues by adjusting injection parameters as well as tooling modification to improve quality issue from dimension out of specification. Regarding misalignment issue, the corrective action also has been done by setting the optimal alignment of position in printing process which are clearly presented in declined trends of defect rate in figure 20 and 21.

In order to verify effectiveness of improvement which have been done in trial stage, the small production batch are produced in period of December 2017-Jan 2018 to ensure that all improvement to solve trial issue have been improved before going to the next stage of actual mass production in February 2018. In the Figure 20 and 21 are classified individual type of defect from IMD components, mostly shown the fluctuated trend because most of them are occurred in a short period of time then significantly declined in the next period after improvement except two type of defect including peel off and difficult to assembly that still gradually increased. Therefore, this research is subjected to focus on improvement of defect rate in period of February-June 2018.

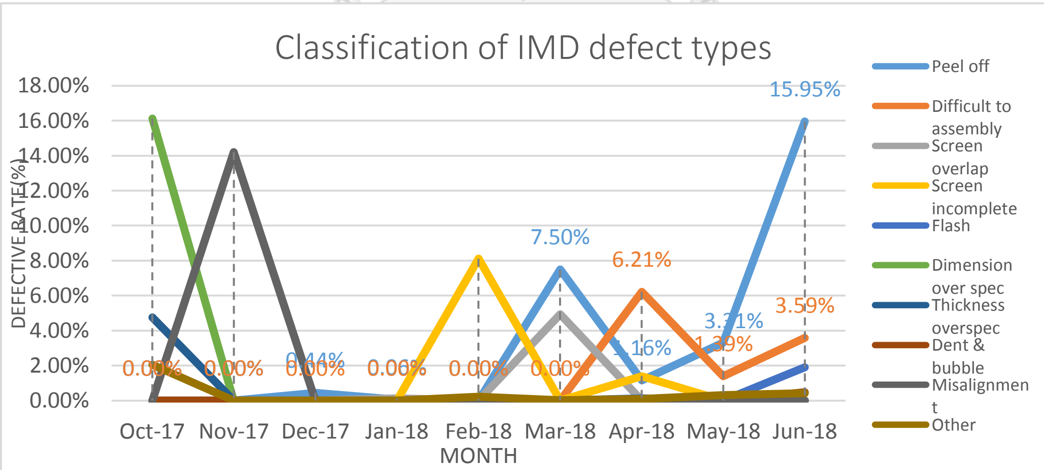


Figure 20 Classification of defect type from IMD components

Regarding individual classification of defects type in Figure 21, It was cleared that many types of defect e.g. misalignment, dimension over spec, screen overlap and screen incomplete have been improved which can be observed by the trend is declined and maintained to stable as straight line in the next period. There are only two problems including peel off and difficult to assembly which required to improve.

Table 3 Defect rate of IMD classified by type of defects

Defective Rate (%)	Oct-17	Nov-17	Dec-17	Jan-18	Feb-18	Mar-18	Apr-18	May-18	Jun-18
Peel off	0.00%	0.00%	0.44%	0.06%	0.00%	7.50%	1.16%	3.31%	15.95%
Difficult to assembly	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	6.21%	1.39%	3.59%
Screen overlap	0.00%	0.00%	0.00%	0.13%	0.00%	4.94%	0.00%	0.00%	0.00%
Screen incomplete	0.00%	0.00%	0.00%	0.00%	8.11%	0.00%	1.40%	0.00%	0.00%
Flash	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.12%	0.01%	1.90%
Dimension over spec	16.13%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Thickness over spec	4.76%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Dent & bubble	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.49%
Misalignment	0.00%	14.21%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Other	2.06%	0.00%	0.00%	0.00%	0.22%	0.02%	0.10%	0.31%	0.42%
Total defect (%)	22.94%	14.21%	0.44%	0.19%	8.34%	12.47%	9.00%	5.02%	22.34%
Total defect Qty	569	110	5	3	749	2257	875	983	5361
Production Q'ty	2480	774	1124	1581	8984	18104	9726	19582	23992

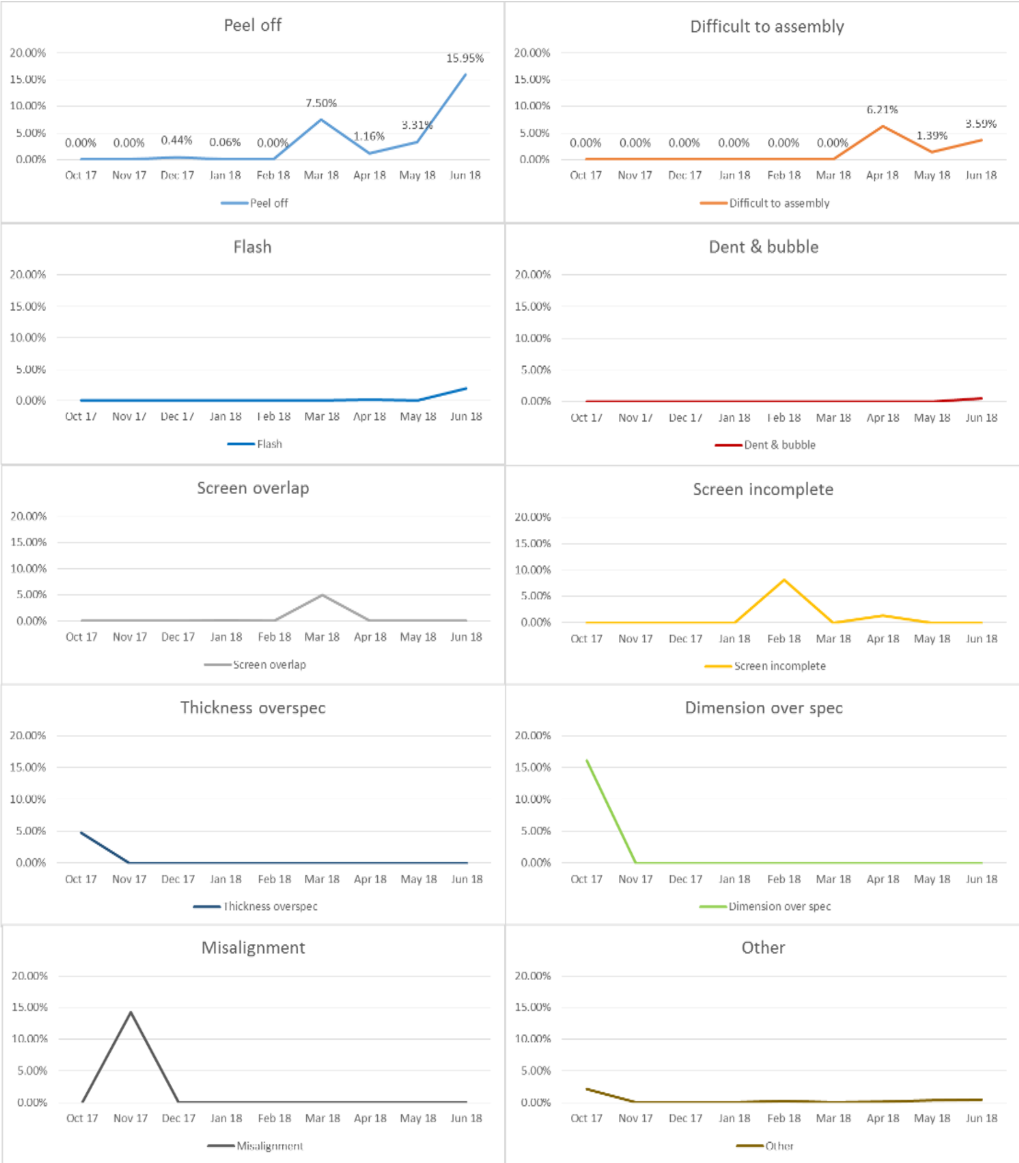


Figure 21 Individual trend of defect type from IMD components

3.2 Classification of defect

The defect classification of in-mould decoration components focused on defect occurred in February-June 2018 are classified by 2 type consists of classification by model to select as follow;

3.2.1 Defect classification by model

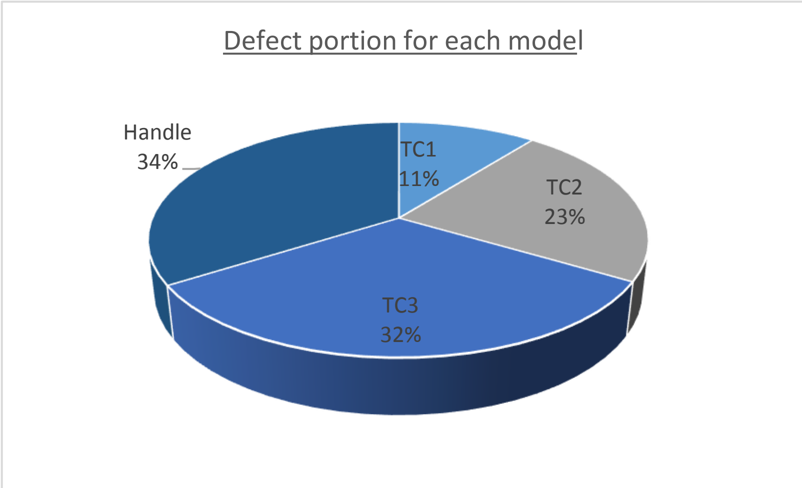
There are 4 series of in-mould decoration components including TC1, a high-end series which is highest price but it has a small volume when compare with other, TC2 is a medium series both of price and volume, TC3, a low-end series but it has high production volume and handle which are commonly used for all model. The production volume of each model, price per unit, rework cost and scrap cost per unit are represented in Table 4, Table 5 and figure 22. The overall defective cost of TC3 series is highest even the number of defects is less than handle. Therefore, TC3 is selected to improve based on highest defective cost and highest production volume.

Table 4 Defective cost and production volume of IMD components

IMD Series	Product category	Price per unit (THB)	Rework cost per unit (THB)	Scrap cost per unit (THB)	Production Volume (Jan-Mar 18) (Pcs)
TC1	Hi-End	218.13	4.0	425.86	25,648
TC2	Medium	191.4	4.0	399.13	20,460
TC3	Low	228.03	4.0	435.76	42,798
Handle	common	148.5	3.0	265.85	95,360

Table 5 Defect classification by model of IMD components

Series	*Defect Q'ty*	*Scrap cost per unit*	*Defective cost (THB)*
TC1	1085	425.86	462,058.10
TC2	2340	399.13	933,964.20
TC3	3322	435.76	1,447,594.72
Handle	3476	265.85	924,094.60
Total	10,223	-	3,767,711.62



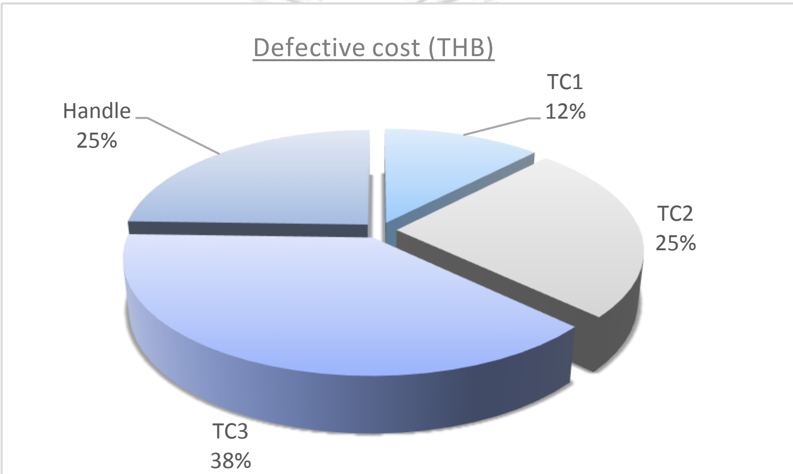


Figure 22 Portion of defect and defective cost by series of IMD

3.2.2 Defect classification by symptom

In this research, the historical data of defect rate from in-mould decoration gathered in February 2017-June 2018 shown as averaged baseline is 11.48%. However, the current defect rate increased sharply to 22.3% in June 2018 which required to improve instantly. The Pareto chart in Fig. 23, focused on the current defect rate gathered in period of February-June 2018, representing almost major defect result from PET film peeled off is 57.4 % and difficult to assembly 16.1% from overall current defect. Therefore, the PET film peeled off is the major that subject to improve firstly. The second one is the PET dimension over specification which effects difficult to assembly is also focused to improve respectively.

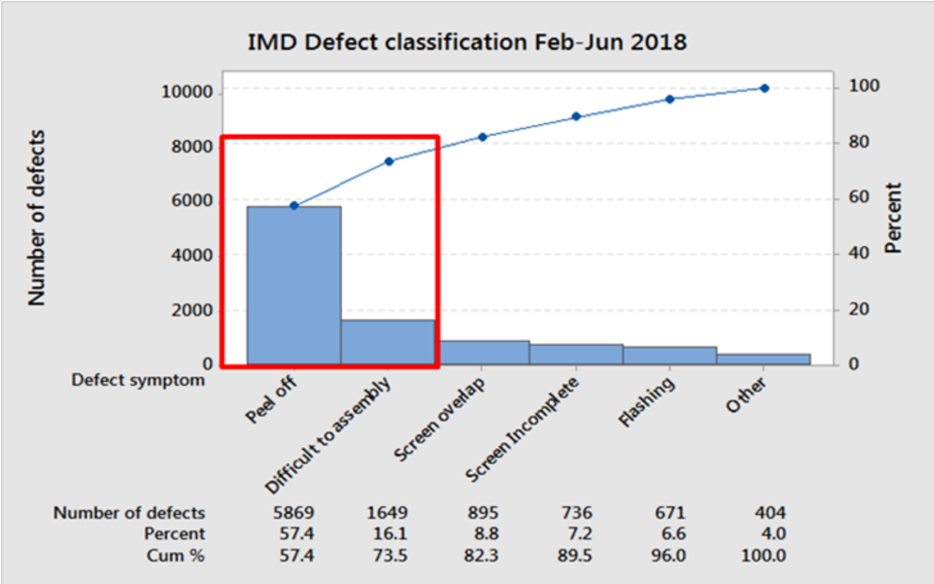


Figure 23 The Pareto chart of IMD defect in Feb-Jun 2018

3.2.3 IMD Peeled off

The figure 24 shown IMD peeled off defects that can be occurred in in-mould decoration are classified by 3 type following;

- **Type I:** Origin peel off
- **Type II:** Middle layer peel off
- **Type III**: PET layer peel off

The IMD peel off defect type I, origin peel off is the peel off between layers of whole printed PET film and ABS substrate. These occurred by insufficient adhesive strength between ABS and PET film during back-moulded process. The second type of defect (Type II) is middle layers peel off which is occurred in the middle layers of screen printing, especially the layers of silver metallic and ink layers. The last type of defect is type III, the highest number of defect are from this type. The peel off defect type III is occurred between layers of PET film with the silver printing based layers which is the metallic based colours which is a weak bonding strength between PET and silver metallic layers.

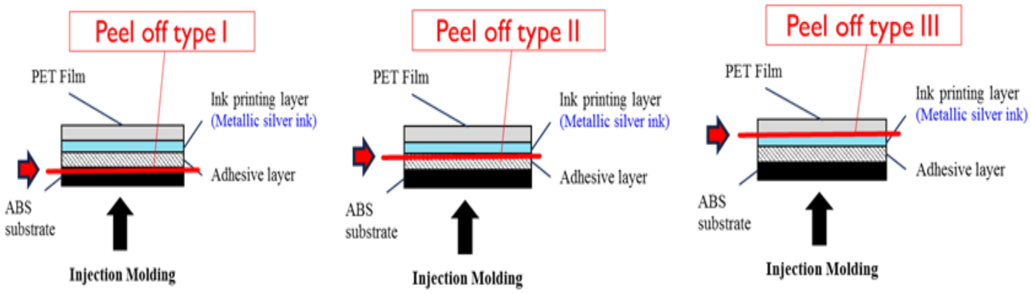


Figure 24 the classification of IMD Peel off

The table 6 represented number of peel off defect classified by 3 types occurred in period of April-Jun 2018. It was found that peel off defect type I is 2%, type II 21% and type III 79% respectively. Almost of peel off represented defect type III which is highest occurred as 79% of other type of peel off represented in Figure 25. Therefore, the peel off defect type III is subjected to study and minimize number of defects.

Table 6 IMD Peel off defect classification

Peel off Type	Apr	May	Jun	Total (%)
I	1	9	68	2%
II	0	133	773	21%
III	0	542	2986	79%

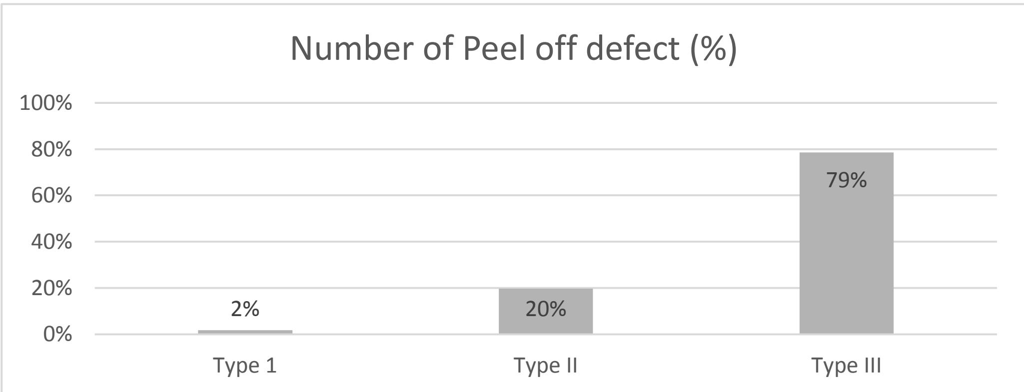


Figure 25 Number of peel off defect classified by 3 type in Apr-Jun 2018

As a result of data collection to classify peel off characteristics of IMD component which will be useful for further analysis in next step. The PET film peeled off type III in Figure 26 is occurred between layers of PET film with the silver printing based layers which is the metallic based colours. The bonding strength between metallic colour and PET film is not sufficient and also the PET film printed with hairline to create graphics effecting to reduce the adhesive strength between two layers of colour and PET film. The unstable adhesion between layer of silver printing and PET film affecting an uncertain measurement result. Because of the solvent-based inks mixing with metallic pigments are being used for silver printing layer whereas the UV-curable inks are applicable in the hairline screen of PET film. It is not compatible between solvent-based inks and UV-curable inks based on difference of chemical and physical characteristics that lead to decrease the adhesion as well as unstable adhesion in IMD components. From these reason, the major cause of PET film peeled off type III is resulting from insufficient adhesive strength between PET and silver metallic layers and also highest defect rate when compare with other. Therefore, the peel off defect type II is subjected to be improved in next step.

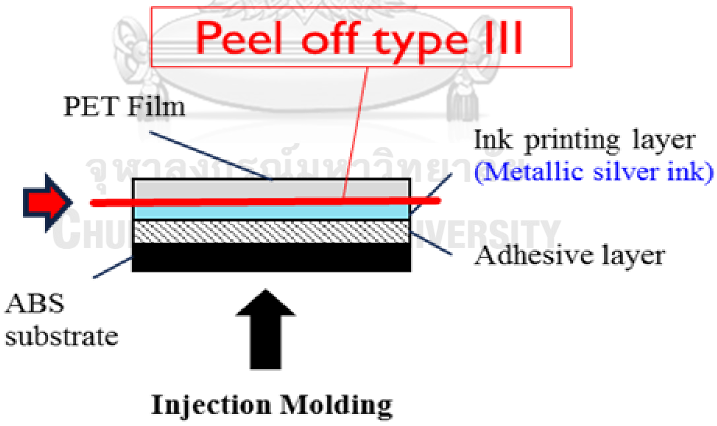


Figure 26 The IMD Peel off type III: PET and silver metallic layer

3.2.4 Difficult to assembly

The IMD part warpage is affecting both dimension and alignment of assembly especially at the back-side of pin position and the corner area. The major cause of warpage in injection moulding resulting from unbalanced cooling system (Lin, Chen et al. 2015) and asymmetrical temperature profile (Wong A.C-Y 1997). In case of IMD process, the melt plastic was injected to the PET film through the cavity side. One side of mould is a metal wall, another side is inserted PET film (Shih-Po Sun 2017). These process induced the asymmetric heat transfer resulting the warpage is easily occurred (Phillips, Claypole et al. 2008).

The part warpage is induced by asymmetric heat transfer (Shih-Po Sun 2017) which is occurred easily in IMD process because one side of mould is the inserted PET film, another side is a metal wall (Woyan, Bruchmüller et al. 2016, Shih-Po Sun 2017). The thermal conductivity of PET film is significantly lower than mould wall so that warpage and surface deformation could be occurred in higher temperature (Wong A.C-Y 1997) direction toward PET film side as shown in the Figure 27.

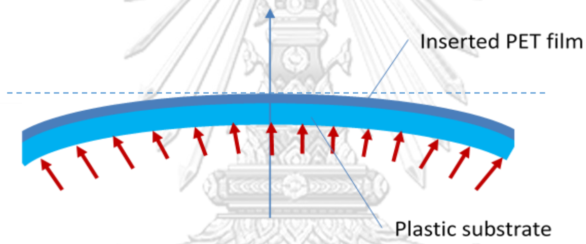


Figure 27 The IMD warpage of substrate and PET film

3.3 Process flow chat

There are four steps of in-mould decoration injection moulding process. The silkscreen printing is a first step of IMD fabrication process where the creation of PET film based on the artwork of graphic designs and colours.

The printing process is done on the underside of the film by completion the number of printing layers consisting of ink printing layers which depends on the number of colours in artwork graphics, the layer of the transparent and the adhesive layer shown in Figure 28. The second step is trimming the final graphic film after printing to be the specified shape and dimension, followed by the thermal forming process. The PET film is carried out by forming the shape to fit both of the position and alignment of the component which is done through a thermal forming machine with positive and negative tools. The final process of IMD is injection moulding by inserting the completed PET film into the cavity of mould then the ABS plastic is moulded to the backside of the forming PET film with completed graphics printing represented in Figure 28.

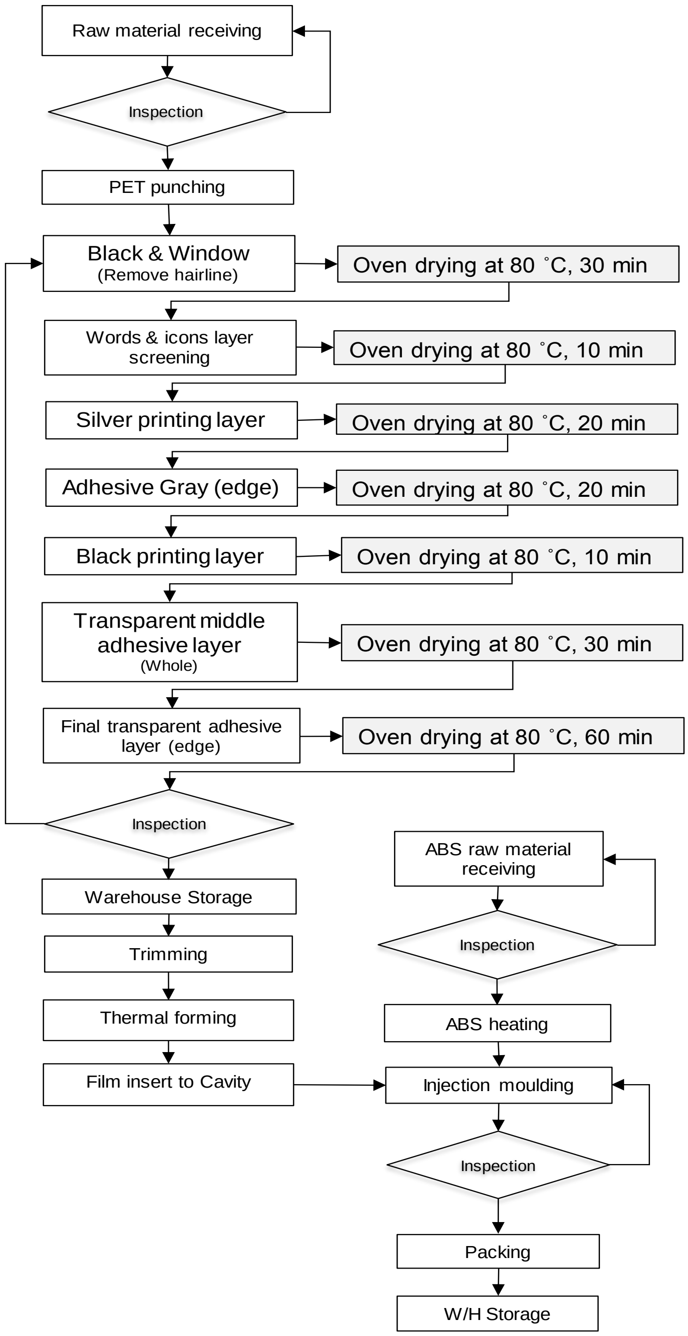


Figure 28 The Process flowchart of IMD components

3.4 Team member

In order to support process improvement in this research, the team member must be set up to conduct six sigma problem solving tools. The team member must be selected from process owner of the case study company who have high experience and strong technical knowledge in IMD manufacturing process. The team members are selected from related department of the case study company consists of list as follows.

3) Manufacturing manager (Team leader)
4) Leader of IMD printing process
5) Leader of injection moulding and thermal forming process
6) Tooling specialist
7) IMD Product development specialist

3.5 The Project Charter

In order to finalize overall project boundaries after clarify all details of problem, the project charter of this research are described in Figure 29 which can be pointed the scope what project will be addressed, Team member, objective, problem background as well as the timeline of implement.

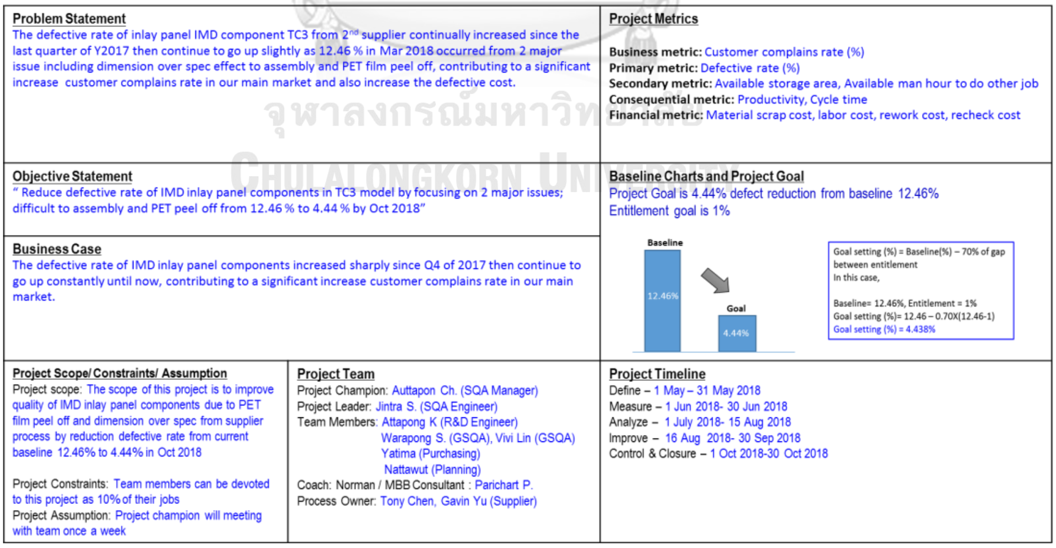


Figure 29 the project charter

CHAPTER IV

CAUSE IDENTIFICATION

After problem identification and studying the details of IMD manufacturing. The measured phase is carried out by the determination of part characteristic and measurement method to measure current performance of process through data collection plan that consists of two main steps including determination of measurement method and measurement system analysis.

In order to determine cause of problem, team members brainstorming are implemented to identify factors affecting PET film peeled off and IMD warpage using the cause-and-effect diagram. Then the prioritized factors are analysed and selected from FMEA to conduct the design of experiment (DOE) to find significant factors and optimal parameter.

4.1 Measurement methods

After the problem identification was clarified, the PET film peeled off and part warpage are required to be improved in this research. The characteristic required to measure the quality level of in-mould decoration component both type of defect are required to define in this stage.

4.1.1 Measurement method of IMD Peel off

The characteristic required to measure the peel off level of in-mould decoration related to a sufficient adhesive strength between PET film and its substrate material(Woyan, Bruchmüller et al. 2016). The adhesive strength reference ASTM D6862 (Standard) is applied to measure a quality characteristic of IMD component by determination of resistance to peel off between PET Film and a substrate layer moulded with ABS resins in Figure 30.

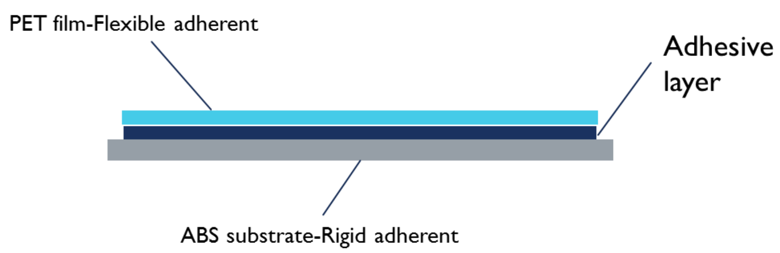


Figure 30 Peel off test samples

The visual inspection is the first stage to screen peeled off defect before preparing the rectangular moulded specimen 15 mm in width, 60 mm in length and thickness variation are in the range of 2.7-3.0 mm by selecting the origin of peel off area (chamfer edge area). If a flexible adherent is difficult to cut or peel, it can take the decision to be passed without testing. After all preparation and preliminary judgment have been done, place specimen at the fixture and testing machine designed by ASTM D6862 (Standard)with crosshead speed 10 mm/min. Then the result of adhesive strength are measured by a peeling test as average of bonding strength in a unit of N/mm.

4.1.2 Measurement method of part warpage

The characteristic of IMD part required to measure warpage level is dimension variation. In this case, the characteristic of IMD components is curvature so that the warpage is occurred toward side of PET film, especially in the corner area of components designed with assembly pins located at the back side of this components. Due to the curvature design of IMD component, the dimension measurement method to measure level of part warpage is limited. Therefore, the appropriated measurement method to measure variation of IMD warpage is carried out by gap measurement between the IMD part and the reference plane designed by the fixture to simulate the assembly plane of IMD component.

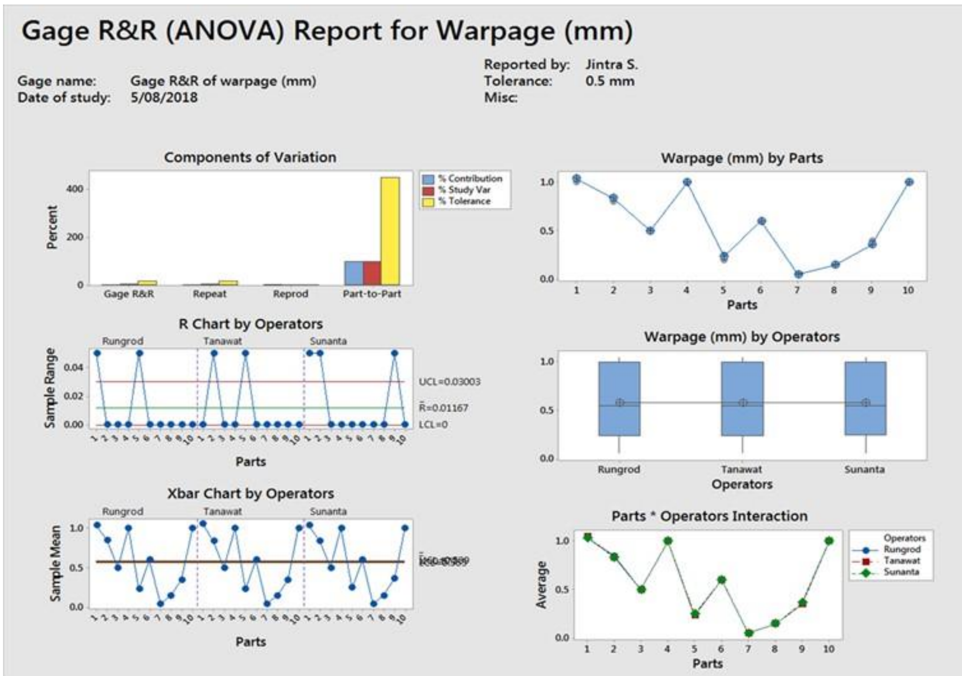
The measurement method is carried out by using the feeler gauge or taper gauge to measure the gap between IMD part and the fixture simulated as the plane of assembly point. The maximum point of gap between IMD part and simulated plane can be measured the warpage level of IMD components.

4.2 Measurement method verification

Measurement System Analysis is used to ensure that the measurement system can be detected variation of part or process by evaluating in term of accuracy, precision and stability of the measurement system.

4.2.1 Measurement verification of part warpage

The variable gage R&R is applied to evaluate whether defined measurement methods can be detected variation of part warpage. The variable gauge R&R for warpage measurement is done by 3 operators that perform an inspection of 10 parts with 3 replicates. By collecting variable data of part warpage from the measurement methods described in 4.2.1, these variable gage R&R were analysed by ANOVA and summarized all details in Figure 31 representing the total percentage of gage study is 3.54%from repeatability .This result can be acceptable to be used this measurement method because it fell to just below 10%.



Gage R&R

```
Parts:        10     Operators:    3
Replicates:    3     Total runs:  90

                                %Contribution
Source               VarComp    (of VarComp)
Total Gage R&R      0.000177            0.13
  Repeatability     0.000177            0.13
  Reproducibility   0.000000            0.00
    Operators       0.000000            0.00
Part-To-Part        0.141053           99.87
Total Variation     0.141231          100.00

Process tolerance = 0.5

                                   Study Var  %Study Var  %Tolerance
Source              StdDev (SD)   (6 × SD)       (%SV)  (SV/Toler)
Total Gage R&R         0.013317    0.07990        3.54       15.98
  Repeatability        0.013317    0.07990        3.54       15.98
  Reproducibility      0.000000    0.00000        0.00        0.00
    Operators          0.000000    0.00000        0.00        0.00
Part-To-Part           0.375571    2.25342       99.94      450.68
Total Variation        0.375807    2.25484      100.00      450.97

Number of Distinct Categories = 39
```

Figure 31 Variable Gage R&R for measurement of part warpage

4.2.2 Measurement verification of peel off

There are two types of Measurement System Analysis applicable in this research to verify peel-off strength measurement including attribute Gage R&R and variable Gage R&R. The attribute measurement systems is used to evaluate repeatability and accuracy of operators who perform the visual inspection for PET film peeled off from IMD component.

The attribute test is done by 3 operators that perform an inspection of 10 parts with 3 replicates. The attribute test result shown in Figure 32 can be summarized that all 3 operators have both percentages of repeatability and accuracy equal to 100%. It was clarified that all operators and inspection method can be acceptable to verify the peeled off issue.

Regarding variable Gage R&R which is done by the same testing method by 3 operators to collect variable data of adhesive strength from the measurement methods described in 4.1.1, these variable gage R&R were analysed by ANOVA (Runger 2010) and summarized all details in Fig. 33 representing the total percentage of gage study is 7.87%, while the result from repeatability is 6.46% and reproducibility is 4.48%, respectively. This result can be acceptable because it fell to just below 10%. From these result can be stated that the measurement system both of adhesive strength and visual inspection are acceptable to use in this research to capable the variation of IMD process.

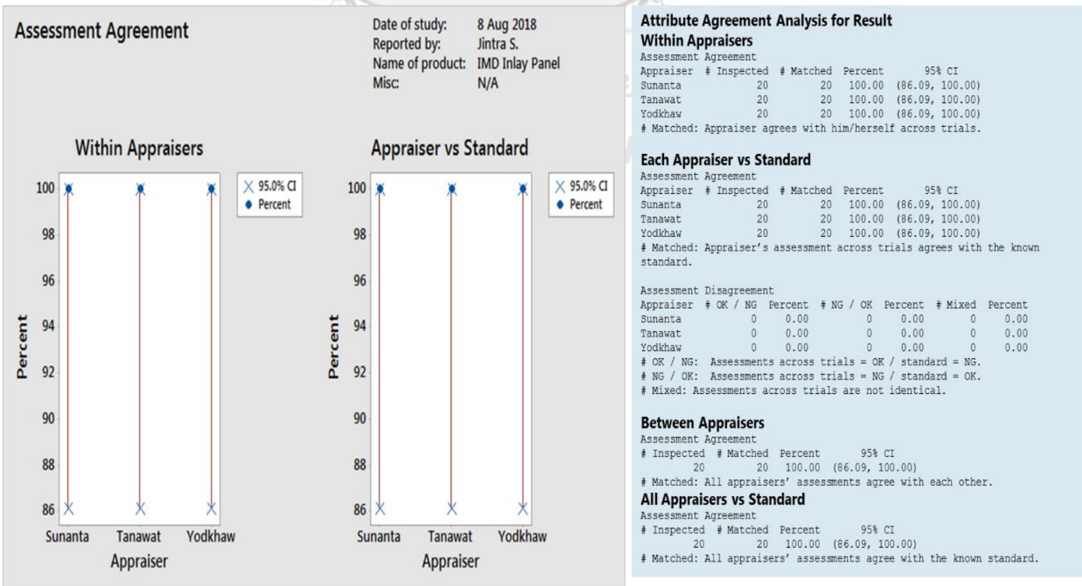
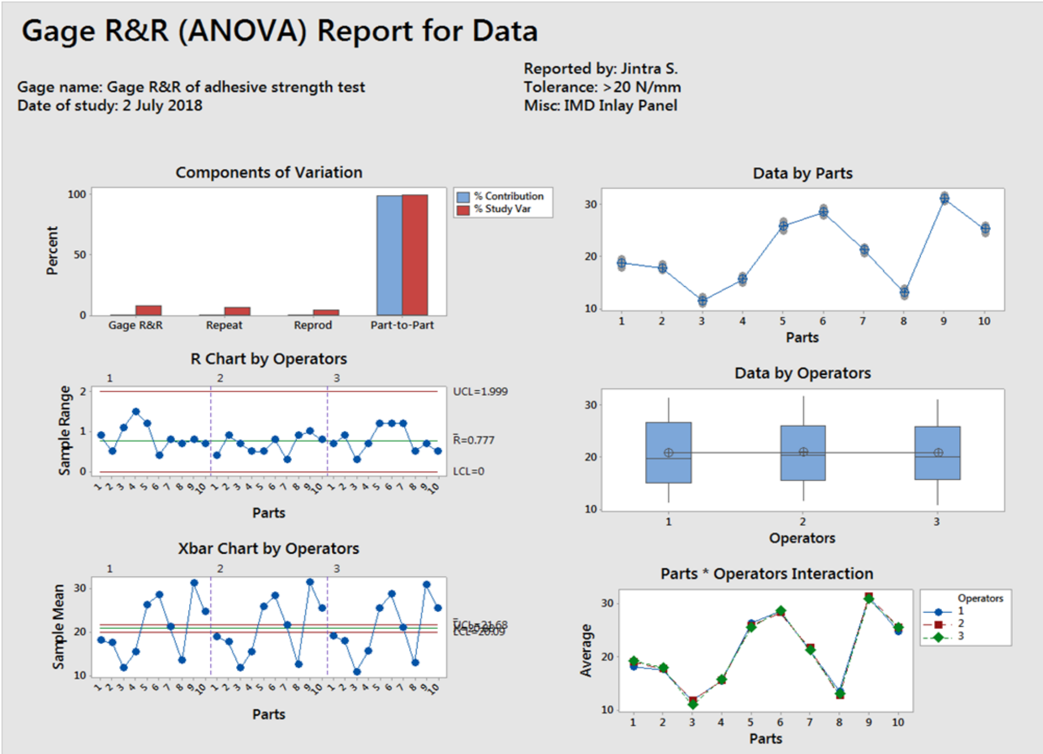


Figure 32 Attribute test performance of visual inspection



Gage R&R

Parts: 10 Operators: 3 Replicates: 3 Total runs: 90

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Parts	9	3577.29	397.477	877.288	0.000
Operators	2	0.19	0.097	0.214	0.810
Parts * Operators	18	8.16	0.453	2.445	0.005
Repeatability	60	11.12	0.185		
Total	89	3596.76			

α to remove interaction term = 0.05

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.2746	0.62
Repeatability	0.1853	0.42
Reproducibility	0.0892	0.20
Operators	0.0000	0.00
Operators*Parts	0.0892	0.20
Part-To-Part	44.1137	99.38
Total Variation	44.3883	100.00

Source	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)
Total Gage R&R	0.52400	3.1440	7.87
Repeatability	0.43050	2.5830	6.46
Reproducibility	0.29874	1.7925	4.48
Operators	0.00000	0.0000	0.00
Operators*Parts	0.29874	1.7925	4.48
Part-To-Part	6.64182	39.8509	99.69
Total Variation	6.66245	39.9747	100.00

Number of Distinct Categories = 17

Figure 33 Variable Gage R&R for measurement of adhesive strength

After verification of measurement system, the visual inspection and adhesive strength are applied to measure the current performance of in-mould decoration parts by sampling 3 pcs of each lot, total 10 lots during the period of May-June 2018 to be inspected by visual inspection and measurement of the adhesive strength. The visual inspection result shown peeled off defect rate was 83% (25 pcs were NG) and average adhesive strength was 15.4 N/mm with a standard deviation equal to 3.19. The preliminary result obviously represented a high defect rate from PET film peeled off and almost adhesive strength of samples are lower than specification at >20 N/mm. Therefore, the root cause analysis for improvement is required to be done in the next step of this research.

4.3 Root Cause Identification

The cause and effect diagram can be a useful technique for factors screening to decide are of interest for each factors. The brainstorming activity from team member who have well process knowledge and experience is required in this phase. The cause and effect diagram uses the traditional causes of measurement, man, machine, material, method and environment to identify the potential causes of problem that will probably lead to be design factors of the experiment in the next step. There are two type of defects from in-mould decoration component will be addressed by cause and effect diagram including IMD part warpage and IMD Peel off.

4.3.1 IMD Part warpage

The cause and effect diagram is applied to establish the relationship between cause and effect of IMD part warpage with five classified factors including man, machine, material, method and environment shown in Figure 34. By brainstorming possible causes of IMD part warpage from team members who have well experiences in injection process of in-mould decoration components to identify all possible causes that might be influenced IMD part warpage. It is found that 4 variable factors selected to verify significant effect to part warpage by DOE then find optimal parameter setting for injection process. Regarding other factors which is not variable factors will be improved and control by SOP and control plan.

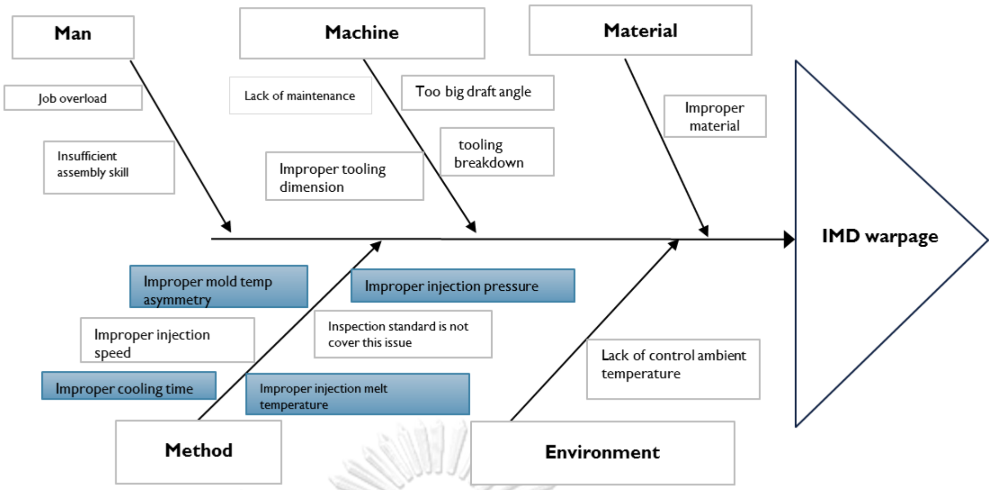


Figure 34 Cause and Effect diagram of IMD part warpage

4.3.2 IMD Peel off

The purpose of this phase is to determine the root cause of defect from PET film peeled off after understanding all process flow chart and clarifying the problem definition. Firstly, all possible causes of PET film peeled off shall be addressed by brainstorming with team members who have experiences in manufacturing process of in-mould decoration. Then using the cause and effect diagram to establish the relationship between cause and effect with five classified factors including man, machine, material, method and environment shown in Figure 35.

The next step of root cause analysis is to determine the high related factors which directly affect to PET film peeled off by using the cause and effect matrix, scoring from many potential causes of peeled off issue provided by cause and effect relation diagram.

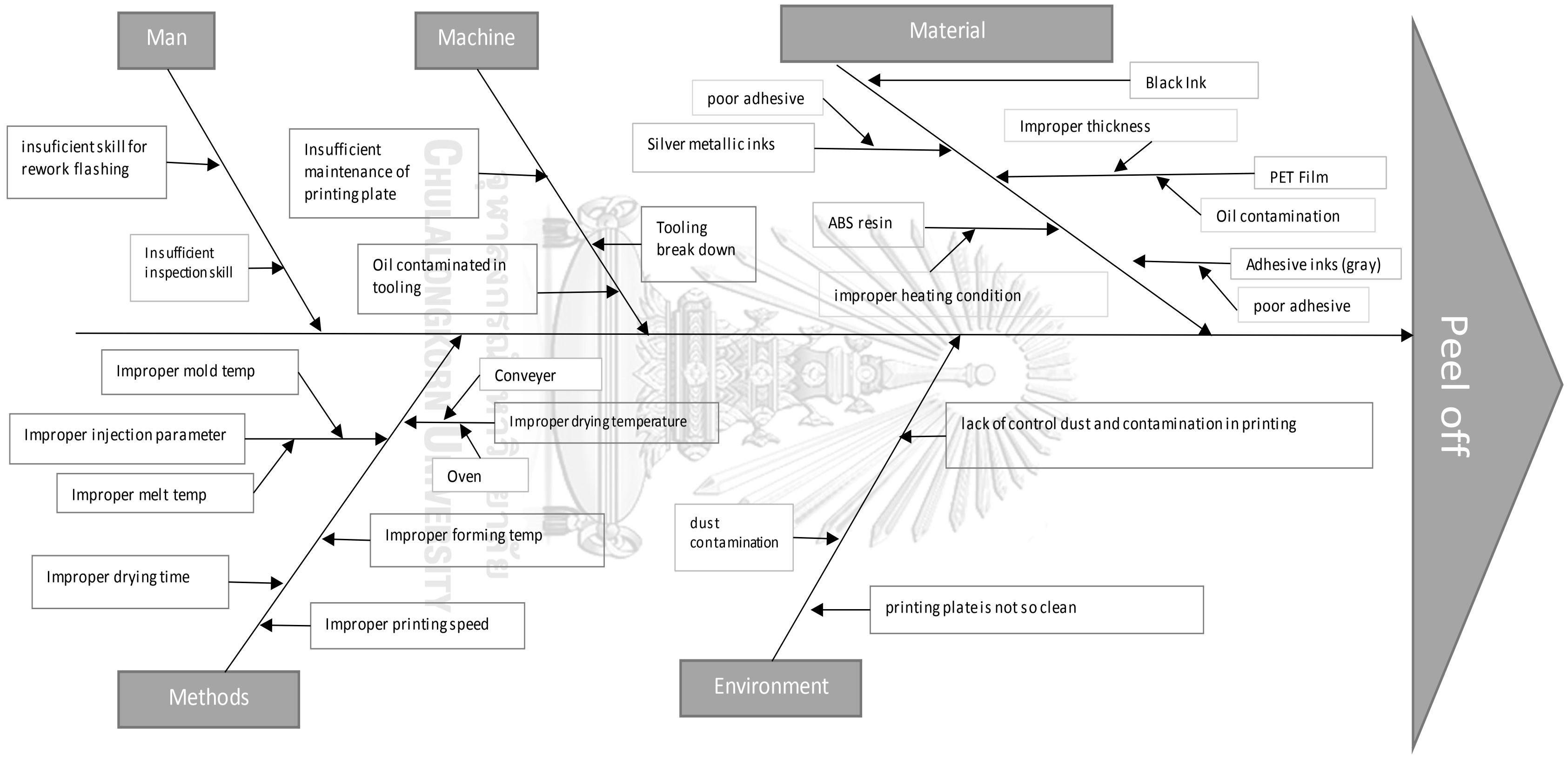


Figure 35 Cause and Effect diagram of IMD Peel off

The cause and effect scoring is evaluated by 4 team members who have well-experienced in this field to select only the factors that highly related to cause of PET film peeled off. As aspect of criteria of score, represented in Table 7. Then summarize score given by 4 members shown in Table 8. The Pareto chart in Figure 36 and Table 10 represented the ranking factors from cause and effect matrix scoring as follows.

1. Poor adhesive of silver metallic ink
2. Poor adhesive of transparent glue layer
3. Improper printing drying
4. Insufficient skill of flash removing
5. Oil contaminated in tooling
6. Improper PET thickness
7. Improper melting temperature
8. Improper moulding temperature
9. Improper forming temperature
10. Improper oven drying time
11. Improper conveyer drying time
12. Improper conveyer speed
13. Insufficient inspection

Table 7 Criteria of scoring matrix

Level	Cause and Effect description	Score
H: High	Highly effect and relate to cause of problem	5
M: Medium	Moderately affect and relate to cause of problem	3
L: Low	Slightly affect and relate to cause of problem	1

Table 8 Scoring matrix by 4 members brainstorming

Factors	No.	Input variable	IMD process	Scoring from Evaluator				Total score
				1	2	3	4	
Man	1	Insufficient skill for rework flashing	Injection	H	M	H	H	18
	2	Insufficient inspection skill	Injection	M	H	M	M	14
Machine	3	Insufficient maintenance of printing plate	Printing	M	L	M	L	8
	4	Oil contaminated in tooling	Injection	H	H	H	M	18
	5	Tooling break down	Injection	H	H	M	L	14
Material	6	Poor adhesive of silver metallic ink	Printing	H	H	H	H	20
	7	Improper heating of ABS	Injection	L	L	M	M	8
	8	Poor adhesive of black ink	Printing	L	L	L	M	6
	9	Improper PET thickness	Printing	H	H	H	M	18
	10	Oil contaminated in PET film	Printing	H	M	H	H	18
	11	Poor adhesive of transparent adhesive layer	Printing	H	H	H	H	20
Method	12	Improper mold temperature	Injection	H	H	H	M	18
	13	Improper melt temperature	Injection	M	H	H	H	18
	14	Improper drying time	Printing	H	H	H	H	20
	15	Improper oven drying temperature	Printing	H	M	H	H	18
	16	Improper conveyer drying temperature	Printing	H	H	M	H	18
	17	Improper forming temp	Forming	L	H	M	L	10
	18	Improper printing conveyer speed	Printing	H	M	H	H	18
Environment	19	Dust contamination	Injection	L	L	L	L	4
	20	Lack of control dust and contamination in printing	Printing	M	L	H	L	10
	21	Printing plate is not so clean	Printing	L	M	L	L	6

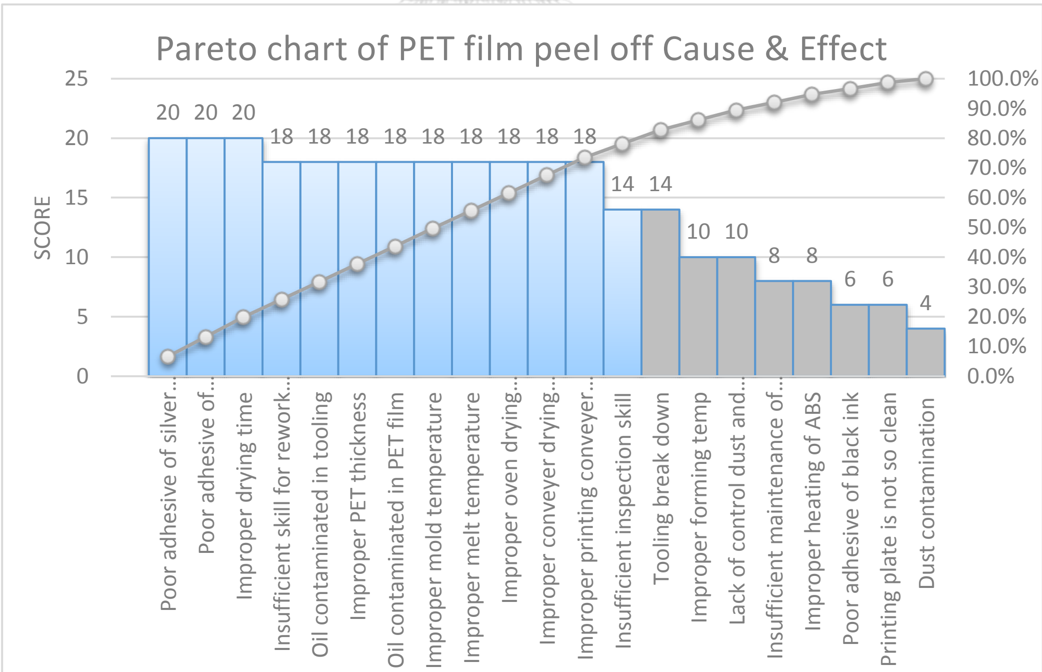


Figure 36 Pareto chart of scoring from Cause and Effect matrix

Table 9 Input variable of 13 factors ranking by 80/20 rule of Pareto chart

Input variable	Score	%	% Cum
Poor adhesive of silver metallic ink	20	7%	7%
Poor adhesive of transparent adhesive layer	20	7%	13%
Improper drying time	20	7%	20%
Insufficient skill for rework flashing	18	6%	26%
Oil contaminated in tooling	18	6%	32%
Improper PET thickness	18	6%	38%
Oil contaminated in PET film	18	6%	44%
Improper mold temperature	18	6%	50%
Improper melt temperature	18	6%	56%
Improper oven drying temperature	18	6%	62%
Improper conveyer drying temperature	18	6%	68%
Improper printing conveyer speed	18	6%	74%
Insufficient inspection skill	14	5%	78%
Tooling break down	14	5%	83%
Improper forming temp	10	3%	86%
Lack of control dust and contamination in printing	10	3%	89%
Insufficient maintenance of printing plate	8	3%	92%
Improper heating of ABS	8	3%	95%
Poor adhesive of black ink	6	2%	97%
Printing plate is not so clean	6	2%	99%
Dust contamination	4	1%	100%

Regarding Table 10 represents summary of score given by 4 specialist from IMD manufacturing process. Then the Pareto chart has been presented in Figure 36. The 80/20 rule of Pareto was applied for score ranking to select potential factors for FMEA Analysis in the next step.

The FMEA is applied in this stage to identify and address 13 potential problems which have been verified by the Cause & Effect diagram and scoring matrix to do the improvements for IMD process. The FMEA of in-mould decoration process by focusing on 13 factors of racking represented in Table 10. These calculated the RPN by using the criteria and score in Table 11.

Table 10 FMEA of in-mould decoration process by focusing on 13 factors of racking

No.	Process Name	Potential Failure Mode	Potential Effect(s) of Failure	S e v	Class	Potential Cause(s)/ Mechanism(s) of Failure	Occur	Current/Proposed Process Controls	Detect	R. P. N.
	Incoming material	Poor UV hairline adhesion	PET is separated from the UV brushed layer (Peel off)	8	☆	UV brushed UV drying tunnel is not enough light intensity	2	Each batch is inspected according to the incoming inspection standard and tested in a hundred grids	4	64
		PET Film thickness variation	Poor Adhesion	8	☆	PET Thickness doesn't meet specification	4	Tighten inspection for thickness of PET	4	128
		PET Film Inspection	Poor Adhesion	8	☆	PET film contamination	4	Tighten inspection for PET raw material	3	96
		Adhesive Ink Inspection	Poor Adhesion	8	☆	Afhesive ink wrong type	4	Tighten inspection for adhesive ink raw material	2	64
		Ink variation	Bad adhesion	8	☆	Ink overdue	2	Incoming inspection	4	64
	Printing	Air bubbles	Peel off/ Poor adhesion	8	☆	Silver layer and UV sheet adhesion NG Silver ink is bad adhensive with UV PET film.	6	Training the QC,doing detergent test and high-low cycle test.	4	192
		Peel off issue between UV layer and silver ink.	Peel off/ Poor adhesion	8	☆	Wrong percentage for Silver ink , improper drying time	8	Add ink or solvent agent follow instruction	4	256
		Poor ink adhesion	Peel off/ poor adhesive	8	☆	Use wrong ink	3	Choose correct ink according to usage and material of print matter	4	96
	Forming	Blank pressing	Peel off	6	☆	Too long heating	2	Shorten heat time	2	24
		Wrong position, asymmetrical edges	Peel off	6	☆	Too short heating	2	Adjust heat time	2	24
	ABS curing	Improper parameter	Poor Adhesion	6	☆	Improper dry temperature	3	Lay "material dry temperature and time synopsis" and technics card on site and monitor technics	2	36
			Poor adhesion	6	☆	Dry machine break down	3	Regular maintenance and daily check	2	36
	Injection	Flash	Need to rework/ Risk to peel off	6	☆	Not enough lock mold strength	8	Verification of operation preparation and adjust technics properly	3	144
			Need to rework/ Risk to peel off	6	☆	Too fast injection	3	Verification of operation preparation and adjust technics properly	3	54
		Contamination	Dent/ Poor adhesion	3	☆	Foreign material on the tooling.	5	Increase the self-inspection for protective film and material crumbles.	4	60
			Peel off	8	☆	Improper mold temperature	6	Adjust mold temperature and verify operation preparation	3	144
		Adhension NG	Peel off	6	☆	Oil on the cavity.	6	Clean the film and tooling in advance.	4	144
			Poor adhesion	8	☆	Silver color not match the plastic material	4	- Adding grey line coverage. - Addimg more whole adhesive layer	4	128
	Final inspection	Wrong judgement	Affect next process and don't meet client's requirements	5	☆	QC lack of experience and don't find the problem	6	Organize QC skill training	6	180

Table 11 FMEA score and criteria

FMEA Scale			
RATING	**DEGREE OF SEVERITY**	**LIKELIHOOD OF OCCURRENCE**	**ABILITY TO DETECT**
1	Customer will not notice the adverse effect or it is insignificant	Likelihood of occurrence is remote < 1 in 1,500,000	Sure that the potential failure will be found or prevented before reaching the next customer
2	Customer will probably experience slight annoyance	Low failure rate with supporting documentation Up to 1 in 150,000	Almost certain that the potential failure will be found or prevented before reaching the next customer
3	Customer will experience annoyance due to the slight degradation of performance	Low failure rate without supporting documentation up to 1 in 15,000	Low likelihood that the potential failure will reach the next customer undetected
4	Customer dissatisfaction due to reduced performance	Occasional failures up to 1 in 2,000	Controls may detect or prevent the potential failure from reaching the next customer
5	Customer is made uncomfortable or their productivity is reduced by the continued degradation of the effect	Relatively moderate failure rate with supporting documentation up to 1 in 400	Moderate likelihood that the potential failure will reach the next customer
6	Warranty repair or significant manufacturing or assembly complaint	Moderate failure rate without supporting documentation up to 1 in 80	Controls are unlikely to detect or prevent the potential failure from reaching the next customer
7	High degree of customer dissatisfaction due to component failure without complete loss of function. Productivity impacted by high scrap or rework levels.	Relatively high failure rate with supporting documentation up to 1 in 20	Poor likelihood that the potential failure will be detected or prevented before reaching the next customer
8	Very high degree of dissatisfaction due to the loss of function without a negative impact on safety or governmental regulations	High failure rate without supporting documentation up to1 in 8	Very poor likelihood that the potential failure will be detected or prevented before reaching the next customer
9	Customer endangered due to the adverse effect on safe system performance with warning before failure or violation of governmental regulations	Failure is almost certain based on warranty data or significant DV testing >1 in 3	Current controls probably will not even detect the potential failure
10	Customer endangered due to the adverse effect on safe system performance without warning before failure or violation of governmental regulations	Assured of failure based on warranty data or significant DV testing >1 in 2	Absolute certainty that the current controls will not detect the potential failure

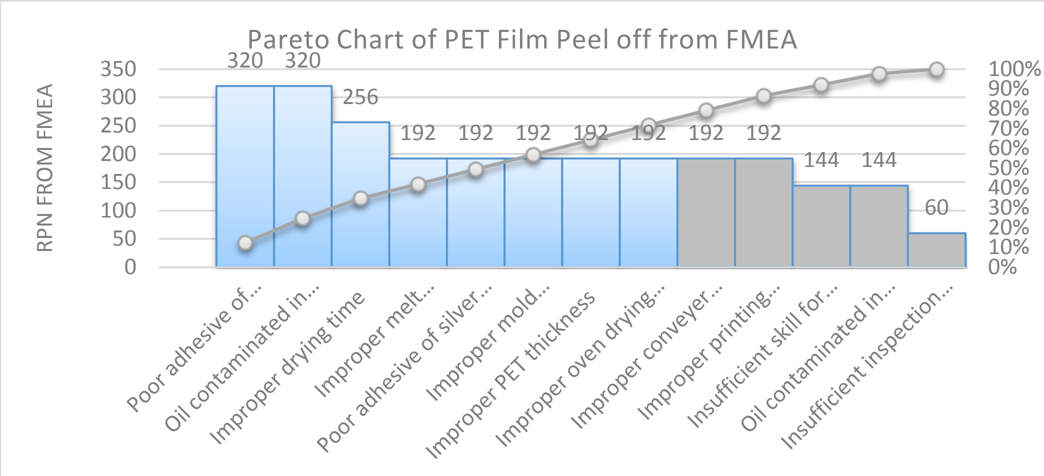


Figure 37 Pareto chart of prioritized RPN from FMEA

Regarding Table 12 represents summary of RPN score ranking from FMEA of IMD manufacturing process in Table 10. Then the Pareto chart has been presented in Figure 37. The 80/20 rule of Pareto was applied for score ranking to select potential factors for the design of experiment (DOE) in the next step. This can be concluded that 9 factors in table 12 have been selected to do further analysis by DOE in next step.

Table 12 factors selected to conduct DOE from highest RPN by FMEA

NO.	Potential Cause of IMD Peel off	RPN by FMEA
1	Poor adhesive of transparent adhesive layer	320
2	Oil contaminated in tooling	320
3	Improper drying time	256
4	Improper melt temperature	192
5	Poor adhesive of silver metallic ink	192
6	Improper mold temperature	192
7	Improper PET thickness	192
8	Improper oven drying temperature	192
9	Improper conveyer drying temperature	192
10	Improper printing conveyer speed	192
11	Insufficient skill for rework flashing	144
12	Oil contaminated in PET film	144
13	Dry halftone	120
15	Wrong operation	72
16	PET is separated from the UV brushed layer	64
16	Insufficent inspection skill	60
17	Light of the overprinted ink	60
18	Improper mold temp	60
19	Foreign material on the tooling.	60
20	Print next color before previous one is dry	60
21	Broken mold interface	54
22	Wrong time and temperature of curing	48
23	Temperature controller don't work	36
24	Improper handling of material	36
25	Improper dry temperature of ABS	36
26	Dry machine break down	36
27	Curve or thin material, improper operation	36
28	Too short heating	24
29	Lack of enough self-checking by worker	12

CHAPTER V

THE DESIGN OF EXPERIMENT

The design of experiment (DOE) is applicable to use in the analysing phase to verify that selected factors from FMEA are statistically significant effect to peel off strength and part warpage. In this chapter, the design of experiment is carried out separately by two experiments including factors influenced to peel off and part warpage.

5.1 The experiment of IMD peel off

5.1.1 Design and Factors selection

In order to conduct the design of experiment to find the optimal parameter setting for improvement and control in the next step. The overall 9 factors have been selected from FMEA in previous chapter but there are only 6 variable factors that can be applied to do the experiment. Aspect of attribute variables will be improve by using standard working and control plan. There are six factors selected from the FMEA to carry out the experiment are listed in Table 13 including drying time of silver printing, adding adhesive transparent layer, PET film thickness, oven drying temperature, injection melting temperature and injection mould temperature. The available design are listed in Figure 38 for the 6 factors by using 2^{k-1} factorial 32 runs based on 2_{VI}^{6-1} with design resolution equal to 6. The Face-centre Central Composite design (CCF) is applied in this experiment to find influenced factors and optimize these response with total 53 runs as represented in Table 14.

	Factors													
Run	2	3	4	5	6	7	8	9	10	11	12	13	14	15
4	Full	III												
8		Full	IV	III	III	III								
16			Full	V	IV	IV	IV	III	III	III	III	III	III	III
32				Full	VI	IV	IV	IV	IV	IV	IV	IV	IV	IV
64					Full	VII	V	IV	IV	IV	IV	IV	IV	IV
128						Full	VIII	VI	V	V	IV	IV	IV	IV

Available Response Surface Designs

Design		Continuous Factors								
		2	3	4	5	6	7	8	9	10
Central composite full	unblocked	13	20	31	52	90	152			
	blocked	14	20	30	54	90	160			
Central composite half	unblocked				32	53	88	154		
	blocked				33	54	90	160		
Central composite quarter	unblocked							90	156	
	blocked							90	160	
Central composite eighth	unblocked									158
	blocked									160
Box-Behnken	unblocked		15	27	46	54	62		130	170
	blocked			27	46	54	62		130	170

Figure 38 Design selection and factors available for the experiment

The highest RPN 9 items are selected as potential causes from FMEA have been selected to do improvement and control. There are only 7 variable items selected to verify by DOE then find optimal setting; Printing drying time of Silver layer, Adhesive layer, PET Film thickness ,Oven Drying temperature, Injection melt temp, Injection mould temp, and conveyer drying temperature. Aspect of conveyer drying temperature has no longer available to do the experiment because of the temperature adjustment is limited to prevent the covered protective film on the top of PET. Regarding other attribute factor such as oil contamination in tooling and others will be implement by using control plan and standard operation procedure (SOP).

Therefore, the experimental design conducts 6 influenced factors with 3 levels listed in Table 13 including drying time of silver printing, adding the adhesive transparent layer, PET film thickness, oven drying temperature, injection moulding temperature and injection melting temperature by applying the face-centred central composite design (CCF), a response surface methodology, to optimize response variable from several influenced factors, then finding the optimal solution for improvement. The response variable of this experiment is the adhesive strength in a unit of N/mm measured by measurement methods reference ASTM D6862.

Table 13 Factors and levels for Face-Centered Central Composite Design (CCF)

Code	Factors	Level		
		-1	0	1
A	Drying time of silver printing (Minute)	20	30	40
B	Adding adhesive transparent layer*	1	2	3
C	PET film thickness	0.18	0.20	0.22
D	Oven drying temp (˚C)	70	80	90
E	Injection melt temp (˚C)	220	235	250
F	Injection mould temp (˚C)	20	35	45

*Adhesive layer

1	Do nothing
2	Adding the middle adhesive layer before silver printing
3	Adding adhesive layer at final printing

Table 14 the design of experiment table of adhesive strength of IMD components

StdOrder	RunOrder	PtType	Blocks	A	B	C	D	E	F	Adhesive strength (N/mm)
17	1	1	1	-1	-1	-1	-1	1	1	15.7
9	2	1	1	-1	-1	-1	1	-1	1	18.3
22	3	1	1	1	-1	1	-1	1	1	14.9
19	4	1	1	-1	1	-1	-1	1	-1	22.1
33	5	-1	1	-1	0	0	0	0	0	24.9
37	6	-1	1	0	0	-1	0	0	0	16.2
6	7	1	1	1	-1	1	-1	-1	-1	22.3
52	8	0	1	0	0	0	0	0	0	21.6
36	9	-1	1	0	1	0	0	0	0	24.1
11	10	1	1	-1	1	-1	1	-1	-1	25.7
49	11	0	1	0	0	0	0	0	0	20.4
38	12	-1	1	0	0	1	0	0	0	23.8
47	13	0	1	0	0	0	0	0	0	24.2
8	14	1	1	1	1	1	-1	-1	1	35.6
35	15	-1	1	0	-1	0	0	0	0	17.7
7	16	1	1	-1	1	1	-1	-1	-1	22.9
18	17	1	1	1	-1	-1	-1	1	-1	20.6
45	18	0	1	0	0	0	0	0	0	19.9
14	19	1	1	1	-1	1	1	-1	1	22.8
43	20	-1	1	0	0	0	0	0	-1	23.5
27	21	1	1	-1	1	-1	1	1	1	27.1
16	22	1	1	1	1	1	1	-1	-1	38.5
29	23	1	1	-1	-1	1	1	1	1	18.8
28	24	1	1	1	1	-1	1	1	-1	37.4
1	25	1	1	-1	-1	-1	-1	-1	-1	14.4
4	26	1	1	1	1	-1	-1	-1	-1	32.9
50	27	0	1	0	0	0	0	0	0	19.2
5	28	1	1	-1	-1	1	-1	-1	1	16.5
2	29	1	1	1	-1	-1	-1	-1	1	20.1
30	30	1	1	1	-1	1	1	1	-1	24.8
41	31	-1	1	0	0	0	0	-1	0	15.2
24	32	1	1	1	1	1	-1	1	-1	33.6
25	33	1	1	-1	-1	-1	1	1	-1	14.9
31	34	1	1	-1	1	1	1	1	-1	25.7
15	35	1	1	-1	1	1	1	-1	1	28.9
51	36	0	1	0	0	0	0	0	0	20.8
13	37	1	1	-1	-1	1	1	-1	-1	15.8
39	38	-1	1	0	0	0	-1	0	0	17.3
3	39	1	1	-1	1	-1	-1	-1	1	22.6
40	40	-1	1	0	0	0	1	0	0	19.5
12	41	1	1	1	1	-1	1	-1	1	37.4
44	42	-1	1	0	0	0	0	0	1	18.7
46	43	0	1	0	0	0	0	0	0	20.4
48	44	0	1	0	0	0	0	0	0	19.3
34	45	-1	1	1	0	0	0	0	0	23.4
20	46	1	1	1	1	-1	-1	1	1	33.1
23	47	1	1	-1	1	1	-1	1	1	30.7
21	48	1	1	-1	-1	1	-1	1	-1	20.4
42	49	-1	1	0	0	0	0	1	0	22.7
26	50	1	1	1	-1	-1	1	1	1	21.6
53	51	0	1	0	0	0	0	0	0	22.8
32	52	1	1	1	1	1	1	1	1	40.2
10	53	1	1	1	-1	-1	1	-1	-1	24.3

5.1.2 The design of experiment

The design selection for the experiment is in place to analyse the following list in Table 13. The experimental result has been done and analysed statistically by using Minitab represented in Figure 39 and 40 respectively. The result from ANOVA representing 4 main effects of influenced factors are significant including drying time, adding an adhesive layer, PET thickness and oven drying temperature clearly observed by P-value less than 0.05 in Figure 40.

Regarding the two-way interaction in Figure 42, it shows that interaction of drying time and the adhesive layer is also significant. The interaction plot represented the high level of drying time (40 min), and adding an adhesive layer at the final printing lead to increase the highest adhesive strength. As aspect of the middle level of drying time (30 min), adding an adhesive layer at the final printing also lead to increase high adhesive strength. On the contrary, when adding the adhesive layer at the middle layer of printing, the highest adhesive strength is represented, while a low level of drying time (20 min) is applicable, which is higher than applying high drying time at 30 and 40 minute. These abnormal result can be occurred in case of performing the experiment by adding adhesive layer at the middle silver layer of PET film. Because of the unstable adhesion at the middle layer of PET film which combine between its UV-curable inks and a solvent-inks using in silver metallic layer resulting the uncertainty of measurement. The unstable adhesion is caused by incompatible between two type of UV ink and solvent-ink in the middle layer of PET film affecting these abnormal result. Therefore, the measurement methods of this experiment should be considered to improve in the future to get better accuracy of experimental result.

The last step of data analysis is testing of assumption from ANOVA by using residual analysis before going to make a conclusion (Montgomery 2015). According to residual analysis (Runger 2010), the normal probability plots are formed to be a straight line and the histogram are formed likes a normal distributed that means residuals are normally distributed (Montgomery 2015). The pattern of residuals versus fitted plots is non-structured that means residuals have a constant variance. Regarding the residuals versus order plots do not shown any pattern or trend, so the residuals are statistically independent. There are 4 residual plots of 3 assumptions represented in Figure 39 as follows;

1) residuals are normally distributed
2) residuals are statistically independent
3) residuals have a constant variance

These can be summarized that all assumption testing of this model are valid to analyse the experimental results, observed by the normal probability plot, residual versus order plot and versus fitted plot respectively.

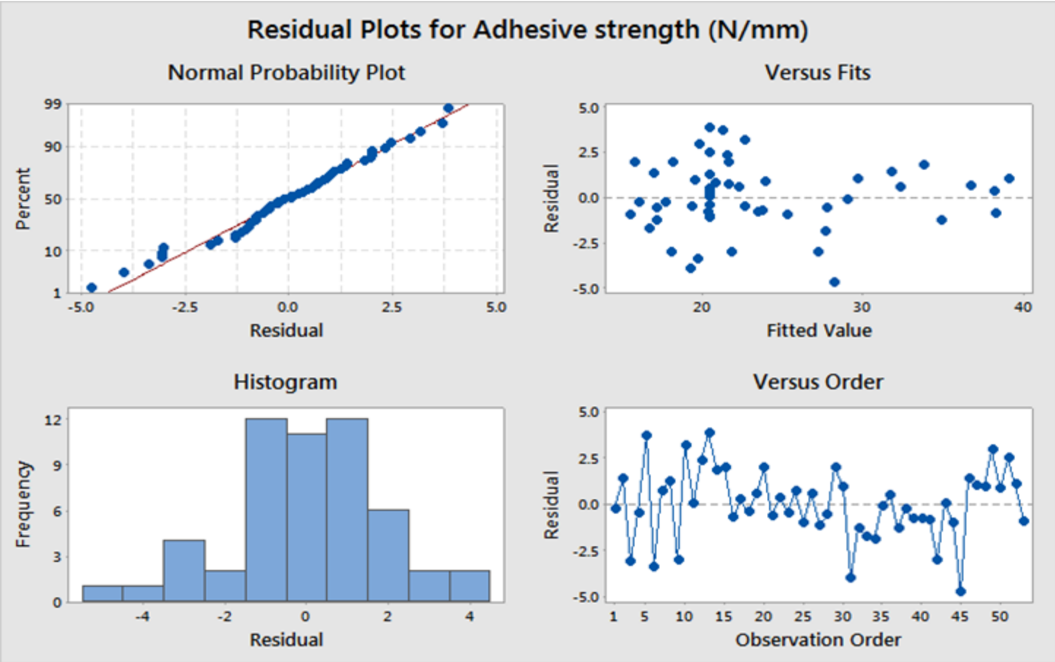


Figure 39 the residual plot of design of experiment

Response Surface Regression: Adhesive strength (N/mm) versus Adhesive str versus Drying time, Adhesive lay, PET thickness, ...

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	10	1998.28	199.83	36.63	0.000
Linear	5	1616.30	323.26	59.26	0.000
Drying time	1	410.22	410.22	75.21	0.000
Adhesive layer	1	1113.80	1113.80	204.19	0.000
PET thickness	1	29.74	29.74	5.45	0.024
Oven drying temp	1	62.24	62.24	11.41	0.002
Inj mold temp	1	0.30	0.30	0.06	0.815
Square	1	256.06	256.06	46.94	0.000
Drying time*Drying time	1	256.06	256.06	46.94	0.000
2-Way Interaction	4	125.92	31.48	5.77	0.001
Drying time*Adhesive layer	1	67.28	67.28	12.33	0.001
Drying time*Oven dryibg temp	1	18.00	18.00	3.30	0.076
Drying time*Inj mold temp	1	20.16	20.16	3.70	0.061
Adhesive layer*Inj mold temp	1	20.48	20.48	3.75	0.059
Error	42	229.10	5.45		
Lack-of-Fit	34	207.17	6.09	2.22	0.118
Pure Error	8	21.92	2.74		
Total	52	2227.38			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.33553	89.71%	87.27%	84.84%

Figure 40 the ANOVA table of design of experiment from Minitab

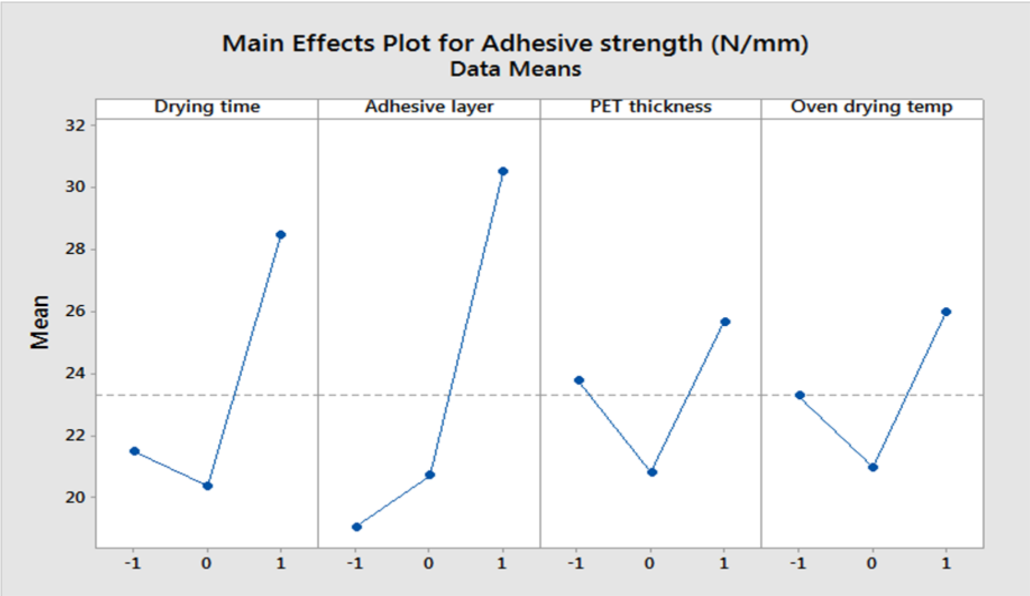


Figure 41 the main effect plot of adhesive strength

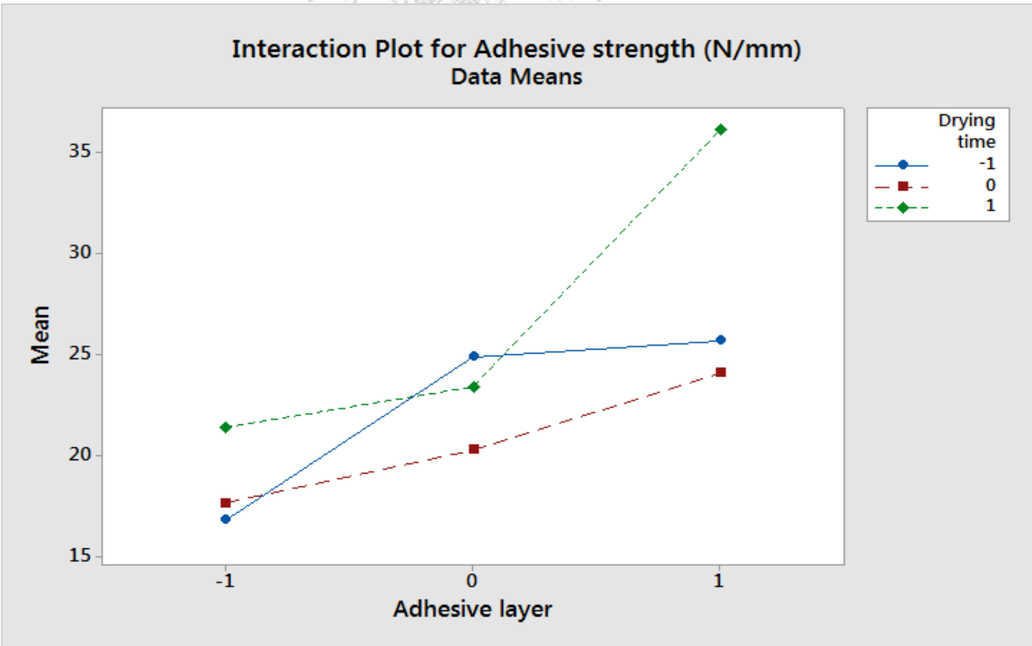


Figure 42 The Interaction plot of the adhesive strength of PET film

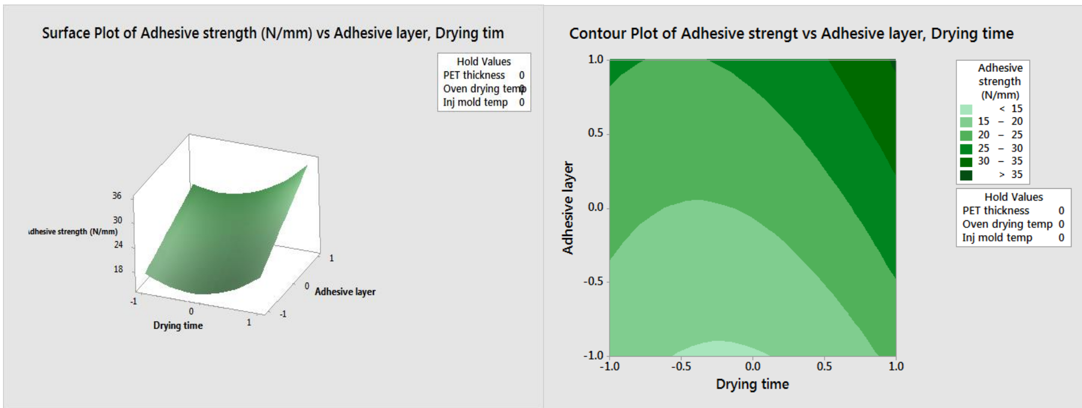


Figure 43 the contour plot of interaction

The contour plot of the interaction can also represented the experiment result similar with the interaction plot in Figure 43. At the high level of drying time (40 min) and adding adhesive layer at final printing lead to increase high adhesive strength. On the contrary, the adhesive strength can be increased when low level of drying time (20 min) is applicable with adding the middle adhesive layer.

5.1.3 The optimal parameter setting

As a result of data analysis from ANOVA in Figure 40, there are 4 factors that significantly influenced to the adhesive strength of PET film including drying time, adhesive transparent layer, PET film thickness, and oven drying temperature. In order to find the optimal setting for maximum adhesive strength, further data analysis is required to be done by same experimental design of 4 factors to increase adhesive strength and improve quality of in-mould decoration process.

The result of the experiment was statistically analysed that can be demonstrated the new optimal setting for 4 influenced parameters shown in Figure 44 and 45. Therefore, the manufacturing process of in-mould decoration should set up optimal conditions to improve peeled off the issue as follows; setting the drying time of silver printing process to be 40 min, adding a transparent adhesive layer at final printing process, using PET thickness 0.22 mm and setting oven drying temperature at 90 ˚C.

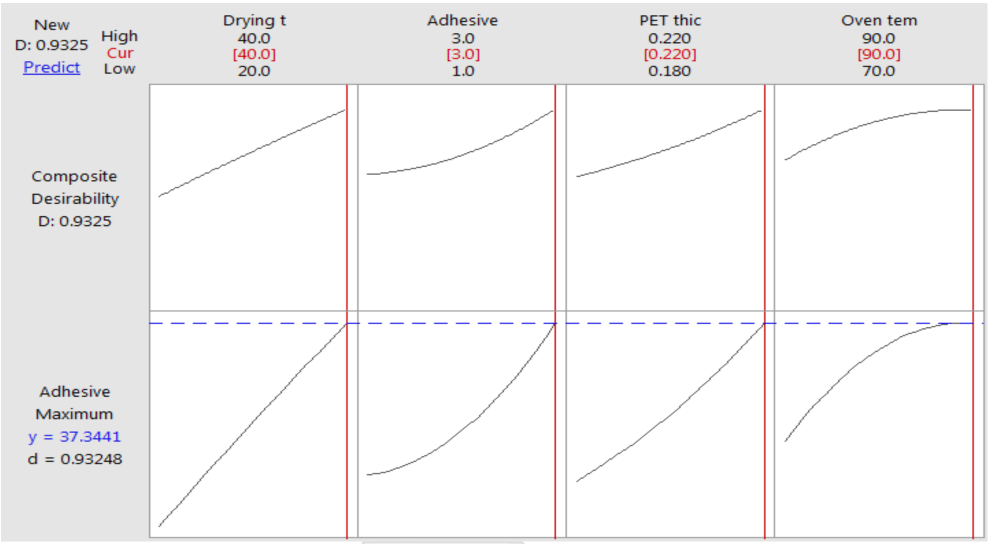


Figure 44 the optimal setting to maximize adhesive strength

Response Optimization: Adhesive strength (N/mm)

```
Parameters
Response                   Goal     Lower Target Upper Weight
Importance
Adhesive strength (N/mm) Maximum     20    40.2              1
1
Solution
                                                Adhesive
                                        Oven    strength
          Drying Adhesive PET          drying   (N/mm)     Composite
Solution time    layer     thickness temp          Fit Desirability
1          40      3        0.22       90        37.9260
0.887427
```

Variable	Unit	Setting
Printing drying time	minute	40
Adhesive layer adding	type	3
PET thickness	mm	0.22
Oven drying temp	˚C	90

Figure 45 the optimal setting parameter to maximize adhesive strength

5.2 The experiment of IMD part warpage

5.2.1 Design and factor selection

In order to conduct the design of experiment for IMD warpage problem to find the optimal parameter setting for improvement and control in the next step. The four factors selected from the cause and effect diagram to carry out the experiment are listed in Table 15 including injection mould temperature, Post injection pressure, cooling time and injection melt temperature.

The available design are listed in table 16 for the 4 factors by using 2^k full factorial with 16 runs. The Face-centre Central Composite design (CCF) is also applied in this experiment to find influenced factors and optimize these response with total 31 runs.

Table 15 Factors and levels for Face-Centered Central Composite Design (CCF)

Code	Factors	Unit	Level -1	Level 0	Level 1
A	Injection mould temperature	˚C	20	35	45
B	Post Injection Pressure	MPa	25	30	40
C	Cooling time	Sec	9	15	18
D	Injection melt temperature	˚C	220	235	250

Table 16 Design selection and factors available for the experiment

Available Response Surface Designs

Design		Continuous Factors 2	3	4	5	6	7	8	9	10
Central composite full	unblocked	13	20	31	52	90	152			
	blocked	14	20	30	54	90	160			
Central composite half	unblocked				32	53	88	154		
	blocked				33	54	90	160		
Central composite quarter	unblocked							90	156	
	blocked							90	160	
Central composite eighth	unblocked									158
	blocked									160
Box-Behnken	unblocked		15	27	46	54	62		130	170
	blocked			27	46	54	62		130	170

There are 4 variable factors are selected as potential causes from the cause and effect diagram to do improvement and control including cooling time, post injection pressure, Injection melt temperature and Injection mould temperature. Regarding other attribute factor will be implement by using control plan and standard operation procedure (SOP).

Therefore, the experimental design conducts 4 influenced factors with 3 levels listed in Table 15 including cooling time, post injection pressure, Injection melt temperature and Injection mould temperature by applying the face-centred central composite design (CCF), a response surface methodology, to optimize response variable from several influenced factors, then finding the optimal solution for improvement. The response variable of this experiment is the warpage variation measured by gap measurement between IMD and assembly fixture.

5.2.2 The design of experiment

The design selection for the experiment is in place to analyse the following list in Table 15 and 16. The experimental result has been done and analysed statistically by using Minitab represented in Figure 46. The result from ANOVA representing 2 main effects of influenced factors are significant including injection mould temperature and cooling time that clearly observed by P-value less than 0.05 in Figure 46 and 47.

According to residual analysis, the normal probability plots are formed to be a straight line and the histogram are formed likes a normal distributed that means residuals are normally distributed. The pattern of residuals versus fitted plots is non-structured that means residuals have a constant variance. Regarding the residuals versus order plots do not shown any pattern or trend, so the residuals are statistically independent. There are 4 residual plots of 3 assumptions that carry out to verify accuracy of model represented in Figure 48 represented as follows;

1) Residuals are normally distributed

2) Residuals are statistically independent

3) Residuals have a constant variance

These can be observed by the normal probability plot, residual versus order plot and versus fitted plot respectively.

Response Surface Regression: Warpage (mm) versus Injection mo, Post Injecti, ...

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	8.14924	0.58209	10.91	0.000
Linear	4	5.98694	1.49674	28.06	0.000
Injection mould temperature	1	4.65125	4.65125	87.19	0.000
Post Injection Pressure	1	0.06722	0.06722	1.26	0.278
Cooling time	1	1.20125	1.20125	22.52	0.000
Injection melt temperature	1	0.06722	0.06722	1.26	0.278
Square	4	1.71136	0.42784	8.02	0.001
Injection mould temperature*Injection mould temperature	1	0.15987	0.15987	3.00	0.103
Post Injection Pressure*Post Injection Pressure	1	0.12929	0.12929	2.42	0.139
Cooling time*Cooling time	1	0.10195	0.10195	1.91	0.186
Injection melt temperature*Injection melt temperature	1	0.08112	0.08112	1.52	0.235
2-Way Interaction	6	0.45094	0.07516	1.41	0.271
Injection mould temperature*Post Injection Pressure	1	0.15016	0.15016	2.81	0.113
Injection mould temperature*Cooling time	1	0.19141	0.19141	3.59	0.076
Injection mould temperature*Injection melt temperature	1	0.01266	0.01266	0.24	0.633
Post Injection Pressure*Cooling time	1	0.08266	0.08266	1.55	0.231
Post Injection Pressure*Injection melt temperature	1	0.01266	0.01266	0.24	0.633
Cooling time*Injection melt temperature	1	0.00141	0.00141	0.03	0.873
Error	16	0.85350	0.05334		
Lack-of-Fit	10	0.52636	0.05264	0.97	0.543
Pure Error	6	0.32714	0.05452		
Total	30	9.00274			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.230962	90.52%	82.22%	63.47%

Figure 46 the ANOVA table of design of experiment from Minitab

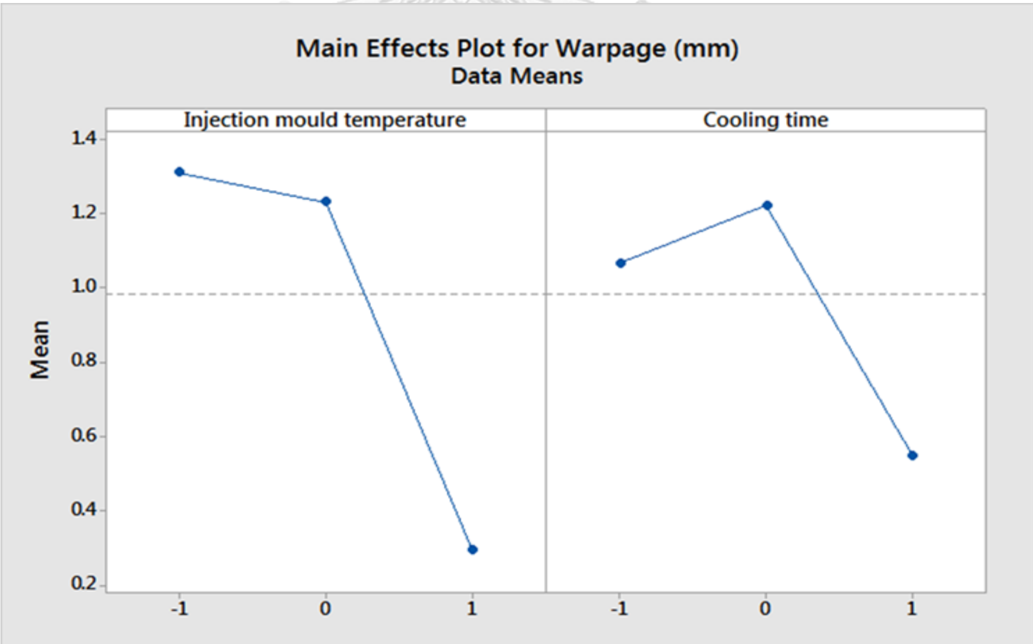


Figure 47 Main effect plot of part warpage

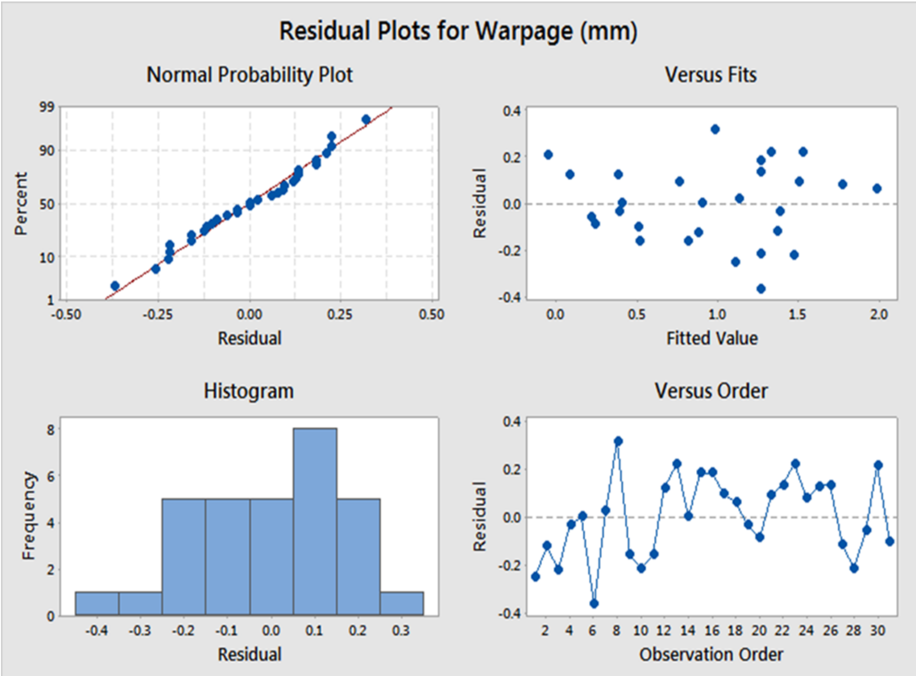
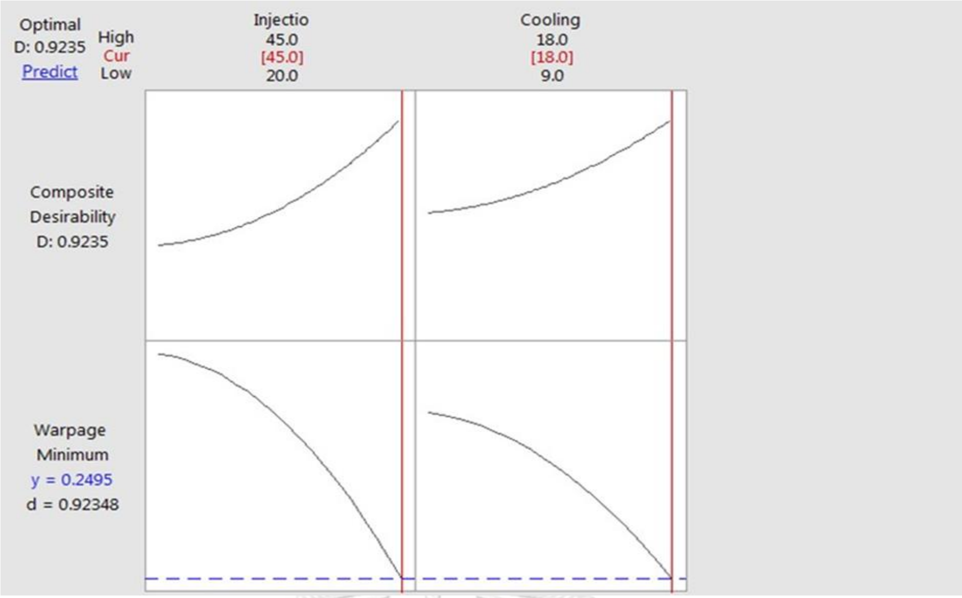


Figure 48 the residual plot of design of experiment

5.2.3 The optimal parameter setting

As a result of data analysis from ANOVA in Figure 46, there are 2 factors that significantly influenced to the IMD warpage including injection mould temperature and cooling time. In order to find the optimal setting to minimize the part warpage, further data analysis is required to be done by same experimental design of 2 factors to get the optimal parameter setting to minimize IMD part warpage and improve quality level of in-mould decoration process.

The result of the experiment was statistically analysed that can be demonstrated the new optimal setting for 2 influenced parameters shown in Figure 49. Therefore, the injection process of in-mould decoration should set up optimal parameters to improve part warpage as follows; setting the mould temperature to be 45 ˚C and cooling time 18 sec.



Variable	Unit	Setting
Injection mould temperature	C	45
Cooling time	Sec	18

Figure 49 the optimal setting parameter to minimize part warpage

CHAPTER VI

CONTROL OF PROCESS

In this phase, all recommended actions have been done by setting new process condition from the previous step. However, the result monitoring is required to validate the effectiveness of result after improvement.

6.1 The effectiveness after improvement

The process capability in Figure 50 represents the result of adhesive strength comparison between before and after improvement. This lead to a conclusion that current process capability (Cpk) have been improved to be 2.99 which is greater than 1.33 by increasing mean of adhesive strength and reducing process variation.

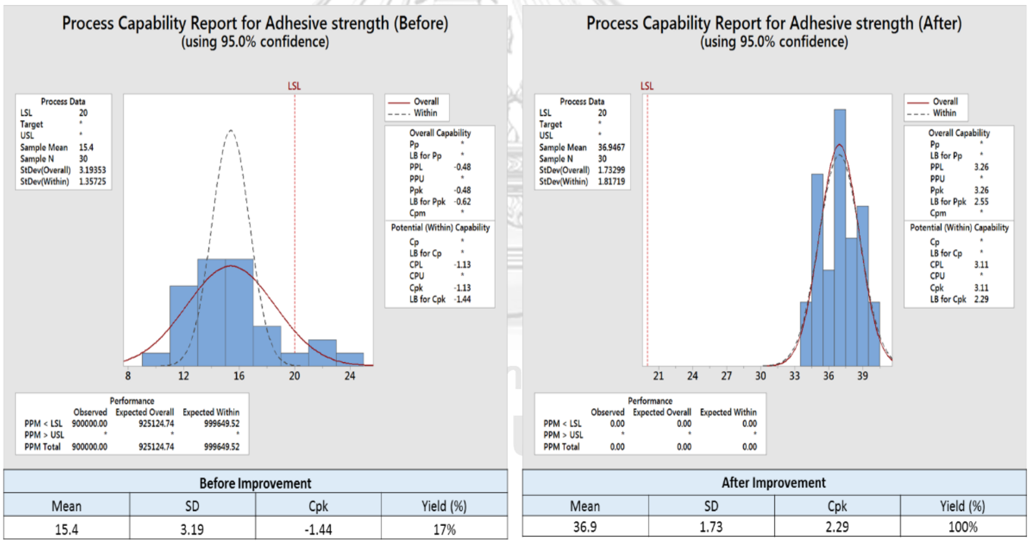
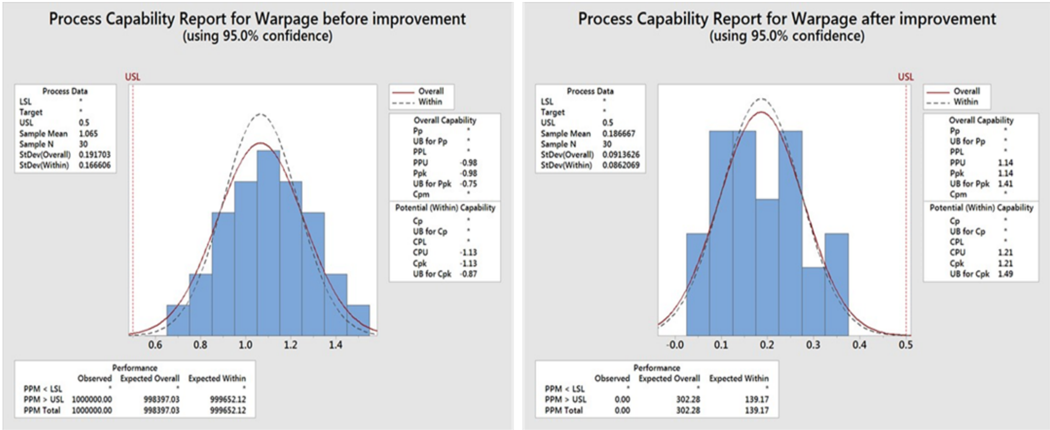


Figure 50 Process Capability of before and after improvement the IMD peel off

The process capability in Fig. 51 represents the result of part warpage comparison between before and after improvement. This lead to a conclusion that current process capability (Cpk) have been improved to be 1.49 which is greater than 1.33 by increasing reducing process variation of part warpage.



Before Improvement			
Mean	SD	UB for Cpk	Yield (%)
15.4	0.16	-0.87	0%

After Improvement			
Mean	SD	UB for Cpk	Yield (%)
36.9	0.116	1.49	100%

Figure 51Process Capability of before and after improvement the part warpage

6.2 The result monitoring

Regarding result monitoring of new lots after implementing the new parameter setting and updated control plan, the result from data monitoring for defect rate comparison over a one-month period after improvement is shown in Figure 52. This can be summarized that the defect rate from in-mould decoration process decreased significantly. In addition, the control plan and standard operation procedure (SOP) must be established then operator training should be done as aspect of new condition setting and control of the critical point to ensure adequate controls are in place to prevent reoccurrences.

The result after improvement shown in figure 53. It is found that defect rate of in-mould decoration process decreased from11.43% average in Feb-June 2018 to1.25% after improvement in July-Oct 2018 which can be calculated as 89% improvement. It is found that IMD peeled off defect is reduce 91.1% and warpage defect is reduce 98.2% of defect before improvement.

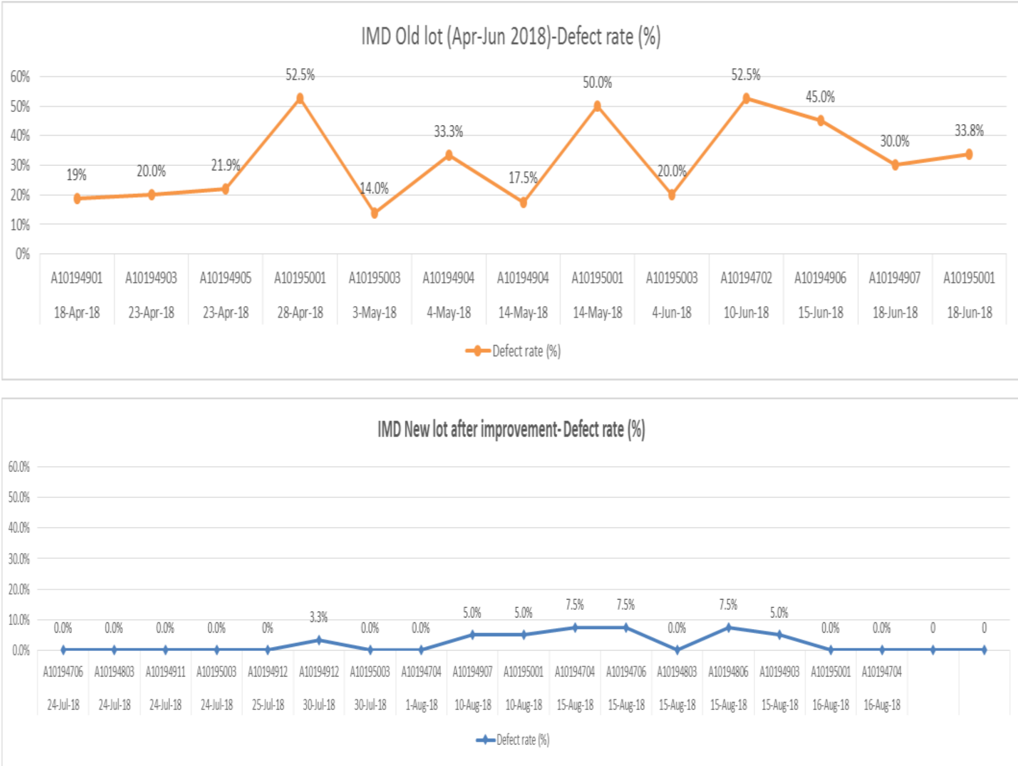


Figure 52 Data monitoring for defect rate comparison of in-mould decoration

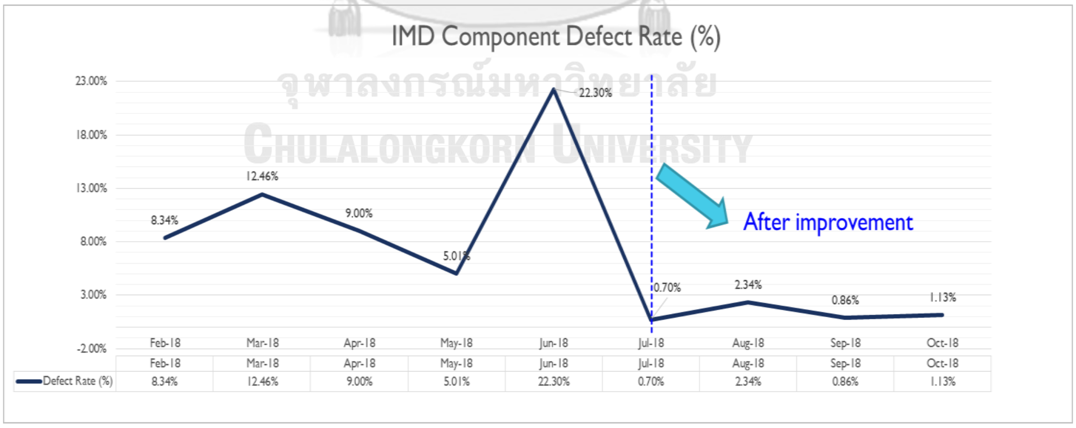


Figure 53 Defect rate of IMD component after improvement

CHAPTER VII

CONCLUSION AND RECOMMENDATION

The in-mould decoration is applicable in injection moulding, a process combining PET film with decorative patterns are moulded together with ABS resins which have been developed to reduce the secondary process of decorative screen printing. In order to reduce defect rate and improve its quality, the five steps of DMAIC Six sigma methodology are implemented. By applying five steps of six sigma methodology, including D-Define, M-Measure, A-Analyse, I-Improve and C-Control, are employed in this research to reduce the defect rate from in-mould decoration process. The five steps of DMAIC activities are carried out by applying quality control and statistical tools are described as follows;

7.1 Define Phase

In the first stage of six sigma is define phase that contains problem descriptions, the impact of business case and benefits after an improvement in order to identify scope that project will be addressed to comply with required objectives by studying details of its process flowchart and historical data. Then, it was finalized by creating a project charter. In this research, the historical data of defect rate from in-mould decoration gathered in February 2018-June 2018 shown as averaged defect rate is 11.43%. However, the current defect rate increased sharply to 22.3% in June 2018 which required to improve instantly. The Pareto chart is plotted to represent the defect rate in February- June 2018, representing almost major defect result from PET film peeled off is 57.4% and difficult to assembly 16.1% from overall defects. Therefore, the PET film peeled off and difficult to assembly are subject to improve in this research.

7.2 Measure Phase

The measured phase is carried out by the determination of part characteristic and measurement method to measure current performance of process through data collection plan that consists of two main steps including determination of measurement method and measurement system analysis.

7.2.1 Measurement method

After the problem identification was clarified, the PET film peeled off is required to be improved in this research. The characteristic required to measure the quality level of in-mould decoration component is related to a sufficient adhesive strength between PET film and its substrate material. The adhesive strength reference ASTM D6862 is applied to measure a quality characteristic of IMD component by determination of resistance to peel off between PET Film and a substrate layer moulded with ABS resins. The visual inspection is the first stage to screen peeled off defect before preparing the rectangular moulded specimen 15mm in width, 60 mm in length and thickness variation are in the range of 2.7-3.0 mm by selecting the origin of peel off area (chamfer edge area). If a flexible adherent is difficult to cut or peel, it can take the decision to be passed without testing. After all preparation and preliminary judgment have been done, place specimen at the fixture and testing machine designed by ASTM D6862 with crosshead speed 10 mm/min. Then the result of adhesive strength are measured by a peeling test as average of bonding strength in a unit of N/mm.

Regarding measurement method of IMD part warpage, carried out by using the feeler gauge or taper gauge to measure the gap between IMD part and the fixture simulated as the plane of assembly point. The maximum point of gap between IMD part and simulated plane can be measured the warpage level of IMD components.

7.2.2 Measurement System Analysis (MSA)

Measurement System Analysis is used to ensure that the measurement system can be detected variation of part or process by evaluating in term of accuracy, precision and stability of the measurement system. There are two types of Measurement System Analysis applicable in this research to verify peel-off strength measurement including attribute Gage R&R and variable Gage R&R.

The attribute measurement systems is used to evaluate repeatability and accuracy of operators who perform the visual inspection for PET film peeled off from IMD component. The attribute test is done by 3 operators that perform an inspection of 10 parts with 3 replicates. The attribute test result shown all 3 operators have both percentages of repeatability and accuracy equal to 100%. It was clarified that both operators and inspection method can be acceptable to verify the peeled off issue. The variable Gage R&R which is done by the same testing method by 3 operators to collect variable data of adhesive strength from the measurement methods. These variable gage R&R were analysed by ANOVA representing the total percentage of gage study is 7.87%, while the result from repeatability is 6.46% and reproducibility is 4.48%, respectively. This result can be acceptable because it fell to just below 10%. From these result can be stated that the measurement system both of adhesive strength and visual inspection are acceptable to capable the variation of IMD process.

After verification of measurement system, the visual inspection and adhesive strength are applied to measure the current performance of in-mould decoration parts by sampling 3 pcs of each lot, total 10 lots during the period of May-June 2018 to be inspected by visual inspection and measurement of the adhesive strength. The visual inspection result shown peeled off defect rate was 83% (25 pcs were NG) and average adhesive strength was 15.4 N/mm with a standard deviation equal to 3.19. The preliminary result obviously represented a high defect rate from PET film peeled off and almost adhesive strength of samples are lower than specification at >20 N/mm. Therefore, the root cause analysis for improvement is required to be done in the next step of this research.

As aspect of variable gauge R&R for warpage measurement is done by 3 operators that perform an inspection of 10 parts with 3 replicates. By collecting variable data of part warpage from the measurement methods. These variable gage R&R were analysed by ANOVA and summarized that total percentage of gage study is 3.54% from repeatability .This result can be acceptable to be used this measurement method because it fell to just below 10%.

7.3 Analyse Phase

In order to determine the root cause of defects from PET film peeled off and IMD part warpage after understanding all process flow chart and clarifying the problem definition. Firstly, all possible causes of PET film peeled off and IMD part warpage shall be addressed by brainstorming with team members who have experiences in manufacturing process of in-mould decoration. Then using the cause and effect diagram to establish the relationship between cause and effect with five classified factors including man, machine, material, method and environment.

7.3.1 Root cause identiification

The next step of root cause analysis is to determine the high related factors which directly affect to PET film peeled off by using the cause and effect matrix, scoring from many potential causes of peeled off issue provided by cause and effect relation diagram. The cause and effect scoring is evaluated by 4 team members who have well-experienced in this field to select only the factors that highly related to cause of PET film peeled off. The Pareto chart was applied for factors ranking from cause and effect matrix scoring. Based on 80/20 rules of Pareto chart, the 80% of prioritized causes to be considered in FMEA analysis consists of 13 factors. The Failure Mode and Effect Analysis (FMEA) was applied in this phase to analyze potential failure risks in the manufacturing process by considering 13 factors from cause and effect matrix. The analyzed RPN from FMEA was prioritized by the the Pareto chart again. Then, the variable factors with high RPN are selected to conduct design and experiment (DOE) to find the optimal solution for improvement to reduce RPN. In addition, other high RPN factors must be classified so that SOP and controls plan are in place to prevent failure in the future.

Regarding IMD part warpage, brainstorming activity is required to identify possible causes of IMD part warpage from team members who have well experiences in injection process of in-mould decoration components to identify all possible causes that might be influenced IMD part warpage. It is found that 4 variable factors selected to verify significant effect to part warpage by DOE then find optimal parameter setting for injection process. Regarding other factors which is not variable factors will be improved and control by standard operation procedure (SOP) and control plan.

7.3.2 The design of experiment for Peel off

The design of experiment (DOE) is applicable to use in the final step of this analysing phase to verify that selected factors from FMEA are statistically significant effect to peel off strength. In order to find the optimal parameter setting for improvement and control in the next step. The six factors selected from the FMEA to carry out the experiment including drying time of silver printing, adding adhesive transparent layer, PET film thickness, oven drying temperature, injection melting temperature and injection mould temperature.

The experimental design conducts six influenced factors with three levels of factors by applying the face-centred central composite design (CCF), a response surface methodology, to optimize response variable from several influenced factors, then finding the optimal solution for improvement. The response variable of this experiment is the adhesive strength in a unit of N/mm measured by measurement methods reference ASTM D6862.

The design selection for the experiment is in place to analyse by Minitab. The experimental result has been done and analysed statistically by using Minitab represented the result in part of ANOVA representing four main effects of influenced factors are significant including drying time, adding an adhesive layer, PET thickness and oven drying temperature clearly observed by P-value less than 0.05. Regarding the two-way interaction, it shows that interaction of drying time and the adhesive layer is also significant. The interaction plot represented a high level of drying time (40 min), and adding an adhesive layer at the final printing lead to increase in high adhesive strength. On the contrary, the adhesive strength can be increased when a low level of drying time (20 min) is applicable whereas adding the middle adhesive layer. There are 4 residual plots of 3 assumptions represented that residuals are normally distributed, residuals are statistically independent and residuals have a constant variance, which can be observed by the normal probability plot, residual versus order plot and versus fitted plot respectively.

7.3.3 The design of experiment for part warpage

The design of experiment for IMD warpage problem to find the optimal parameter setting for improvement and control in the next step is required to be done with similar step of experiment and method of peel off issue. The four factors selected from the cause and effect diagram to carry out the experiment are including injection mould temperature, Post injection pressure, cooling time. Aspect of other attribute factor will be implement by using control plan and SOP.

Therefore, the experimental design conducts 4 influenced factors with 3 levels by applying the face-centred central composite design (CCF), a response surface methodology, to optimize response variable from several influenced factors, then finding the optimal solution for improvement. The response variable of this experiment is the warpage variation measured by gap measurement between IMD and assembly fixture. The experimental result has been done and analysed statistically by using Minitab. The result from ANOVA representing two main effects of influenced factors are significant including injection mould temperature and cooling time that clearly observed by P-value less than 0.05.

7.4 Improve Phase

As a result of data analysis from Minitab, there are 4 factors that significantly influence to the adhesive strength of PET film including drying time, adhesive transparent layer, PET film thickness, and oven drying temperature. In order to find the optimal setting for maximum adhesive strength, further data analysis is required to be done by same experimental design of 4 factors to increase adhesive strength and improve quality of in-mould decoration process. The result of the experiment was statistically analysed that can be demonstrated the new optimal setting for 4 influenced parameters. Therefore, the manufacturing process of in-mould decoration should set up optimal conditions to improve peeled off the issue as follows: setting the drying time of silver printing process to be 40 min, adding a transparent adhesive layer at final printing process, using PET thickness 0.22 mm and setting oven drying temperature at 90 ˚C.

As aspect of part warpage, the result of the experiment was statistically analysed by using the same method with peel off that can be demonstrated the new optimal setting for 2 influenced parameters including mould temperature and cooling time. Therefore, the injection process of in-mould decoration should set up optimal parameters to improve part warpage as follows; setting the mould temperature to be 45 ˚C and cooling time 18 sec.

7.5 Control Phase

In this phase, all recommended actions have been done by setting new condition from the previous step. However, the result monitoring is required to validate the effectiveness of result after improvement. The process capability is applied to represent the result of adhesive strength comparison between before and after improvement. This lead to a conclusion that current process capability (Cpk) have been improved to be 2.99 by increasing mean of adhesive strength and reducing process variation. Regarding process capability of part warpage, result of improvement have been improved to be 1.49 after adjusting process parameters.

Regarding result monitoring of new lots after implementing the new parameter setting and updated control plan, the result from data monitoring for defect rate comparison over a one-month period after improvement. This can be summarized that the defect rate from in-mould decoration process significantly decreased from11.43% average in Feb-June 2018 to1.25% after improvement in July-Oct 2018 which can be calculated as 89% improvement. It is found that IMD peeled off defect is reduce 91.1% and warpage defect is reduce 98.2% of defect before improvement .In addition, the control plan and standard operation procedure (SOP) shall be established then operator training should be done as aspect of new condition setting and control of the critical point to ensure adequate controls are in place to prevent reoccurrences.

7.6 Recommendations

The manufacturing process of in-mould decoration injection is an applicable in injection moulding, a combining process of PET film with decorative patterns are moulded together with ABS resins which have been developed to get many advantages not only reduce the secondary process of decorative screen printing but also enhance surface durability with brilliance of graphics. However, the main problem in IMD process is a high defect rate due to sensitive process conditions, quality of PET film, printing inks and substrate materials so that a sufficient quality control must be in place for IMD process.

The challenge to achieve high quality of IMD process is to obtain a sufficient adhesion between PET film, adhesive inks and the ABS substrate material. By studying overall IMD process, influenced parameters have been selected to do experiment then statistically analysed to find significant factors. The optimal parameter setting have been implemented to improve and maintain the adhesive strength of IMD component. The experimental result demonstrates some limitations from measurement method of adhesive strength, has been carried out by peeling force measurement between layer of PET film, adhesive inks and substrate material. This is due to the unstable adhesion between layer of silver printing and PET film affecting an uncertain measurement result. Because of the solvent-based inks mixing with metallic pigments are being used for silver printing layer whereas the UV-curable inks are applicable in the hairline screen of PET film. It is not compatible between solvent-based inks and UV-curable inks due to difference of chemical and physical characteristics that lead to decrease the adhesion as well as unstable adhesion in whole area of IMD components. From these reason, the challenge lies in development of measurement method to get better accuracy of measurement result in the future research.

The experimental results suggested that the adhesive strength can be improved by adding adhesive layer at final printing layer, increasing double drying time and drying temperature in silver printing layers that can be slightly impacted manufacturing cost. By comparing with overall cost and other benefits in term of quality, the impacted cost is only a small portion of overall manufacturing cost which can be acceptable to improve quality level that can reduce high scrap cost. Therefore, the cost-effective benefit from improvement should be considered in case of future research.

In conclusion, there are two major directions are possible in case of future research. Firstly, the better design of measurement method for adhesive strength of IMD component should be modified to capable the better experiment result. Second, the cost-effective benefit from improvement should be considered in case of future research. Moreover, the current design of this IMD component using the solvent-inks mixing with metallic pigments in silver printing layer which is provided unstable adhesion with UV ink in PET film that can be major cause of PET film peeled off. In the future, the colour and graphic design of IMD should be considered to capable more efficient of manufacturing process. Another recommendation is considering about cleaning of facility and working station. So that the cleaned room of workshop all 4 steps of IMD process are recommended this company to prevent appearance defect from dust and contamination.

REFERENCES

Chen, H.-L., et al. (2013). "Effects of insert film on asymmetric mold temperature and associated part warpage during in-mold decoration injection molding of PP parts." International Communications in Heat and Mass Transfer **41**: 34-40.

Chen, S.-C., et al. (2008). "Study on the thermoforming of PC films used for in-mold decoration." International Communications in Heat and Mass Transfer **35**(8): 967-973.

Chen, S.-C., et al. (2010). "Effect of decoration film on mold surface temperature during in-mold decoration injection molding process." International Communications in Heat and Mass Transfer **37**(5): 501-505.

Hassan, A., et al. (2010). "Conceptual process planning – an improvement approach using QFD, FMEA, and ABC methods." Robotics and Computer-Integrated Manufacturing **26**(4): 392-401.

Hsieh, L. Y. and K.-H. Chang (2013). "Yield improvement on in-mold decoration manufacturing through parameter optimization." International Journal of Precision Engineering and Manufacturing **14**(10): 1823-1828.

Jonny and J. Christyanti (2012). "Improving the Quality of Asbestos Roofing at PT BBI using Six Sigma Methodology." Procedia - Social and Behavioral Sciences **65**: 306-312.

Kevin Linderman, R. G. S., Adrian S. Choo (2006). "Six Sigma: The role of goals in improvement teams." Journal of Operations Management **24**(6): 779-790.

Lee D. , C. W.-A., HuangT.-W. , Liu S. –J. (2013). "Factor influence the warpage in In-Mold Decoration Injection molded composites." Polymer Processing.

Lin, Y.-H., et al. (2015). "Effect of asymmetric cooling system on in-mold roller injection molded part warpage." International Communications in Heat and Mass Transfer **61**: 111-117.

Montgomery, D. C. (2015). Design and Analysis of Experiment John Wiley & Sons.

Phillips, C. O., et al. (2009). "Finite element modelling of low temperature forming of polymer films with application in in-mould decoration." Materials & Design **30**(3): 537-550.

Phillips, C. O., et al. (2008). "Mechanical properties of polymer films used in in-mould decoration." Journal of Materials Processing Technology **200**(1-3): 221-231.

Puentes, C. A., et al. (2009). "Determination of effects of production parameters on the viability of polycarbonate films for achieving in-mold decoration in resin infused composite components." Composites Part A: Applied Science and Manufacturing **40**(4): 368-375.

Pugna, A., et al. (2016). "Using Six Sigma Methodology to Improve the Assembly Process in an Automotive Company." Procedia - Social and Behavioral Sciences **221**: 308-316.

Renu, R., et al. (2016). "A Knowledge Based FMEA to Support Identification and Management of Vehicle Flexible Component Issues." Procedia CIRP **44**: 157-162.

Roger G. Schroeder, K. L., Charles Liedtke, Adrian S. Choo, (2008). "Six Sigma: Definition and underlying theory." Journal of Operations Management **26**(4): 536-554.

Runger, D. C. M. a. G. C. (2010). Applied Statistics and Probability for Engineers John Wiley & Sons.

Shih-Po Sun, T.-H. S., David Hsu (2017). "Ink-wash and Warpage Defect Prediction from the In-Mold Decoration Process simulation." SPE ANTEC Anaheim.

Simanová, Ľ. and P. Gejdoš (2015). "The Use of Statistical Quality Control Tools to Quality Improving in the Furniture Business." Procedia Economics and Finance **34**: 276-283.

Standard, A. I. ASTM D6862 Standard Test Method for 90 Degree Peel Resistance of Adhesives.

Wessiani, N. A. and S. O. Sarwoko (2015). "Risk Analysis of Poultry Feed Production Using Fuzzy FMEA." Procedia Manufacturing **4**: 270-281.

Wong A.C-Y , L. K. Z. (1997). "Thermal effects on the behavior of PET films used in the in-mould-decoration process involved in plastics injection moulding." Journal of Materials Processing Technology **63**.

Woyan, F., et al. (2016). Process parameters affecting the bonding of in-mold decoration of injection molded components.

Woyan F. , K. M., Schneidmadel S. (2014). Process parameter Affecting the Quality of Functionalized In-Mold Decoration Injection Molded Composites. 58th ILMENAU SCIENTIFIC COLLOQUIUM Technische Universitat Ilmenau 08.

VITA

NAME	Jintra Supapan
DATE OF BIRTH	20 Dec 1988
PLACE OF BIRTH	Nakhonratchasima
INSTITUTIONS ATTENDED	Bachelor’s Degree of Engineering Biomedical Engineering, Prince of Songkla University, Songkla
HOME ADDRESS	Rayong, Thailand