APPLICATION OF STATISTICAL PROCESS CONTROL

IN INJECTION MOULD MANUFACTURING

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2004

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(*B. Eng*)

A THESIS SUBMITTED

FOR THE DEGREE OF MASTER OF ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

NATIONAL UNIVERSITY OF SINGAPORE

2004

ACKNOWLEDGEMENT

First of all, I would like to express my sincere gratitude to my supervisor, Associate Professor Lee Kim Seng and Associate Professor Wong Yoke San, from the Department of Mechanical Engineering, NUS, whose broad knowledge in many fields and invaluable advice, guided me and gave me inspiration all the time during the course this research. Their patience, encouragement and support always gave me great motivation and confidence in conquering the difficulties encountered in the research. Their kindness will always be gratefully remembered.

I would also like to thank Associate Professor Xie Min and Dr. Cai Danqing, from the Department of Industrial and System Engineering, NUS for their advice and kind help to this research.

I would also like to express my gratitude to Mr. Hee Pin Tat, Mr. Goh Yan Chuan and Mr. Wong Lee Kheong, Fu Yu Manufacturing Limited, who shared their precious experience and offered their generous help toward this research.

I am also grateful to my colleagues, Mr. Atiqur Rahman, Miss Du Xiaojun, Miss Low Leng Hwa, Mr. Saravanakumar Mohanraj, Dr. Sun Yifeng, Mr. Woon Yong Khai, and Miss Zhu Yada for their kind help, support and encouragement to my work. The warm and friendly environment they created in the lab made my study in NUS an enjoyable and memorable experience. I would also like to thank Dr. Mohammad Rabiul Alam for his kind advice and help in my study and research. I also thank Dr. Liu Kui, Dr. Qian Xinbo, and Dr. Zhao Zhenjie, from the Neuro-sensor Lab, for their kind support to my study and work.

I am grateful to National University of Singapore for offering me a chance in coming here, providing me all the resources and facilities and financing me with two years of scholarship to support my study and research work.

I wish to express my deep gratitude to my parents, my parents-in-law and my brother for their moral support. Finally, I sincerely thank my husband, Yang Jing for his love, understanding and support all the time. This thesis is dedicated to him.

TABLE OF CONTENTS

SUMMARY

In an injection moulding process, the quality of the injection mould is very important as it may affect the quality of plastic products which the mould produces and the smoothness of injection, cooling and ejection in the moulding process. An injection mould is an assembly of a group of mould parts, which perform different functions. These parts are manufactured by a series of machining processes. The quality of mould parts are to a large extent determined by the performance of these machining processes. The main concern of this research is to improve the performance of these processes.

Statistical Process Control has been widely and successfully applied in many industries since it originated when Shewhart first proposed the concept of control chart in the 1920's. As the traditional application of SPC demands a huge amount of data, the application of SPC in the short-run or small volume production situations faces many challenging problems. In recent years, to solve the above mentioned problems, short-run SPC methods are proposed by some researchers. These research works mainly focus on the data transformation methods and part family formation methods. Some application practices have been done in machining processes. However, the manufacture of injection mould has its own traits, high variation of machining process and high variation of parts, which raises some problems for the application of short-run SPC methods in this area. To solve these problems, this research focuses on the following aspects:

Injection mould part and mould part manufacturing process analysis

This research proposed to classify the mould parts into standardized part and non-standardized part according to whether they are directly involved in forming the plastic

product. Those not involved in forming the plastic product are identified as standardized parts and the features on them are identified as standardized features. Those features that directly form the plastic product are identified as non-standardized part, the features on which are further classified as standardized features and non-standardized features according to whether they directly form the plastic product.

SPC planning for the manufacture of injection mould

Firstly, the machining processes in the mould shop are identified as different SPC processes according to the specific rules and the part family memberships are identified according to the specific rules, based on the engineering knowledge and statistical analysis of the historical data. For the standardized part, an approach of SPC plan template is proposed to standardize and simplify the process of generating SPC plan. For the non-standardized part, the standardized features can be treated similarly as the standardized parts. The methods and rules for the generation of SPC plan for the non-standardized features of each new mould project are stated.

SPC implementation for the manufacture of injection mould

Once the SPC is well planned, it is implemented and the implementation process can be computerized with the help of CAD / CAM technology, database technology, statistical software, pattern recognition technology, artificial intelligence technology and precise measurement technology. The possible causes corresponding to the different out-of-control patterns can be referred to the ones generalized from other manufacturing practices. They also need to be generalized from the practice of mould manufacturing with the accumulation of application experiences.

NOMENCLATURE

SYMBOLS

ε	error
ϕ	Diameter
μ	Mean of a sample group
σ	Standard variance
D	Dimension
x, y, z	Cartesian coordinate system
X	Individual measurement
$\overline{X}$	Average of measurements
$\overline{\overline{X}}$	Average of average
R	Range
$\overline{R}$	Average of ranges
S^2	Deviation
S	Standard Deviation

SUBSCRIPTS AND SUPERSCRIPTS

Plotpoint	Plot point in control chart

i	Part type number
j	Sample number
ij	j_{th} part of i_{th} part type
n	Sample size

ABBREVIATIONS

ANOVA	Analysis of Variance
CAD	Computer-aided Design
CAM	Computer-aided Manufacturing
DB	Database
CI	Confidence Interval
CL	Center Line
CMM	Coordinate Measuring Machine
CNC	Computer Numerical Control
CUSUM	Cumulative Sum
DF	Degree of Freedom
EDM	Electric Discharge Machining
EWMA	Exponential Weighted Moving Average
HB	Hardness of Brinell
HRC	Hardness of Rockwell
LCL	Lower Control Limit

MR	Moving Range
MiniTab®	General Statistical Software
StDev	Standard Deviation
SPC	Statistical Process Control
UCL	Upper Control Limit

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION

1.1 Background

With the increasing demand by customers for high quality and low cost products in the global market, the need for quality improvement has become increasingly important in all industries in recent years.

In order to supply defect-free products to customers and to reduce the cost on defective parts in production, Statistical Process Control (SPC) techniques have been widely used for quality assurance. SPC originated when Shewhart control charts, such as Average and Range charts, were invented by W. A. Shewhart at Western Electric during the 1920's. In Average and Range chart, sample means are plotted on the Average chart to detect the shift of process mean, while sample range or standard deviations are plotted on the Range or Standard Deviation chart, respectively, to detect the shift of process variation. In later years, Individual and Moving range chart, Cumulative Sum chart, Exponentially Weighted Moving Average chart are developed to monitor process in different situations. Control chart, as the main tool in SPC was proven to be very effective in many industries. Histogram, Check Sheet, Pareto Chart, Cause and Effect Diagram, Defect Concentration Diagram, and Scatter Diagram are combined with Control Chart to serve as the "Magnificent Seven" powerful tools to effectively locate problem and find causes. They made SPC very useful in improving the performance of the process and the quality of the products.

Most of the successful applications of SPC are for mass productions. The nature of multi-product and short-run of injection mould manufacturing will further create challenging problems for the mould maker to maintain high quality through the application of SPC. Hence it is important to develop an effective approach in the manufacture of injection moulds in this research.

1.2 Problem Statements

Many definitions such as “low volume”, “short-run” or “small batch” can be found in the literatures to describe a production process in which the batch size or lot size is mall, usually less than 50 units. This kind of production process presents challenging problems in the application of SPC.

The main problem associated with low volume production is due to lack of sufficient data to properly estimate process parameters, i.e. process mean and variance, the meaningful control limits for control charts are hard to attain. The availability of rational homogeneous subgroups is the basic assumption of traditional SPC. In low-volume production, this kind of homogeneous subgroup does not exist. To solve it, short-run SPC methods are proposed.

Firstly, the important basis of short-run SPC is to focus on the process, not the parts. If the process is in control and capable, quality of the parts manufactured by it will be guaranteed. To improve the performance of the process, the various parts manufactured by it are taken for analysis. To solve the contradiction between variations of parts and demand of sample number, the concept of forming part family, which results in increasing the number of samples, was proposed. A part family means family of products “that are made by the same process that have common traits such as the same material, configuration, or type of control characteristic”. (Griffth, 1989) To form a part family, it must meet two requirements: homogeneous variance and equal mean (Koons and Luner, 1991, Evans and Hubele 1993). The equal mean here means the mean of coded data or transformed data, which is usually the difference between the measured value and nominal value on one particular quality characteristic. Under the assumptions of homogeneous variance and equal mean, quality characteristics with different nominal values but similar process variations can be plotted on the same control chart using the coded data. Process parameters and control limits are calculated based on these coded data collected from different part types. But most of research works focused on the short-run productions, in which a certain number of part types are alternatively produced.

An injection mould is a mechanical tool in which molten plastic is injected at high pressure to produce plastic products. Figure 1.1 shows the injection moulding process of plastic product. An injection mould allows the manufacturers to mass-produce of the plastic parts that are highly identical in terms of dimension and appearance. For each plastic product, one single cavity mould, a multi-cavity mould or several identical moulds may be needed. For each new plastic product design, a new mould has to be made. Therefore, the manufacture of injection mould is characterized as one-off.

A mould assembly usually consists of mould base, cavity insert, core insert, other accessories and standard components. Figure 1.2 shows an example of an injection mould assembly. Slider or lifter is needed if there is an undercut in the plastic part. To manufacture the part, a series of machining processes are needed.

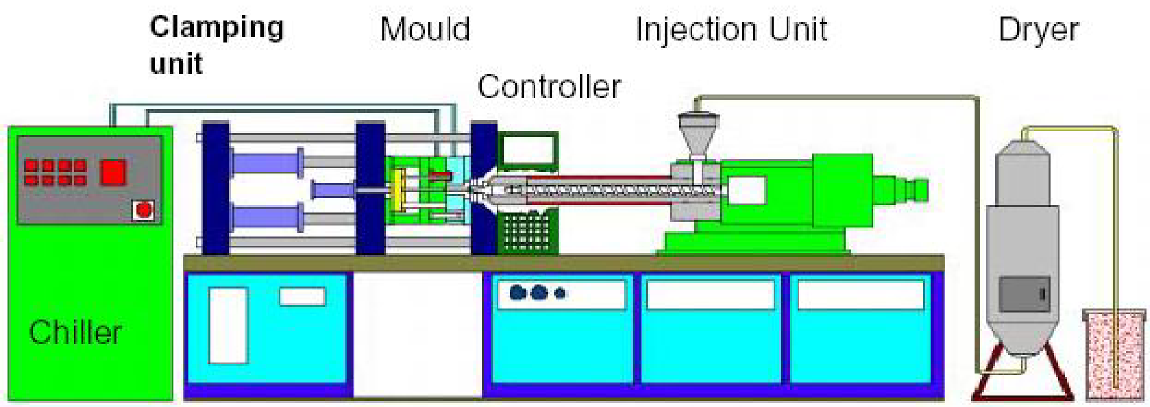


Figure1.1 Injection moulding process of plastic product

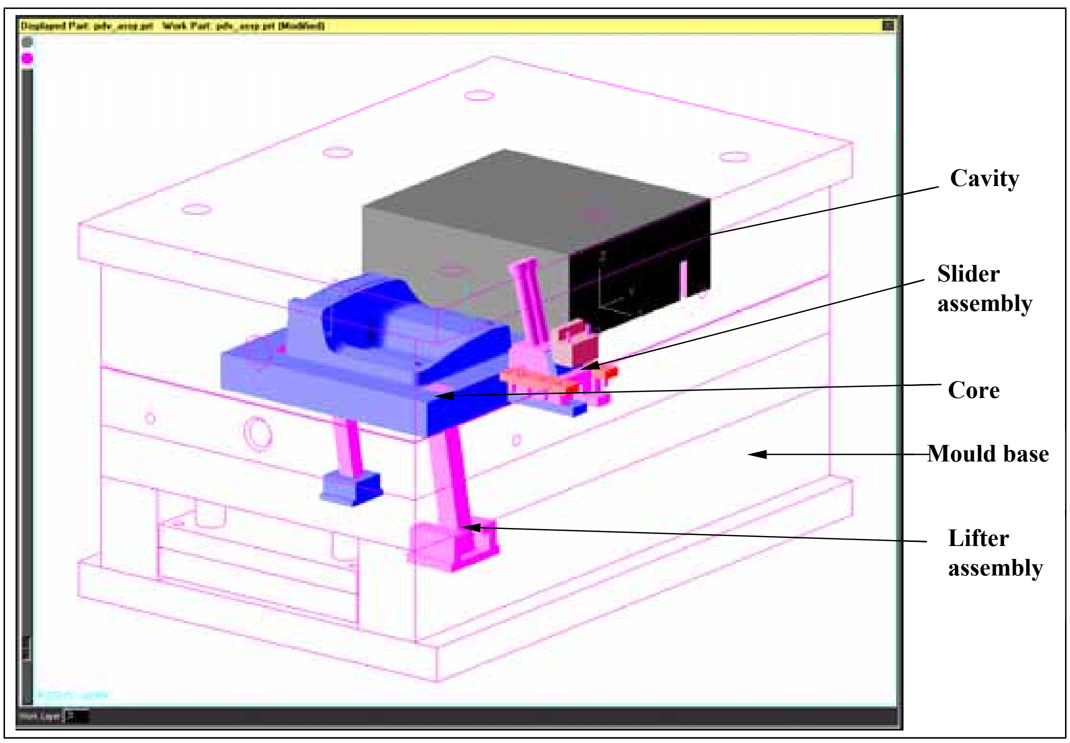


Figure 1.2 An injection mould assembly (Alam, 2001)

Due to the high diversity of plastic products, the shapes, dimensions, and features of mould parts can be very different one from another. The manufacturing processes of the mould parts can also be very diverse in terms of process type, machine type, machine setting, cutting tool, workpiece holding and fixturing, and cutting conditions. The problem of high variation of parts and high variation of manufacturing processes makes the application of SPC in the manufacture of injection mould more challenging compared with other short-run production systems.

1.3 Research Objectives

The application of short-run SPC in the manufacture of injection mould consists of two main parts – SPC planning and SPC implementation. SPC planning involves defining and identifying SPC processes, forming and identifying part families, selecting data transformation methods, and selecting control charts. SPC implementation involves collecting data, transforming data, plotting transformed data on control charts, analyzing and interpreting the charts and suggesting possible causes for out-of-control situations. As SPC implementation in the manufacture of mould is similar to other those used in manufacturing industries, which have been studied by other researchers, SPC planning is thus the main part of this research.

The main objective of this research is to develop a framework consisting of methods and procedures on SPC application in the manufacture of injection mould.

The second objective is to analyze, summarize and generalize the characteristics of different mould parts and the different machining features on the parts and the manufacturing processes of the mould parts.

The third objective is to propose an approach to define and identify a suitable SPC process. The part family is formed and identified based on the characteristics of the mould parts manufacturing to make the application of control charts both statistically meaningful and operable.

CHAPTER 2 LITERATURE REVIEW

2.1 Traditional Statistical Process Control

Statistical Process Control (SPC) is a systematic set of tools to solve process-related problems. Through the application of SPC tools, possible reasons that cause a process to be out of control can be identified and corrective actions can be suggested. A control chart is the primary tool of SPC and basically used to monitor the process characteristics, e.g., the process mean and process variability (Duncan, 1988, Montgomery, 2001).

The most common types of variable control charts include:

(1) Average and Range (X and R) Charts

(2) Average and Standard Deviation (X bar and S) Charts

(3) Individual and Moving Range (X and MR) Charts

Collectively, above charts are usually called Shewhart charts, as they are based on the theory developed by Dr. Walter A. Shewhart. As Shewhart charts are relatively insensitive to small shifts in the process, two effective charts may be used to supplement them when there are small shifts in the process.

(1) Cumulative Sum Control (Cusum) Chart

(2) Exponentially Weighted Moving Average (EWMA) Control Chart

As they are effective in detecting small shifts, but not as effective as Shewhart charts in detecting large shifts, an approach of using a combined Cusum-Shewhart or EWMA-Shewhart is proposed. Simply adding the Shewhart chart to Cusum chart or EWMA chart can effectively improve the responsiveness to both large and small shifts (Montgomery, 2001).

The control charts in traditional SPC are designed to monitor a single product with large production runs. The availability of rational homogeneous subgroups is the basic assumption of traditional SPC. Many researchers proposed that 20-25 samples with sample size of 4-5 from a single part type should be used to calculate the meaningful control limits (Duncan, 1986, Griffith, 1996, Montgomery, 2001). Therefore, at least 80-125 units are needed for setting up a control chart. Since low-volume production does not have the aforementioned type of homogeneous subgroups, short-run SPC methods have been proposed.

2.2 Short-run Statistical Process Control

A short-run problem can be characterized in several ways, but the problem essentially concerns insufficient data or untimely data for the determination of control limits. Usually it belongs to the following general categories:

1. Not having enough parts in a single production run to achieve or maintain control limits of the process;
2. The process cycles are too short that even large-size production runs are over before data can be gathered;
3. Many different parts are made for many different customers (in small-lot sizes)

To apply SPC to any of the above situations, the main emphasis is not on the parts, but on the process. Parts are the media to convey the information of the process performance, and the main concern is the process.

Short-run SPC methods work on a variety of different parts, each with a different nominal value for the concerned quality characteristic. To make the control chart statistically meaningful, appropriate data transformation and part family formation are needed (Griffith, 1996).

2.2.1 Data transformation methods

Several data transformation methods have been proposed in the literature by Bothe (1988), Cullen (1989), Evans (1993), and Crichton (1988) respectively. The most representative ones are discussed below:

2.2.1.1 Bothe's approach

The most commonly used and the simplest data transformation method, Deviation-from-nominal, was first proposed by Bothe (1988). It uses the deviation between the measured and nominal values as the individual data point. This method can be used for both Individual Chart and Average and Range Charts. This method is used for process variability that is approximately the same for all part types (Al-salti et al, 1992).

2.2.1.2 Bothe and Cullen's approach

Subsequently, Bothe and Cullen proposed another data transformation method, that divides the value of the deviation from nominal by the range of the part type (Bothe et al., 1989). This method can also be used in both Individual Chart and Average and Range Chart.

For Individual Chart, the plot point is

$$X_{\text{plotpoint}} = \frac{X_A - \text{nominal}}{\overline{R}_A} \qquad (2.1)$$

where X_A is the measured value of one part of type A, and $\overline{R}_A$ is the historical average range of part type A. It can be calculated using equation in below:

$$\overline{R}_A = \frac{\sum_{j=1}^{m} R_{Aj}}{m}$$

(2.2)

where R_{Aj} is the range of the j_{th} historical subgroup of part type A. m is the number of historical subgroups of part type A.

For Average and Range charts, the plot points are:

$$\overline{X}_{plotpoint} = \frac{\overline{X}_A - \overline{\overline{X}}_A}{\overline{R}_A} \tag{2.3}$$

$$R_{plotpoint} = \frac{R_A}{\overline{R}_A} \tag{2.4}$$

where $\overline{X}_A$ is the average of measured value of part type A. It can be calculated using the equation in below:

$$\overline{X}_A = \frac{\sum_{i=1}^{n} X_{Ai}}{n}$$

(2.5)

where X_{Ai} is the i_{th} measured value of part type A. n is the number of measurements.

$\overline{\overline{X}}_A$ is the mean of $\overline{X}_A$. It can be calculated using the equation in below:

$$\overline{\overline{X}}_A = \frac{\sum_{j=1}^{m} \overline{X}_{Aj}}{m}$$

(2.6)

where $\overline{X}_{Aj}$ is the j_{th} subgroup of part type A. m is the number of subgroups of part type A.

R_A is the historical average range of part type A. $\overline{R}_A$ can be calculated using equation 2.2.

This method is used when the variation of the process differs significantly with different part types.

2.2.1.3 Evans and Hubele's approach

In this method, similar to Bothe and Cullen's approach, the value of deviation from nominal is divided by the tolerance of the part type A (Evans et al., 1993).

For Individual Chart, the plot point is

$$X_{plotpoint} = \frac{X_A - nominal}{T_A} \quad (2.7)$$

where X_A is the measured value of one part of type A, and T_A is the tolerance of part type A.

For Average and Range Charts, the plot points are:

$$\overline{X}_{plotpoint} = \frac{\overline{X}_A - \overline{\overline{X}}_A}{2T_A} \quad (2.8)$$

$$R_{plotpoint} = \frac{R_A}{2T_A} \quad (2.9)$$

where $\overline{X}_A$ is the average of measured value of part type A. It can be calculated using equation 2.5. $\overline{\overline{X}}_A$ is the mean of $\overline{X}_A$. It can be calculated using equation 2.6. T_A is the tolerance of part type A.

This method is used when the tolerance of different part types are significantly different and the process variation also differs with the different tolerances.

2.2.1.4 Crichton's approach

In this approach, the deviation from nominal is divided by the nominal value (Crichton, 1988).

For Individual chart, the plot point is

$$X_{\text{plotpoint}} = \frac{X_A - \text{nominal}}{\text{nominal}} \tag{2.10}$$

where X_A is the measured value of one part of type A.

For Average and Range chart, the plot points are:

$$\overline{X}_{\text{plotpoint}} = \frac{\overline{X}_A - \overline{\overline{X}}_A}{\overline{\overline{X}}_A} \tag{2.11}$$

$$R_{\text{plotpoint}} = \frac{R_A}{\overline{\overline{X}}_A} \tag{2.12}$$

where $\overline{X}_A$ is the average of measured value of part type A. It can be calculated using equation 2.5. $\overline{\overline{X}}_A$ is the mean of $\overline{X}_A$. It can be calculated using equation 2.6.

This method is used when process variability differs significantly from one part to another and also increases with the nominal size.

2.2.2 Part family formation

For simple short-run productions, parts are manufactured with constant process parameter setting, but variation in size. Parts made by the same process naturally belong to the same part family. Only data transformation is needed to apply traditional control charts to the short-run productions. But in modern manufacturing practices, situations are always not so simple. Parts made by the same process may be very different from one to another in material or geometrical characteristics. As a result, the corresponding process parameter settings may be different. In these complicated situations, after data transformation, there are still four types of variation that exists in the transformed data produced by a particular process, as shown in Figure 2.1.

Variation Type I refers to the variation caused by the differences between parts, such as difference in material or in geometrical characteristics.

Variation Type II refers to the variation caused by the different process parameter settings.

Variation Type III refers to the variation caused by the shift of the process.

Variation Type IV refers to the inherent process variation, which can be reduced by improving process capability.

The purpose of SPC is to eliminate type III variation, and to reduce type IV variation. A statistically meaningful control chart is supposed to present only variation type III and type IV. Therefore, variation type I and type II should be separated from variation type III and type IV in the control chart.

To remove the effect of variation type I and type II, the part family has to be carefully formed to isolate these two types of variation, so that they will not co-exist within one part family. Koons and Luner (1991) and Evans and Hubele (1993) both considered the effect of type II variation. In their approaches, these two types of variation are removed by forming suitable part families.

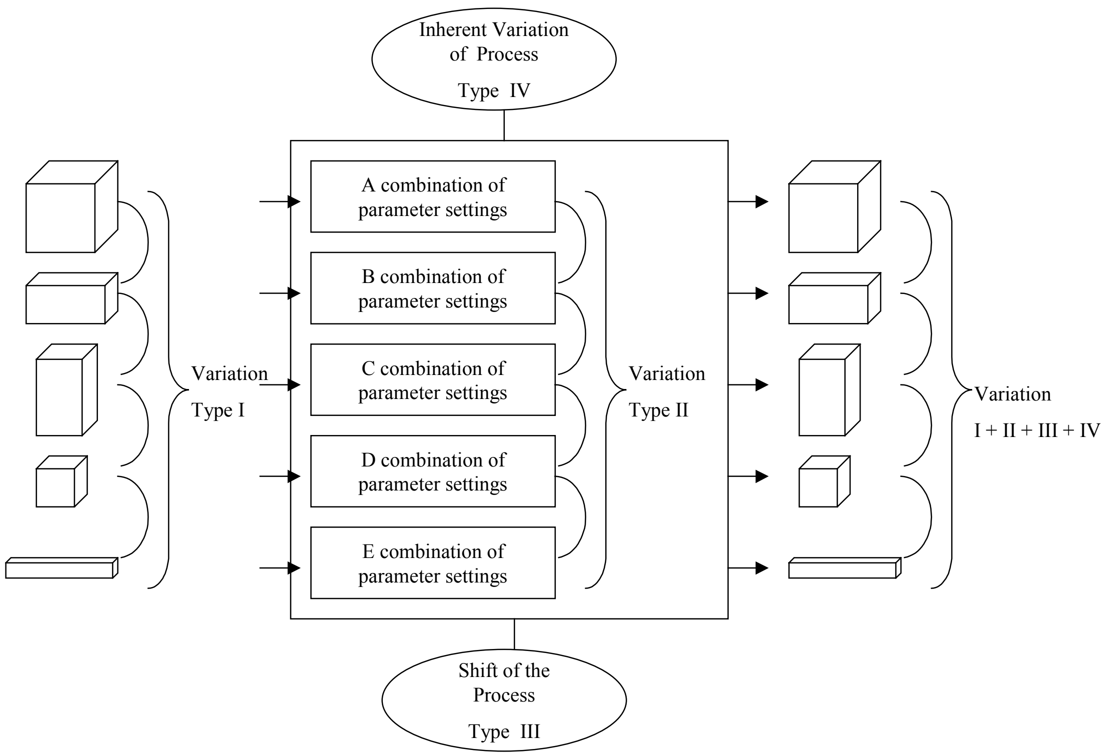


Figure 2.1 Types of variation existing in short-run productions.

Koons and Luner's approach

As the operating factors of a process might systematically affect the process performance, it is proposed that process performance would be monitored separately for each combination of the potentially significant factors. If subsequent analysis fails to show that the operating factor has significant effect, it would be taken as a single process regardless of the setting of that factor.

In Koons and Luner's approach (1991), it was done in a way that is characterized by "division". Initially, it is assumed that all data set is produced from a single process. The validity of this assumption is tested by statistical analysis. The predetermined characteristic of each part is measured and recorded. Prior to the test, the data set is transformed by using *Deviation from Nominal*, which is subtracting the nominal value from the measured value. The variance of each subgroup is used as a measure of subgroup variability. The subgroup variances are displayed in a Variance (S^2) Chart. The limits of the variance chart are calculated using the chi-square distribution.

$$LCL = \chi^2_{0.999} \frac{\overline{S}^2}{(n_j - 1)} \tag{2.13}$$

$$UCL = \chi^2_{0.001} \frac{\overline{S}^2}{(n_j - 1)} \tag{2.14}$$

The subgroup that exceeds the control limits are analyzed. If there is any special cause, such as an improper set-up, it is taken out. After taking out the outliers due to special causes, the variance chart is revised with new control limits, and new outliers are analyzed and taken out if further special causes are found. This is continued until all points are within the control limits or no special causes are found to explain the outliers. The subgroup corresponding to the outlier will be taken out to form a separate part family.

The next step is to determine whether any of the operating factors has systematic effect on the variation between subgroups. Multiple regression is used, in which the variance of the subgroups is used as dependent variable and operating factors are used as independent variables. Data sets associated with the different settings of an operating factor, which is found to have significant effect on the variation, are formed in separate part families (Koons et al., 1991).

Evans and Hubele's approach

In Evans and Hubele's approach, measured data on the predetermined quality characteristics are transformed first using:

$$y_{ij} = \frac{(x_{ij} - \text{nominal})}{\text{tolerance}} \tag{2.12}$$

where x_{ij} represents the original measurements of part j in part type i. This transformation permits comparison of data taken from parts with different tolerance.

Firstly, data of similar parts made by the same process, which is in statistical control, are collected and transformed using above formula. The information on all process parameters is also collected, such as machine setting and tools, which may contribute to the part variability. A one-way ANOVA is performed on the Levene transformed data to test the homogeneity of variance between different part types. The Levene transformation is shown as:

$$z_{ij} = \left| y_{ij} - \bar{y}_i \right|$$

(2.13)

where $\bar{y}_i$ is the mean of all the value of part type i.

Then the part types are formed with homogeneous variance into one preliminary family based on the result of ANOVA on z_{ij}. ANOVA is performed to each preliminary part family to determine whether the difference between the mean of the part types in this family exists.

If no significant difference is found, this preliminary family is finalized as a part family. For the preliminary family in which means between part types are found to be significantly different, multiple comparisons are performed, such as Duncan's test, to identify the subsets with specific difference in means. Part family is formed with subsets with no significant difference in means.

Subsets with significant difference in means are taken out to form separate families. The process parameters associated with each part are now used to identify family membership, according to which the future coming parts with the same process parameters can be identified and added to the corresponding part family (Evans and Hubele, 1993).

Review of the two approaches

The above two approaches both proposed a set of procedures on the formation of part families in small-volume productions. Statistical analysis is used to avoid type I and type II variations in the same part family. In both approaches, type I and type II variations are treated together. If any factor among the inherent characteristics of parts, such as material of the part or associated process parameter setting, it will be used to identify the family membership.

One of the differences between these two approaches is that Koons and Luner's approach is more characterized as "division", starting from large "preliminary family", and using S^2 chart to screen out the subsets which are outliers and form them into separate families. Evans and Hubele's approach is more characterized by "grouping", starting with small data subgroups with same process parameter settings, performing ANOVA and multiple comparisons to identify the difference in variances and means between subgroups. Subgroups with no significant difference in variances and means are grouped to a larger part family. Those with significant difference in variance or mean are left as separate families (Lin et al., 1997).

Another difference is that in Koons and Luner's approach, the equality of means is not tested. If difference in the means between the part types exists, this difference will be introduced and be mixed up with the variability caused by any process shift.

These two approaches are both based on productions, where part types are produced intermittently and several part types are manufactured in alternate batches. In this kind of circumstances, data of one particular part type can be sufficiently collected. The processes, which manufacture these part types, are not too many nor too complex to be aggregated or analyzed. However, most of the injection moulds are made in one-off or in very small batches. It is not easy to aggregate all mould parts in advance, because one particular part type may only be produced in one piece, and not be produced again. In mould manufacturing, there is a large number of the processes involved and the processes are relatively complex, with many process parameters involved. Therefore, when proposing part family formation methods, the characteristics of mould manufacturing have to be carefully considered.

Application of group technology in part family formation

A classification and coding system (C & C) used for short-run SPC part family formation is proposed by Mamoun Al-salti et al. (1994). This C & C system consists of two main codes: a primary code which contains the information on the part, such as the basic shape, size, material and the initial form of the part, and a secondary code which contains the manufacturing information of the part, such as machine tool, machining process, measuring device, cutting tool, cutting tool holding method and workpiece holding method. Each of the items can be taken as a variable and expressed as a digit of the code. Statistical analysis, including F-test and ANOVA, is used to determine whether the variable significantly affects the concerned quality characteristics. If not, the corresponding digit can be freed to form a larger family.

This approach classifies type I and type II variations according to the primary and secondary codes, respectively. It lists all the factors which may affect the concerned quality characteristics and represents these factors by the code digits. Through using the coding system to identify part family membership, this C & C system provides the possibility to automate the part family formation work.

However, the aforementioned method assumes that the parts only have limited number of simple machining features for each machining operation. When applying to parts with large number of complex machining features, which may involve different machining types and operations, such as injection mould parts, it is very hard for the proposed digit system to accommodate huge amount of information. Therefore, further considerations are needed when applying it to complex mould part manufacturing processes.

2.2.3 Short-run SPC control charts

Variations in short-run processes are generally similar to those in other productions, and it is necessary only to identify and eliminate special cause through the use of control charts. The cause variation is characterized by as points beyond control limits or a pattern of points that indicate a change in the process. Common cause variation occurs in every process. It is desirable to minimize it as much as possible. With reduced common cause variation the control charts manifests more narrow control limits.

The control charts most commonly used in short-run productions are:

Average and range chart ($\overline{X}$ and R chart)

The traditional average and range chart can be used in short-run situations after data transformation. It applies when the subgroups of identical parts exist (Montgomery, 2001).

Individual and moving-range chart (I and MR chart)

The traditional individual and moving range chart can also be used in short-run situations after data transformation. It applies when process has limited output. Results in destructive testing, or testing more than one piece is prohibitive due to cost (Nugent, 1990), The control limits calculation formulas are shown in Appendix C.

2.3 Control Chart Interpretation

The control charts have the ability to detect and identify special causes, by means of presenting a particular pattern. There are 15 common control chart patterns, cycles, freaks, gradual change in level, grouping or bunching, instability, interaction, mixtures, natural pattern, stable forms of mixture, stratification, suddenly shift, systematic variables, tendency of one chart to follow another, trends, unstable forms of mixtures (Western Electric Co., Inc., 1976). The pattern information is vital for process diagnosis and correction as there is a strong cause-and-effect relationship between the pattern features and root causes. Some typical chart patterns and the corresponding causes are shown in Appendix D.

More patterns and corresponding causes can be identified and generalized from data of practice in industry by a company. Once a particular pattern is present, the corresponding causes are checked. The information on machine tool, measuring tool, part, operator, environmental factors, and other possible sources is collected and investigated to determine and eliminate the causes.

Modern technology on pattern recognition helps automate the chart pattern recognition and artificial intelligence technology can help automate the search for the causes. This offers possibility of automation and computerization of SPC in the manufacture of injection mould, when combining with the computer-aided data collection and data recording, computerized statistical analysis and control charting (Evans et al., 1988, Swift et al., 1995, Tontini,1996, Al-Ghanim et al., 1996, Anagun, 1998).

CHAPTER 3 INJECTION MOULD MANUFACTURING

Plastic products are increasingly applied in various industries nowadays. Among the different categories of plastics, thermoplastic is most commonly used and produced in the largest scale. Most thermoplastic product is made by injection moulding process. Plastic injection moulding process requires an injection mould, which forms the molten plastic into a product. An injection moulding machine then injects molten plastic resin into the mould, and ejects the formed parts. The entire moulding processes involve the mould-filling phase, packing phase, holding phase, cooling phase and lastly the ejection phase. Through moulding process, an injection mould can mass produce plastic parts with highly identical in size and shape (Mennig, 1998). Quality of the plastic products depends very much on the design and quality of injection mould.

A plastic injection mould assembly consists of cavity, core, slider, lifter, mould base and other accessories. Each of these mould parts has its own special function during the moulding process. Therefore, each individual mould part needs to be designed and precisely manufactured with rules and experiences to guarantee that the whole mould performs the required functions, such as making the melt flow smoothly, cool evenly and eject successfully.

3.1 Injection mould manufacturing process

Nowadays, mould manufacturing company's work involve mould design when given the plastic product design drawing from customer, mould part fabrication, mould assembly and mould testing. Some mould companies do both mould making and injection moulding, so they also supply the plastic products directly to the customers. With the development of computer-aided design and manufacturing technology, the mould manufacturing processes are becoming more automated. But a fully automated manufacturing system has not been adopted in most the mould companies. Usually they have different departments doing design, process planning, and machining work respectively. In the mould shop, there are different types of machines, performing different type of operations and workpieces are manually moved from one process to the next. After all the mould parts are manufactured, they are assembled. Before testing the mould in the moulding machine, visual inspection and ejection movement checking are done in the assembly department. After that, then first-article test can be done in the moulding machine. Some modifications may be needed. Finally, the mould is delivered to customer. A general mould manufacturing process is shown in Figure 3.1.

3.2 Classification of injection mould parts and features

Among all the mould parts, some parts are directly involved in forming the plastic product, while others perform other functions, such as guiding the mould ejection movement, and supporting other parts. Even though the shape of the plastic products may vary from one to another, the mould parts that do not involve in forming the plastic product do not vary. They may have fixed shape and fixed features to perform the fixed function, only varying in sizes to match with the plastic products with of sizes. Therefore their manufacturing processes can be standardized by standardizing the process plan. These parts are identified as standardized parts. The features on these parts can therefore be identified as standardized features. While other parts, which have features that directly form the profile of plastic product, are identified as non-standardized parts. On these parts, there are still some features, which are not involved in forming the plastic product profile. They perform fixed functions, such as supporting or positioning, and have fixed shape, such as the external cubic profile of the core and cavity insert. Therefore, the features on non-standardized parts can be further divided into standardized features and non-standardized features. Like the standardized parts, the manufacture of standardized features on the non-standardized parts can also be standardized, while the manufacture of non-standardized features have to be designed for each new mould project, according to the given plastic product design file.

In the following sections, the main mould parts, slider and lifter, core and cavity will be discussed, and the classification of their features will be illustrated.

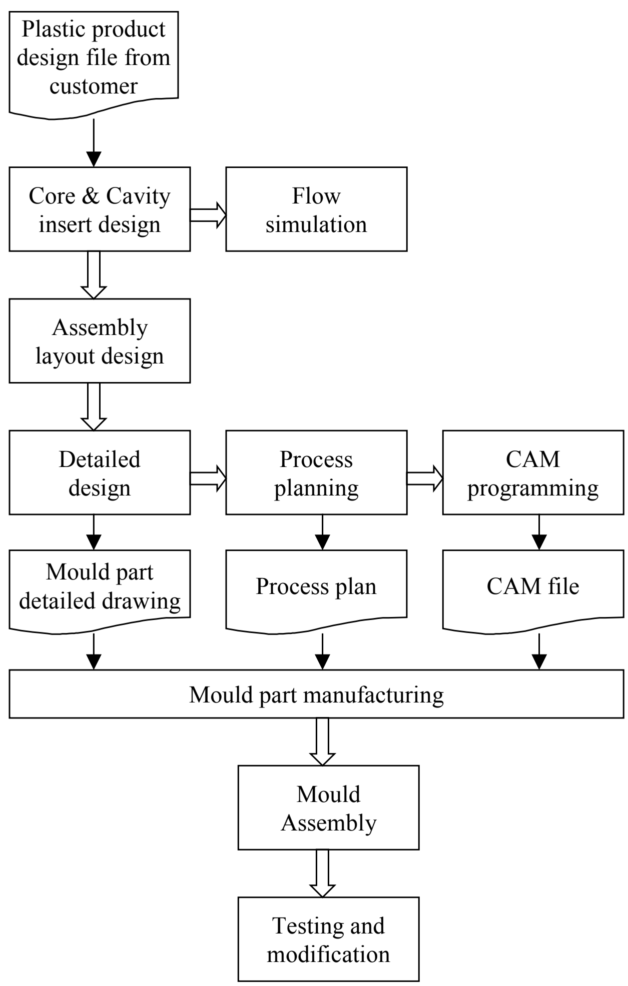
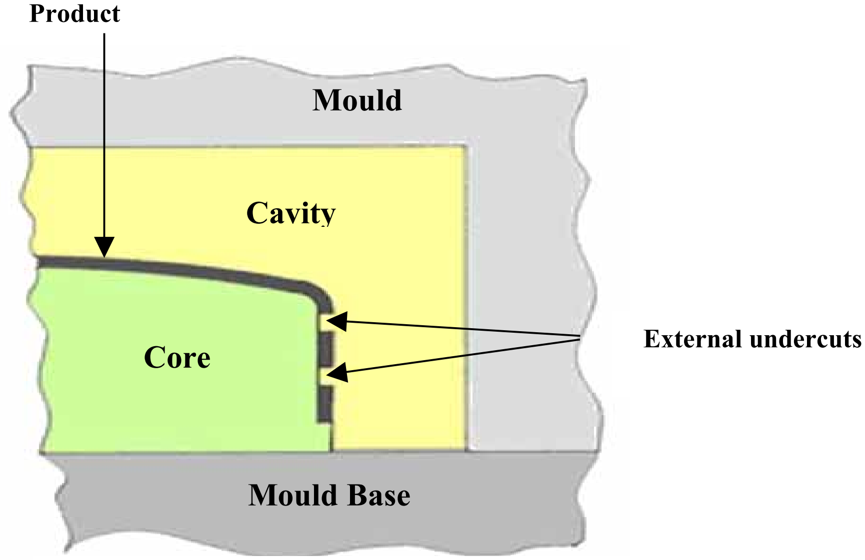


Figure 3.1 A general mould manufacturing process

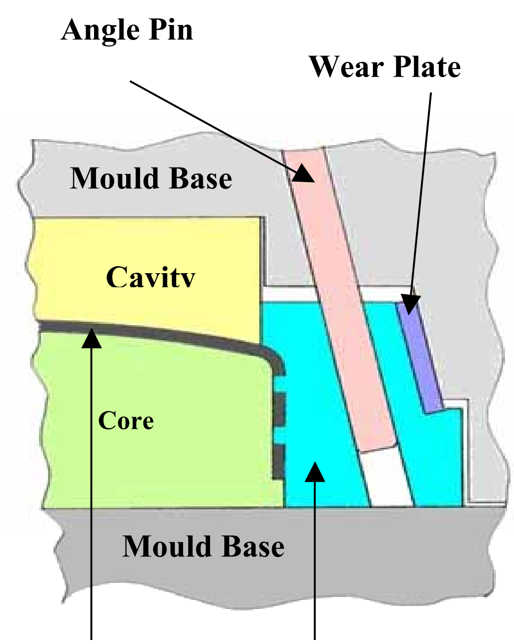
3.2.1 Slider and lifter

The main function of a slider in injection mould is to form an external undercut in the plastic part. Figure 3.2 illustrates the working principle of a slider. Mould companies usually have several typical types of sliders. Figure 3.3 a shows one type of the sliders. This type of slider consists of a slider body, slider head, wear plate, guide, heel block, angle pin and stop block. The angle pin moves up and down the slider body while the guides provide the moving action for the slider body and are attached to the moving half of the mould base. The wear plate is a rectangular plate, which prevents the slider body from wearing out. The heel block is the locking engagement. The stop block resists the slider body from moving out from its actual stroke length.

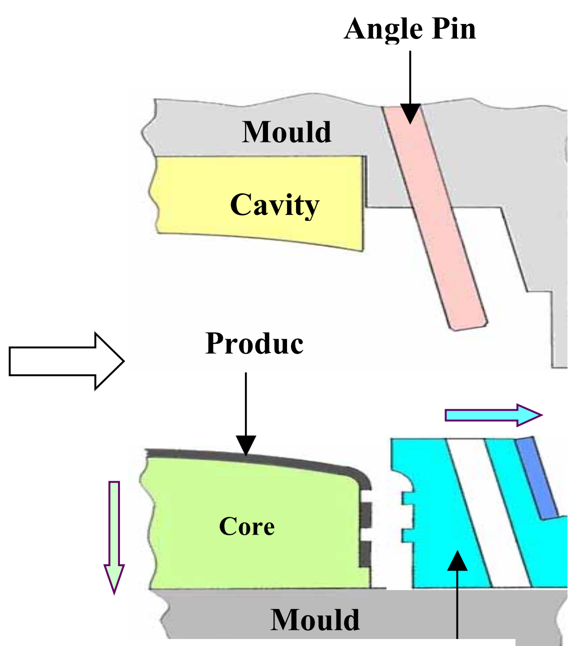
Slider head is the key part of slider, which forms the undercut of the plastic product. It can be a separate component attached to the slider body by connecting components, when it has complex shape and has to be machined separately. Figure 3.3 b shows the profile of a slider head. If its shape is not too complex to machine, it can be made integrated into the slider body.



(a) A product with external undercuts in a mould



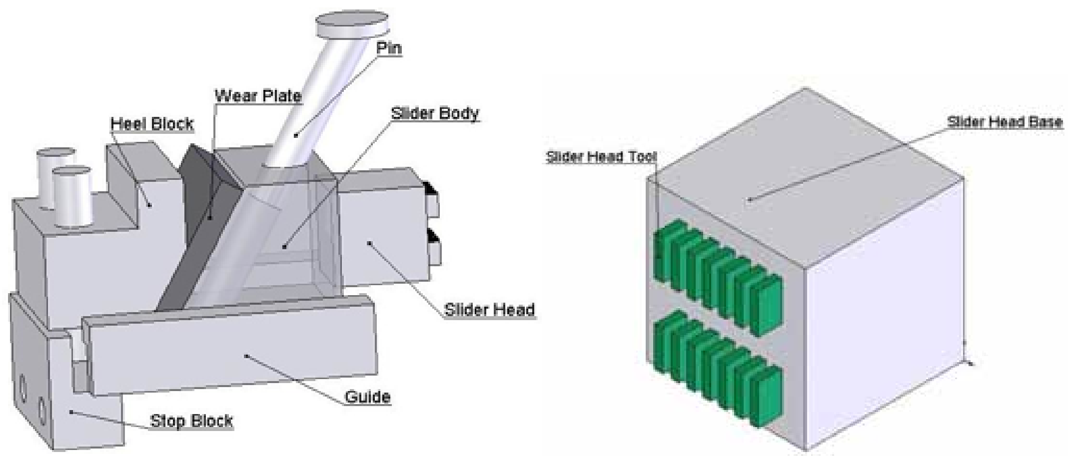
(b) A slider is incorporated into the mould



(c) Slider releases product

Figure 3.2 The working principle of slider

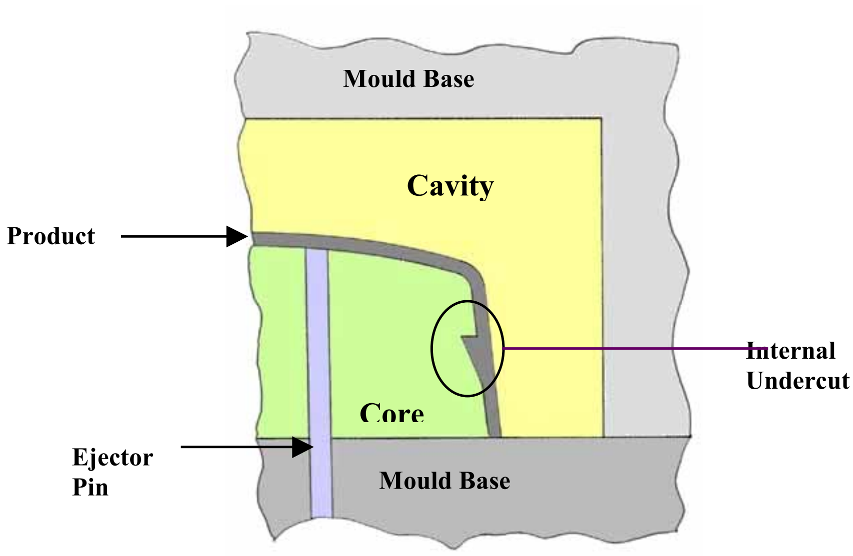
Among all the slider parts, it can be found that most of them perform fixed function, such as the wear plate, guide, heel block, angle pin and stop block. Therefore, they can all be identified as standardized parts. A slider body without the slider head can also be identified as a standardized part. A slider body with attached slider head has to be identified as non-standardized part. The features on the body portion can be identified as standardized features and the features on the head portion are identified as non-standardized features.



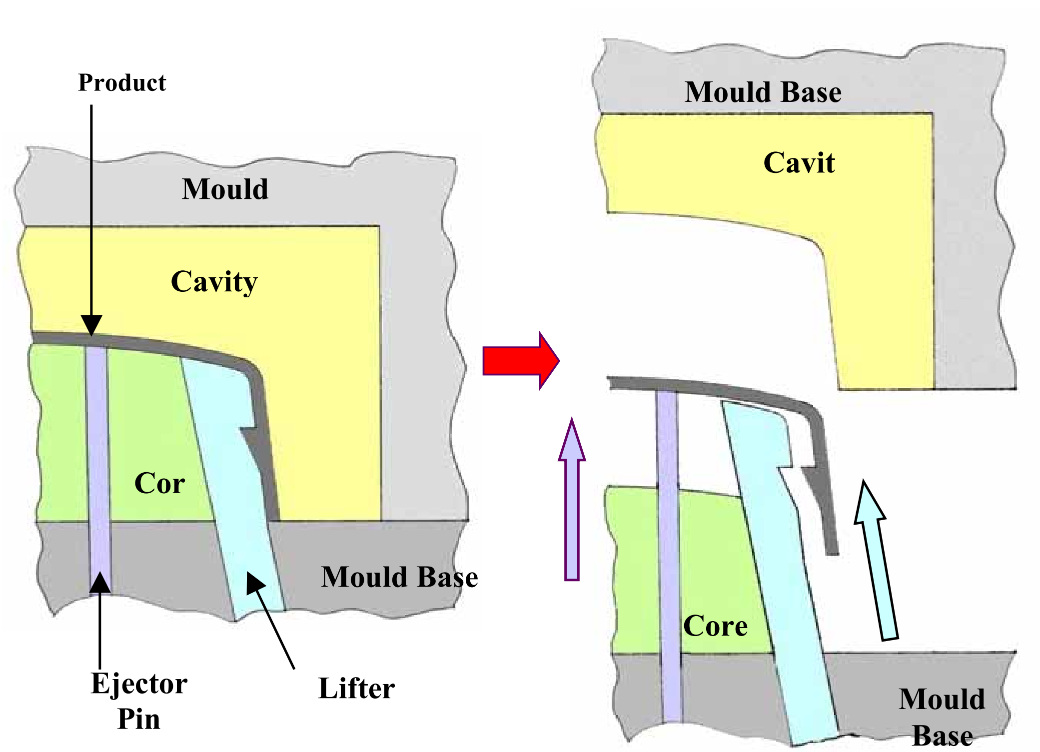
(a) (b)

Figure 3.3 The assembly of a typical type of slider and the slider head portion

Lifters are used to form internal undercuts as shown in Figure 3.4. The internal undercut cannot be formed directly by the core, since the product will be damaged during the ejection process. Therefore, a lifter has to be added. When the mould opens, the lifter slides away from the undercut at an angle, as the part is being pushed out of the core. At the end of the ejection stroke, the lifter would have totally released itself from the undercut.



(a) A product with internal undercut in a mould



(b) A lifter is incorporated into the mould (c) Part releases with the help of lifter

Figure 3.4 The working principle of lifter.

Figure 3.5 shows an example of a typical type of lifter assembly. This type of lifter assembly consists of lifter body, lifter head, lifter base, guide bush, wear plate, etc. The lifter head forms the profile of the undercut and it is usually integrated with the lifter body. The lifter base supports the lifter body during ejection. The guide bush provides the moving pass of the lifter body. The wear plate is a rectangular plate, which prevents the lifter body from wearing out.

Similar to the slider parts, it can be found that most of lifter parts such as wear plate, guide bush, and lifter base perform fixed function, not involving the formation of the undercut profile,. Therefore, they can all be identified as standardized parts. The lifter body has to be identified as non-standardized part, because the lifter head on it involves forming the undercut on the plastic product. Similar to the slider body, the features on the body portion of the lifter can be identified as standardized features and the features on the head portion are identified as non-standardized features.

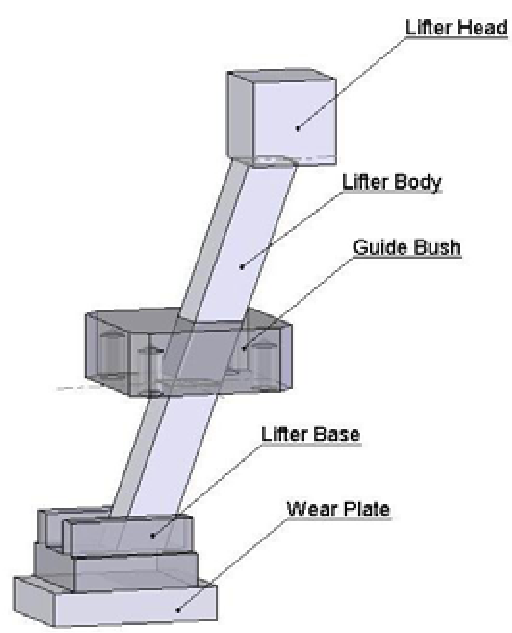


Figure 3.5 The lifter assembly of a typical type of lifter

3.2.2 Core and cavity inserts

Core and cavity inserts are the most crucial components of the injection mould. They directly form the main body of the plastic products. They are identified as non-standardized parts. Usually they have rectangular external shape with specific dimension in order to insert into the pocket in the core plate and cavity plate as shown in Figure 3.6. In the cavity and core plates, corresponding rectangular pockets are machined to contain the core and cavity inserts. They also have screw holes and positioning holes to attach the inserts to the mould base. The external rectangular profile and these holes can be identified as standardized features. The internal features on the core and cavity inserts vary with the plastic product. Like the slider head and lifter head, they are identified as non-standardized features.

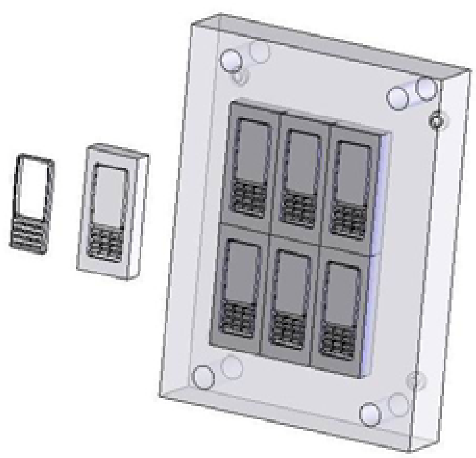


Figure 3.6 An example of plastic product, cavity insert and cavity plate

3.3 Process planning for mould parts manufacturing

Process planning, which is an important link in the manufacturing cycle, defines in detail the processes that transform raw material into the desired form. It mainly comprises of:

- Selection of processes and tools for processing a part and its features;

- Selection of starting surfaces and datum surface to ensure precise processing;
- Selection of holding fixtures and clamping facility;
- Determine the sequence of operations;
- Selection of cutting conditions for each operation (Halevi et al., 1995).

In the mould manufacturing industry, mould parts, that are non-standardized may have many features with very complex shape; the process planning work can be very complicated and time-consuming. It can be observed that in a particular company, for a particular standardized mould part, the machining processes and their sequences are rather fixed. Therefore, a process plan template approach was proposed (Alam, 2000). The dimension of the standardized part can vary with the plastic product, which may cause some minor change in the process plan, such as cutter size, and cutting parameters. An example of process plan template for a type of slider body will be given in section 4.4.

For the non-standardized parts, only the process plan for the standardized features, like the external cubic profile of core and cavity inserts and the positioning holes on core and cavity inserts, can be standardized. Since these features are usually machined before the machining of the core and cavity internal profile, the processes for these features are usually the first several steps in the process plan.

For the non-standardized features on the non-standardized part, mainly the internal profile, which forms the main part of the plastic product, the process has to be planned according to the plastic product design drawing. The machine tool, fixture, cutter, cutting conditions are selected for each new mould project based on the specific conditions.

CHAPTER 4 SPC PLANNING FOR INJECTION MOULD MANUFACTURING

Due to the complexity of injection mould manufacturing, the application of statistical process control in the various machining processes of injection mould manufacturing has to be carefully planned. Firstly, the quality characteristics of concern have to be clarified. Check Sheet and Pareto Chart can be used here to help find out and prioritize the quality characteristics to be improved. In the manufacture of mould parts, most of the concerned quality characteristics are the dimensional accuracy and positional accuracy. There are also some other quality characteristics, such as geometrical accuracy and surface roughness. As sufficient data cannot be obtained for meaningful statistical analysis, SPC methods are not suggested. Process should be clearly defined, appropriate data transformation method should be selected and part family should be correctly formed to make the control chart more statistically meaningful. Suitable control chart should be selected to both monitor the large sudden shift of the process as well as the small gradual shift. In this chapter, process identification, part family formation, data transformation method selection and control chart selection will be discussed.

4.1 Defining and identifying SPC process

In SPC, the objective is to improve the performance of the process, through which the product quality can be improved. Therefore, in a manufacturing system, which contains various process types, it is crucial to initially clearly define the "SPC processes". It has to be noted that the SPC process can be different from the machining process. To define SPC process, the machining process has to be analyzed first.

For mould manufacturing, different types of process are used. For the corresponding processes, different types of machine are used, including the conventional milling machine, CNC milling machine, CNC graphite milling machine, radial drilling machining, grinding machine, EDM die-sinking, EDM wire-cut, and so on. In a mould company, there may be a number of machines available of the same machine type, and each machine may be able to perform different types of operation. For each operation type, different types of cutting tools may be available. For each type of cutting tool, different cutting parameters may be applied. At the same time, different fixtures or workpiece holding methods are available for the selection. To better understand the problem, several definitions have to be clarified. The process type means the typical machining process, such as milling, EDM, and grinding, etc. Operation type refers to the different operations which can be performed using one particular machine. For example, a CNC milling machine can be used for milling, drilling and chamfering, as shown in Figure 4.1.

Therefore, each particular operation is performed with a combination of many factors, including the cutter type, cutter number, fixture type, fixture number and combination of cutting parameter settings (Anderson et al., 1991). Cause-and-effect diagram can be used here as a powerful tool to help list all the possible relevant factors. As discussed in section 2.2.2, the effects of these factors on the quality characteristics of the parts machined have to be analyzed to isolate variation type II. The factors are listed in detail as follow:

<u>Factors of cutter</u>: cutter type, including cutter material, cutter size, and cutter geometry, cutter holding method, and cutter number

Factors of fixture: fixture type, including fixture size, workpiece holding method, and fixture number

Factors of cutting parameters: cutting speed, feed rate, and depth of cut (for milling) (Lee et al., 1998, Lacalle et al., 2001)

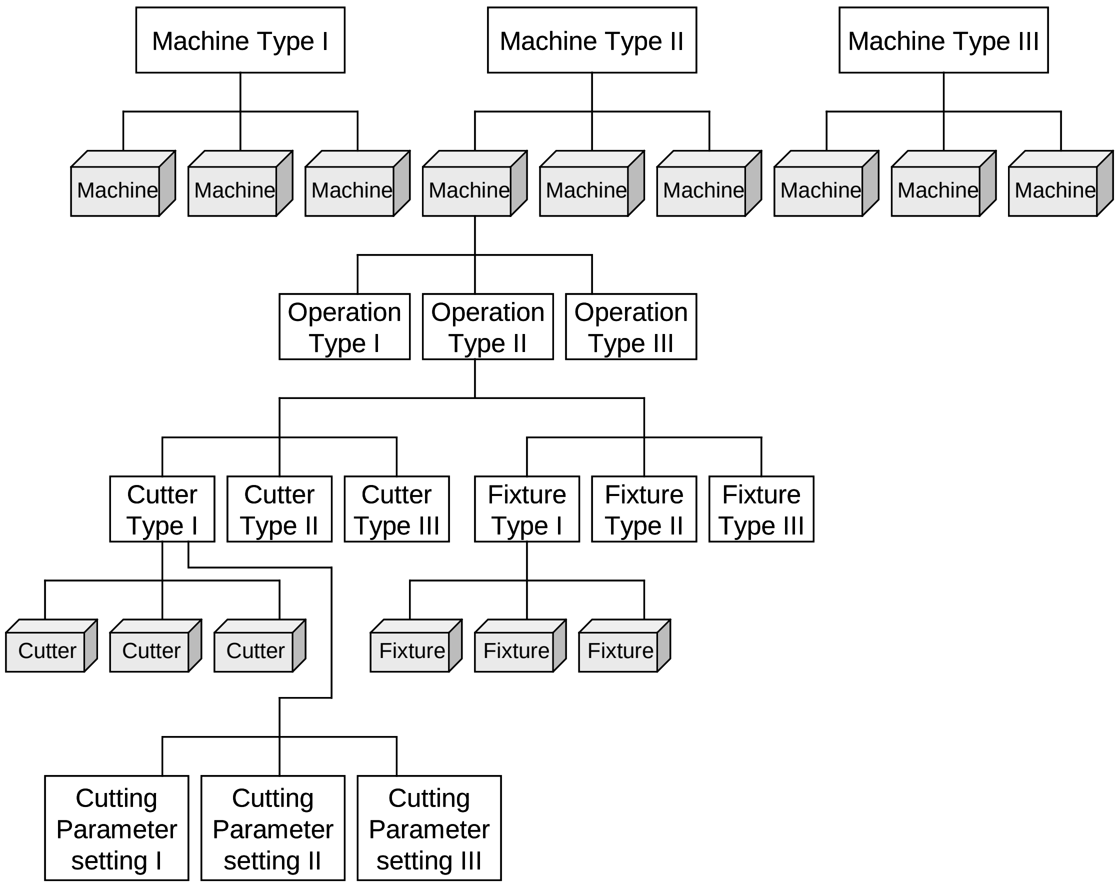


Figure 4.1 The machining processes in mould shop

Before applying statistical methods to analyze the effect of one factor, engineering knowledge can be applied first to remove some factors which are obviously irrelevant to the concerned quality characteristics. When engineering knowledge is not sufficient to identify significance of the factor's effect, the historical data are referred and statistical analysis are used.

To investigate the effect of one particular factor, multiple regression techniques can be used, and ANOVA and multiple comparison techniques can also be used (Montgomery, 1996).

If any factor is found to have non-significant effect on the concerned quality characteristics, this means that its setting will not affect the identification of SPC process. The setting of the leftover factors, which have significant effect on the concerned quality characteristics, will be used to identify the SPC process. The operations with different settings of these factors will be regarded as different SPC processes and will be treated separately. If no factor is found to significantly affect the concerned quality characteristics, one operation type of the machine will be taken as a natural SPC process. It has to be noted that for different concerned quality characteristics, the effect of the factors may be different. One factor may have significant effect on one particular quality characteristics, but not the others.

In mould manufacturing, usually a limited number of quality characteristics are of concern. These are the dimensional accuracy, positional accuracy and surface roughness. Therefore, by careful analysis of all the machining processes in the mould shop, SPC processes can be defined and the definitions of the SPC processes are applied to identify the SPC process when the process plan and production schedule of a part are given.

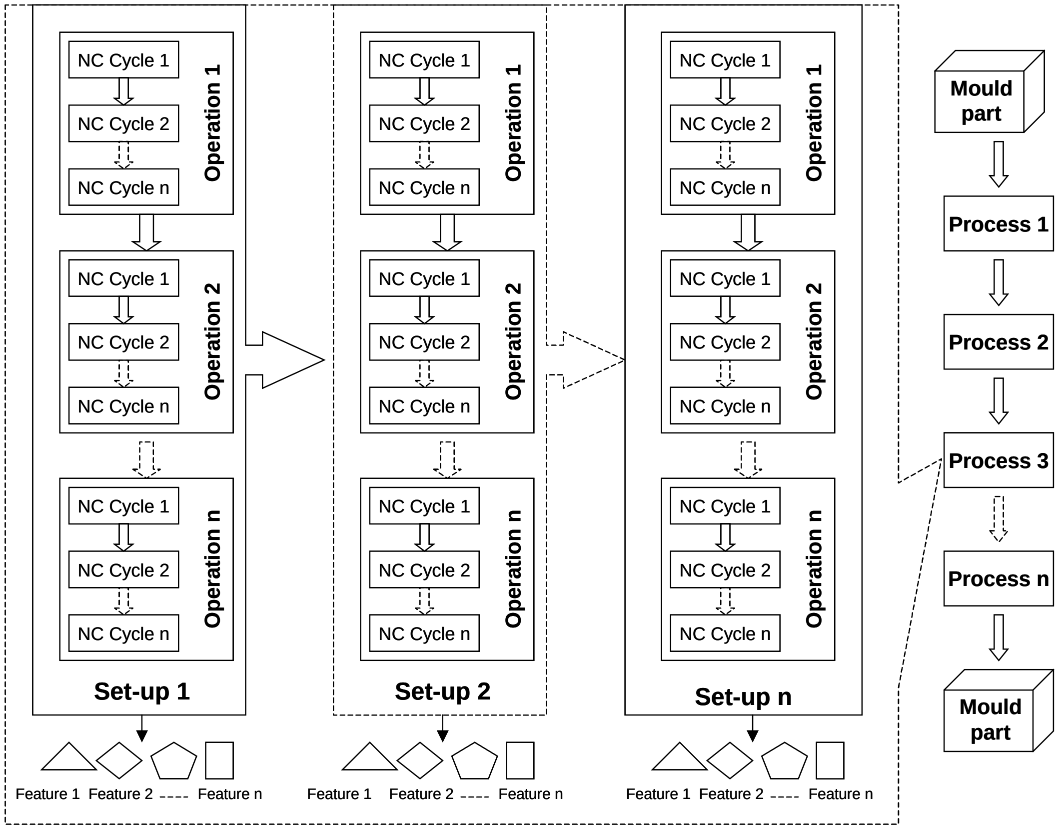


Figure 4.2 The processes of machining mould part

Figure 4.2 shows the process of machining a mould part. It may need several machining processes. In each process, there are several set-ups. In each set-up, several operations are required to generate the features. By referring to the summarized definitions of the SPC process, the SPC process involved for this part are identified and the corresponding relationship between the machining feature and the SPC process are also identified. It is suggested that the machining feature can be taken as the unit product of an SPC process, if they can be measured and their quality characteristics can be expressed separately. The measured results are used to plot the control chart after data transformation.

4.2 Forming and identifying part family

By defining the SPC processes, the type II variation can be isolated. However, for the parts passing through the same SPC process, the type I variation, which is the variation caused by the part's own characteristics, has to be investigated. Similar to analyzing the effect of the process factors, part factors are listed and their effect on the concerned quality characteristics are analyzed, for which the Cause-and-effect Diagram can be used. As discussed in section 4.1, if the machining feature is taken as the unit product of one SPC process, both the characteristics of the part and the feature have to be investigated, which mainly refer to the material of the part and the geometrical characteristics of the feature. After applying engineering knowledge and statistical methods, the effect of these factors, which are related to part and feature's own characteristics on the concerned quality characteristics, are being identified. The factor that significantly affects the concerned quality characteristics is used to identify the part family membership.

After listing all the possible factors, engineering knowledge are first applied to remove the factors which obviously do not have significant effect on the concerned characteristics. The statistical methods are then used to analyze the effect of the leftover factors, in the same way as for defining the SPC processes.

After all the factors are analyzed, factors which are found to have significant effect on the concerned quality characteristics are used to identify the part family membership. If no factor is found to have significant effect on the concerned quality characteristic, all the features produced by the same SPC process will be naturally grouped in one part family. Figure 4.3 shows the concept of the SPC process identification and part family identification.

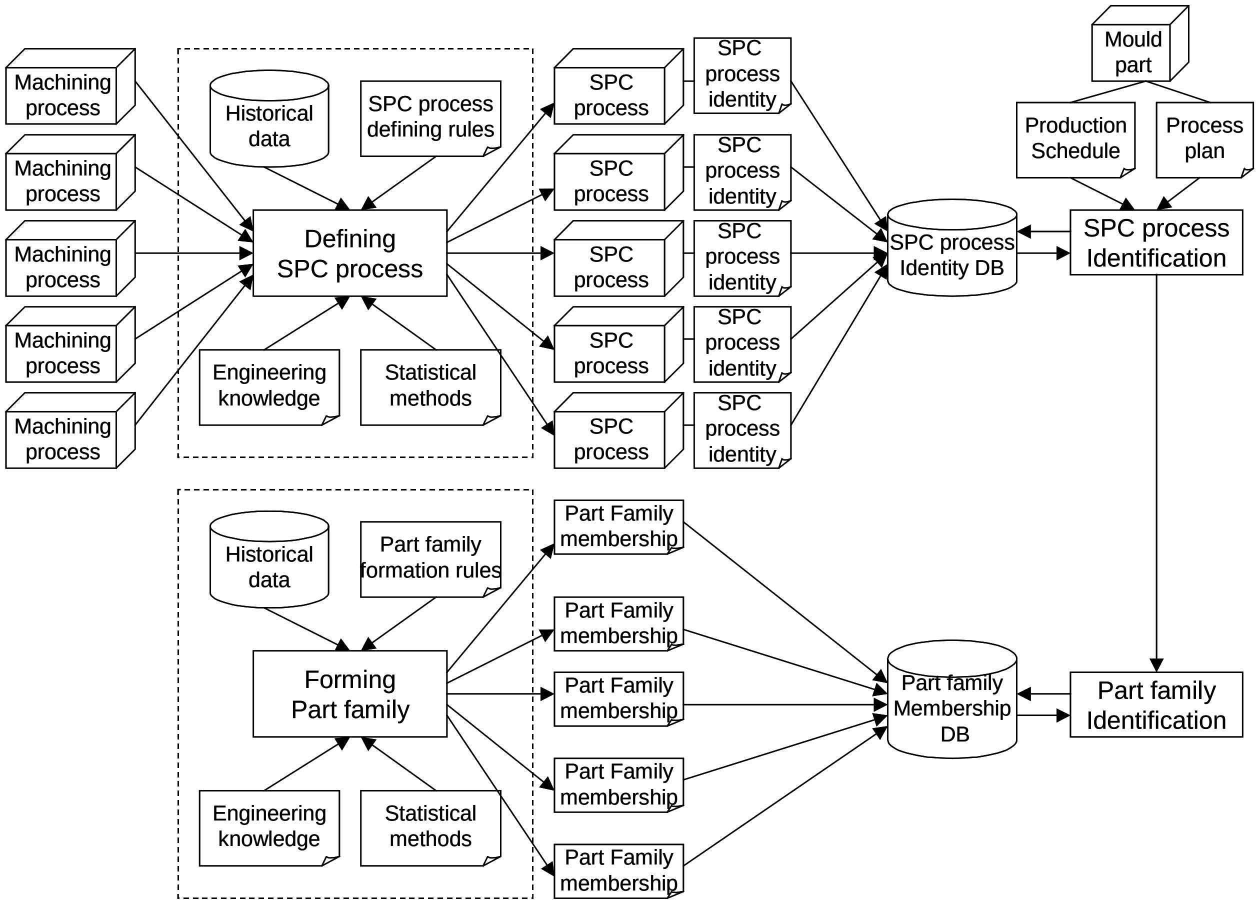


Figure 4.3 SPC process identification and part family identification

4.3 Identification of quality characteristics

Since the purpose of SPC is to monitor and to improve the performance of the process, the quality characteristics of the parts have to be related to the characteristics of the process.

An end-milling process as shown in Figure 4.4 is taken as an example to illustrate this. Usually the direction identical or parallel with the axis of the cutting tool is taken as the Z direction. It is assumed that the machining accuracy in Z direction is of concern. A cubic shape part with two pocket features on the two faces is taken as an example part of this process. These two pockets are machined by two operations in two set-ups as shown

Figure 4.5. If the depth of the pockets, D1 and D2, are the two of concerned quality characteristics of the part, the operation and the set-up for machining of these two features have to be studied carefully. It is found that D1 and D2 are both affected by the machining accuracy in the Z direction, therefore, they can be taken as the same quality characteristics to be plotted on same control chart, even though they are not in the same coordinate system of the part.

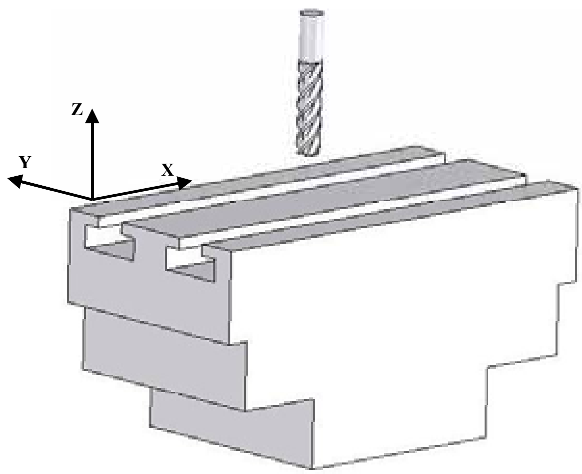


Figure 4.4 The coordinate system of an end-milling process

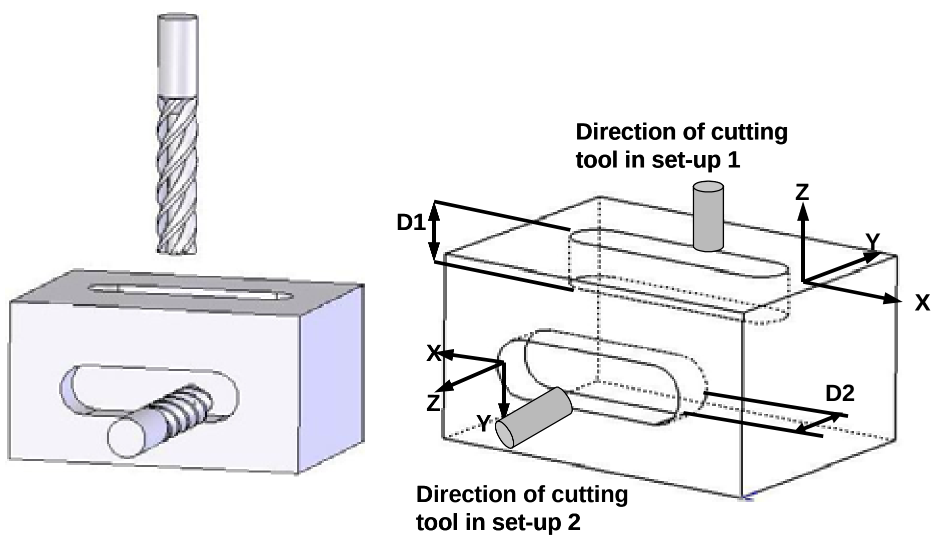


Figure 4.5 An example of a part with two end-milling features

4.4 SPC planning for standardized part and features

For standardized mould parts and standardized features of the non-standardized mould parts, they have fixed shape and performs fixed functions, therefore the quality characteristics can be summarized. Figure 4.6 shows several common types of slider used in a mould company.

For a simple shape undercut, the slider head is easier to machine, therefore it can be integrated to the slider body, like type 3, 4, 5, 6 and 7. For more complex or large size undercut, the slider head is not easy to machine as an integrated part of the slider body. It has to be machined as a separate part and connected to the slider body. Type 1 and type 2 sliders are for this kind of situation.

The main portion of the type 3, 4, 5, 6 and 7 is the slider body which consists of only standardized features.

For these standardized parts, they have some fixed features, such as plane, slot, step and holes. Once a type of slider is chosen, these features only vary in dimension. It has to be noted that the cooling hole is a special feature here, because its size and position have to be designed depending on the position of the undercut. However, in practice, the diameter and position of these cooling channels are not as crucial as other holes and will not be discussed here.

The quality characteristics of other standardized features can be summarized. Since the process plan template of these features is proposed to be possible (Alam et al., 2001), a SPC plan template can be worked out. The type 3 slider body is taken as an example for illustration.

The proposed process plan template for type 3 slider body is shown in Figure 4.7.

The summarized quality characteristics of this slider body is shown in Figure 4.8.

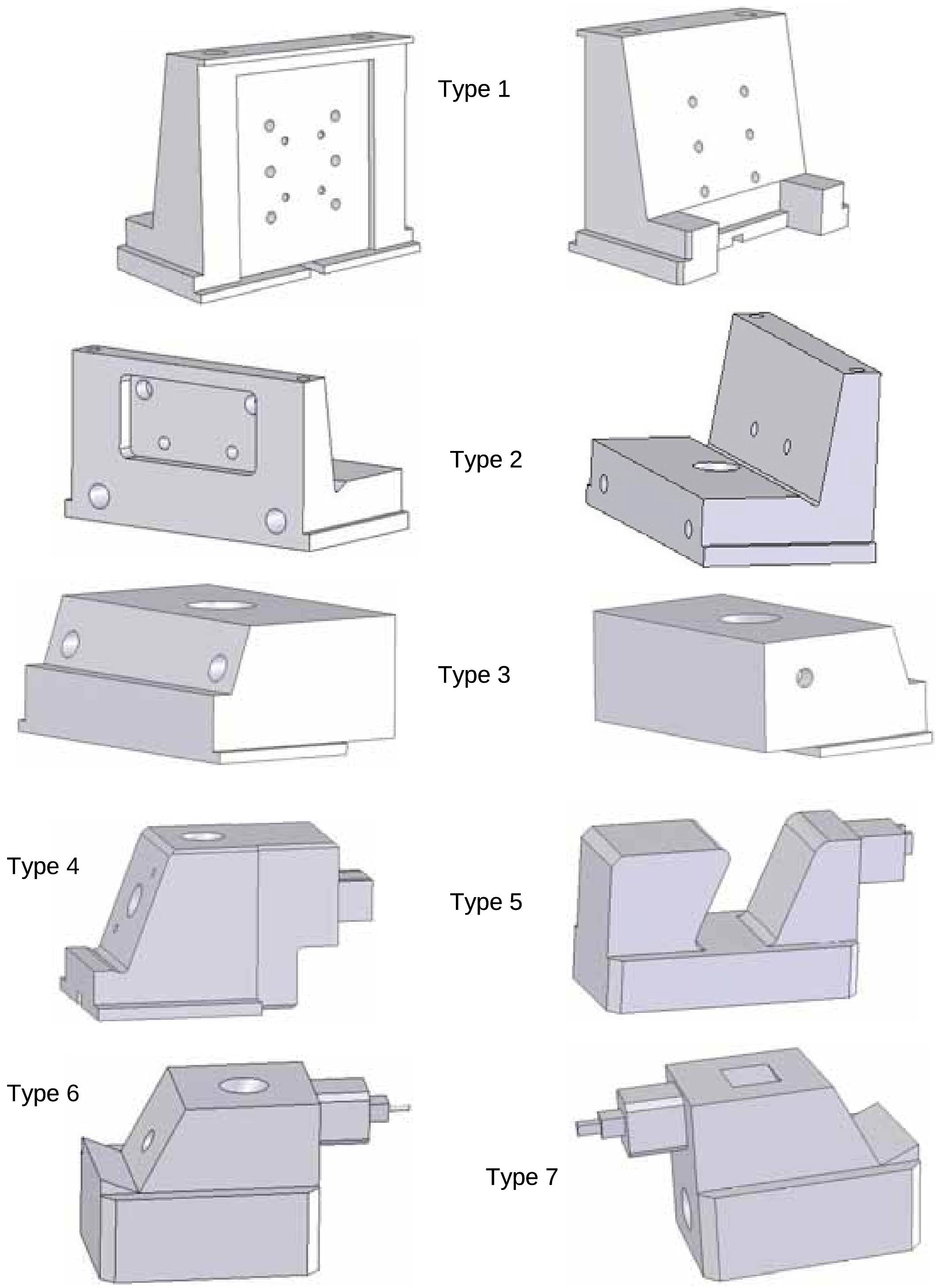
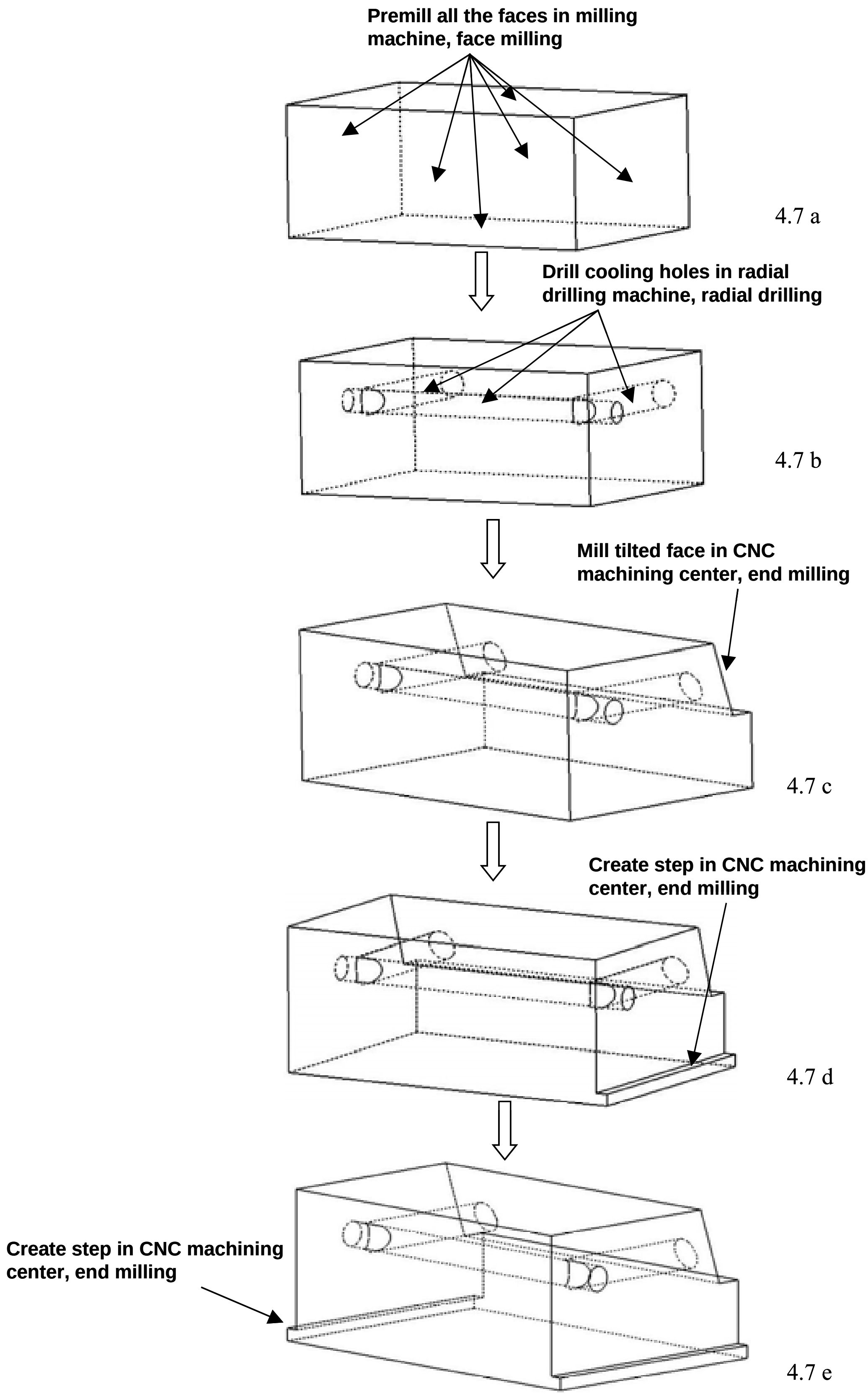


Figure 4.6 Several common types of slider and slider body



Premill all the faces in milling machine, face milling
4.7 a
Drill cooling holes in radial drilling machine, radial drilling
4.7 b
Mill tilted face in CNC machining center, end milling
4.7 c
Create step in CNC machining center, end milling
4.7 d
Create step in CNC machining center, end milling
4.7 e

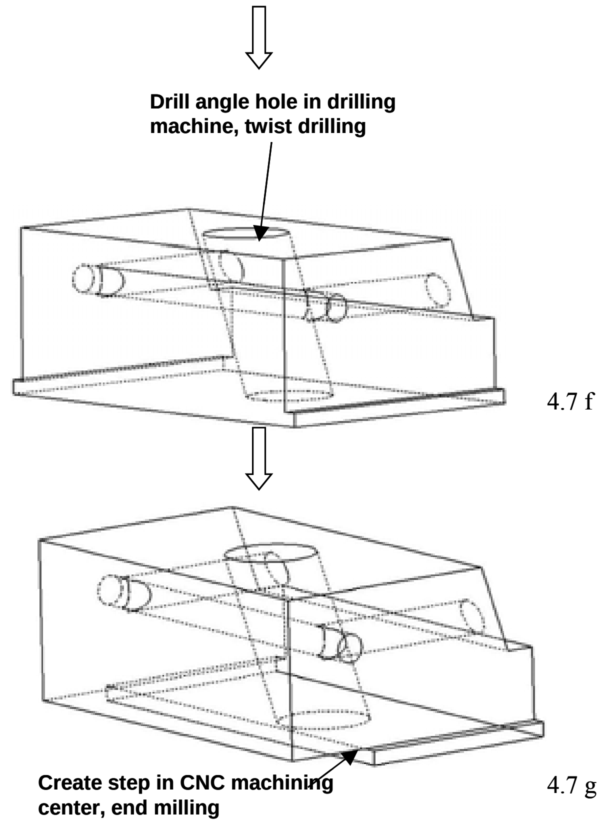


Figure 4.7 Proposed process plan template for Type 3 slider body

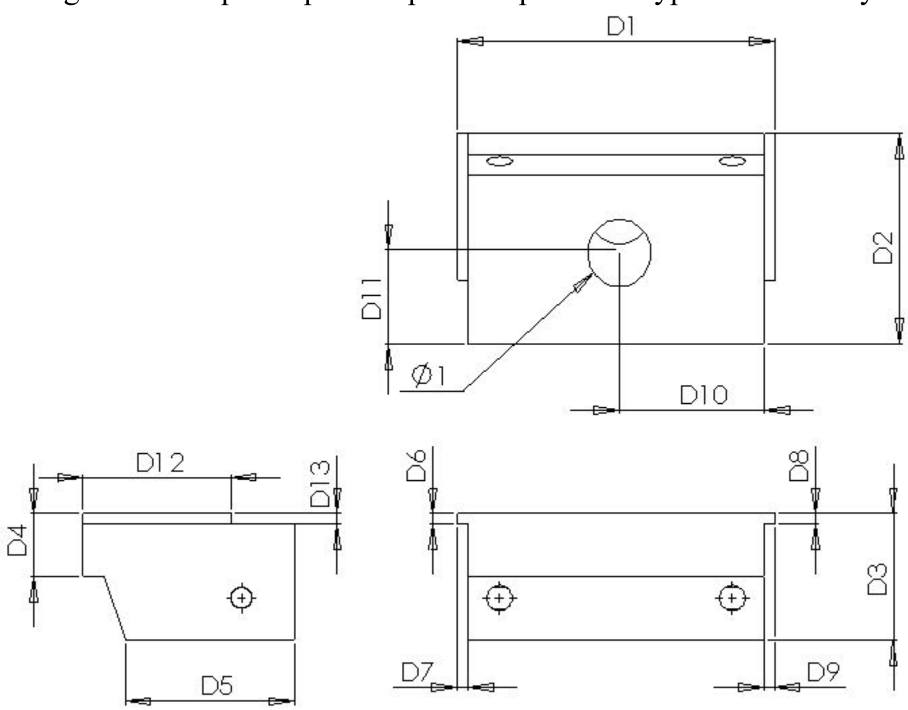


Figure 4.8 The quality characteristics of Type 3 slider body

The quality characteristics and the corresponding process type, set-up, operation type forms the SPC plan template, since the SPC planning is easier and time is saved. Table 4.1 gives the example of SPC plan template for Type 3 slider body shown in Figure 4.7.

Table 4.1 An example of SPC plan template for Type 3 slider body

Mould Part	**Quality characteristics**	**Machine type**	**Corresponding process**	**Set-up**	**Machining Direction**
Slider body (Type 3)	D1	Milling machine	Face milling	1	Z
Slider body (Type 3)	D2	Milling machine	Face milling	2	Z
Slider body (Type 3)	D3	Milling machine	Face milling	3	Z
Slider body (Type 3)	D4	CNC machining center	End milling	1	Z
Slider body (Type 3)	D5	CNC machining center	End milling	1	Z
Slider body (Type 3)	D6	CNC machining center	End milling	2	X
Slider body (Type 3)	D7	CNC machining center	End milling	2	Z
Slider body (Type 3)	D8	CNC machining center	End milling	3	X
Slider body (Type 3)	D9	CNC machining center	End milling	3	Z
Slider body (Type 3)	D10	CNC machining center	Drilling	4	X
Slider body (Type 3)	D11	CNC machining center	Drilling	4	Y
Slider body (Type 3)	Ø1	CNC machining center	Drilling	4	
Slider body (Type 3)	D12	CNC machining center	End milling	5	X
Slider body (Type 3)	D13	CNC machining center	End milling	5	Z

With this SPC plan template, the quality characteristics produced by the same process type are grouped together awaiting further identification to generate the SPC plan (Table 4.2).

Table 4.2 Reorganized SPC plan template for Type 3 slider body

Mould Part	**Quality characteristics**	**Machine type**	**Corresponding process**	**Set-up**	**Machining Direction**
Slider body (Type 3)	D1	Milling machine	Face milling	1	Z
Slider body (Type 3)	D2	Milling machine	Face milling	2	Z
Slider body (Type 3)	D3	Milling machine	Face milling	3	Z
Mould Part	**Quality characteristics**	**Machine type**	**Corresponding process**	**Set-up**	**Machining Direction**
Slider body (Type 3)	D4	CNC machining center	End milling	1	Z
Slider body (Type 3)	D5	CNC machining center	End milling	1	Z
Slider body (Type 3)	D7	CNC machining center	End milling	2	Z
Slider body (Type 3)	D9	CNC machining center	End milling	3	Z
Slider body (Type 3)	D13	CNC machining center	End milling	5	Z
Mould Part	**Quality characteristics**	**Machine type**	**Corresponding process**	**Set-up**	**Machining Direction**
Slider body (Type 3)	D6	CNC machining center	End milling	2	X
Slider body (Type 3)	D8	CNC machining center	End milling	3	X
Slider body (Type 3)	D12	CNC machining center	End milling	5	X
Mould Part	**Quality characteristics**	**Machine type**	**Corresponding process**	**Set-up**	**Machining Direction**
Slider body (Type 3)	D10	Drilling machine	Twist drilling	1	X
Slider body (Type 3)	D11	Drilling machine	Twist drilling	1	Y

With each new mould, the detailed process plan for the standardized parts are worked out by the process planner and the material of the mould part is chosen. SPC process identification and part family identification can then be done, with the definitions predetermined in advance. It has to be noted here that different machines of the same machine type are monitored separately. Therefore, the machine number has to be indicated in the SPC plan after getting the production schedule. The quality characteristics, part type, part number and control chart point number are also indicated in the SPC plan for future use when cause-finding is needed for out-of-control situations. (Table 4.3)

Table 4.3 An example of proposed SPC plan

Machine No. ***** SPC process No. ****** Part Family No. 001 Quality characteristic type: Face milling -Z			
Quality characteristics	Mould Part	Part Number	Point No. in chart
D1	Slider body	****	****
D2	Slider body	****	****
D3	Slider body	****	****
….	….	….	….

Machine No. Makino V55 SPC process No. V55-1-FM-1 Part Family No. 001 Quality characteristic type: End milling -Z			
Quality characteristics	Mould Part	Part Number	Point No. in chart
D4	Slider body	****	****
D5	Slider body	****	****
D7	Slider body	****	****
D9	Slider body	****	****
….	….	….	….

4.5 SPC planning for non-standardized features

Non-standardized features rquire more consideration compared to standardized features. As these features vary with the various shapes of plastic product from one mould to another, it is not practical to apply the process plan template or the SPC plan template. As these features are usually machined by CNC machining and EDM, the SPC planning for these features have to be made based on the individual situation of each mould project.

4.5.1 Identification of quality features

A feature machined by CNC or EDM can be a regular-shape machining feature, a feature of free-form shape, or the combination of both. For the regular-shape machining features, the quality characteristics can be defined in the regular way, like height of a step, width of a slot, depth of a pocket or diameter of a hole, etc.

Some of the CNC or EDM machining features are a combination of some small regular-shape features, so their quality characteristics have to be subdivided into the quality characteristics of these small features. Figure 4.9 shows an example of a complex-shape pocket in the core (feature 1), which can be machined in one CNC milling operation. However, this feature contains many quality features that have to be measured separately. In feature 2, the four aligned slots can be machined in one EDM operation, but have to be recognized as four quality features if they are measured separately.

The quality characteristics of the feature with free-form surfaces are not easy to define. However, free-form features are very common in core and cavity inserts.

In the mould shop, the quality characteristics, mainly referring to dimensional accuracy and geometrical accuracy, are being measured by coordinate measuring machines, for both regular-shape features and free-form shape features. Therefore, the characteristic of the CMM has to be considered when defining quality characteristics and SPC plan for non-standardized features.

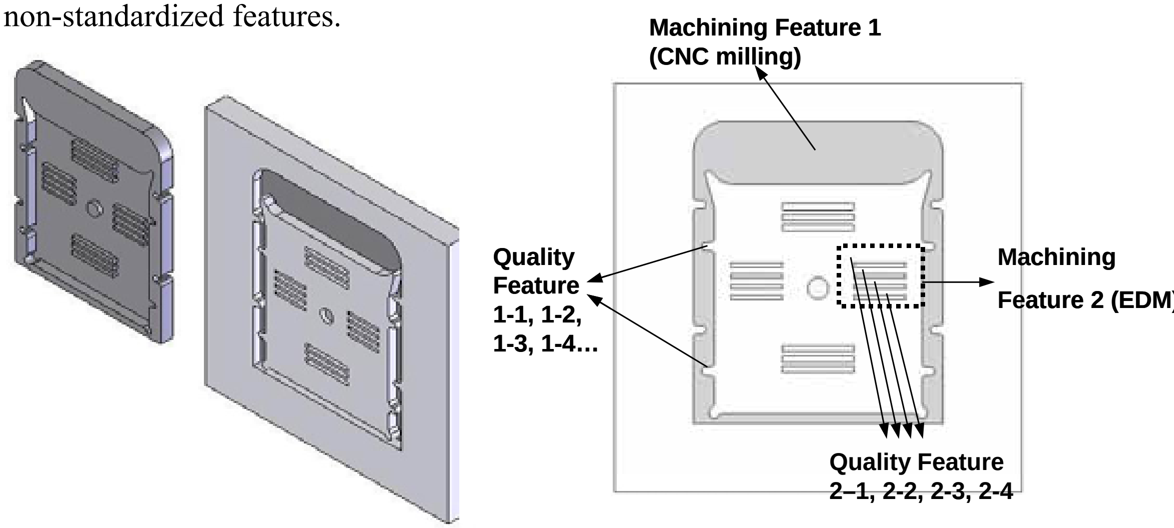


Figure 4.9 An example of machining feature and quality feature

4.5.2 Measuring quality features of non-standardized features

Being one of the most powerful metrological instruments, coordinate measuring machines (CMMs) are widely used in most manufacturing plants. CMMs are referred to those machines that give physical representations of a three-dimensional rectilinear Cartesian coordinate system as shown in Figure 4.10. The basic function of coordinate metrology consists of measurement of the actual shape of a workpiece, its comparison with the desired shape, and the evaluation of the metrological information, such as size, form, location, and orientation. The actual shape of the workpiece is obtained by probing the surface at discrete measuring points. Every measuring point is expressed in terms of its measured coordinates (Bosch, 1995).

In the mould shop, the coordinate measuring machine (CMM) is usually used to measure the dimensional and geometrical accuracy of the mould parts. In most of the cases, CMM is used to measure the quality characteristics of the non-standardized features, due to its high accuracy. The quality of non-standardized features, which directly form the plastic product, is of major concern. As the original CMM measurement results are the coordinate value of the actual points on the workpiece, they cannot be directly used as meaningful data to analyze. Some work was proposed to use deviation ε as the quality characteristic variable to monitor the process. Deviation, ε, can be obtained by subtracting properly aligned referenced model coordinates value from the direct CMM measurement. Alternatively, ε may also be obtained as the distance between the observed point S and surface of the nominal model C, in the direction of vector V which is normal to the surface of model C (Ho, E. S., 1998), as shown in Figure 4.11. According to the mould shop practice, the former method to define deviation is used.

For the free-form shape feature or the combination of regular-shape and free-form shape feature, whose quality characteristic cannot be defined in the usual way, this method of measuring the coordinate points can be applied in the same way as the regular shape features. The measuring points are usually determined by the design department of a mould company.

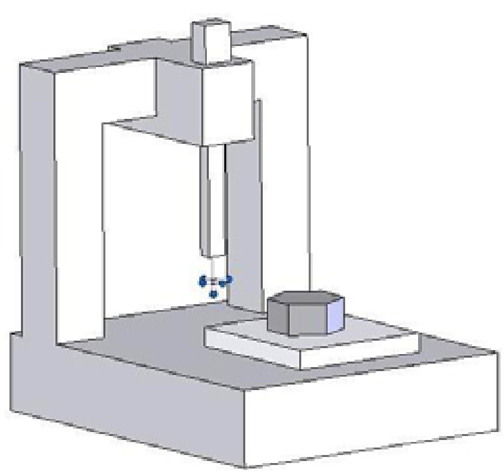


Figure 4.10 Coordinate measuring machine

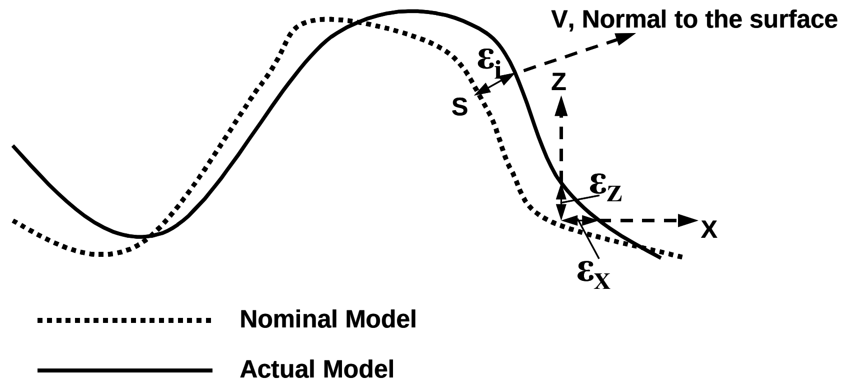


Figure 4.11 The definition of deviation ε in CMM measurement

It has to be noted that if the pattern of the control chart reflects the changing trend with time, the machining features and sub-features have to be numbered in the sequence in which they are being machined, so that they can be plotted in the chart in the corresponding sequence if they belong to same control chart. In the chart, the element machined earlier will always be plotted towards the left of the control chart.

4.6 Selection of data transformation method

As discussed in section 2.2.1, the different data transformation methods have their own applications. When selecting a suitable data transformation method, the characteristics of the mould part have to be considered.

Bothe's approach is used when the process variability is approximately the same for all parts. Cullen and Bothe's approach is used when the variation of process differs significantly with different part types. Evans and Hubele's approach is used when the tolerances of different part types are significantly different and the process variation also differs with the different tolerances. Crichton's approach is used when process variability differs significantly from one part to another and also increases with the nominal size.

In the approach proposed in this study, as the SPC process identification and part family identification already prevent the part types with significantly different variability from appearing in the same control chart. The tolerance and the size of the part can both be taken as factors of the parts own characteristics whose effect on the variability of the part are considered and analyzed when forming part family. Therefore, their effect on the variability of the process will not be introduced in same control chart. Within the same part family, only Bothe's approach (Deviation from Nominal) is used to normalize the data.

4.7 Selection of control chart

The most common control chart, average and range chart, does not apply for one-off manufacturing situations, because the subgroup of identical products do not exist. In the analysis, the machining feature is taken as the "unit product" in processes, even though there are multi-cavity moulds, which have more than one identical core, and cavity inserts. One core or cavity insert usually has more than one machining feature, which means the identical machining features usually are not machined consecutively. Therefore, these identical features cannot form the subgroups for average and range chart.

Instead, individual-moving range chart is instead proposed here, which uses the individual measurement as the data point after data transformation. As the individual-moving range chart is not so sensitive to small process shift, EWMA or Cusum chart is proposed to be used as a supplement to monitor small process shift.

CHAPTER 5 SPC IMPLEMENTATION FOR INJECTION MOULD MANUFACTURING

SPC planning can be done before the start of real production, if sufficient information of process plan and production schedule is given. SPC implementation starts from the data collection in the actual production. Data collection mainly refers to measuring the planned quality characteristics of the parts and data recording includes both recording the measurement results of the parts, and recording the information of the process. After data is collected and recorded as planned, control chart is created with the transformed data from the grouped part family either manually or with help of computer software. Analyzing the control chart is the most crucial and challenging work in SPC implementation stage.

A good interpretation of the control chart can convey much information about the performance of the process. Both industry and statistical knowledge are needed when interpreting the chart pattern and suggesting the possible causes for out-of-control situations.

5.1 Data collection and data recording

In a mould shop, the manufacturing of a mould part usually involves more than one machining process. The measurement can be done either immediately after the machining process, or after completing all the machining processes. Note that if a succeeding process affects the quality characteristics produced by preceding process, this has to be taken into consideration.

In mould manufacturing, the common measurement devices are used to measure the quality characteristics of some mould parts. Coordinate measuring machines (CMMs) are more commonly used to measure the critical dimensions and positions. The working principle of CMM has been discussed in section 4.4.2. Nowadays, with the development of CMM software, it becomes more and more convenient to manage the measurement data and export it to database or statistical analysis software tools. Many CMM software packages are available to do statistical analysis and control charting (Robertson 1989, Wolf et al., 2000, Richey et al., 2001). The measurement data of the non-computerized measuring methods have to be recorded manually into database or statistical analysis software tools.

For further statistical analysis and cause finding, the measurement data and relevant process information should be well organized and stored in database. The database should contain the following data:

Process data:

Machine data:	machine type, machine number, operation type
Cutting tool data:	tool type, tool number, tool holder type
Workpiece holding data:	workpiece holding method, fixture type, fixture number
Cutting parameters data:	for example, for milling process, consist of depth of cut, cutting speed, feed rate

Operator data (if needed);

Product data:	Material, mould number, part number, feature number
Quality data:	Quality characteristic type, measured value, nominal value, transformed value

Since these data are used for cause-finding, the corresponding relations among quality data, process data and product data have to be well managed in the database for further use (Vosniakos et al., 1997). Figure 5.1 shows the corresponding relationship among quality data, process data and product data in database.

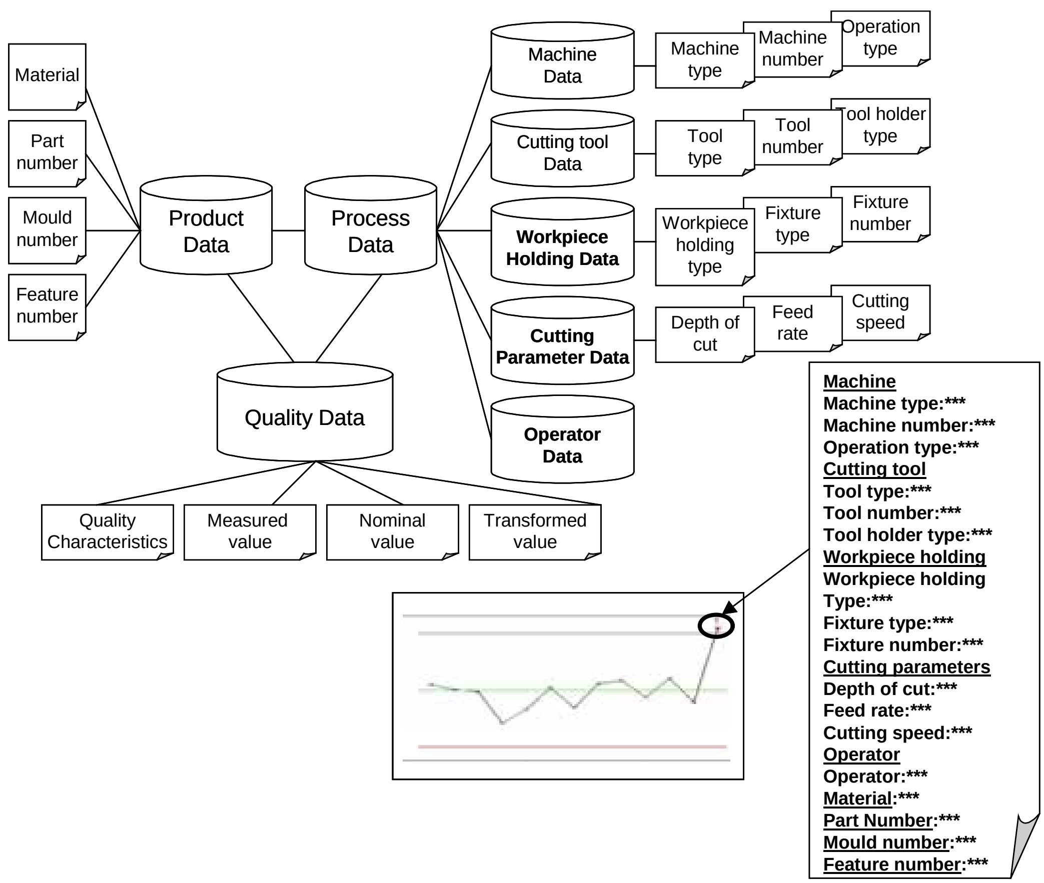


Figure 5.1 Relationship among product data, process data and quality data in database

5.2 Control charting and chart interpretation

When control chart was first developed by Shewhart, it was drawn manually. Nowadays, there are lots of software available to do statistical analysis and control charting. In this study, the function of ANOVA will be needed, when defining SPC process and forming product family. The function of control chart and the key tool will also be used.

A wide variety of chart patterns can be observed in control charts, and the causes corresponding to one particular pattern have been generalized (shown in Appendix D), as discussed in section 2.3. Different industries have their own specific special causes, which occur in their production processes. Therefore, the cause-finding is a domain-specific work even though some common rules can be summarized generally. In practice, some patterns are commonly seen in the control charts. The causes can be well generalized and if any pattern exists, the root cause can be quickly located and the correction actions can be taken in time.

CHAPTER 6 CASE STUDIES

Four case studies have been conducted and these characterise in the following three aspects:

Defining and identifying SPC process (case study 1)

Forming and identifying part family (case study 2)

Control charting and cause finding (case study 3 and 4)

Statistical analysis methods, ANOVA and Test-for-equal-variances are used in this chapter to analyse the equality of means and variances. The detailed introduction and explanations of ANOVA and Test-for-equal-variances are shown in Appendix A. Individual-moving range charts and Cusum chart are used in this chapter. The equations of their centerline and control limits are shown in Appendix C.

6.1 Case study 1 --- Defining and identifying SPC process

6.1.1 Process selection

In this case, the CNC milling process was selected as the process for consideration and end milling was taken as the operation type.

Milling is the process of cutting away material by feeding a workpiece past a rotating multiple tooth cutter. The cutting action by the multiple teeth around the milling cutter provides a fast method of machining. The machined surface may be flat, angular or curved. The surface may also be milled to any combination of shapes.

A MakinoV55 vertical machining center is the machine of analysis. Its specifications are as follows.

Table Size: 39.4" x 19.7"

Product X: 35.4"

Product Y: 19.7"

Product Z: 17.7"

Spindle RPM: 14,000 (20K, 30K)

Rapid Traverse: 1,969 in/min

Cutting feed rate: 1,968 in/min

Maximum Workpiece: 39.3" x 24.8" x 17.7"

Maximum Payload: 1,540 lbs

The depth accuracy, which is represented by the Z coordinate value of the CMM measurement result of the workpieces, is taken as the concerned quality characteristics. In practice, the Z direction usually refers to the direction normal to the machine table, which is an important quality characteristic. For core and cavity inserts, the Z direction is usually normal to the parting surface, whose accuracy may significantly affect the dimensional accuracy of the plastic products.

6.1.2 Preliminary analysis of process factors

At the beginning of the study, the factors, which may affect the quality characteristics, have to be identified and analysed.

<u>Factor of fixture:</u>

Only one fixture is used in this machine throughout the entire period of this study, thus fixture factor would not be discussed in this case study.

<u>Factor of cutter:</u>

Three types of cutter are selected for analysis: bull-nose cutter, end mill cutter and ball-nose cutter.

- For bull-nose cutter: Two commonly used cutter diameters are selected for analysis: One cutter with diameter of 12mm, with edge radius of 0.5mm and the other with diameter of 4 mm, with the edge radius of 0.5mm
- For end mill cutter: the cutters are grouped into two groups:

  Group 1: the cutter with diameter from 1mm to 4 mm

  Group 2: the cutter with diameter from 6 mm to 10 mm
- For ball nose cutter: only the cutter with radius of 3mm are taken for analysis

Cutter size will also be analyzed as a factor. The bull-nose cutter with diameter of 12mm, with edge radius of 0.5mm and the end-mill cutter with diameter from 6 mm to 10 mm are classified as large-size type in this study. The bull-nose cutter with diameter of 4 mm, with the edge radius of 0.5mm and the end-mill cutter with diameter from 1mm to 4 mm are classified as small-size cutters. In practice, the classification of cutter size can be finer if given sufficient data in order to produce more statistically meaningful analysis.

<u>Factor of cutting conditions</u>:

In this study, the cutting conditions used were selected by the process planner based on the chosen cutter. A table giving the cutting conditions, corresponding to the workpiece material, cutter type and cutter diameter is referred to when choosing the cutting conditions. The cutting conditions are the dependent variables, while workpiece material, cutter type and cutter diameters are the independent variables. Therefore, in this study, the cutting conditions are not discussed separately as they are dependent on the workpiece material and the chosen cutter.

Note that this study illustrates only the procedures of the proposed approach. Due to some constraints, other factors, such as the cutter length-width ratio, cutter material, and radius of the bull-nose round corner, with or without insert and other factors are not discussed. In production practice, these factors can be similarly analysed but will require collection of more data.

6.1.3 Steps of Analysis

Step1:

The factor of the cutter type is analyzed by taking a certain number of machining features from different mould parts of same material machined by same machine. They are machined by different types of cutters.

The source data are shown in Appendix B-1.

The ANOVA analysis data (output of Minitab):

One-way ANOVA: transformed value versus cutter type

```
Analysis of Variance for C2
Source     DF        SS        MS        F        P
C1          2 0.0000015 0.0000007     0.01    0.990
Error      47 0.0035134 0.0000748
Total      49 0.0035149
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev ------+---------+---------+---------+
ball-nos   14  0.000071  0.005413  (--------------*---------------)
bull-nos   18  0.000500  0.009919     (-------------*------------)
end-mill   18  0.000333  0.009267    (-------------*-------------)
                                  ------+---------+---------+---------+
Pooled StDev = 0.008646           -0.0030    0.0000    0.0030    0.0060
```

The above output results show that:

From the ANOVA results, it was noted that no significant difference was found in the means among these three types of cutters, because the P-value of 0.990 shows strong evidence to accept H_0, which assumes that the means are equal. Test-of-equal-variance was done to test the equality of the variance among these cutter types. The output graphs from MiniTab are shown in Figures 6.1, 6.2, 6.3, and 6.4.

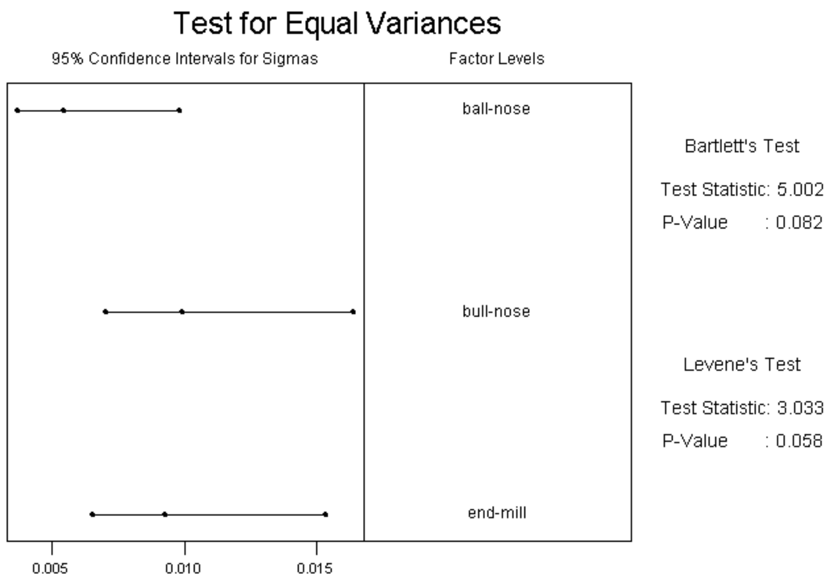


Figure 6.1 Test for Equal Variances among ball-nose, bull-nose and end-mill cutter

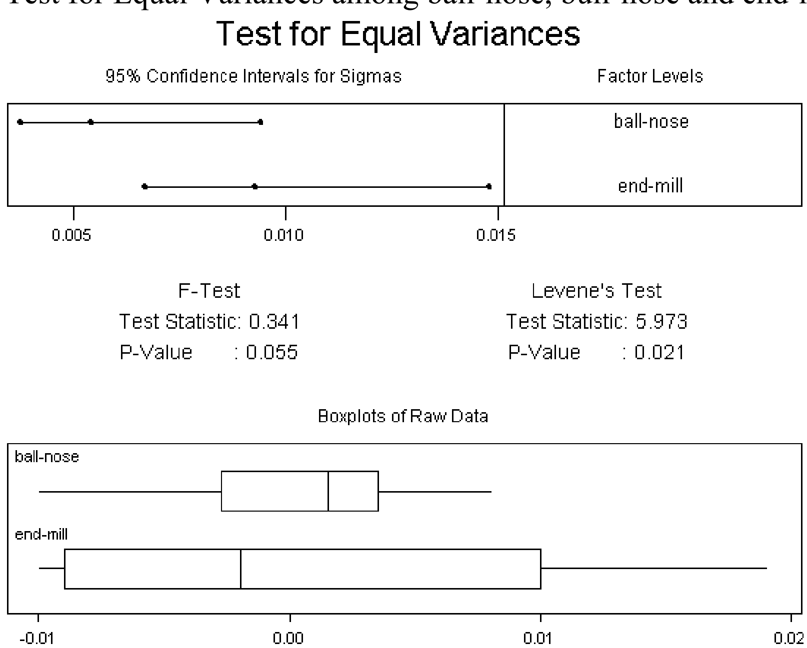


Figure 6.2 Test for Equal Variances between ball-nose and end-mill cutter

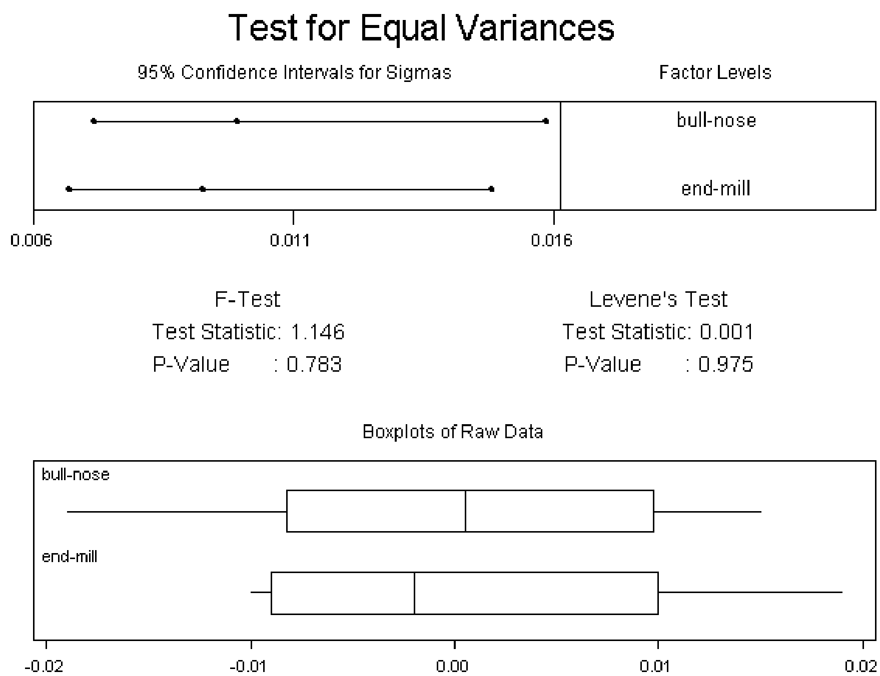


Figure 6.3 Test for Equal Variances between bull-nose and end-mill cutter

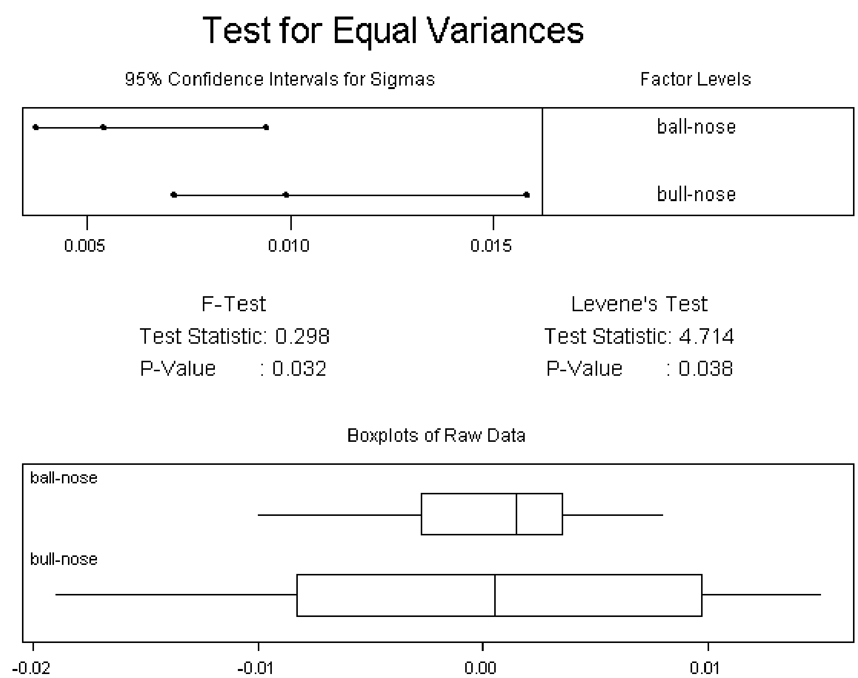


Figure 6.4 Test for Equal Variances between ball-nose and bull-nose cutter

In the Test-for-equal-variances of the three types of cutter, the P-value of 0.058 in Levene's Test shows evidence to more likely reject H_o (which assumes that all the variances are equal) than accept it. Then the Test-for-equal-variance was done between the pairs of these three types of cutters. The results of the paired-tests show that:

1. The P-value of 0.975 in the Levene's Test (Figure 6.3) shows strong evidence to accept H_o (which assumes the variances of bull-nose cutter and end mill cutter are equal).
2. The P-value of 0.021 in the Levene's Test (Figure 6.2) shows evidence to more likely reject H_o (which assumes the variances of ball-nose cutter and end mill cutter are equal) than accept it.
3. The P-value of 0.038 in the Levene's Test (Figure 6.4) shows evidence to more likely to reject H_o (which assumes the variances of ball-nose cutter and bull-nose cutter are equal) than accept it.

Therefore, it is suggested that:

1. The processes where ball-nose cutters are involved have to be treated as a separate SPC process.
2. The processes where bull-nose cutters and end-mill cutters are involved can be taken as the same SPC processes.

Step 2:

The factor of cutter size is analyzed in this step.

The bull-nose cutter with diameter of 12mm, with edge radius of 0.5mm and the end-mill cutter with diameter from 6 mm to 10 mm are classified as large-size type in this study.

The bull-nose cutter with diameter of 4 mm, with the edge radius of 0.5mm and the end-mill cutter with diameter from 1mm to 4 mm are classified as small-size.

Source data are shown in Appendix B-2.

The ANOVA analysis result is as below (output of MiniTab):

One-way ANOVA: transformed value versus Size type

```
Analysis of Variance for C16
Source     DF        SS        MS        F        P
C13         1 0.0007694 0.0007694    11.07    0.002
Error      34 0.0023634 0.0000695
Total      35 0.0031328
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -------+---------+---------+--------
large      17  -4.5E-03  0.008639   (-------*-------)
small      19  0.004789  0.008059                      (-------*------)
                                  --------+---------+---------+--------
Pooled StDev = 0.008337                -0.0050    0.0000    0.0050
```

The ANOVA output result shows that there is significant difference in the mean between the large-size type of cutter and small-size type of cutter, because the P-value of 0.002 shows strong evidence to reject H_o, which assumes that the means are equal. This result suggests that the cutter size type has to be taken as a factor, which has an effect on the concerned quality characteristic. Therefore, the processes where large-size cutters are involved should be treated as a separate SPC process from the processes where small-size cutters are involved.

6.1.4 Conclusions

Based on the above analyses, it can be suggested that the CNC milling processes performed on this Makino V55 vertical machining center can be identified as SPC processes with the following characteristics:

1. Processes where the bull-nose cutters and end-mill cutters are involved should be identified in different SPC process from the ones where ball-nose cutters are involved;
2. Processes where the large diameter bull-nose cutters and end-mill cutters are involved should be identified in different SPC process from the ones where small diameter bull-nose cutters and end-mill cutters are involved.

6.2 Case study 2 – Forming and identifying part family

6.2.1 Process selection

The process under consideration is selected from one of the SPC processes discussed in case study 1, which is the CNC milling process on a Makino V55 vertical machining center where large diameter bull-nose and end-mill cutters are involved. The depth accuracy, which is represented by the Z coordinate value of the CMM measurement result of the workpieces, is still taken as the concerned quality characteristics.

6.2.2 Preliminary analysis of the factors

In this study, the characteristics of the part are discussed. As discussed in chapter 4, the machining feature is taken as the unit part of the concerned SPC process, so the characteristics of the machining features are regarded as the characteristics of the part. The factors which may affect the concerned quality characteristic are discussed in the following.

<u>Factor due to part material</u>: Four types of steel commonly used in injection mould are used in this study, which are 8407, 618hh, 718hh, and 2311. Their chemical composition, hardness and other characteristics are shown in Appendix B-3.

Factor due to geometric characteristics of the feature:

Usually the geometric characteristics of the CNC milling features are classified as:

- Flat surface: large area or small area;
- Free-form surface (three dimensional surface);
- Step: with or without fillet;
- Slot, with or without fillet;
- Pocket, with or without fillet.

For the mould parts and features used in this study, the geometric characteristics of the feature are found to be correlated with the cutter used. For example, large area of flat surface is usually machined by face milling. If the area is not large enough, it is usually machined by end milling using bull-nose cutter of large diameter and free-form surface is always machined by using the ball-nose cutter. Step, slot and pocket with fillet are usually machined using bull-nose cutter and those without fillet are usually machined using end-mill cutter.

As the SPC process is selected for analysis, the features used in this study are all medium area flat surface feature, which are machined by using bull-nose or end-mill cutter with large diameter (ϕ10R0.5-ϕ12R0.5). Therefore, in this study, only part material is analyzed as the factor of the part characteristics. The source data are shown in Appendix B-4.

6.2.3 Analysis and Conclusions

The ANOVA analysis results based on the above data are as below:

One-way ANOVA: Transformed versus Material

```
Analysis of Variance for C5
Source     DF        SS        MS        F        P
C1          3  0.000028  0.000009     0.07    0.974
Error      64  0.008013  0.000125
Total      67  0.008041
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev --------+---------+---------+--------
2311       17  -0.00006   0.00917   (---------------*--------------)
618hh      18  -0.00056   0.01199  (--------------*--------------)
718hh      16  -0.00056   0.01093 (---------------*---------------)
8407       17   0.00100   0.01233     (---------------*--------------)
                                  --------+---------+---------+--------
Pooled StDev =  0.01119                -0.0035    0.0000    0.0035
```

From the ANOVA results, it was noted that no significant difference was found in the means among the four types of part materials - 8407, 618hh, 718hh and 2311, because the P-value of 0.974 shows the strong evidence to accept the H_0, which assumes the means are equal. Test-of-equal-variance was done to test the equality of the variance among these cutter types. The output graphs from MiniTab are shown in Figures 6.5 to 6.11.

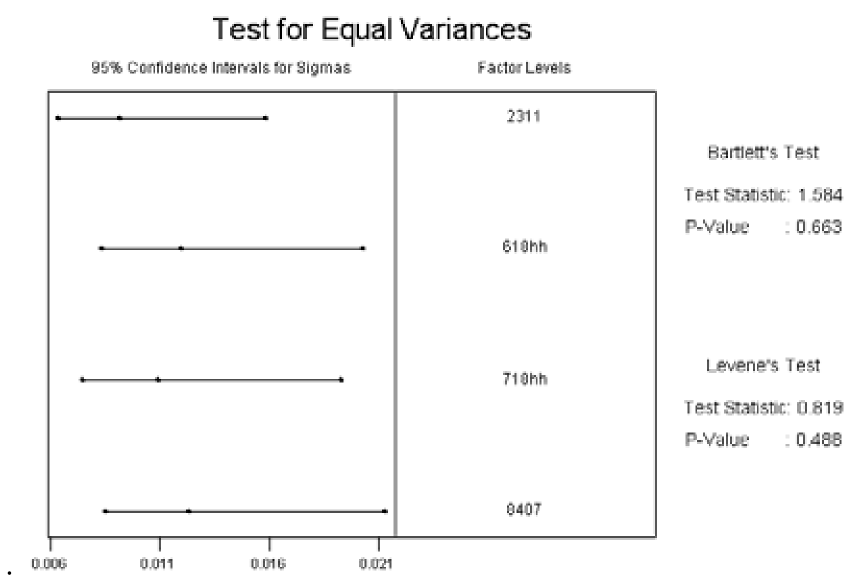


Figure. 6.5 Test for Equal Variances among 8407, 718hh, 618hh, and 2311

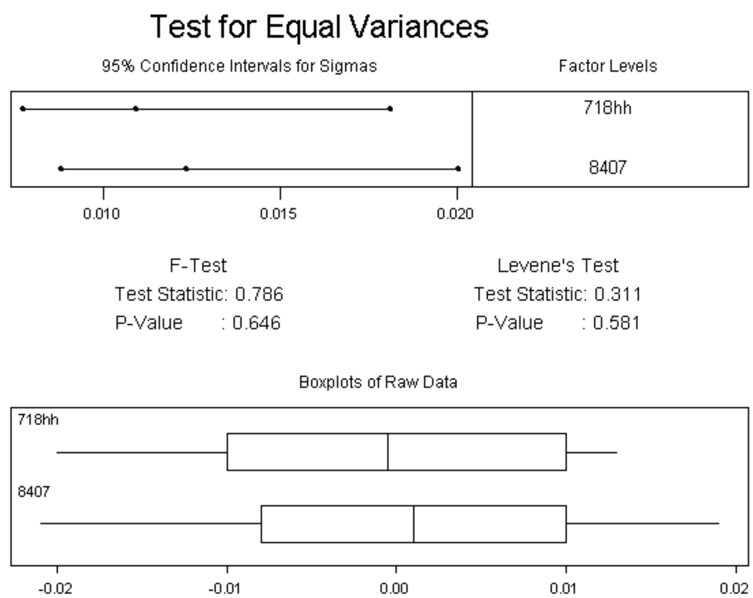


Figure 6.6 Test-for-equal-variances between 8407 and 718hh

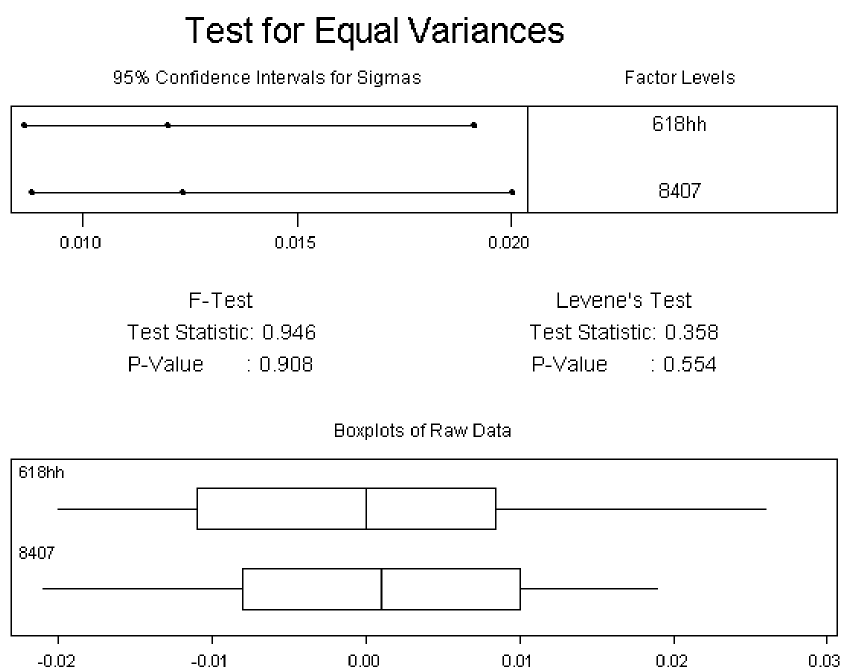


Figure 6.7 Test-for-equal-variances between 8407 and 618hh

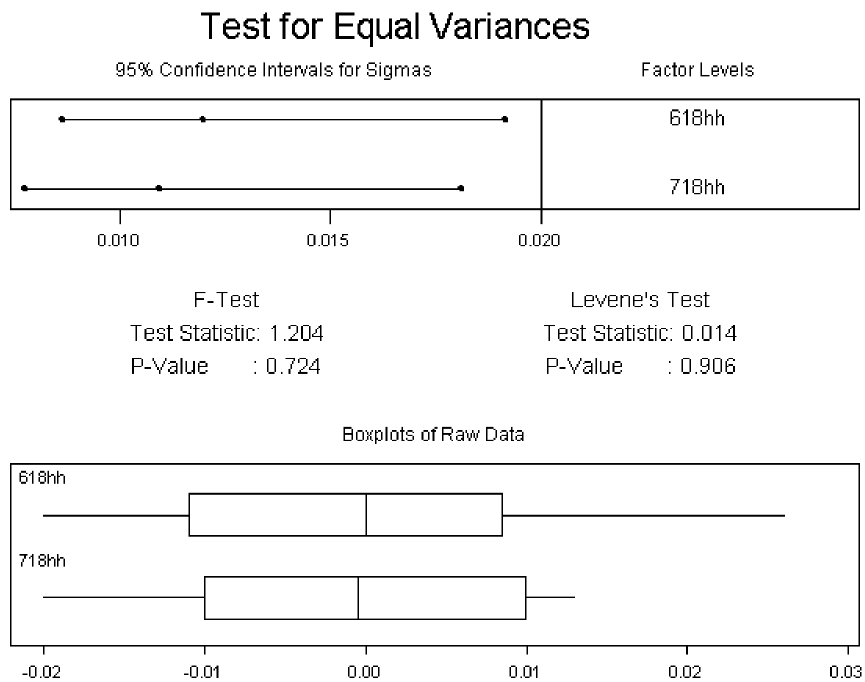


Figure 6.8 Test-for-equal-variances between 618hh and 718hh

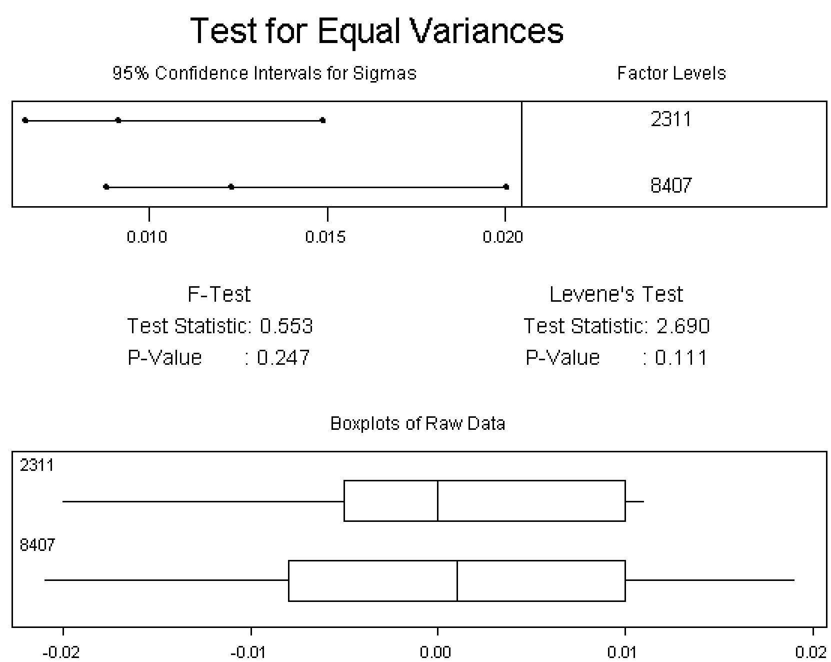


Figure 6.9 Test-for-equal-variances between 8407 and 2311

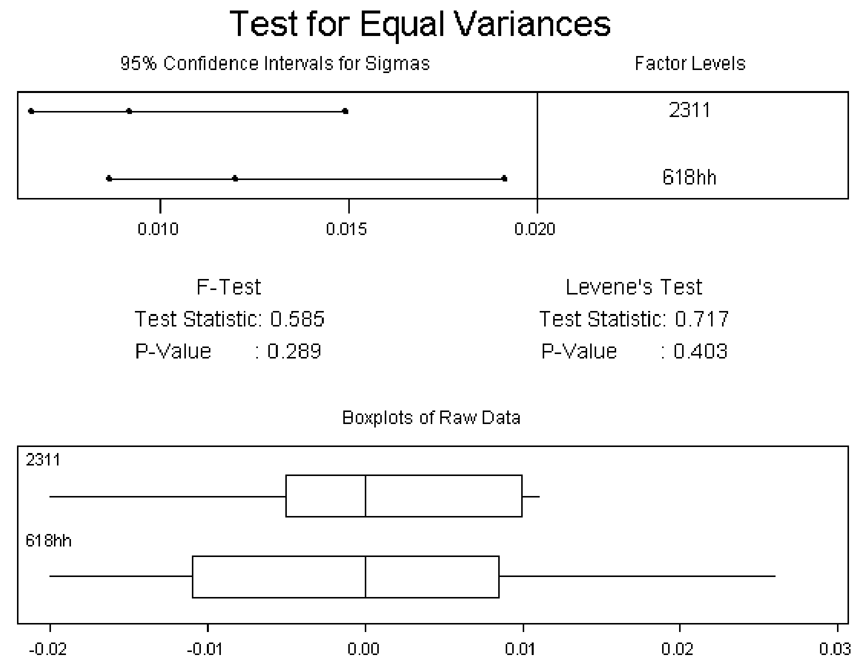


Figure 6.10 Test-for-equal-variances between 2311 and 618hh

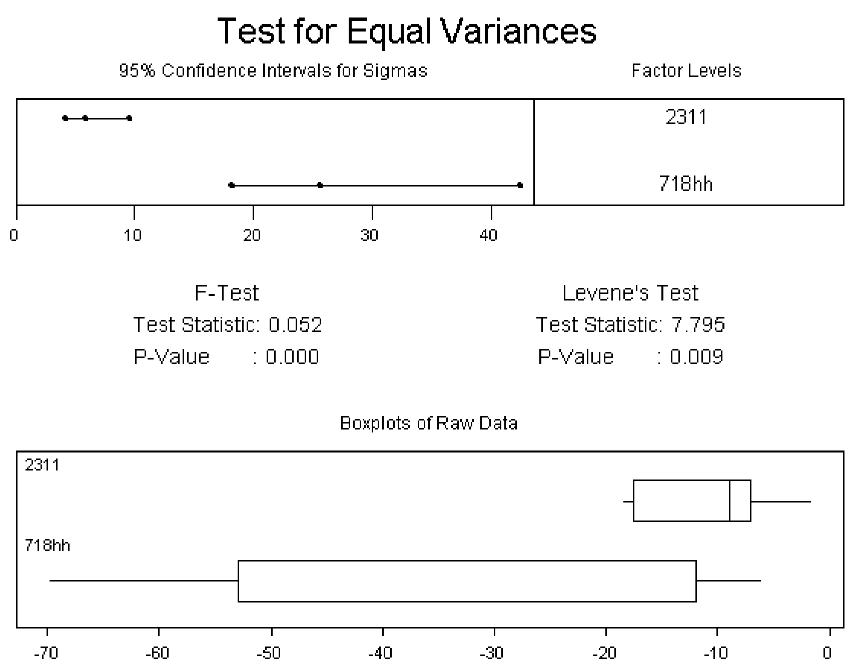


Figure 6.11 Test-for-equal-variances between 2311 and 718hh

The above Test-for-equal-variance results show a significant difference in the variances among the four materials - 8407, 618hh, 718hh and 2311, as shown in Figure 6.5. The P-value of 0.488 in Levene's Test does not show strong evidence to reject or accept H_o, which assumes the variances are equal. Then the Test-for-equal-variance was done between the pairs of the four materials - 8407, 618hh, 718hh and 2311. The results of the paired-tests show that

1. The P-value of 0.906 in the Levene's Test (Figure 6.8) shows evidence more likely to accept H_o (which assumes the variances are equal) than reject it.
2. The P-value of 0.009 in the Levene's Test (Figure 6.11) shows strong evidence to reject H_o (which assumes the variances are equal). Significant differences between the variances of 2311 and 718hh was found.
3. For other pairs, no significant evidence was shown to either accept or reject H_0, (which assumes the variances are equal).

Therefore, it is suggested that in one SPC process:

1. the parts made of 618hh and 718hh can be formed into same part family.
2. the parts made of 8407 and 2311 should be formed into two other separate part families.

6.3 Case study 3- A family of six-cavity mould core inserts

Six identical core inserts of a multi-cavity mould are used in this case study. As they are the same in material and geometry, they were machined in the same machine with the same settings. Thus, they belong to the same product family in the same SPC process. The complex-shaped pocket (Figure 6.12) can be machined in one CNC milling operation. The concerned quality characteristic is still taken as the depth accuracy, which is the same as the previous two case studies. They can be obtained by measuring the Z coordinate value in a given position (X, Y) using a coordinate measuring machine. The measurements were taken in 8 different points, as shown in Figure 6.12. The data of target value, measured value and coded data are shown in Appendix B-5. Figure 6.13 shows the result of plotting these data into individual and moving range charts, whose control limits are calculated based on historical data.

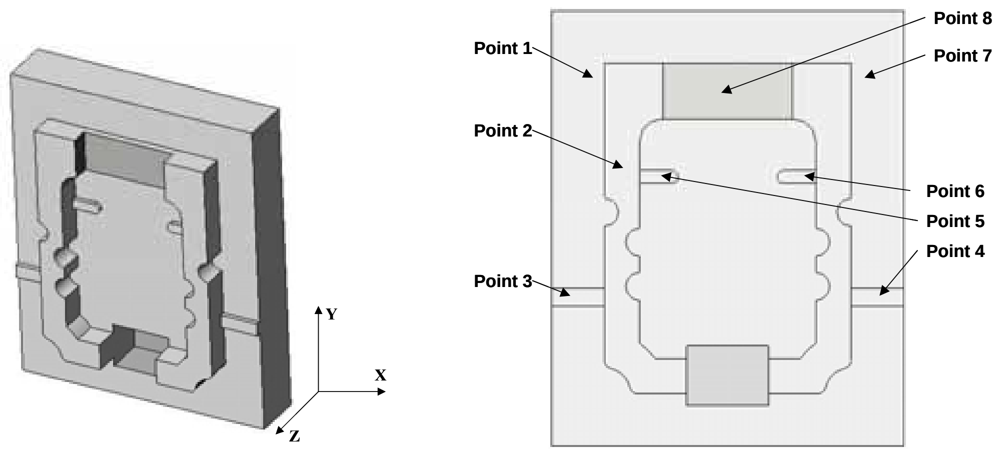


Figure 6.12 Part used for case study 3 and the measuring points on it

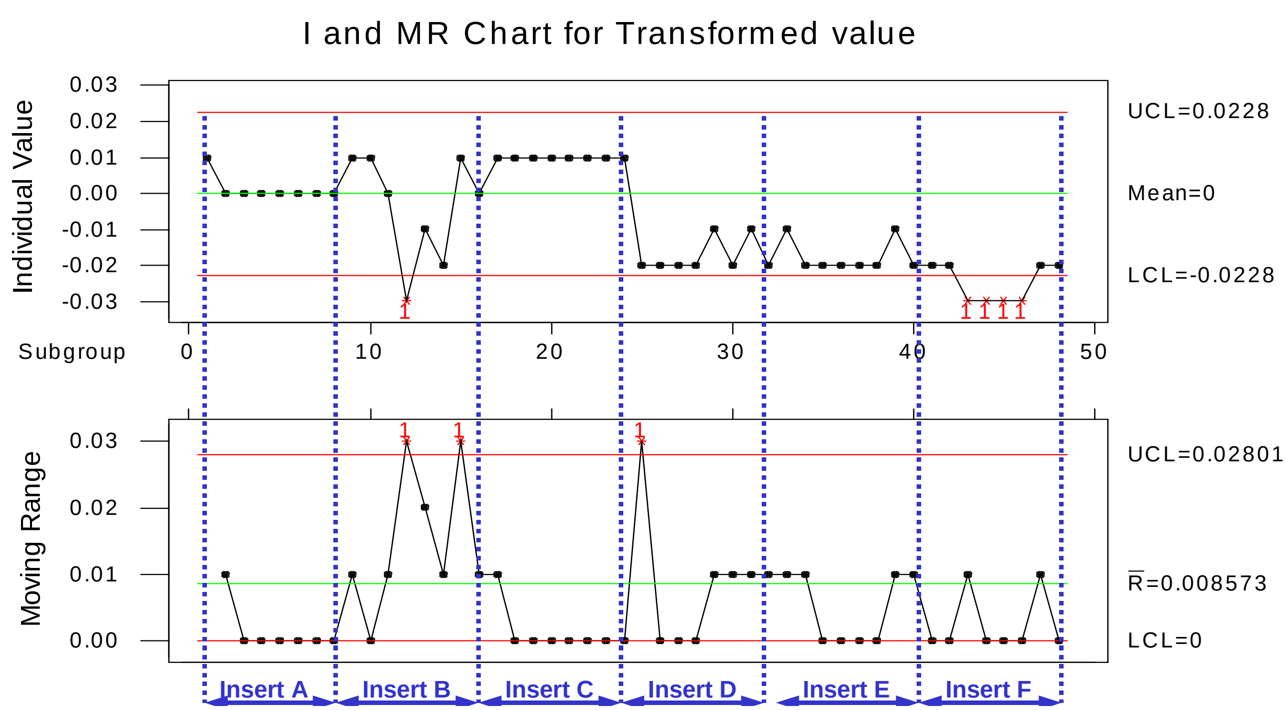


Figure 6.13 Individual and moving range chart for case study 3

From this chart, it can be obviously observed that the data is not randomly distributed around the centerline. According to the typical chart patterns and corresponding causes, which are summarized in the manufacturing practice (Appendix D), some possible causes are proposed. This chart presents a "sudden shift in level" pattern. The typical causes of this pattern are: New operator, new inspector, new test set, new machine, new machine setting, or change in set-up or method.

After investigation, it is found that no new operator, new inspector, new test set, new machine or new machine setting is involved. Checking up with the data from the process database, it is found that the inserts A, B, C are machined in a group in one set-up, and inserts D, E, F are machined together in another set-up immediately after A, B and C. Therefore, "change in set-up" is suggested as the cause. Correlating the chart point with the part number and feature number, it is found that the data points of insert C are all above the centerline and all the data points of inserts D, E, and F are below the centerline. The data points of insert B have large variation, with one point falling outside the control limits. Based on the industry and company experiences, some detailed causes can be further suggested:

1. Workpiece holding problem for the second operation;
2. Cutting tool coordinate positioning problem for the second operation.

6.4 Case study 4 -A family with mixed mould parts

29 features from 9 mould parts are taken in this case study from one SPC process with a large diameter bull-nose mill cutter. They are made of material 618hh and 718hh, and therefore, they belong to the same part family. The source data of nominal value,

measured value, transformed value data point number in the control chart and its relevant process information are shown in Appendix B-6.

The Individual and Moving Range Charts from MiniTab are shown in Figure 6.14.

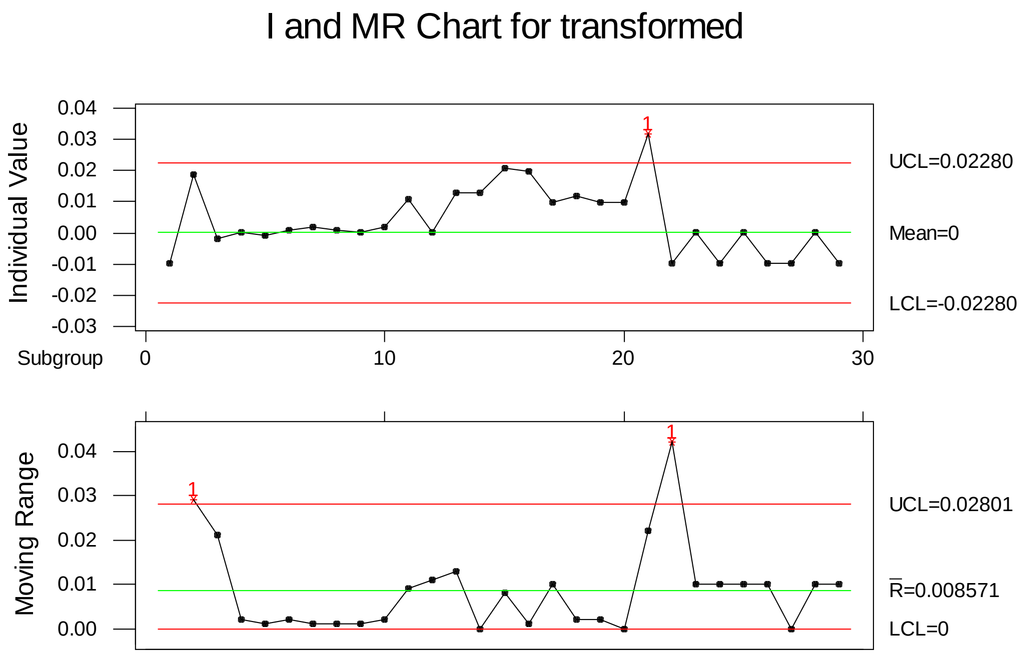


Figure 6.14 Individual and Moving Range Charts for case study 4

From this chart, it can be observed that the data is not randomly distributed around the centerline. It can be observed from the 6th point to the 22nd that there is no point below the centerline, which indicates an out-of-control pattern. The Cusum Chart from MiniTab is shown in Figure 6.15.

The Cusum Chart also indicates an out-of-control signal. Especially in the Cusum chart, (Figure 6.15) it is clearly observed that the process presents out-of-control from the 16th points to the 21st point. According to the characteristics of the Cusum chart, the cause-finding should start from the data point which is lifted above the centerline of Cusum chart, to find out where the process initially start to shift. It can be observed that from investigating the data source, the data points start to be lifted above the centerline from the 11th point in Cusum chart, so it can suggested the process shift occurs from there. Investigating the source data and relevant parameters, it is found that none of the data point from the set-up 3, 4, 5 and 6 is below zero. Therefore, it can be suggested that there might be some workpiece holding problem for these set-ups.

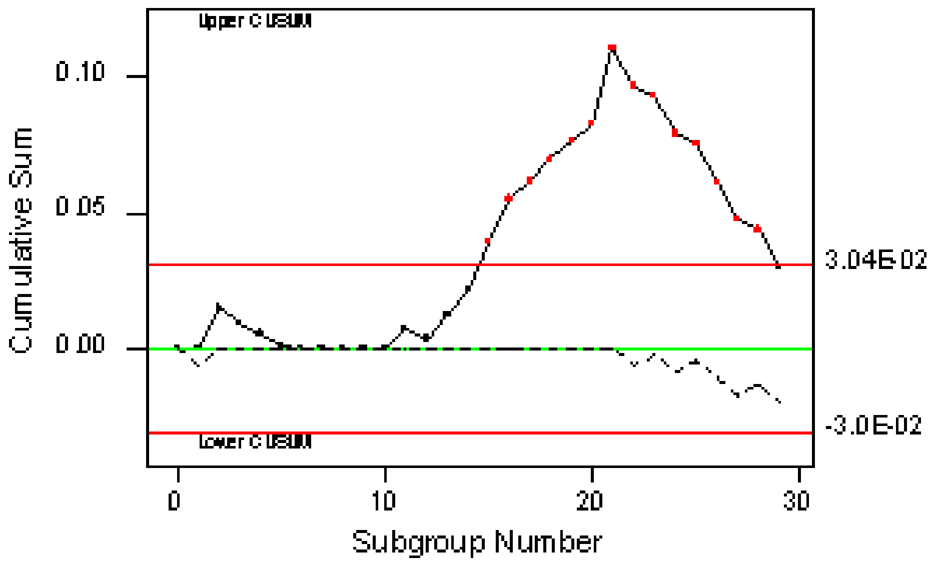


Figure 6.15 Cusum chart for case study 4

6.5 Conclusions

In these four case studies, the methods and procedures proposed in this study on how to define SPC process, how to form part family and how to use control charts to identify the possible causes for out-of-control situations are illustrated respectively using the real data collected from a mould manufacturing company. The feasibility and importance of application of Statistical Process Control in injection mould manufacturing are demonstrated.

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

7.1 Conclusions

The traditional SPC theory demands huge amount of data from the identical products produced by a particular process for meaningful statistical analysis. However, the injection mould production is characterized as one-off or low volume, which cannot provide sufficient data needed in traditional SPC. Several short-run SPC approaches were adopted to generate sufficient data from short-run or small-volume situations for meaningful statistical analysis and control charting by means of data transformation and part family formation. However, there are still some problems when directly applying these approaches to the manufacture of injection mould.

1. Unlike other short-run productions, in which a certain number of part types are produced alternately, in the manufacture of injection mould, one mould can be very different from another in terms of dimension, shape, features, and material. The high variations in parts makes the part family formation very complex for the injection mould parts.

2. The fabrication of injection mould parts involves many different machining processes. Each process may have different settings of the process parameters for the different part. The high variation in process makes the situation more complex and thus more difficulty for the part family formation.

This research proposed to solve the above problems and the issues in implementing the approach in mould production are discussed.

7.1.1 SPC planning for the manufacture of injection mould

In the proposed approach, the problem of high variation in process can be solved by defining SPC process. The clearly defined SPC process can help simplify the problem on the complexity of different process parameter settings' effect on the process output. After the SPC processes are clearly defined, the definitions of the SPC process can be used to identify the identity of each single new machining process for the incoming new mould part.

In order to deal with the problem of high variations in mould parts, mould parts are proposed to be classified as standardized part and non-standardized part. For standardized parts, the process plan for them can be standardized to some extent by means of process plan template. With the process plan template for these parts, the SPC plan template can be proposed, based on which it could be much easier to work out the SPC plan once given the detailed process plan and production schedule. Time spent on SPC planning can be saved in this way. For non-standardized parts, the features on them are proposed to be classified into standardized features and non-standardized features. The standardized features can be treated in a similar way as the standardized parts. The non-standardized features have to be treated separately. The SPC planning for these features has to be done each time for each new incoming mould according to the rules of part family formation and identification.

7.1.2 SPC implementation for the manufacture of injection mould

After the SPC plan has been worked out, the SPC implementation in the manufacture of the injection mould can be done with reference to the experience of SPC implementation in other industries.

The concerned quality characteristics of the mould parts are measured, and the measured data and transformed data should be carefully recorded and stored in the database. At same time, the information on the process, which produces this measured data, also has to be well recorded and stored in the database corresponding to the measured data for future cause finding.

The transformed data can then be easily exported and the control charts can be generated with the help of the available statistical analysis software, such as MiniTab. These data management work and statistical analysis work can be done efficiently nowadays with the help of computer.

Control chart interpretation is the most crucial and challenging work in SPC implementation stage. Both engineering knowledge in mould making industry and statistical knowledge in general applications are used here. Once the non-random pattern presents, the possible causes corresponding to these patterns generalized from other manufacturing industries are referred to in order to find out the real cause. The often-occurred chart patterns should be summarized. With the accumulation of time and experience from the practice of SPC implementation in mould making industry, the control chart interpretation will become much easier.

7.2 Recommendations for future work

The directions in which this work could be further explored and enhanced are as follows:

1. The proposed approach in this research does not discuss in details all the common machining processes in mould part fabrication. Some processes, such as grinding, EDM die-sinking and EDM wire-cut which are also commonly used in mould part

making should be carefully studied as their process characteristics may be quite different from those of the CNC milling and drilling processes. This proposed approach could be improved to achieve a more general and comprehensive level while having a wider study on all the machining processes in the mould shop.

2. A more comprehensive study on the mould parts, especially on the non-standardized mould part, can be done to explore whether there are any more aspects of the mould part and the production processes that can be standardized. Since in SPC, the information on the process performance is supposed to be fed back as timely as possible, a more standardized framework can save the time to a large extent.

3. Gage Repeatability and Reproducibility Study are not covered in this research. This part of work should be included to make the measurement results convey a more accurate and more precise information of the process.

4. Sampling plan is not discussed in this research. This research is based on the current existing sampling plan in the mould shop. A well designed sampling plan will make the control chart more meaningful and more sensitive to the process shift

5. Performance of control chart is not discussed in this research. Studies on Operating Characteristics and Average Run Length of control charts can be done to better design the control charts and to obtain more accurate information on the processes.

6. Nowadays, with the demand of manufacturing automation, the computer-aided production scheduling and computer-aided process planning, together with computer-aided design and computer-aided manufacturing call for computerization and automation of SPC to automate the whole production. The work on computerization

and automation in SPC implementation has been explored. Many advanced automatic measuring devices and software packages have been developed. Statistical analysis software have been widely available in the market and are becoming more mature and more convenient for users to use and manipulate. The work on computerized control chart interpretation and cause finding has also been explored with the development of an intelligent system and neural network technology. However, the work on computerization of SPC planning is still very challenging. Many difficulties may be faced in feature recognition, feature classification, and quality characteristics identification when automating part family identification. The improved solutions to these problems will help the whole automation process of SPC application in the manufacture of injection mould.

7. In an integrated manufacturing system, SPC can be integrated with computer-aided process planning and computer-aided production scheduling, as SPC planning needs the information on process plan and production schedule. The SPC analysis result on the performance of process and machines can be fed back to the process planner and production schedule planner for a more optimized selection of machine and process parameters.

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Appendix A

Appendix A-1 Introduction to ANOVA

(Engineering Statistics Handbook, http://www.itl.nist.gov/div898/handbook)

ANOVA is a general technique that can be used to test the hypothesis that the means among two or more groups are equal, under the assumption that the sampled populations are normally distributed.

In one-way ANOVA, the null hypothesis is: there is no difference in the population means of the different levels of factor A (the only factor). The alternative hypothesis is: the means are not the same.

In an analysis of variance the variation of the response measurements partitioned into components that correspond to different sources of variation. The total variation in the data is split into a portion due to random error and portions due to changes in the values of the independent variable(s).

The variance of n measurements is given by

$$s^2 = \frac{\sum_{i=1}^{a}(y_i - \bar{y})^2}{n-1}$$

where $\bar{y}$ is the mean of the n measurements.

The first term in the numerator is called the "raw sum of squares" and the second term is called the "correction term for the mean". Another name for the numerator is the "corrected sum of squares", and this is usually abbreviated by Total SS or SS(Total).

The SS in a 1-way ANOVA can be split into two components, called the "sum of squares of treatments" and "sum of squares of error", abbreviated as SST and SSE, respectively

Algebraically, this is expressed by:

Total SS = SST + SSE

$$\sum_{i=1}^{a}\sum_{j=1}^{n}(y_{ij}-\bar{y})^2 = n\sum_{i=1}^{a}(\bar{y}_i.-\bar{y}..)^2+\sum_{i=1}^{a}\sum_{j=1}^{n}(y_{ij}-\bar{y}_i.)^2$$

where k is the number of treatments and the bar over the y.. denotes the "grand" or "overall" mean. Each n_i is the number of observations for treatment i. The total number of observations is N (the sum of the n_i).

The mathematical model that describes the relationship between the response and treatment for the one-way ANOVA is given by

$$y_{ij} = \mu + \tau_i + \varepsilon_{ij}$$

where Y_{ij} represents the j_{th} observation ($j = 1, 2, ...n_i$) on the i_{th} treatment ($i = 1, 2, ..., k$ levels). So, Y_{23} represents the third observation using level 2 of the factor. μ is the common effect for the whole experiment, τ_i represents the i_{th} treatment effect and ε_{ij} represents the random error present in the j_{th} observation on the i_{th} treatment.

The errors ε_{ij} are assumed to be normally and independently (NID) distributed, with mean zero and variance σ^2. μ is always a fixed parameter and $\tau_1, \tau_2 \ldots \tau_k$ are considered to be fixed parameters if the levels of the treatment are fixed, and not a random sample from a population of possible levels. It is also assumed that μ is chosen so that $\sum_{i=1}^{a}\tau_i = 0$ holds. This is the fixed effects model.

The sums of squares SST and SSE previously computed for the one-way ANOVA are used to form two mean squares, one for treatments and the second for error. These mean squares are denoted by MST and MSE, respectively. These are typically displayed in a tabular form, known as an ANOVA Table. The ANOVA table also shows the statistics used to test hypotheses about the population means.

When the null hypothesis of equal means is true, the two mean squares estimate the same quantity (error variance), and should be of approximately equal magnitude. In other words, their ratio should be close to 1. If the null hypothesis is false, MST should be larger than MSE.

The mean squares are formed by dividing the sum of squares by the associated degrees of freedom.

Let $N = \Sigma n_i$. Then, the degrees of freedom for treatment, DFT = k - 1, and the degrees of freedom for error, DFE = N - k.

The corresponding mean squares are:

MST=SST / DFT

MSE = SSE / DFE

The test statistic, used in testing the equality of treatment means is: F = MST / MSE.

The critical value is the tabular value of the F distribution, based on the chosen level and the degrees of freedom DFT and DFE.

The calculations are displayed in an ANOVA table, as follows:

ANOVA table

Source	SS	DF	MS	F
Treatments	SST	k-1	SST / (k-1)	MST/ MSE
Error	SSE	N-k	SSE / (N-k)	
Total (corrected)	SS	N-1		

Appendix A-2 Introduction to Test-for-equal-variance (Levene's test)

(Engineering Statistics Handbook, http://www.itl.nist.gov/div898/handbook)

Levene's test (Levene 1960) is used to test if *k* samples have equal variances. Equal variances across samples is called homogeneity of variance. Some statistical tests, for example the analysis of variance, assume that variances are equal across groups or samples. The Levene test can be used to verify that assumption.

Levene's test is an alternative to the Bartlett test. The Levene test is less sensitive than the Bartlett test to departures from normality. If you have strong evidence that your data do in fact come from a normal, or nearly normal, distribution, then Bartlett's test has better performance.

The Levene test is defined as:

H_o: $\sigma_1=\sigma_2=\ldots=\sigma_k$

H_1: $\sigma_i=\sigma_j$ for at least one pair (i, j)

Test Statistic:

Given a variable Y with sample of size N divided into k subgroups, where N_i is the sample size of the ith subgroup, the Levene test statistic is defined as:

$$W = \frac{(N-k)\sum_{i=1}^{k} N_i(\overline{Z}_{i.} - \overline{Z}_{..})^2}{(k-1)\sum_{i=1}^{k}\sum_{j=1}^{Ni}(\overline{Z}_{ij} - \overline{Z}_{i.})^2}$$

where $\mathbf{Z_{ij}}$ can have one of the following three definitions:

1. $Zij = \left|Y_{ij} - \overline{Y}_{i.}\right|$

where $\overline{Y}_{i.}$ is the mean of the i_{th} subgroup.

2. $Zij = \left|Y_{ij} - \tilde{Y}_{i.}\right|$

where $\tilde{Y}_{i.}$ is the mean of the i_{th} subgroup.

3. $Zij = \left|Y_{ij} - \overline{Y}_{i.}'\right|$

where $\overline{Y}_{i.}'$ is the trimmed mean of the i_{th} subgroup.

$\overline{Z}_{i.}$ are the group means of the Z_{ij} and $\overline{Z}_{..}$ is the overall mean of the Z_{ij}.

The Levene test rejects the hypothesis that the variances are equal if

$$W > F_{(\alpha, k-1, N-k)}$$

where $F_{(\alpha, k-1, N-k)}$ is the upper critical value of the F distribution with k-1 and N-k degrees of freedom at a significance level of α.

In the above formulas for the critical regions, the Handbook follows the convention that F_α is the upper critical value from the F distribution and $F_{1-\alpha}$ is the lower critical value.

Appendix B

Appendix B-1 Source data for case study 1- step 1

Cutter type	Sample No.	Cutter	Size type	Nominal value	Measured value	Transformed value
bull-nose	bu-1	ϕ 4R0.5	small	-16.142	-16.13	0.012
bull-nose	bu-2	ϕ 4R0.5	small	-14.422	-14.42	0.002
bull-nose	bu-3	ϕ 4R0.5	small	-10.392	-10.40	-0.008
bull-nose	bu-4	ϕ 4R0.5	small	-15.248	-15.25	-0.002
bull-nose	bu-5	ϕ 4R0.5	small	-13.085	-13.07	0.015
bull-nose	bu-6	ϕ 4R0.5	small	-21.759	-21.76	-0.001
bull-nose	bu-7	ϕ 12R0.5	large	-26.550	-26.56	-0.010
bull-nose	bu-8	ϕ 12R0.5	large	-26.679	-26.67	0.009
bull-nose	bu-9	ϕ 12R0.5	large	-32.066	-32.07	-0.004
bull-nose	bu-10	ϕ 12R0.5	large	-15.517	-15.51	0.007
bull-nose	bu-11	ϕ 12R0.5	large	-6.991	-7.01	-0.019
bull-nose	bu-12	ϕ 4R0.5	small	-16.142	-16.14	0.002
bull-nose	bu-13	ϕ 4R0.5	small	-14.422	-14.41	0.012
bull-nose	bu-14	ϕ 4R0.5	small	-10.392	-10.39	0.002
bull-nose	bu-15	ϕ 4R0.5	small	-13.085	-13.07	0.015
bull-nose	bu-16	ϕ 4R0.5	small	-21.759	-21.76	-0.001
bull-nose	bu-17	ϕ 12R0.5	Large	-28.591	-28.60	-0.009
bull-nose	bu-18	ϕ 12R0.5	large	-15.517	-15.53	-0.013
end-mill	em-1	ϕ 1-ϕ 4	small	-18.500	-18.51	-0.010
end-mill	em-2	ϕ 1-ϕ 4	small	-16.836	-16.83	0.006
end-mill	em-3	ϕ 1-ϕ 4	small	-16.937	-16.93	0.007
end-mill	em-4	ϕ 1-ϕ 4	small	-15.993	-15.99	0.003
end-mill	em-5	ϕ 6-ϕ10	large	-15.012	-15.02	-0.008
end-mill	em-6	ϕ 6-ϕ10	large	-21.010	-21.02	-0.010
end-mill	em-7	ϕ 6-ϕ10	large	-17.440	-17.43	0.010
end-mill	em-8	ϕ 6-ϕ10	large	-30.351	-30.36	-0.009
end-mill	em-9	ϕ 6-ϕ10	large	-10.720	-10.71	0.010
end-mill	em-10	ϕ 1-ϕ 4	small	-18.500	-18.49	0.010
end-mill	em-11	ϕ 1-ϕ 4	small	-17.591	-17.58	0.011
end-mill	em-12	ϕ 1-ϕ 4	small	-16.937	-16.94	-0.003
end-mill	em-13	ϕ 1-ϕ 4	small	-16.009	-15.99	0.019
end-mill	em-14	ϕ 6-ϕ10	large	-15.015	-15.02	-0.005
end-mill	em-15	ϕ 6-ϕ10	large	-21.009	-21.01	-0.001
end-mill	em-16	ϕ 6-ϕ10	large	-17.445	-17.45	-0.005

end-mill	em-17	ϕ 6-ϕ10	large	-30.341	-30.35	-0.009
end-mill	em-18	ϕ 6-ϕ10	large	-10.720	-10.73	-0.010
ball-nose	ba-1	R3	-------	-6.025	-6.02	0.005
ball-nose	ba-2	R3	-------	-4.273	-4.27	0.003
ball-nose	ba-3	R3	-------	-5.983	-5.98	0.003
ball-nose	ba-4	R3	-------	-32.568	-32.57	-0.002
ball-nose	ba-5	R3	-------	-13.009	-13.01	-0.001
ball-nose	ba-6	R3	-------	-10.003	-10.00	0.003
ball-nose	ba-7	R3	-------	-15.995	-16.00	-0.005
ball-nose	ba-8	R3	-------	-6.020	-6.03	-0.010
ball-nose	ba-9	R3	-------	-4.270	-4.28	-0.010
ball-nose	ba-10	R3	-------	-5.983	-5.98	0.003
ball-nose	ba-11	R3	-------	-32.568	-32.56	0.008
ball-nose	ba-12	R3	-------	-13.009	-13.01	-0.001
ball-nose	ba-13	R3	-------	-10.000	-10.00	0.000
ball-nose	ba-14	R3	-------	-15.995	-15.99	0.005

Appendix B-2 Source data for case study 1- step 2

Cutter type	Size type	Nominal value	Measured value	Transf. value
bull-nose	small	-16.142	-16.13	0.012
bull-nose	small	-14.422	-14.42	0.002
bull-nose	small	-10.392	-10.4	-0.008
bull-nose	small	-15.248	-15.25	-0.002
bull-nose	small	-13.085	-13.07	0.015
bull-nose	small	-21.759	-21.76	-0.001
bull-nose	large	-26.55	-26.56	-0.01
bull-nose	large	-26.679	-26.67	0.009
bull-nose	large	-32.066	-32.07	-0.004
bull-nose	large	-15.517	-15.51	0.007
bull-nose	large	-6.991	-7.01	-0.019
bull-nose	small	-16.142	-16.14	0.002
bull-nose	small	-14.422	-14.41	0.012
bull-nose	small	-10.392	-10.39	0.002
bull-nose	small	-13.085	-13.07	0.015
bull-nose	small	-21.759	-21.76	-0.001
bull-nose	large	-28.591	-28.6	-0.009
bull-nose	large	-15.517	-15.53	-0.013
bull-nose	small	-18.5	-18.51	-0.01
bull-nose	small	-16.836	-16.83	0.006
bull-nose	small	-16.937	-16.93	0.007
bull-nose	small	-15.993	-15.99	0.003
bull-nose	large	-15.012	-15.02	-0.008
bull-nose	large	-21.01	-21.02	-0.01
bull-nose	large	-17.44	-17.43	0.01
bull-nose	large	-30.351	-30.36	-0.009
bull-nose	large	-10.72	-10.71	0.01
bull-nose	small	-18.5	-18.49	0.01
bull-nose	small	-17.591	-17.58	0.011
bull-nose	small	-16.937	-16.94	-0.003
bull-nose	small	-16.009	-15.99	0.019
bull-nose	large	-15.015	-15.02	-0.005
bull-nose	large	-21.009	-21.01	-0.001
bull-nose	large	-17.445	-17.45	-0.005
bull-nose	large	-30.341	-30.35	-0.009
bull-nose	large	-10.72	-10.73	-0.01

Appendix B-3 Properties of the material discussed in case study 2

(http://www.assab.se/prod_toolsteel_pms.asp)

(http://www.ghcook.com/20plusnew.htm)

Material	Typical chemical composition				HB (Brinell)	HRC (Rockwell)	Characteristics
	C	M_n	C_r	M_o			
8407	0.37	0.40	5.30	1.40	185	13.2	Good high temperature strength and extreme thermal fatigue resistance steel for die casting Tools for extrusion, hot pressing, moulds for plastics.
718hh	0.37	1.40	2.00	2.00	340-380	35-40	Modified pre-hardened plastic mould steel. Very good polishability. Injection moulds for thermo-plastics, extrusion dies for thermo-plastics, blow moulds, forming tools, press- brake dies, structural components, shafts.
618hh	Similar as 718hh						
2311	0.37	1.40	1.90	0.2	280-325	29-35	Hardened and tempered mould steel. Suitable for plastic mould tools where further heat treatment and consequent risk of distortion is to be avoided. It is also suitable for pressure die casting tools. If a higher hardness is required the tools should first be annealed and then the following details observed.

Appendix B-4 Source data for case study 2

Material	Sample No.	Nominal value	Measured value	Transformed value	Material	Sample No.	Nominal value	Measured value	Transformed value
8407	1	-2.870	-2.88	-0.010	618hh	1	-49.514	-49.51	0.004
8407	2	-20.268	-20.27	-0.002	618hh	2	-47.491	-47.48	0.011
8407	3	-24.227	-24.21	0.017	618hh	3	-4.509	-4.52	-0.011
8407	4	-3.939	-3.92	0.019	618hh	4	-2.488	-2.50	-0.012
8407	5	-10.000	-9.99	0.010	618hh	5	-9.860	-9.86	0.000
8407	6	-10.720	-10.71	0.010	618hh	6	-45.110	-45.11	0.000
8407	7	-20.000	-20.02	-0.020	618hh	7	-35.841	-35.86	-0.019
8407	8	-21.516	-21.50	0.016	618hh	8	-30.000	-30.00	0.000
8407	9	-15.000	-14.99	0.010	618hh	9	-36.040	-36.06	-0.020
8407	10	-3.480	-3.47	0.010	618hh	10	-62.220	-62.23	-0.010
8407	11	-26.550	-26.56	-0.010	618hh	11	-21.239	-21.25	-0.011
8407	12	-32.066	-32.07	-0.004	618hh	12	-64.159	-64.16	-0.001
8407	13	-22.934	-22.94	-0.006	618hh	13	-54.895	-54.88	0.015
8407	14	-10.519	-10.54	-0.021	618hh	14	-90.140	-90.14	0.000
8407	15	-9.223	-9.22	0.003	618hh	15	-37.776	-37.75	0.026
8407	16	-10.651	-10.65	0.001	618hh	16	-39.790	-39.78	0.010
8407	17	-7.924	-7.93	-0.006	618hh	17	-63.958	-63.95	0.008
					618hh	18	-70.000	-70.00	0.000
Material	**Sample No.**	**Nominal value**	**Measured value**	**Transformed value**	**Material**	**Sample No.**	**Nominal value**	**Measured value**	**Transformed value**
718hh	1	-11.313	-11.30	0.013	2311	1	-18.000	-17.99	0.010
718hh	2	-6.243	-6.23	0.013	2311	2	-17.500	-17.49	0.010
718hh	3	-6.203	-6.22	-0.017	2311	3	-17.500	-17.50	0.000
718hh	4	-69.802	-69.81	-0.008	2311	4	-18.000	-18.02	-0.020
718hh	5	-12.000	-11.99	0.010	2311	5	-7.000	-7.00	0.000
718hh	6	-12.000	-11.99	0.010	2311	6	-7.500	-7.50	0.000
718hh	7	-67.330	-67.35	-0.020	2311	7	-7.000	-7.01	-0.010
718hh	8	-12.000	-11.99	0.010	2311	8	-7.500	-7.49	0.010
718hh	9	-53.000	-53.01	-0.010	2311	9	-1.659	-1.66	-0.001
718hh	10	-53.000	-53.00	0.000	2311	10	-4.759	-4.76	-0.001
718hh	11	-12.000	-11.99	0.010	2311	11	-11.105	-11.12	-0.015
718hh	12	-11.979	-11.98	-0.001	2311	12	-18.341	-18.33	0.011
718hh	13	-67.322	-67.32	0.002	2311	13	-7.085	-7.08	0.005
718hh	14	-11.979	-11.98	-0.001	2311	14	-1.659	-1.66	-0.001
718hh	15	-53.000	-53.01	-0.010	2311	15	-12.915	-12.92	-0.005
718hh	16	-53.000	-53.01	-0.010	2311	16	-8.895	-8.90	-0.005
					2311	17	-15.241	-15.23	0.011

Appendix B-5 Source data for case study 3

Measurement point #	Nominal	Measured. -A	Transf. -A	Data # in Chart	Set-up No.	Measured -B	Transf. -B	Data # in Chart	Set-up No.
1	-9.61	-9.6	0.01	1	1	-9.6	0.01	9	2
2	-1.01	-1.01	0	2	1	-1	0.01	10	2
3	-8.6	-8.6	0	3	1	-8.6	0	11	2
4	-8.6	-8.6	0	4	1	-8.63	-0.03	12	2
5	-8.6	-8.6	0	5	1	-8.61	-0.01	13	2
6	-8.6	-8.6	0	6	1	-8.62	-0.02	14	2
7	-1.01	-1.01	0	7	1	-1	0.01	15	2
8	-0.8	-0.8	0	8	1	-0.8	0	16	2
Measurement point #	Nominal	Measured. -C	Transf. -C	Data # in Chart	Set-up No.	Measured -D	Transf. -D	Data # in Chart	Set-up No.
1	-9.61	-9.6	0.01	17	1	-9.63	-0.02	25	2
2	-1.01	-1	0.01	18	1	-1.03	-0.02	26	2
3	-8.6	-8.59	0.01	19	1	-8.62	-0.02	27	2
4	-8.6	-8.59	0.01	20	1	-8.62	-0.02	28	2
5	-8.6	-8.59	0.01	21	1	-8.61	-0.01	29	2
6	-8.6	-8.59	0.01	22	1	-8.62	-0.02	30	2
7	-1.01	-1	0.01	23	1	-1.02	-0.01	31	2
8	-0.8	-0.79	0.01	24	1	-0.82	-0.02	32	2
Measurement point #	Nominal	Measured. -E	Transf. -E	Data # in Chart	Set-up No.	Measured -F	Transf. -F	Data # in Chart	Set-up No.
1	-9.61	-9.62	-0.01	33	2	-9.63	-0.02	41	2
2	-1.01	-1.03	-0.02	34	2	-1.03	-0.02	42	2
3	-8.6	-8.62	-0.02	35	2	-8.63	-0.03	43	2
4	-8.6	-8.62	-0.02	36	2	-8.63	-0.03	44	2
5	-8.6	-8.62	-0.02	37	2	-8.63	-0.03	45	2
6	-8.6	-8.62	-0.02	38	2	-8.63	-0.03	46	2
7	-1.01	-1.02	-0.01	39	2	-1.03	-0.02	47	2
8	-0.8	-0.82	-0.02	40	2	-0.82	-0.02	48	2

Appendix B-6 Source data for case study 4

Nominal value	Measured value	Transf. value	Cutter	Mould no.	Material	Set-up No.	Data No. in chart
-2.870	-2.88	-0.010	Φ12R0.5	0013-ca-1	618hh	1	1
-3.939	-3.92	0.019	Φ12R0.5	0013-ca-1	618hh	1	2
-20.268	-20.27	-0.002	Φ12R0.5	0013-ca-1	618hh	1	3
-2.870	-2.87	0.000	Φ12R0.5	0013-ca-2	618hh	2	4
-3.939	-3.94	-0.001	Φ12R0.5	0013-ca-2	618hh	2	5
-20.268	-20.27	0.001	Φ12R0.5	0013-ca-2	618hh	2	6
-9.732	-9.73	0.002	Φ12R0.5	0013-co-1	618hh	3	7
-26.061	-26.06	0.001	Φ12R0.5	0013-co-1	618hh	3	8
-27.130	-27.13	0.000	Φ12R0.5	0013-co-1	618hh	3	9
-9.732	-9.73	0.002	Φ12R0.5	0013-co-2	618hh	4	10
-26.061	-26.05	0.011	Φ12R0.5	0013-co-2	618hh	4	11
-27.130	-27.13	0.000	Φ12R0.5	0013-co-2	618hh	4	12
-6.203	-6.19	0.013	Φ10R0.5	0016-co	718hh	5	13
-6.243	-6.23	0.013	Φ10R0.5	0016-co	718hh	5	14
-11.321	-11.30	0.021	Φ10R0.5	0016-co	718hh	5	15
-12.000	-11.98	0.020	Φ12R0.5	0030-ca-1	718hh	6	16
-12.000	-11.99	0.010	Φ12R0.5	0030-ca-1	718hh	6	17
-67.332	-67.32	0.012	Φ12R0.5	0030-ca-1	718hh	6	18
-12.000	-11.99	0.010	Φ12R0.5	0030-ca-2	718hh	6	19
-12.000	-11.99	0.010	Φ12R0.5	0030-ca-2	718hh	6	20
-67.332	-67.30	0.032	Φ12R0.5	0030-ca-2	718hh	6	21
-53.000	-53.01	-0.010	Φ12R0.5	0030-co-1	718hh	7	22
-53.000	-53.00	0.000	Φ12R0.5	0030-co-1	718hh	7	23
-53.000	-53.01	-0.010	Φ12R0.5	0030-co-1	718hh	7	24
-53.000	-53.00	0.000	Φ12R0.5	0030-co-1	718hh	7	25
-53.000	-53.01	-0.010	Φ12R0.5	0030-co-2	718hh	7	26
-53.000	-53.01	-0.010	Φ12R0.5	0030-co-2	718hh	7	27
-53.000	-53.00	0.000	Φ12R0.5	0030-co-2	718hh	7	28
-53.000	-53.01	-0.010	Φ12R0.5	0030-co-2	718hh	7	29

Appendix C

Appendix C-1

The Individual and Moving Range Charts (X and MR charts)

The X and MR chart is a refinement of run chart. Individual measurements are plotted instead of average of sample, and at the same time, the moving range between measurements are also recorded and charted. Control limits are used to monitor the process. MR value is the positive difference between two consecutive measurements, $MR = |x_2 - x_1|$.

The control limits can be calculated using the following formulas:

Upper control limit for the Individual chart:

$$UCL_X = \overline{X} + E_2 \overline{MR}$$

Lower control limit for the Individual chart:

$$LCL_X = \overline{X} - E_2 \overline{MR}$$

Upper control limit for the Moving Range chart:

$$UCL_{MR} = D_4 \overline{MR}$$

Lower control limit for the Moving Range chart:

$$LCL_{MR} = D_3 \overline{MR}$$

Where D_3, D_4 and E_2 are constants.

Appendix C-2

The Cumulative Sum Control Chart (Cusum Chart)

The Cusum chart incorporates all the information of the samples by plotting the cumulative sums of the deviations of the sample values from a target value. Suppose $\bar{X}_j$ is the average of the j_{th} sample, μ_0 is the target of the process mean, the cumulative sum control chart is formed by plotting the statistic against sample number i:

$$C_i = \sum_{j=1}^{i} (\bar{x}_j - \mu_0)$$

Because they include information of several samples, cumulative sum chart is more effective than Shewhart charts for detecting small process shifts. Furthermore, they are very effective when sample size n=1.

There are two ways to represent Cusum, the tabular (or algorithmic) cusum and the V-mask form of the cusum. Of the two representations, the tabular cusum is preferred and more often used.

The tabular cusum works by accumulating deviations from μ_0 that are above target with one statistic C^+ and deviations from μ_0 that are below target with one statistic C^-. The statistics C^+ and C^- are called one-sided upper and lower cusums, respectively. They are computed as follows:

$$C_i^+ = \max\left[0, x_i - (\mu_0 + K) + C_{i-1}^+\right]$$

$$C_i^- = \max\left[0, (\mu_0 - K) - x_i + C_{i-1}^-\right]$$

Where the starting values are $C_0^+ = C_0^- = 0$.

K is usually called the reference value and it is often chosen about halfway between the target μ_0 and out-of-control value of the mean μ_1 that is interested to detect.

If either C_i^+ or C_i^- exceeds the decision interval H, the process is considered out of control. A common selection of H is the five times the process standard deviation σ.

Appendix D

Typical control chart patterns and corresponding causes

(Western Electric Co., Inc. Statistical Quality Control Handbook)

Cycles

Cycles are short trends in the data which occur in repeated patterns. The causes of cycles are processing variables which come and go on a more or less regular basis. In the case of machines, they may be associated with a succession of movements, positions or heads. In the case of manually controlled operations, they may be associated with fatigue patterns, shipping schedules, conditions affecting the day and night shifts. In some types of product, they may be associated with seasonal effects which come and go more slowly.

The causes for the cycle patterns in X bar chart and Individual chart are as follows:

- Seasonal effect such as temperature and humidity
- Worn positions or threads on locking devices
- Roller eccentricity
- Operator fatigue
- Rotation of people on job
- Difference between gages used by inspectors
- Voltage fluctuation

Freaks

Freaks result from the presence of a single unit or a single measurement greatly different from the others. Such units are generally produced by an extraneous system of causes.

Another common source of freaks is a mistake in calculation. Occasionally an apparent freak is the result of a plotting error.

The causes for the freak pattern in X bar chart and Individual chart are as follows:

X bar chart

- Wrong setting, corrected immediately
- Error in measurement
- Error in plotting
- Data obtained on a non-linear scale
- Incomplete operation
- Omitted operation
- Breakdown of facilities
- Accidental inclusion of experimental units

Individual chart

- Accidental damage in handling
- Incomplete operation
- Omitted operation
- Breakdown of facilities
- Experimental unit
- Set-up part
- Error in subtraction
- Occasional parts from end of a rod or strip
- Measurement error
- Plotting error

- Some obvious physical abnormality which can be detected by examining the units in the sample that produce the freak point

Gradual Change in Level

A gradual change in level will ordinarily indicate one of the two things:

1. There is some element in the process which is capable of affecting a few units at first and them more and more as time goes on. After the change has taken place the chart tends to settle at some new level.
2. It may be that some element in the process has been changed abruptly, but because of the amount of product, it shows up gradually at the later operations.

The causes for the gradual change in level patterns in X bar chart and Individual chart are as follows:

- Gradual introduction of new material, better supervision, greater skill or care on the part of the operator
- Change in maintenance program
- Introduction of process controls in this or other areas

Grouping or Bunching

It is an indication of unnaturalness if all or most of the similar measurements occur quite close together. When measurement cluster together in such a non-random pattern it indicates the sudden introduction of a different system of causes.

The causes for the grouping or bunching pattern in X bar chart and Individual chart are as follows:

X bar chart

- Measurement difficulties

- Change in the calibration of a test set or measuring instrument
- Different person making the measurements
- Shift in distribution for a limited period.

Individual chart

- Extraneous cause resulting in a totally different distribution for a limited period of time
- Errors in plotting

Sudden Shift in Level

A sudden shift in level is shown by a positive change in one direction. A number of consecutive points appear on one side of the chart only.

On an X bar chart or Individual chart, this type of pattern indicates the sudden introduction into the process of a new element or cause (usually a simple or single cause) which moves the center of the distribution to a new location and then ceases to act on it further. The pattern shifts up or down from the centerline and rapidly establishes itself around the new level.

The causes for the sudden shift in level pattern in X bar chart and Individual chart are as follows:

X bar chart and Individual chart

- Change to a different kind of material
- New operator
- New inspector
- New test set
- New machine

- New machine setting
- Change in set-up or method

Individual chart

- New equipment
- Change to different material or different supplier of piece parts

Trend

A trend is defined as continuous movement up or down, a long series of points without a change of direction. Trends may result from any cause which work on the process gradually.

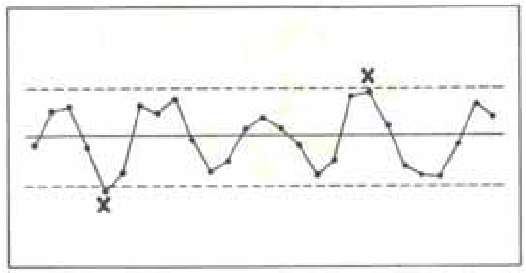
The causes for the trend pattern in X bar chart and Individual chart are as follows:

X bar chart and Individual chart

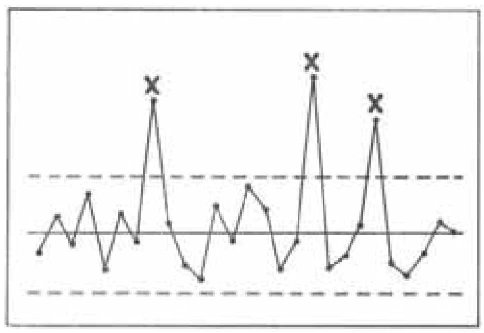
- Too wear
- Wear of treads, holding devices or gages
- Aging
- Inadequate maintenance on test set
- Seasonal effects, including temperature and humidity
- Operator fatigue
- Increase or decrease in production schedules
- Gradual change in standards
- Gradual change in proportions of lots
- Poor maintenance or housekeeping procedures
- Pumps becoming dirty
- Degreaser becoming exhausted

The graphs of the above-mentioned patterns are shown as follows:

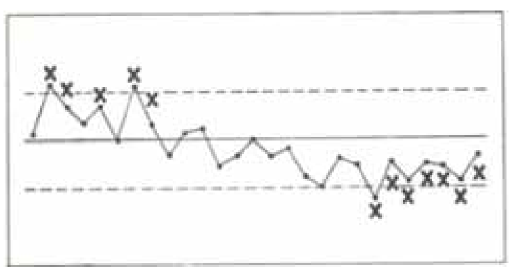
Cycles



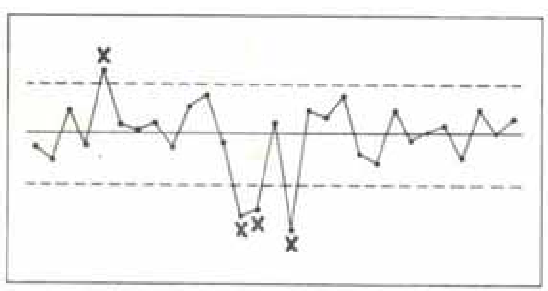
Freaks



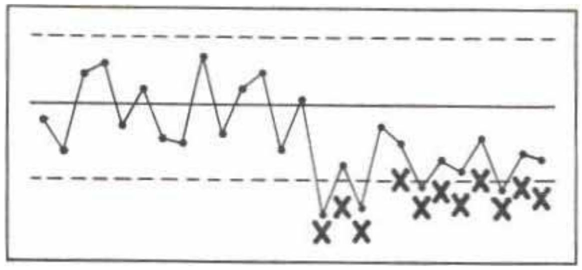
Gradual Change in Level



Grouping or Bunching



Sudden Shift in Level



Trend