On-line Quality Control and Experimental Design Analysis for Plastic Injection Moulding

A Thesis presented in partial fulfilment of the requirements
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to

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Abstract

This thesis describes automatic quality data acquisition and experimental design methods for product quality improvement.
The approach used, focuses on the computer based, process and product quality data acquisition from the shop floor. The collected data was then analysed by the 'design of experiments' method, an advanced statistical quality analysis method, to determine which process parameters influence product quality.

Many advanced statistical quality control methods have been developed for maintaining manufacturing product quality. In spite of this development, most manufacturing organisations depend on downstream statistical quality control methods, such as control charts and sampling inspection. These downstream methods, which require more time to collect quality information after the process, cannot always prevent quality problems, or produce prompt quality improvements.

A case study is presented which is concerned with the implementation of an on-line data collection system and the 'design of experiments' methods. A plastic injection moulding machine was used for this project, using an instrumented mould designed for process data collection, together with interfaced dimension and weight measurement instruments.
The results clearly indicate the process parameters which are important to product quality.

By the use of integrated on-line quality data collection systems and 'design of experiments' methods, rapid reaction to process problems, and quality design activities should be able to be easily adopted by manufacturing industries.

Acknowledgments

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Chapter 1

Introduction and Overview of Thesis

This chapter describes the object and aims of this research work followed by a summary of each chapter.

1.1 Foreword

This research thesis describes a method of computer based, on-line process and product data collecting to control product quality from the plastic injection moulding machine. The collected quality data is then analysed by the 'design of experiments' method to determine the optimum process input parameters for target quality characteristics.

The on-line quality data collecting method, which is called 'Automatic Quality Data Acquisition System (AQDAS)' in this thesis, were devised and developed to collect the process parameters with special instrumentations, and product quality measurements.

The AQDAS developed through this research, can be applied to a wide range of manufacturing industries with relatively low cost.

1.2 Objectives of the research work

Exhibited dimensional shrinkage on a plastic product is the most difficult product quality problem to control. The reason is that many input parameters affect directly and indirectly the product quality.

The aims of this research are to devise a low cost automatic quality data acquisition system and to determine the optimum level of the input process parameters to achieve target product quality characteristics.

Two main objectives were outlined for this research. They were as follows:

- To devise a computer based, shop floor data collection system for process parameters and product data for a plastic injection moulding machine.

  For the process parameters, the three following parameters were chosen to be measured with special instrumentation.

    - Injection pressure in the mould cavity,
    - Temperature of the polymer when it is injected into the cavity,
    - Temperature of the polymer when it is being injected from the nozzle.

  For the product parameters, the product dimensions and weight were measured.

- To use the 'design of experiment' methodology used to analyse the resultant data and to use the analysed results to optimise the settings for the injection moulding machine.

1.3 Summary of contents

Chapter 2 describes the main units of the injection moulding machine and the operation of its product moulding process. In addition key features of the plastic injection moulding machine and designed mould which were used for this research project are described.

Chapter 3 describes instrumentation methods for computer based shop floor quality data acquisition methods which were devised to collect the process and product quality data for the injection moulding machine and its product.

Chapter 4 describes the implementation of a real time quality data acquisition on the shop floor. The structure of Automatic Quality Data Acquisition System (AQDAS) and its development process was described. The collected process and product data are shown and displayed as graphics.

Chapter 5 describes the design process of experiments and shows experimental design results for product quality characteristics. Optimum input process parameters were suggested for the designed plastic product.

Chapter 6 discusses the achievements from the research project and makes recommendations for further studies.

1.4 General References

The following general references were used for this project.

Gofton, Peter W. (1986), *Mastering serial communications*, San Francisco, Sybex.

John, Vernon (1992), *Introduction to Engineering Materials,* New York, Industrial Press Inc.

Walton, J. (1991), *Engineering design: from art to practice*, St. Pual, West Publishing Co.

Minitab Reference Manual Release 10 for Windows (1994), USA, Minitab Inc.

Chapter 2

Plastic Injection Moulding

This chapter describes the main units of the injection moulding machine and the operation of its product moulding process. In addition, key features of the plastic injection moulding machine and the experimental mould which was used for this research project are described.

2.1 Introduction to Injection Moulding Machine

Injection moulding is one of the widely used polymer processing methods, and was developed from the late nineteenth century. The basic principle of injection moulding is to inject plasticised raw polymer material into a closed mould which is designed for a particular shape of product.

The main units of injection moulding machine are the injection unit and the clamping unit which houses the mould (Morton-Jones, 1989). Figure 2.1 shows a typical type of plastic injection moulding machine.

Figure 2.1 Plastic injection moulding machine

2.1.1 Injection Unit

The typical injection unit comprises a reciprocating screw within a barrel which is fitted with electrical element heaters to help plasticise the polymer.

When the polymer material is supplied into the barrel from the hopper, the reciprocating screw moves the polymer material to the injection nozzle. During this process, the polymer material is heated partly from the barrel heaters and partly from friction. As the screw rotates, it causes a shearing reaction on the polymer raw material which causes friction and melts the raw material. Another main function of the reciprocating screw in an injection moulding machine is to inject the plasticised polymer into the mould cavity. Its screw core diameter decreases from the feed end to the output end to allow compression of the polymer.

The injection nozzle connects the injection unit to the mould sprue (the injection channel), and a valve in the barrel closes during injections to prevent back-flow of molten polymer. The injection unit does the plasticising part of the process. During the plasticising phase, the output end is sealed by a valve, and the screw accumulates a reservoir in front of itself by moving backwards against the head pressure. When this phase is complete, the sealing valve opens, the screw stops rotating and pressure is applied to it so that it becomes a ram or piston which forces the accumulated melt through the connecting nozzle into the mould.

The injection unit is shown on the figure 2.2, and its detail parts are diagrammatically shown on the figure 2.3.

Figure 2.2 Injection unit

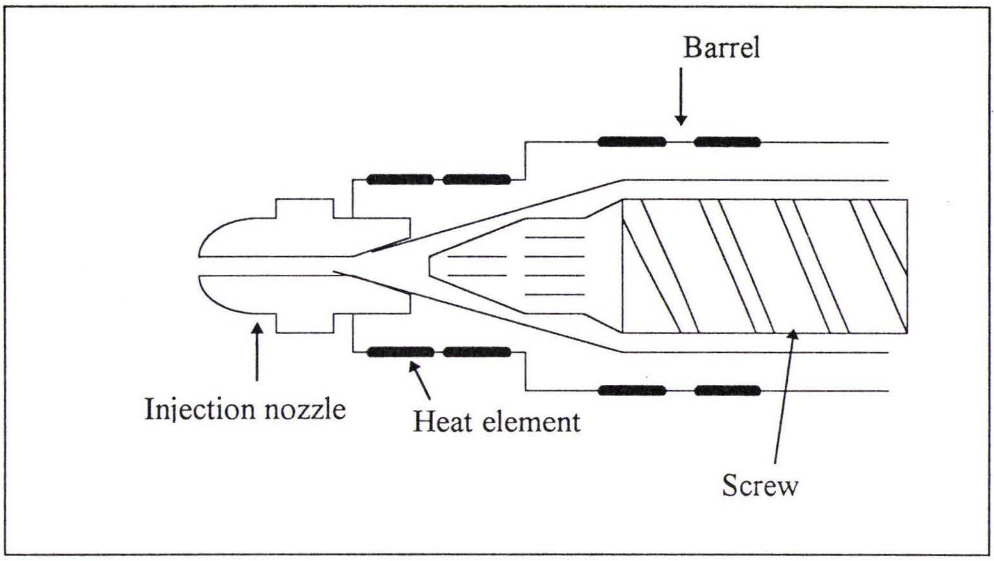


Figure 2.3 Detail parts of injection unit

2.1.2 Clamping Unit

The function of clamping unit is to hold the mould closed with sufficient force to resist the injection pressure using a hydraulically operated toggle system or full mechanical toggle system. For a hydraulic force mechanism is related to pressure and area by the following equation:

$$F = P \times A$$

where $F =$ force, $P =$ pressure, and $A =$ area.

This clamping force (F) is needed to prevent 'flash' at the mould mating surfaces, and it must be great enough to resist the pressure generated by the injection cycle.

2.1.3 Mould

The mould is mechanically fastened in the clamping unit, and is interchangeable to allow different products to be moulded. The main features of the mould are; the cavity, injection channel (sprue), cooling channels and ejector pins (Figure 2.4).

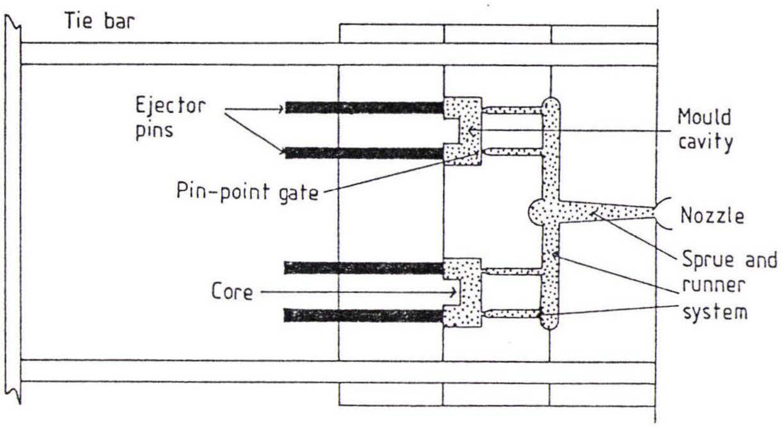


Figure 2.4 Mould and its main features

The plasticised material is injected through the sprue to the cavity and maintained under holding pressure while it cools into the designed product shape. Some moulds are fitted with water cooling channels to control the mould temperature. When the plastic material has sufficiently solidified, the machine opens, separating the two halves of the mould. In some moulds, ejector pins are used to push the solid plastic product to release it from the mould.

It is widely known that the mould design is a complex matter which strongly influences the quality of a moulded product, in terms of dimensional and geometrical accuracy.

2.2 Injection Moulding Process

Once the polymer in the barrel is plasticised by the action of the screw and heaters, the process of injection moulding for each produced can be divided into five stages.

- Stage 1: Mould closing

  The clamping unit moves against the nozzle to close the two parts of mould.

- Stage 2: Injection and plunger dwell

  The barrel screw turns and moves raw polymer material from the hopper into the barrel which is heated by electrical elements. Simultaneously, the plasticised material is injected into the mould cavity by the screw which acts as plunger.

- Stage 3: Holding and cooling

  The screw acts as plunger remains forward for sometime, still maintaining pressure through the nozzle while the material in the mould is cooling and setting.

- Stage 4: Plunger withdrawal and solidification

  The plunger withdraws, the mould remaining closed while the injected polymer solidifies, and a fresh supply of polymer falls from the feed hopper.

- Stage 5: Mould opening and release

  The clamping unit opens the half of mould, and in some moulds ejector pins release the product from the mould.

When an injection moulding process cycle finishes, the opened mould starts to move towards the nozzle for new moulding cycle. Figure 2.5 shows a flow chart of the injection moulding process.

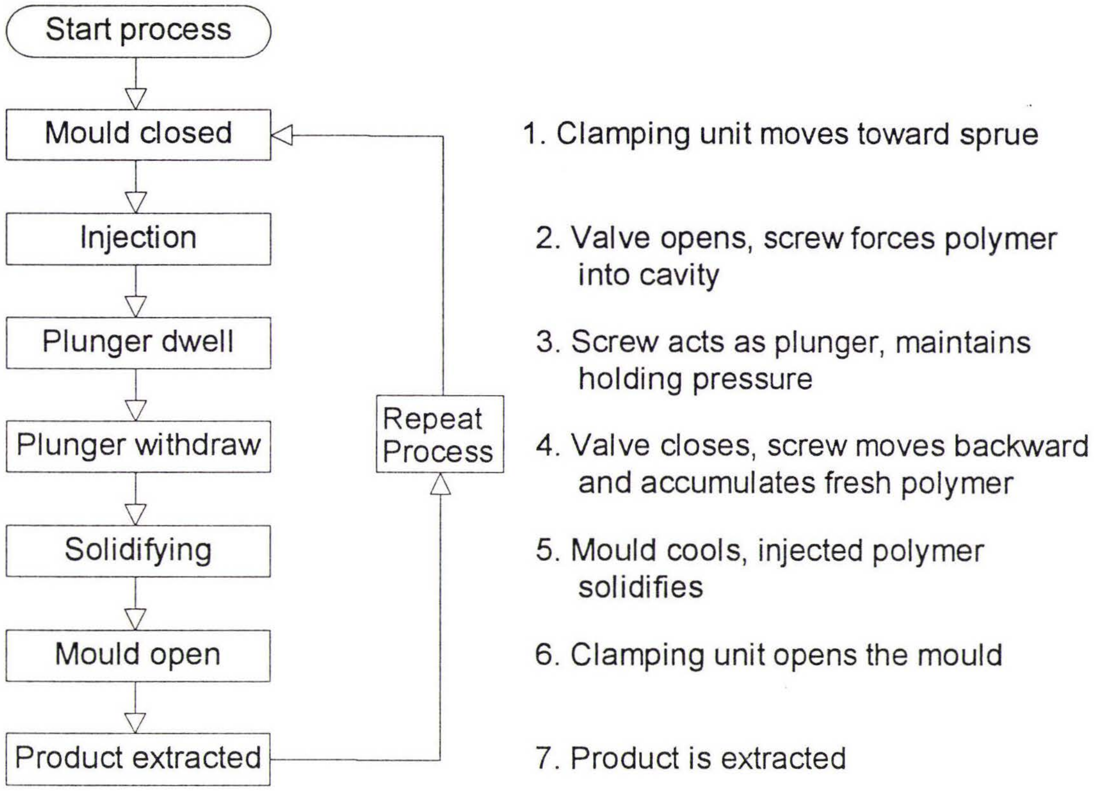


Figure 2.5 Injection moulding cycle flow charts

Rubin (1979) describes the advantages and disadvantages of the injection moulding as follows:

Advantages of Injection Moulding:

- Parts can be produced at high production rates.
- Large volume production is possible.
- Relatively low labor cost per product is obtained.
- Process is highly susceptible to automation.
- Parts require little or no finishing.
- Many different surfaces, colours, and finishes are available.
- Good decoration is possible.
- For many shapes this process is the most economical way to fabricate.

- Process permits the manufacture of very small parts which are almost impossible to fabricate in quantities by other methods.
- Minimal scrap loss result as runners, gates, and rejects can be reground and reused.
- Same item can be moulded in different materials, without changing the machine or mould in some cases.

Disadvantages and problems of injection moulding

- Intense competition often results in low profit margins.
- Mould cost are high.
- Moulding machinery and auxiliary equipment costs are high.
- Process control is difficult.
- Quality of the product is often difficult to determine immediately.

These last two disadvantages are of particular concern to this study, which aimed to investigate the interaction between process control parameters and resulting product quality, which is often poorly understood in industry.

2.3 Injection Moulding Machine in Department of Production Technology

The Department of Production Technology possesses an injection moulding machine with 100 tonnes clamping force.

The main purpose of this machine is for use in undergraduate experiments and postgraduate research projects. It is also regularly used for commercial orders when the machine is not used for academic purposes.

The main features of this injection machine are (Welltec, 1989):

- The reciprocating screw moves the polymer material and injects the molten material to the mould (Screw type).
- The clamping unit composes a mechanical toggle system with tie rods.

- Processing times, temperatures, pressures and speeds can be controlled from the digital control panel.
- Injection nozzle and barrel have four separated heating elements which can be controlled individually.

This machine has open loop control system which is built into the machine itself. The accuracy of setting parameters was unknown and it was thought necessary to verify their accuracy as part of this study.
The machine specifications are shown in Appendix A, Injection moulding machine specifications.

2.4 Experimental mould and product design

The experimental mould and product were designed by the author to collect the process and product quality data from the injection moulding. To obtain the exhibited dimensional shrinkage, the experimental product was designed to be a thick and simple flat shape. The figure 2.6 shows the moulded experimental product.

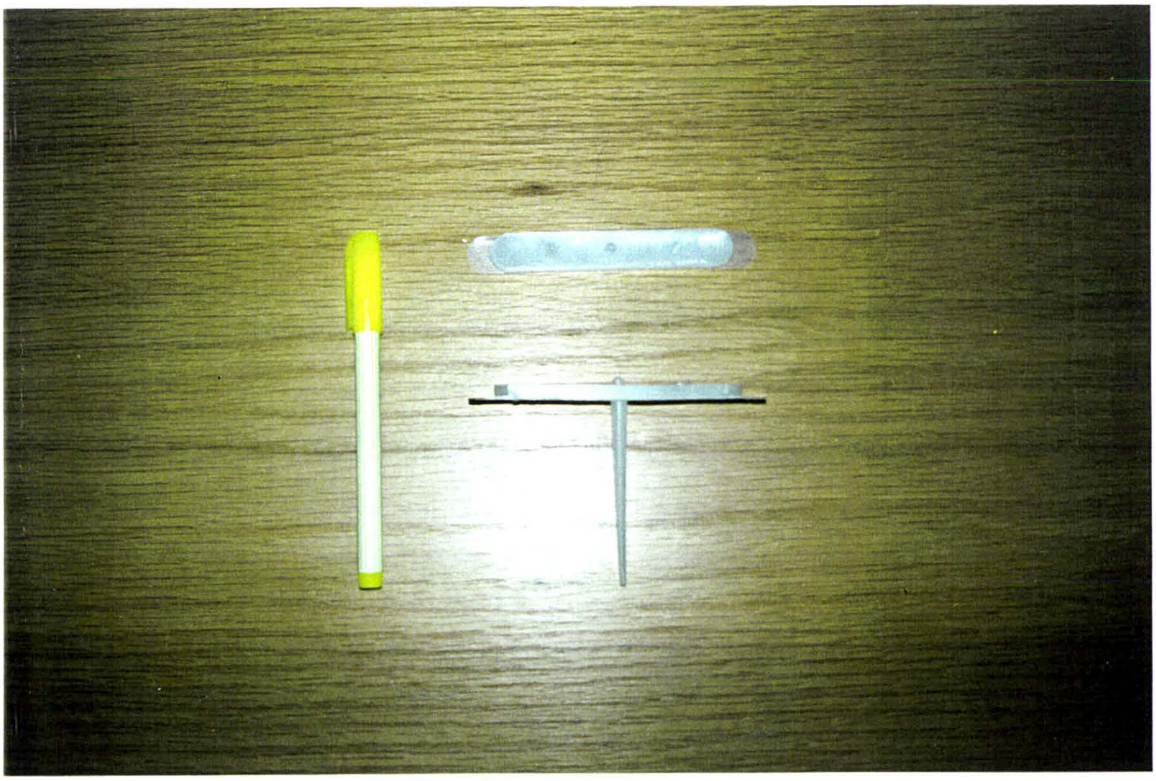


Figure 2.6 Moulded experimental product

The detail mould drawings are shown in Appendix B, Mould design drawings, and the figure 2.7 shows the cavity and sprue. Stainless steel was used for this mould material with ±0.1 mm general tolerances. Ejector pins and cooling channels were not used on this mould.

To measure the polymer temperature and the injection pressure in the cavity, a special type of thermocouple and a mechanical pressure sensing instrumentation was designed and built on the back of the mould cavity part (Figure 2.8). The detail of instrumentation is described in Chapter 3.

Figure 2.7 Designed mould cavity and sprue parts.

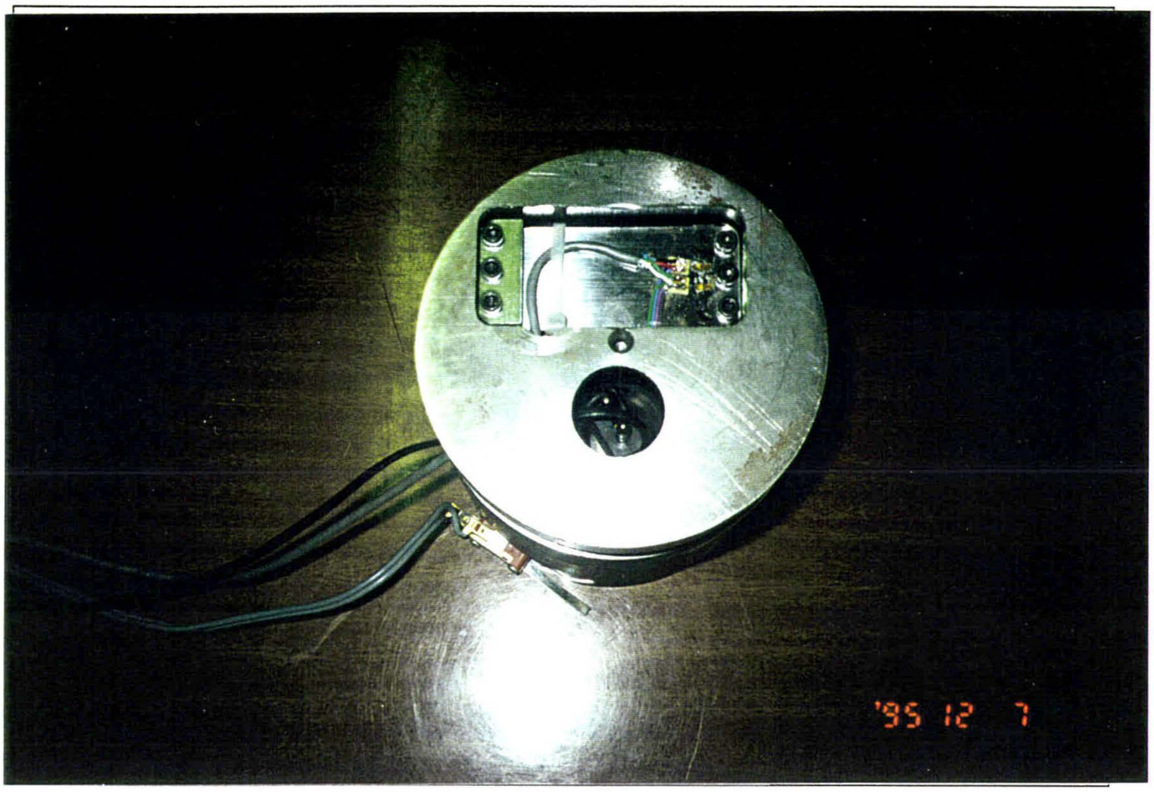


Figure 2.8 Instrumentations on the mould

Chapter 3

Computer based Process and Product Data Acquisition

This chapter describes the computer-based, shop floor quality data acquisition methods and instrumentations which were devised to collect the process quality data and the product quality data from the injection moulding machine.

3.1 Introduction

In the plastics industry, there are two main difficulties for quality control. Firstly, effective process control is often hard to achieve. Secondly, the product quality is difficult to determine immediately.

The main reasons for these difficulties are:

- Many input parameters affect the product quality, such as; temperature, pressure, humidity, time, etc.
- Delayed reaction of product quality features. The released product continues to shrink until the plasticised polymer becomes completely solidified. This shrinkage rate is one of the main quality control issues of a plastic product, and shrinkage is not necessarily uniform and may cause changes in geometry.
- Quality control has depended on inspection, with limited use of low level statistical methods, such as control charts.

Computer based shop floor quality data acquisition and on-line quality control with more advanced statistical methods - such as statistical process control and design of experiments - can be used to overcome these difficulties and to achieve a better quality product. The first benefit of this computer-based data acquisition is a rapid reaction when the process deviates from normal status and produces nonconforming product. The second is to provide information to the shop floor operators and focus their attention on quality control. The third reason is to reduce overall cost for quality improvement and corrective actions by providing information to analyse process parameter interactions with product quality characteristics. (Tannock, 1989).

Therefore, the computer based on-line quality data acquisition can be considered as one of the essential requirements for quality improvement activities.

After a brainstorming session involving machine operators and technicians to determine important input parameters for the injection moulding, the cavity pressure, cavity melting temperature and injection nozzle temperature were chosen to be measured and collected as process parameters. To determine the product quality status, the weight and dimensions were to be measured and recorded. It was important that the collected quality data should be easily accessible from the supervisory computer and analysed to pre-determine the product quality.

3.2 Process Data Acquisition

The following sections describe the process data acquisition system in more detail. The concept of computer based on-line process data acquisition was shown on the figure 3.1.

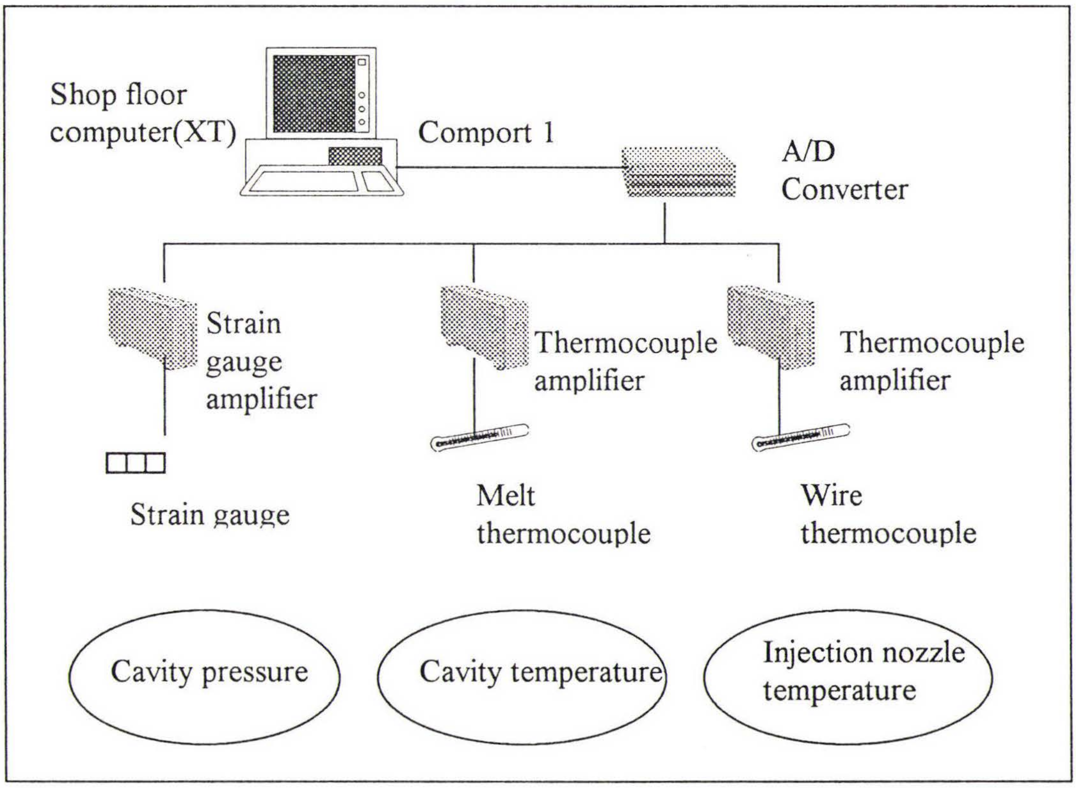


Figure 3.1 Process data acquisition diagram

3.2.1 Injection Pressure

The injection pressure is an important process parameter to determine the product quality. A machine's injection pressure capability depends on the diameter of the screw, the diameter of the piston of the hydraulic injection cylinder, and the hydraulic pressure available. For the same machine and mould combination, mould clamping pressure limits the size of item which can be moulded (Morton-Jones, 1989).

The injection moulding machine in the Department of Production Technology has three separately controllable stages of injection pressure which can inject the polymer material up to a specified 1950 kilogram force per square centimetre (Kgf/cm^2) maximum pressure (Welltec, 1989).

This injection pressure can be controlled from the numeric control panel which is located on the machine itself. The operating manual indicates that numeric settings can be adjusted from 20 to 120 Kgf/cm^2.

This discrepancy in specified injection capability was the subject of discussion with the machine operators and technicians in the department. They considered that the numeric settings were actually tonnes on the basis of their feeling and experience.

To measure the injection pressure and define the units of numeric input on the control panel, several methods were considered as follows:

- Tie rod method

This method uses strain gauges, which are attached on the machine tie rods, and measure the compressive strain in the tie rods. This method was widely used in the plastics industry (Measurements group fax correspondence, 1994).

When this method was discussed with experts, several problems were raised. Firstly, the calibration, strain versus injected pressure, is difficult. Secondly, its accuracy was questioned when the clamping force acts towards the mould.

- Diaphragm pressure transducer

The diaphragm transducer (strain gauge) is specially designed to measure the pressure from a diaphragm. A diaphragm transducer, which is attached on the diaphragm surface, measures the diaphragm deflections and generates them as analog signals proportional to pressure.

A design was prepared to fit a diaphragm pressure transducer into a experimental mould, as this method was considered one of the most accurate and effective. Unfortunately, this method had to be discarded as the transducer delivery from the maker would have taken several months.

- Pressure pin method

When ejector pins are used in a mould, these can be employed as part of a pressure sensing mechanism. For this experiments, a similar method was chosen.

This method uses a steel pin which is similar to the ejector pin, and a strain gauge plate. Strain gauges are attached on the both sides of the strain gauge plate. The strain gauge plate is fixed on the back of the mould block (Figure 3.2).

When an injection cycle occurs, the injected polymer appearing in the mould cavity exerts a force on the pressure pin. Simultaneously, the other sharp end of the pressure pin contacts the strain gauge plate and deflects the plate in a manner which is amenable to simple analysis.

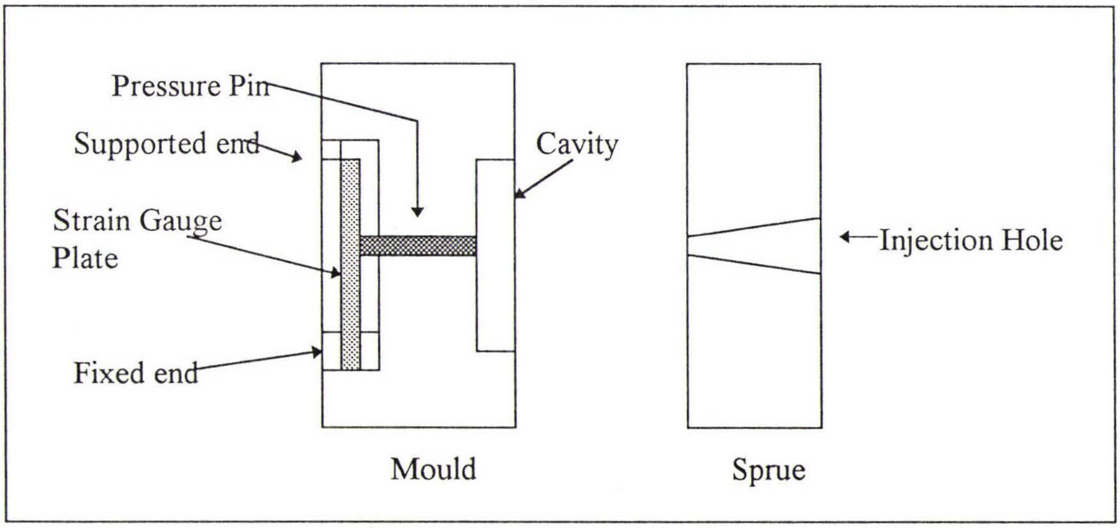


Figure 3.2 Pressure pin method

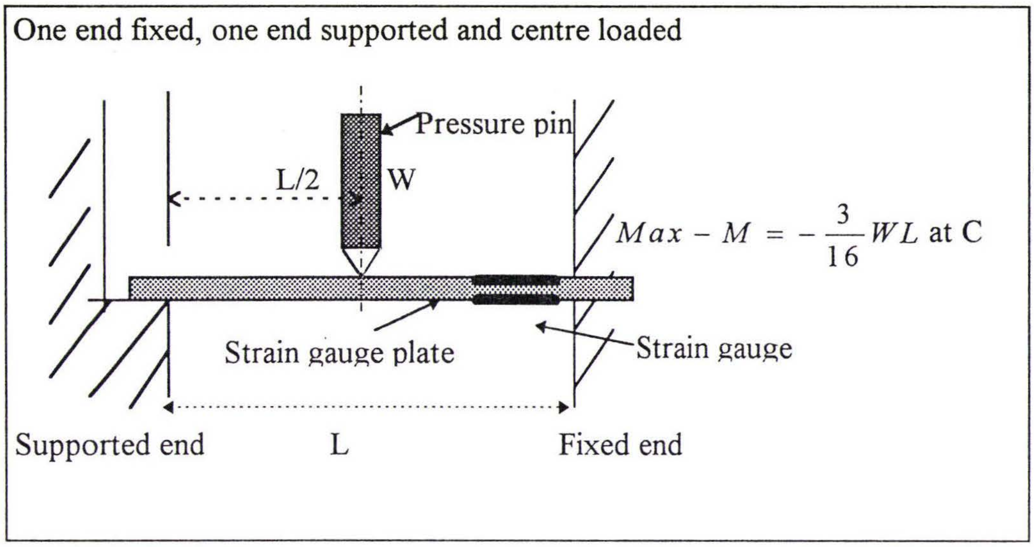


Figure 3.3 Moment formula for strain gauge plate

3.2.1.1 Design considerations for pressure data collection. A high carbon steel was used for the pressure pin (Silver steel) and for the strain gauge plate (Spring steel). To design the dimension of the pin and plate, the bending moment formula (Roark, 1965) was used (Figure 3.3). Appendix C, design calculations for strain gauges, gives details of the design analysis. The specifications of the pressure pin and the strain gauge plate are also shown in the Appendix B, mould design drawings.

3.2.1.2 Strain gauge and Wheatstone bridge. The strain gauge is widely used to measure mechanical strains, as well as, loads, torques, pressures, vibrations, and numerous other physical variables (Perry, 1962). It consists of a grid or filament of very small diameter wire or thin metallic foil mounted on paper or plastic. The filament material used has the property of linear variation of electrical resistance with strain.

To indicate the actual cavity pressure and its changes, a Wheatstone bridge circuit with four strain gauges was used for the experiment. Before mounting strain gauges on the plate, the surface was cleaned with methyl alcohol. An anaerobic adhesive was used to attach the gauges to the cleaned surface. Figure 3.4 illustrates the bridge circuit and the strain gauge attachment positions.

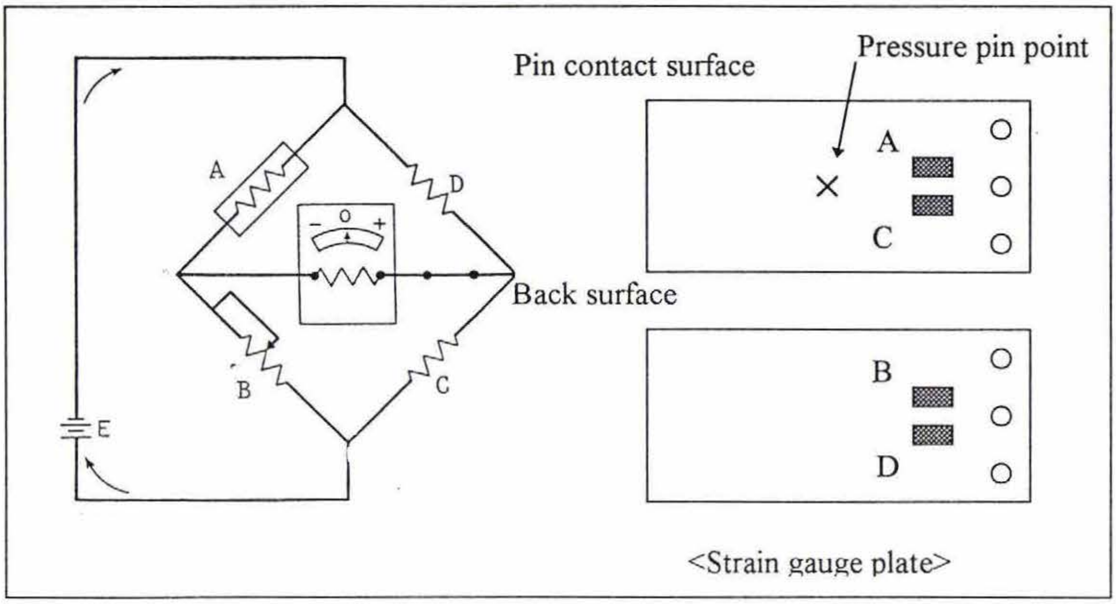


Figure 3.4 Wheatstone bridge circuit and mounted strain gauge

3.2.1.3 Calibration of the strain data. To calibrate the strain from the Wheatstone bridge circuit versus the pressure, a hydraulic press was used to load a special pressure pin which was made longer than the standard length to stand proud of the mould surface. Four different forces, equivalent to weights of 0, 100, 150 and 200 kilograms were loaded. These forces were calculated as exerted pressures on the pressure pin surface area as follows:

$$\textit{Weight (kg)} \times \textit{Pressure surface area } (m^2) \times G\ \textit{(gravity)} = \textit{Pressure } (Kgf / m^2)$$

An analog digital converter (ADC) was used to convert the electrical voltages from the bridge circuit to digital values. This ADC had different data converting speeds for different resolutions which ranged from 8 to 16 bit. As both injection cycle and data receiving speeds were considered, the 14 bit resolution was used for this experiment. The regression graph for weights and strain gauge data are shown in Figure 3.5, and is linear in form. The regression equation was used for the AQDAS programming.

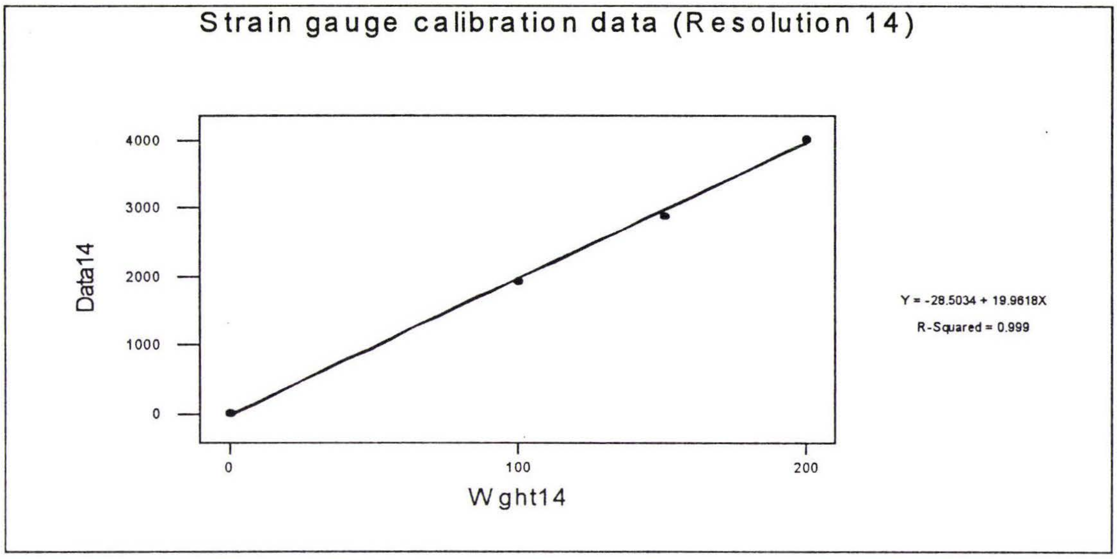


Figure 3.5 Strain gauge calibration graph for resolution 14 bit

3.2.2 Injection nozzle temperature

The machine barrel is heated by thermostatically controlled heating elements in the normal manner.

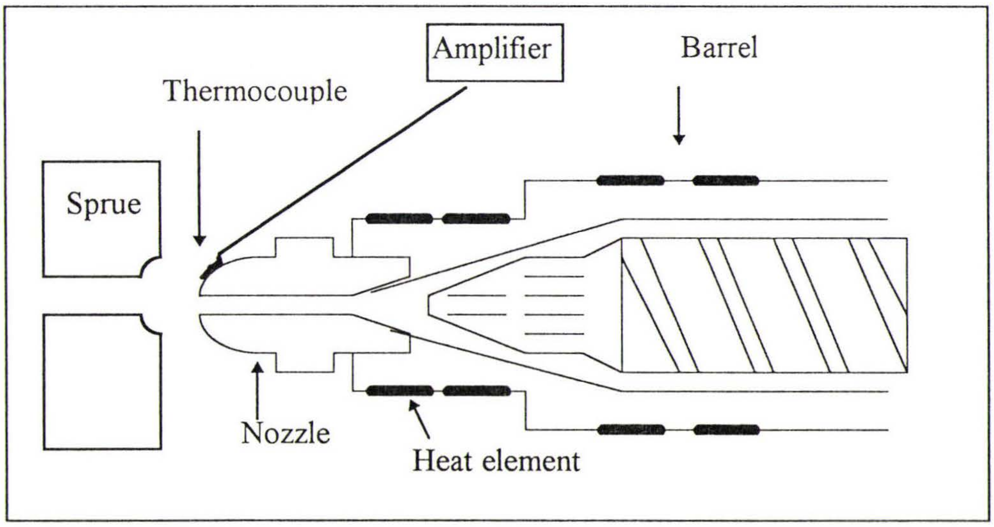


Figure 3.6 Injection nozzle and wire thermocouple location

The injection nozzle also has a separate heating element which can control the injection temperature immediately before injection. To measure the polymer temperature, a T type welded tip thermocouple - copper for positive and copper-nickel for negative - was attached on the nozzle end (Figure 3.6). This thermocouple converts thermal energy directly into an electric voltage when a temperature gradient exists between the two end junctions of a pair of copper and copper-nickel wires.

3.2.2.1 Calibration of the wire thermocouple.

To calibrate the thermocouple data which is converted to digital data, four different temperatures were provided as; ice water (0 °C), room temperature with closed space (20 °C) and boiled water (100 °C). A thermometer was used to verify these four temperatures. Maintaining temperatures of the boiled water was found difficult to control. These temperatures have a small variances ($\pm$5 °C). The regression graph for temperature and wire thermocouple data is shown on the Figure 3.7. It was linear in form.

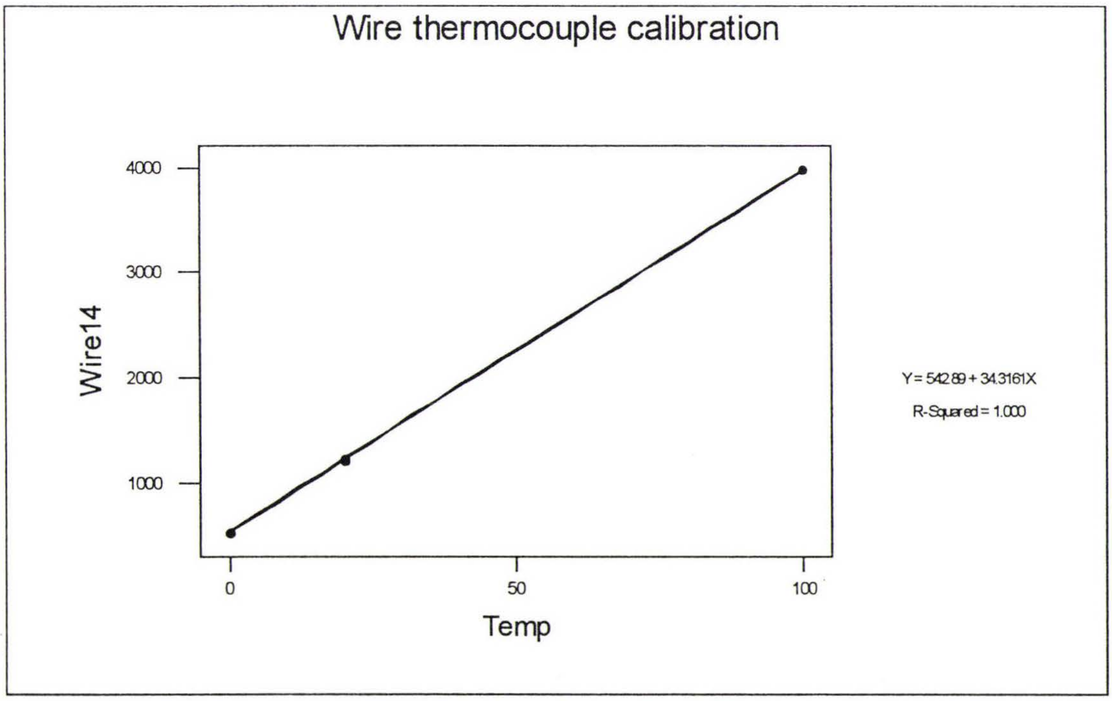


Figure 3.7 Wire thermocouple calibration graph for resolution 14 bit

3.2.3 Cavity temperature

When the injected polymer appears in the cavity, the plasticised polymer contacts the cavity surface and starts to decrease its temperature. To measure the polymer temperature as it enters the cavity and its changes, a specially designed J type thermocouple - iron for positive and constantan for negative - was used.

This melt thermocouple is housed in a stainless steel sheath. It is specially designed to withstand very high pressures and enables direct measurement of the plasticised polymer material.

To mount the melt thermocouple, a hole was drilled and tapped in the mould with ±0.05 mm tolerances. The details are shown on the Appendix B, mould design drawings.

3.2.3.1 Calibration of the melt thermocouple data.

The calibration procedures followed were the same as for the wire thermocouple calibration. The regression graph for the melt thermocouple is shown on the figure 3.8.

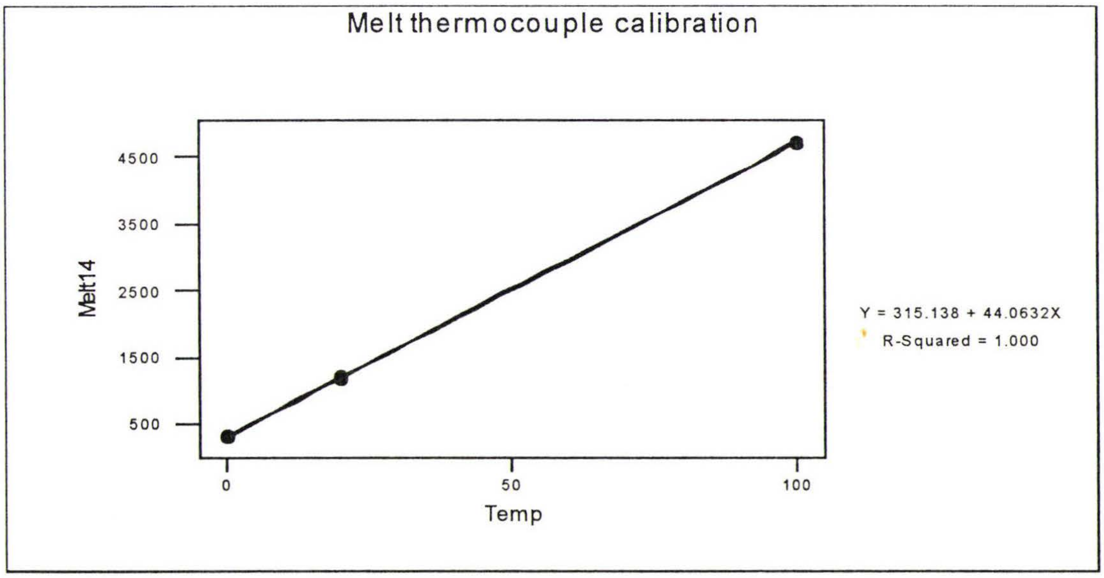


Figure 3.8 Melt thermocouple calibration data for resolution 14 bit

3.3 Product Data Acquisition

The figure 3.9 shows the concept of the on-line product data acquisition.

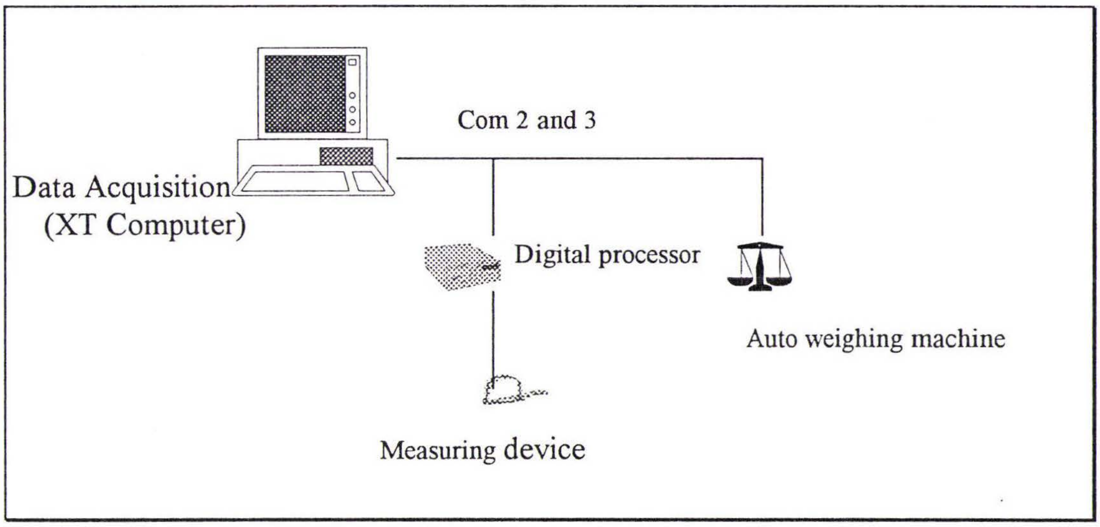


Figure 3.9 Product data acquisition diagram

3.3.1 Weight

The product weight was measured by a Mettler automatic weighing machine which has a data transmission port. This port was connected to the RS-232C communication port in the shop floor data receiving computer, and read whenever a component was to be weighed. The AQDAS programme read the RS-232C port as required in the programme.

3.3.2 Dimensions

The dimensional accuracy of a plastic product is the most critical product quality characteristic. For the product dimension characteristics, the length, width, thickness and centre point thickness were measured. Centre point shrinkage of the product appeared as a difference between thickness and centre-point thickness.

A Mitutoyo vernier calliper was used to measure the length, width and thickness (outside), and a micrometer fitted with specially designed point measuring tips was used to measure the centre point thickness.

These measuring devices had data transmission ports and buttons. When the data transmission button was pressed, the pressure effected the dimensions. To prevent this effect, a pedal switch was used.

The figure 3.10 shows the pedal switch used for measuring dimensions.

Figure 3.10 Measuring the product dimensions using the pedal switch

Chapter 4

Implementation of the Automatic Quality Data Acquisition System (AQDAS)

This chapter describes the importance of real time quality data collection and the development and implementation of the Automatic Quality Data Acquisition System (AQDAS). This was used to capture and process the data from the moulding process and the product, provided by the sensors described in chapter 3.

4.1 Introduction

In most cases, industrial quality data collection systems are limited to reporting after process failure or non-conformance has occurred in the production line. However, the implementation of real time data collection has long been considered as the key to a successful computerised quality information system for injection moulding (Bernhardt, 1983).

The use of real time data collection in injection moulding is based on a strategy of presenting data in real time to process operators and supervisors, so they can know at all times how each production machine is performing with respect to its specifications. With this information readily available at all times in the plant, personnel can correct problems as they occur. Moreover, this information can be used to prevent problems and improve product quality using advanced statistical analysis methods, such as regression analysis, design of experiments and statistical process control. Having information readily available on the computer monitor beside the operating machine can be a strong motivator to stimulate quality improvement activities on the production line.

The previous chapter described the sensor system used in data acquisition. This chapter describes the computer hardware and software used to collect and analyse the process and product data.

Many sophisticated injection moulding machines are fitted with similar AQDAS (Figure 4.1) as standard, and with such machines all that is required is to download data from a serial port on the machine controller to a statistical processing computer. The system described in this chapter was developed as a low cost data acquisition system to collect process and product data from the injection moulding machine in the Department of Production Technology for experimental purposes.

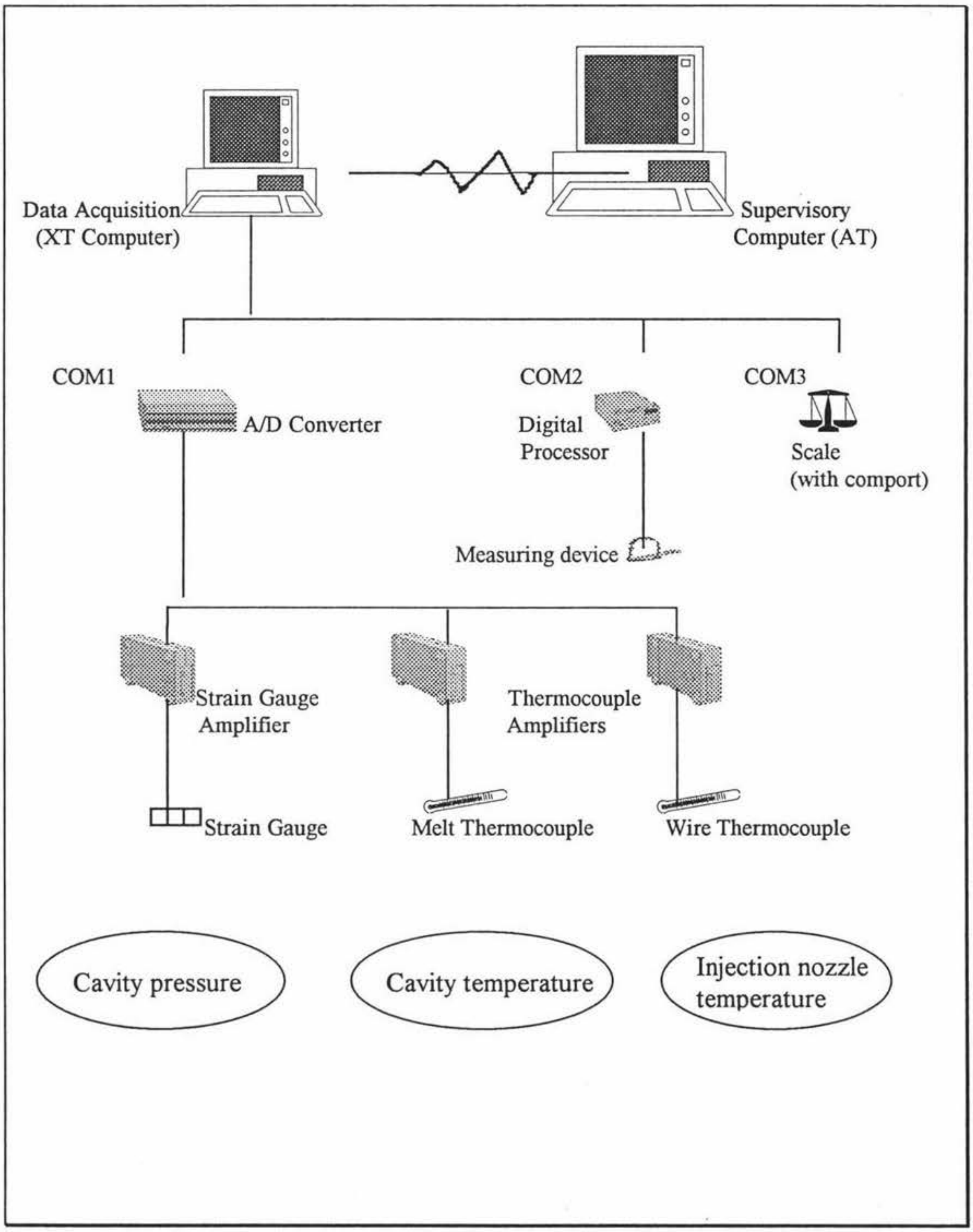


Figure 4.1 Automatic Quality Data Acquisition System (AQDAS)

4.2 Requirements for AQDAS

Keats (1989) described the characteristics which should be considered for data collection systems as; accuracy, speed, cost-effectiveness and adaptability.

Accuracy indicates how closely the data collected resembles the actual parameters. This accuracy is closely related to the speed and the cost-effectiveness. When the data collecting application is too complex, the data collection speed will be sacrificed. Otherwise, its system cost will be increased. A cost effective system that monitors and collects the data from process with optimum accuracy and speed with minimum cost is the most desirable. Also, the system should be adaptable to different environments with minor modifications.

With these considerations, the principle requirement of AQDAS were defined as follows:

- Cost effective data acquisition from sensors and measuring devices

  The process quality data from sensors and the product data from measuring devices should be collected with simple equipment. For cost effectiveness, the equipment should be relatively inexpensive and readily available from electronics and computer hardware suppliers without sacrificing accuracy and speed.

- Storage for the quality data

  The collected data should be stored on the monitoring computer for review and analysis by suitable software.

- Adaptability and communication with users

  The data collection system (program) should be easy to operate by the users. For this, the system should adopt the menu-driven method, and provide the essential information on the screen. The collected data should be displayed on the monitor to provide the machine operating and the output product quality information to the operator. Also, the system structure should be simple and easy to modify with minor changes of the system to adapt to different environments.

- Networking

  When the real environment of plastic industry was considered, such as vibration, humidity, high temperature, etc., the data collecting computer needs to be a simple and relatively low cost machine. This data collecting computer (shop floor monitoring computer) should be connected to the supervisory computer. It should be possible to access the quality data file from the supervisory computer or other terminal, and to analyse the data to improve the product quality whenever it is required. This networking requirement was not implemented due to lack of networking facilities at the time the system was first established.

Additionally, the AQDAS should be implemented using low cost hardware to encourage its adoption by industry. Also, the operating program should be programmed using a popular programming language, which can be easily used, implemented and modified by the users.

4.3 AQDAS hardware choice

For monitoring and collecting process quality data from the injection moulding machine, a personal computer, sensors, amplifiers and an analogue to digital converter (ADC) were required. (The detailed sensor instrumentation was described in the chapter 3.)

- IBM compatible XT computer with three serial communication ports

  For the reasons of cost, environment and flexibility, an IBM XT compatible microcomputer fitted with a hard drive and three serial communication ports was chosen for data collection.

  There was little demand for the XT computer for other purposes in the department since the introduction of faster and more advanced microprocessors.

- Analog to Digital converter (ADC)

  An ADC was used to convert the output voltages to digital data from the sensors. The ADC is very widely used in the industry and can be easily obtained at relatively low cost from electronic's suppliers. Also, the ADC used for this research project came bundled with digital data acquisition software, ADC16POL. This provided software was used as one module of the main program after simple modification.

- Strain gauge amplifier

  A strain gauge amplifier which was specially designed for the strain gauge was used for the injection pressure data. There are many choices, but the Philips strain gauge amplifier was used as it was available in the department.

- Thermocouple amplifier

  Two types of thermocouple amplifiers, J and T type, were used for the melting temperature data and the nozzle temperature data. These amplifiers were chosen from the Radio Spares (RS) catalogue.

For the product data collection, an automatic weighing machine, vernier callipers and a micrometer were chosen.

- Automatic weighing machine

  The weighing machine used had a capability of measuring to 0.1 gram accuracy and fitted with a data transmission port. This port was connected to the data collecting computer with a serial cable.

- Vernier callipers and micrometer

  A Mitutoyo vernier callipers was used to measure the product length, width, and thickness. For the centre point thickness, a Mitutoyo micrometer was used with a specially made sharp end caps to the sink centre point (see section 3.3.2).

  These measuring devices were fitted with the data transmission ports, and these port were connected to the computer by a serial cable.

4.4 AQDAS application design

The AQDAS application was developed using the Turbo Pascal programming language and development environment. Turbo Pascal was used as the operating speed in the XT computer was fast enough to detect the process and product quality data from the serial communication ports without having to use assembly language programming.

The AQDAS programme consisted of a main program and two additional modules (units); ADC16POL and ASYNC4U (Figure 4.2).

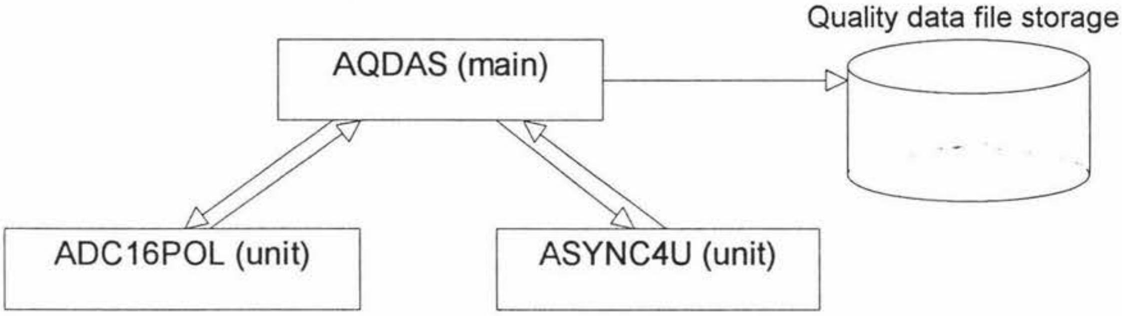


Figure 4.2 Main and unit programs of AQDAS

The ADC16POL unit was commercially designed for the ADC, and the ASYNC4U unit is a unit supplied with the Turbo Pascal professional version, which is intended for serial communication.

The main AQDAS programme communicates to these two units and collects the process and product quality data in the sequence selected by the user. Also, it was developed to store the quality data to the quality data file on a real time basis.

4.4.1 Software Development.

Several problems were detected with the initial AQDAS program which was programmed as a fixed sequence of process data acquisition and product data acquisition for each production cycle. The problems were:

- The output voltage from strain gauges amplifier changed slightly from one production cycle to the next. This caused calibration and zeroing problems.
- The released product from the mould exhibited dimensional shrinkage until the plastic material cooled down completely. This meant that a delay was necessary before acquiring product data, which was thus not synchronised with process data.

For the second trial, the AQDAS program was divided into three subprograms; calibration, process data acquisition and product data acquisition. A menu screen was added to select these three different functions (Figure 4.3). The selectable operating steps were displayed on the screen for the user's convenience.

```
        Step 1. Resolution and data saving file were selected as >>');

              <R>esolution >>    14 bits

               Data saving file:

                    <1> Process Data File      >> address_process

                    <2> Process SubData File  >> address_sub

                    <3> Product Data File      >> address_product

        Step 2. Strain gauge calibration >>

              <C>alibrate the strain gauge

        Step 3. Select data receiving program

              <I>njection process data

              <P>roduct data

        E<x>it this program

  >>>> Press the character or number in < >.
```

Figure 4.3 Menu screen for the AQDAS program

- Step 1: resolution and data saving file

The first step shows the ADC resolution status and the data file storage addresses which can be changed from the shop floor monitoring computer.

The ADC-16 has a selectable resolution range from 8 bit to 16 bit. When the data collection speed and injection cycle time were considered, the main program was programmed to provide two suitable choices of resolution, 12 bit and 14 bit.

The quality data storage was divided into three categories; the process data file, the subprocess data file and the product data file. The process data file stored the average injection pressure, cavity temperature and nozzle temperature from each injection moulding cycle. The subprocess data file stored all the collected data from sensors to analyse the pressure and temperature changes of each injection moulding cycle. The product data file stored the product weight, length, width, thickness and centre-point thickness.

- Step 2: strain gauge calibration

The second step is the strain gauge calibration and zeroing which was programmed to compensate for the small changes of the strain gauge amplifier output.

It was known from early trials that the mould clamping force had an effect on the injection pressure sensor output (Figure 4.4). To remove this clamping force effect and obtain the real plastic injection pressure data from the strain gauge circuit, the calibration program was executed from the time when the mould was closed. This calibration mould cycle was carried out without polymer injection. As the mould opened, the collected pressure data was calculated as compensation data, and the main injection pressure acquisition program was automatically amended using this data.

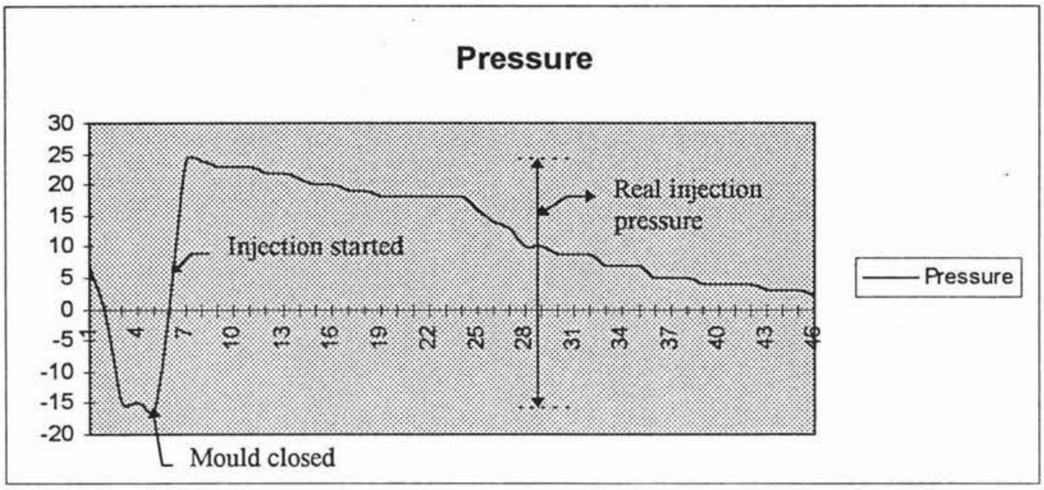


Figure 4.4 Collected pressure data from one moulding cycle

- Step 3: process and product data acquisition

For step three, injection process data acquisition and product acquisition menus were provided.

The machine operator can continue his work without waiting for the polymer temperature to cool down. The released product from the mould is put on the table in its production sequence. The product weight and dimensions are measured and stored in the same sequence after a batch has been produced.

Two monitoring computers - process data monitoring and product data monitoring - or multitasking and multiple data inputs could be used for a more effective application. In this research, one computer was used for both the process and product data monitoring purposes.

The detailed flow chart of the AQDAS program is shown on the Figure 4.5, and the AQDAS main programme is attached on the Appendix D, AQDAS program.

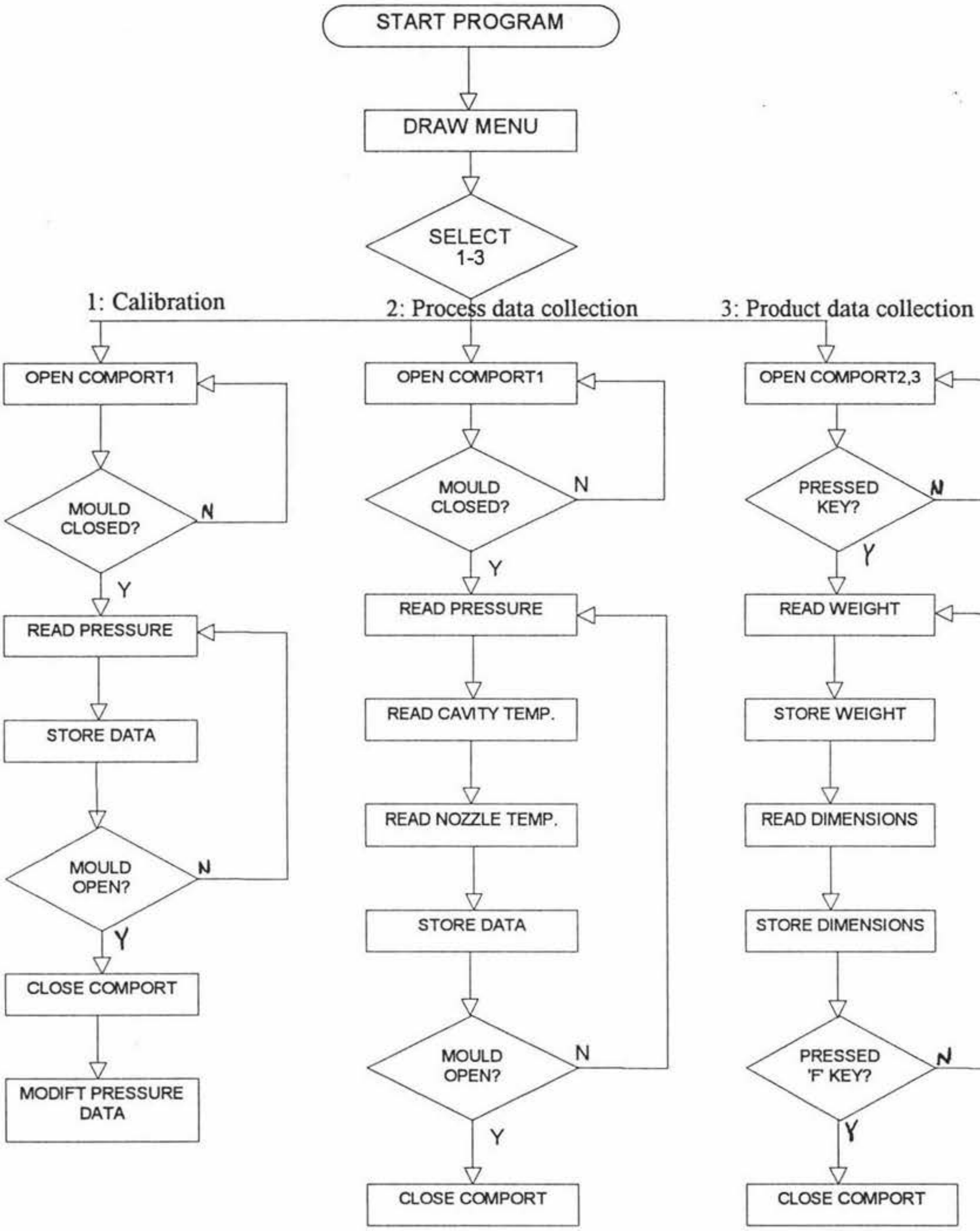


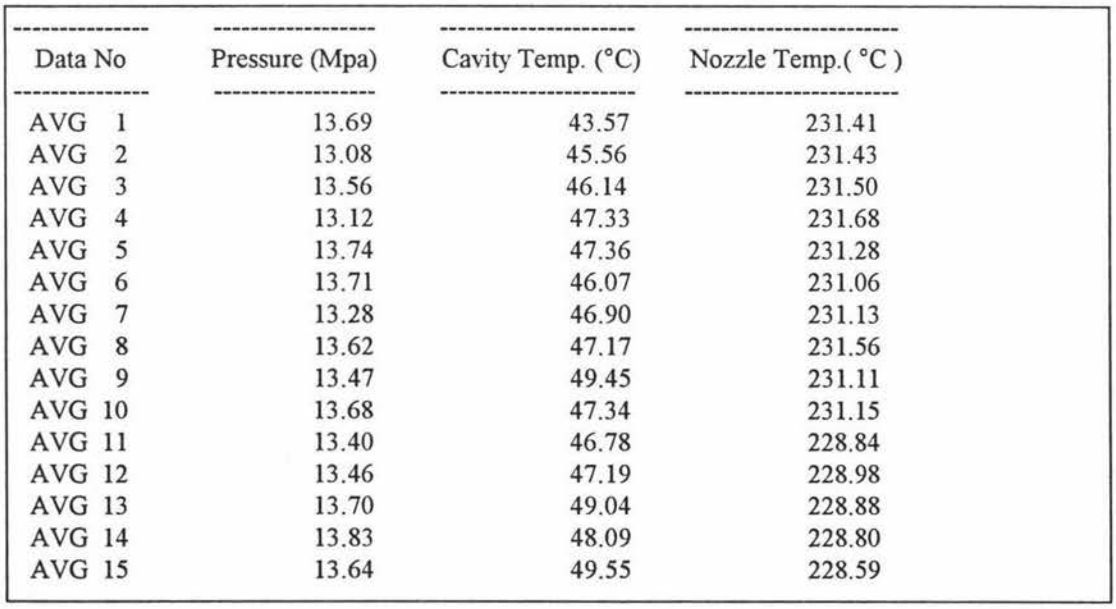
Figure 4.5 AQDAS program flow chart

4.4.2 Monitoring quality data acquisition

When the injection cycle starts, the measuring sensors send the strain gauge and thermocouple data to the ADC-16 through amplifiers. The AQDAS program receives these process quality data as the desired sequence, namely, injection pressure, cavity melting temperature and injection nozzle temperature, through the serial communication port and stores the data in the quality data files as ASCII code files. The Figure 4.6 shows the received process data from the AQDAS program.

After the end of the injection and moulding cycle, the machine releases a moulded plastic product. The product is weighed on the automatic weighing machine.

After measuring the weight, vernier callipers were used to measure four different dimensions - length, width, thickness, and center point thickness - of the product. The AQDAS program collects these product weight data and the four dimensions through the serial communication ports, and stores them on the quality database as ASCII files. The Figure 4.7 shows the received product data from the AQDAS program.



```
---------------   -----------------   ---------------------   -----------------------
  Data No          Pressure (Mpa)      Cavity Temp. (°C)       Nozzle Temp.( °C )
---------------   -----------------   ---------------------   -----------------------
 AVG  1                 13.69                  43.57                   231.41
 AVG  2                 13.08                  45.56                   231.43
 AVG  3                 13.56                  46.14                   231.50
 AVG  4                 13.12                  47.33                   231.68
 AVG  5                 13.74                  47.36                   231.28
 AVG  6                 13.71                  46.07                   231.06
 AVG  7                 13.28                  46.90                   231.13
 AVG  8                 13.62                  47.17                   231.56
 AVG  9                 13.47                  49.45                   231.11
 AVG 10                 13.68                  47.34                   231.15
 AVG 11                 13.40                  46.78                   228.84
 AVG 12                 13.46                  47.19                   228.98
 AVG 13                 13.70                  49.04                   228.88
 AVG 14                 13.83                  48.09                   228.80
 AVG 15                 13.64                  49.55                   228.59
```

Figure 4.6 Process quality data (product no. 1 - 15)

Data No.	Weight (g)	Length	Width	Thickness	CentreTh. (mm)
1	9.2	97.97	15.48	5.84	5.271
2	9.3	98.09	15.44	5.84	5.321
3	9.2	98.11	15.52	5.86	5.280
4	9.2	98.21	15.50	5.85	5.280
5	9.0	98.20	15.58	5.87	5.160
6	9.2	98.41	15.60	5.87	5.179
7	9.2	98.32	15.50	5.87	5.214
8	9.1	98.40	15.56	5.87	5.243
9	9.3	97.97	15.61	5.87	5.108
10	9.1	98.04	15.63	5.87	5.120
11	9.3	98.51	15.58	5.88	5.139
12	9.3	98.53	15.59	5.88	5.276
13	9.1	98.36	15.64	5.87	5.020
14	9.3	98.51	15.62	5.89	5.136
15	9.3	98.49	15.64	5.88	5.163

Figure 4.7 Product quality data (product no. 1 - 15)

4.5 Quality data analysis on the supervisory computer

The transmission of the stored quality data from the shop floor monitoring computer to the supervisory computer was done by floppy disks due to the lack of networking facilities. This transferred data was analysed by the Excel program and the Minitab program.

When the quality data was analysed on the supervisory computer, the relationships between the machine setting parameters and the real process parameters were defined.

4.5.1 Process parameters analysis

The injection pressure and the nozzle temperature of the plastic injection moulding machine were considered as the most significant parameters for product quality, and the most difficult machine setting parameters for which to determine their setting accuracy. Also the cavity melting temperature was considered as a key parameter which determines the product quality.

- Injection pressure

The machine used for this research had three distinct stages of operation, namely, filling, packing and holding pressure. The unit of injection pressure was uncertain before this experiment as technicians in the Department of Production Technology considered the machine setting unit of injection pressure was a Tonne force, on the other hand, the injection machine operating manual shows the injection pressure unit as a Kilogram Force per square centimetre (Kgf / cm^2).

For the experiments, three different injection pressures were set as, 20, 50 and 20, from the first, second and third injection stage to provide a consistent injection pressure.

Figure 4.8 shows the measured injection pressure from the first injection pressure to the third injection pressure graphed as a function of time. The first and the second injection pressure were measured as their actual injection pressure. The graph shows that the third injection pressure, the holding stage, did not effect to the cavity inside when the second injection, packing stage, was finished. The holding pressure could not be measured because the plastic in the cavity started to solidify and the pressure sensors, therefore, did not register the true pressure.

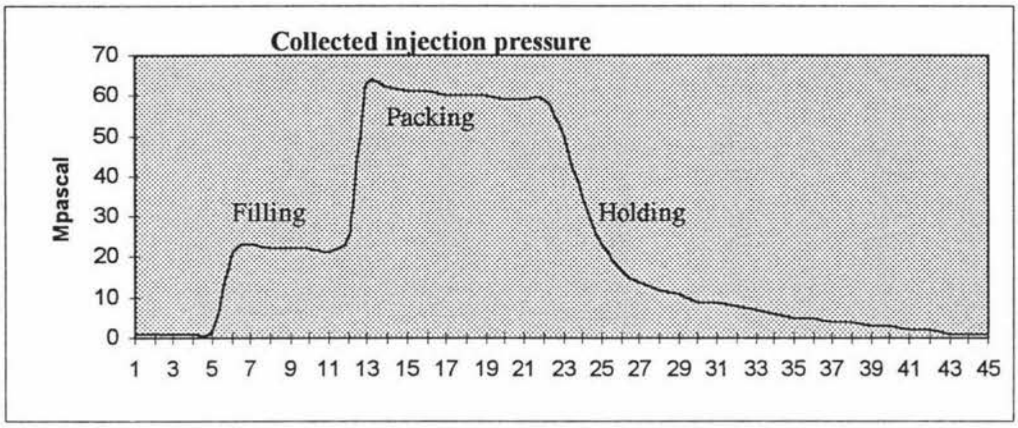


Figure 4.8 Collected injection pressure (1 stage - 20, 2 stage - 50, 3 stage - 20)

From the experimental results, the machine setting unit was close to a Mega Pascal as shown below:

Setting Pressure (unit= ?)	20	50
Received Pressure (Mpascal)	21.3	62.1

The received injection pressure from the machine setting 20, was very close to 20 Mega Pascals. On the other hand, the received injection pressure from the machine setting 50, had a small variance (12.1 Mpascal) from 50 Mega Pascals.

- Nozzle temperature

For the factorial two-level experimental design, the injection machine was set at two different temperatures for both the nozzle and barrel, namely, 200°C and 240°C. The received temperature data (Figure 4.9) from the thermocouple proved to be very similar to the machine setting temperature as shown below:

Setting Temperature (°C)	200.0	240.0
Received Temperature (°C)	190.9	229.5

The received temperatures were slightly lower than the setting temperatures. This result can be explained as the nozzle outside surface has a lower temperature (approximately 10°C) than the plasticised polymer temperature which flows inside of the injection nozzle.

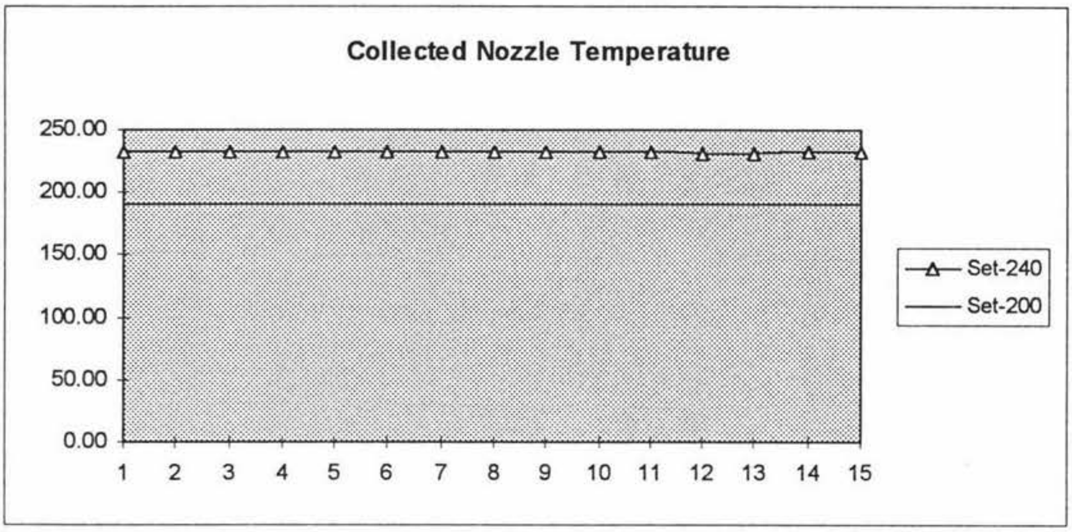


Figure 4.9 Collected nozzle temperature from 200 and 240 machine settings

- Cavity melting temperature

The melt thermocouple is housed in a stainless steel sheath designed to withstand very high pressures. This sheath had considerable thermal inertia, making the output lag behind the melt temperature.

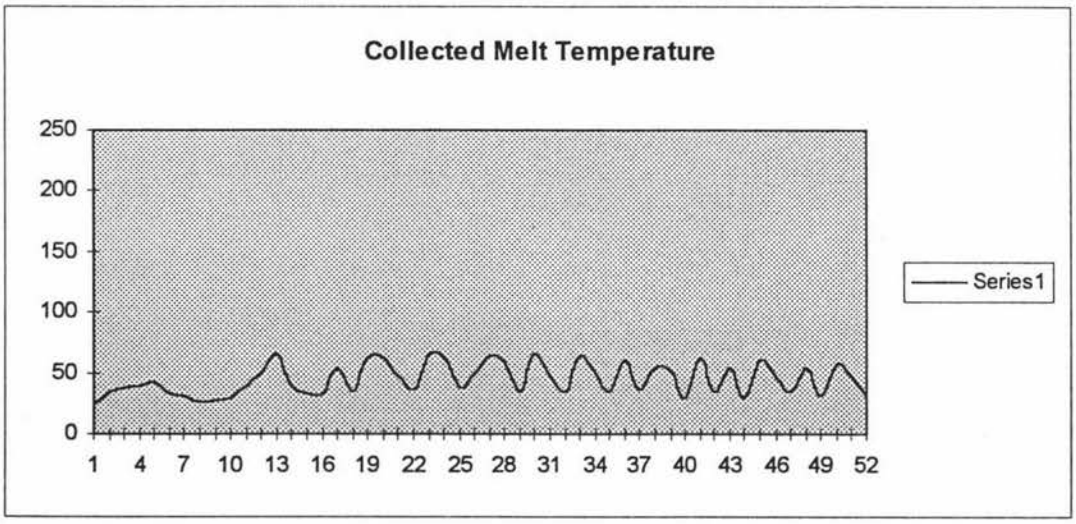


Figure 4.10 Collected cavity melt temperature

During the experiments, it was found that the injection moulding cycle time (approximately 30 second) was shorter than the heat transfer time. Therefore the measured cavity melt temperature was much lower than the filling polymer temperature. This type of thermocouple was recommended to be used where the consistent temperature can be supplied. Figure 4.10, collected cavity melt temperature, shows repeated sine curves in graph. It was assumed that this sine curve was produced from the circuit problems.

4.6 Summary

The implementation of real time quality data acquisition is the key success factor for the computerised quality data information system. A low cost on-line quality data acquisition system, Automatic Quality Data Acquisition System (AQDAS), was developed and implemented for the real time quality data acquisition from the injection moulding machine to collect the process data and the product data. Using this, the shop floor operator or supervisor can monitor information about the machine operating process.

Some uncertain machine setting parameters, pressure and temperature, were measured and defined in scientific units providing better understanding of the injection moulding process.

Moreover, this data acquisition system collected and stored the quality data in real time for further experimental design analysis.

Chapter 5

Designed experiments and results

This chapter describes the design process of experiments and shows the experimental results for better product quality.

5.1 Introduction

There are two main statistical approaches for process and product improvements; statistical process control (SPC) and 'Design of experiments (DOE)'.

Experimental design consists of purposeful changes of inputs or factors to observe the corresponding changes in the outputs or responses of a process. The process can be defined as some combination of machines, materials and people to complete a purposed task. Experimental design is a scientific approach which allows the user to better understand a process and determine how inputs affect the response.

The methods of 'Designed experiments' were firstly developed by Fisher in the United Kingdom in the 1940s, and applied to experiments concerned with agricultural yields. For the experiments, the agricultural land was divided into designed number of small sections and different cultivating conditions were provided to determine the best conditions to obtain the desired results.

As a result of many statisticians' works, 'Designed experiments' have been widely used for agricultural experiments, social surveys, as well as in manufacturing industries to improve the process and product quality.

Montgomery (1991) describes SPC as passive control methods, and DOE as active control methods. SPC methods require time delays. The operator or supervisor should watch the process until the process produces products, and wait until they can obtain the process information. Moreover, SPC does not always give much information when the process is "in control".

While SPC techniques are used to monitor production DOE requires a series of experiments be conducted before production to determine the settings for process input parameters to obtain desired results. Advanced DOE can lead to the determination of the optimum process input conditions for desired product quality.

Barnes (1995) described the purposes of experimental design for an engineer or technologist who tests different strategies of a new product or trouble shoots problems in on-line processes as follows:

- To gain understanding of the relationship between the input factors and the output response efficiently.
- To determine the settings of input factors which optimise the response of output.
- To build a mathematical model relating the response to the input factors (parameters), which is often referred to as process or product characteristic.

For the purpose of this project, to determine the optimum input parameter settings for minimising the product dimensional shrinkage, two different 'Designed experiments' methods, Plackett-Burman and Factorial two-level design, were used and analysed.
The Plackett-Burman design was chosen as an initial screening method to select key input parameters which have significant effects on the product dimensional shrinkage.
To analyse the detail effects and interactions of chosen key factors, the Factorial two-level design was used.

5.2 The experimental design process

The summaries of experimental design process (Schmidt, 1992) are as follows:

- **Step 1. State the problem to be solved.**

In a plastic product manufacturing plant, high temperature polymer, raw material is injected into a closed mould which is designed for a particular shape of a product. The product when released from the mould exhibits dimensional shrinkage until the plastic material has completely cooled down.
This dimensional shrinkage rate depends on the settings of the process input factors.

- **Step 2. Determine the objective of the experiment and measurement method.**

The objective of the experiment is to minimise the dimensional shrinkage rate which is an essential quality problem for any plastic product.

As measurements of product quality, the following 5 product characteristics were chosen.

1. Weight
2. Length
3. Width
4. Thickness at the outside
5. Thickness at the centre point

A sample plastic shape was designed to enable measurements of these 5 parameters to be taken. The detailed product shape is explained in Chapter 2.

- **Step 3. Identify the factors that are believed to influence the performance characteristics.**

After brainstorming, a cause and effect diagram was produced (Figure 5.1), and 11 input factors and two input levels for each input factors were chosen as in the Table 5.1.

- **Step 4. Select orthogonal arrays and assign factors to columns.**

A twelve run, eleven factor, five replicate, Plackett-Burman design was selected to screen the chosen 11 key input factors.

Factorial two level design was chosen for the screened input factors to determine the optimum input levels which minimise the dimensional shrinkage.

- **Step 5. Conduct the experiment and analyse the data.**

- **Step 6. Interpret the results and select optimum levels of most influential control factors.**

The details of step 5 and 6, experimentation and result interpretation, are described in the following sections.

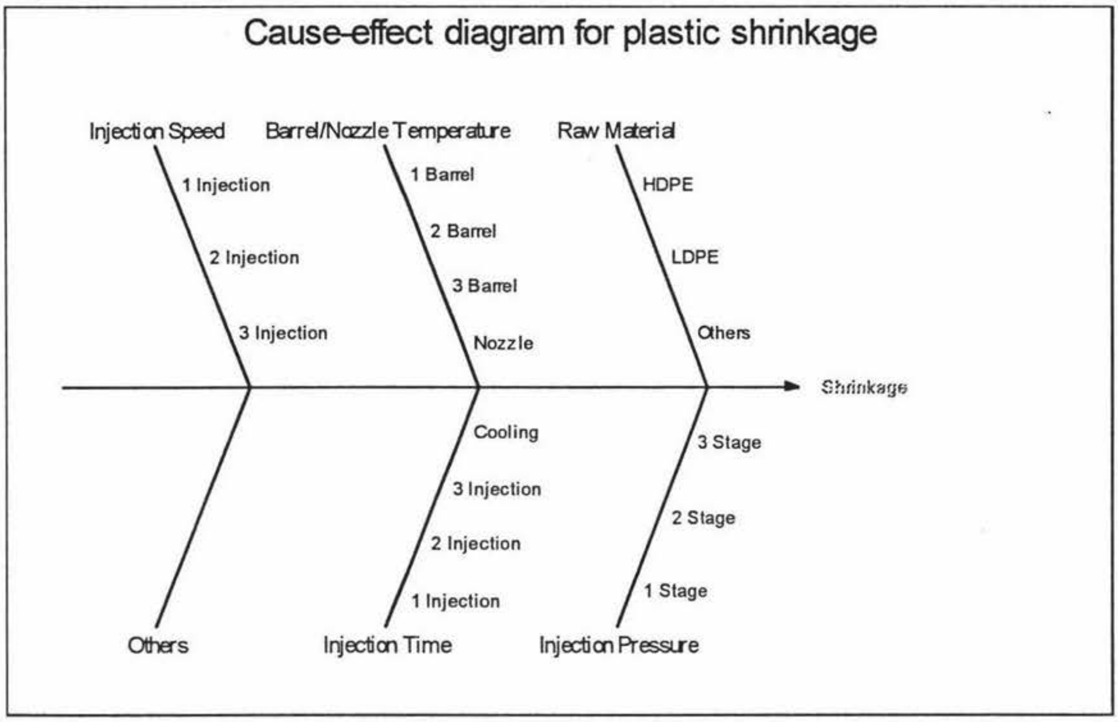


Figure 5.1 Cause and effect diagram for causes of shrinkage in plastic products

Factors	Low Level (-)	High Level (+)
1st Injection Time (Sec*10)	80	100
2nd Injection Time (")	50	80
Cooling Time (")	200	300
1st Injection Pressure	50	100
2nd Injection Pressure	50	100
3rd Injection Pressure	20	50
1st Injection Speed	30	80
2nd Injection Speed	20	30
2nd Barrel Temperature	180 °C	265 °C
3rd Barrel Temperature	180 °C	265 °C
Nozzle Temperature	180 °C	275 °C

* The values without unit are machine setting values.

Table 5.1 Selected 11 input factors and their high (+) and low (-) input levels

5.3 Plackett-Burman designs

5.3.1 Introduction

Plackett-Burman designs, developed in the 1940s, are used for initial screening experiments where a large number of factors need to be screened. These designs are two level fractional factorial designs for analysing $k = n - 1$ factors in n runs where n is a multiple of 4 (Box, 1978).

The Plackett-Burman design provides a single generating vector for a particular number of runs (n), to generate the remaining vectors. The generating vectors for different n are as follows:

$n = 8$, (+ + + - + - -)
$n = 12$, (+ + - + + + - - - + -)
$n = 16$, (+ + + + - + - + + - - + - - -)
$n = 20$, (+ + - - + + + + - + - + - - - - + + -)
$n = 24$, (+ + + + + - + - + + - - + + - - + - + - - - -)

The second column takes the last value of the first column as its first value, and then the rest of the first column values slide below that value. The next column follows this rule. Finally, the last n^{th} row is always (-).

An experiment with 12 runs each with 5 replicates using a Plackett-Burman design was chosen to screen the 11 input factors. Two experiments were carried out to determine which factors affect the characteristics of the experimented products produced by a plastic injection moulder, and to test the Automatic Quality Data Acquisition System (AQDAS) program.

5.3.2 Conducting the Plackett-Burman design

The first experiment was used to test the data receiving function of the Automatic Quality Data Acquisition System (AQDAS) program, and to screen for key factors. From this experiment, several points for software improvements were discovered. (The details of AQDAS and the software developments were described in the chapter 4.)

The table 5.2 shows the design matrix for a 12 run, 11 factor Plackett-Burman design matrix. The (+) value denotes the high input condition, and (-) value denotes the low input condition from the input factor.

The 11 factors chosen were allocated to the table columns as follow:

Column	Factor	Column	Factor
A	1 Injection Time	G	1st Injection Speed
B	2 Injection Time	H	2nd Injection Speed
C	Cooling Time	I	2nd Barrel Temperature
D	1st Injection Pressure	J	3rd Barrel Temperature
E	2nd Injection Pressure	K	Nozzle Temperature
F	3rd Injection Pressure		

Run	A	B	C	D	E	F	G	H	I	J	K
1	+	-	+	-	-	-	+	+	+	-	+
2	+	+	-	+	-	-	-	+	+	+	-
3	-	+	+	-	+	-	-	-	+	+	+
4	+	-	+	+	-	+	-	-	-	+	+
5	+	+	-	+	+	-	+	-	-	-	+
6	+	+	+	-	+	+	-	+	-	-	-
7	-	+	+	+	-	+	+	-	+	-	-
8	-	-	+	+	+	-	+	+	-	+	-
9	-	-	-	+	+	+	-	+	+	-	+
10	+	-	-	-	+	+	+	-	+	+	-
11	-	+	-	-	-	+	+	+	-	+	+
12	-	-	-	-	-	-	-	-	-	-	-

Table 5.2 Plackett-Burman design for 11 factors with 12 runs

The Table 5.2 can be translated into treatment conditions as in Table 5.3. Five experimental products were produced from the each treatment combination, making a total of 60 products. The value in the Table 5.3 is the actual setting value from the injection machine control panel.

After making the experimental products, each product's weight, length, width, thickness and centre point thickness were measured under the AQDAS environment. The measured quality data was saved as a ASCII file format on the monitoring computer's hard disk.

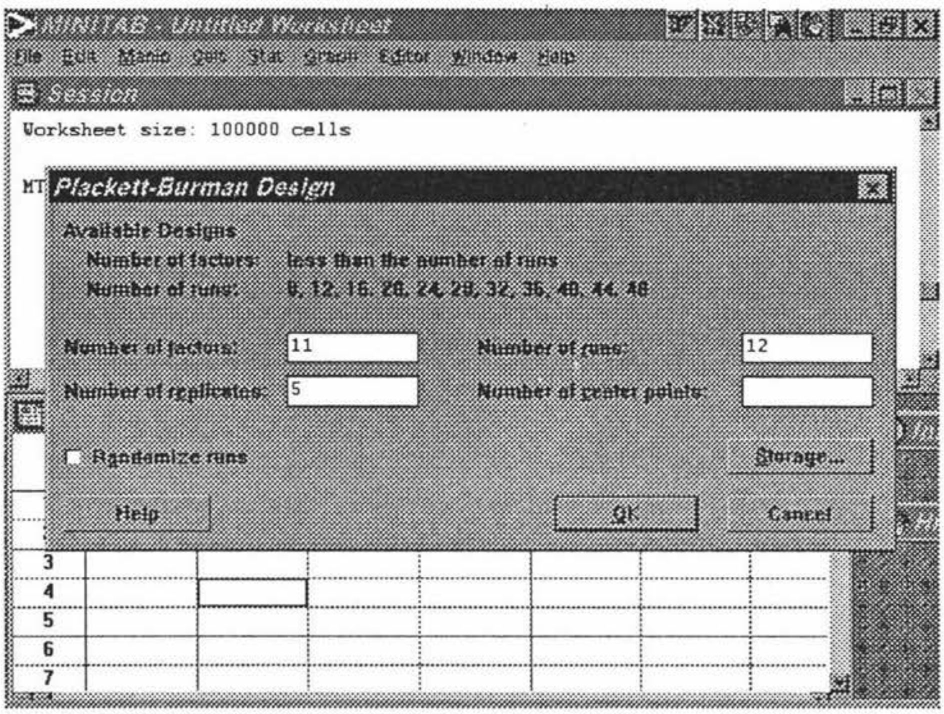
Run	A	B	C	D	E	F	G	H	I	J	K
1	100	50	30	50	50	20	80	30	265	180	275
2	100	80	20	100	50	20	30	30	265	265	180
3	80	80	30	50	100	20	30	20	265	265	275
4	100	50	30	100	50	50	30	20	180	265	275
5	100	80	20	100	100	20	80	20	180	180	275
6	100	80	30	50	100	50	30	30	180	180	180
7	80	80	30	100	50	50	80	20	265	180	180
8	80	50	30	100	100	20	80	30	180	265	180
9	80	50	20	100	100	50	30	30	265	180	275
10	100	50	20	50	100	50	80	20	265	265	180
11	80	80	20	50	50	50	80	30	180	265	275
12	80	50	20	50	50	20	30	20	180	180	180

Table 5.3 Treatment table for Plackett-Burman design

5.3.4 Result analysis

The collected quality data files from the AQDAS were imported into the 'Minitab' program using the ASCII file import function.

This ASCII file import function can be executed with simple macro program in the Minitab environment. The imported data was analysed by the Minitab program. The screen display of a Plackett-Burman design is shown in Figure 5.2.



```
Worksheet size: 100000 cells
```

Plackett-Burman Design

Available Designs
Number of factors: less than the number of runs
Number of runs: 8, 12, 16, 20, 24, 28, 32, 36, 40, 44, 48

Number of factors: 11
Number of runs: 12
Number of replicates: 5
Number of center points:

☐ Randomize runs

Figure 5.2 Plackett-Burman design in Minitab program

The effects of the input factors for the product quality characteristics were tabulated in the Table 5.4. The absolute values of effects were re-arranged in rank order of significance, for each product characteristic (1 for the most significant effect and 11 for the smallest effect). To select the key input factors for Factorial two-level design experiments, the rankings of each factor's effect, were added in the 'Sum' column. Then the sum values were rearranged in rank orders from the lowest to the highest (1 to 11) respectively. Finally, the key input factors were chosen from the order 1 to 6 as in Table 5.5 (The detail analysis results from the Minitab program are shown in Appendix E, entitled Analysis results from Minitab.).

The 6 key input factors chosen for the Factorial two-level experiments were as follows:

- 1 Injection Time
- 2 Injection Time
- 1 Injection Pressure
- 2 Injection Pressure
- 2 Injection Speed
- Barrel Temperature stage 3

	Weight	Length	Width	Thickness	Thick-Cen
1 Injection Time	0.08667	0.1587	0.0200	0.00567	0.06500
2 Injection Time	0.11333	0.1700	0.0027	0.01100	0.06433
Cooling Time	-0.02000	0.1547	-0.0267	-0.01033	-0.04100
1 Inj. Pressure	-0.04000	0.2873	0.0107	0.02100	-0.05833
2 Inj. Pressure	0.00000	0.1580	0.0727	0.03233	-0.11700
3 Inj. Pressure	0.00000	-0.0607	0.0120	0.01300	-0.06900
1 Inj. Speed	0.05333	0.0133	-0.0140	0.01100	0.06967
2 Inj. Speed	-0.02000	-0.0167	-0.0107	-0.00967	0.01167
Barrel Temp 2	-0.06667	-0.0247	-0.0007	-0.00967	-0.10567
Barrel Temp 3	-0.11333	-0.1467	-0.0080	-0.01033	-0.13900
Nozzle Temp	0.00667	0.0287	0.0140	0.00500	0.24330

Table 5.4 Input factors and their effects

	Weight	Length	Width	Thick	Thk-C	Sum	Order
1 Injection Time	**3**	**3**	**4**	**8**	**8**	**26**	**5**
2 Injection Time	**1**	**2**	**8**	**4**	7	**22**	**2**
Cooling Time	8	5	3	5	8	29	7
1 Inj. Pressure	**6**	**1**	**8**	**2**	**8**	**25**	**4**
2 Inj. Pressure	**8**	**4**	**1**	**1**	**2**	**16**	**1**
3 Inj. Pressure	8	7	7	8	4	34	10
1 Inj. Speed	5	8	5	6	5	29	7
2 Inj. Speed	**7**	**8**	**2**	**3**	**6**	**26**	**5**
Barrel Temp 2	4	8	8	8	3	31	9
Barrel Temp 3	**2**	**6**	**6**	**7**	**1**	**22**	**2**
Nozzle Temp	8	8	8	8	8	40	11

Table 5.5 Significance order for input factors

5.4 Factorial two level experimental design

5.4.1 Introduction

A set of experiments that looks at k factors in n observations with each factor at two levels is called a two level factorial design. The observations in a two level experiment are not analysed separately, but as a unit to provide independent assessments of the effects of each factor under study. The number of observations in such an experiment is given by taking the number of levels to the power of the number of factors (Barker, 1985):

$$t_c = 2^k \qquad (t_c\text{: Treatment combination})$$

The objectives of this full factorial two level experiments were to define the relations between the machine settings and product quality, and to determine the optimum input levels of the chosen factors to obtain the desired product quality.
As a result of the Plackett-Burman design, six factors had been chosen as the key input factors which affect the characteristics of product quality. An intensive full factorial designed experiment was carried out for the six chosen factors to determine their effects and in turn to find the optimum input levels (machine setting levels). The optimum is defined as the settings which produce a product with a minimum shrinkage and an optimum weight.

The key aspects of product quality for injection moulded products are identified as follows:

- *Shrinkage of the centre point thickness*: The centre point shrinkage (sink) of the surface is one of the most important considerations for plastic product quality which should be minimised.

- *Shrinkage of the product length*: The dimensions of a plastic product tend to shrink for a certain time period after the product is released from the mould. Minimising the product length shrinkage is another important consideration for the experiment.

- *Product weight*: A higher product weight requires a greater amount of material. Injection moulded products are frequently specified for lightness, and excessive material used is unnecessary.

The chosen factors and machine input settings are as shown in Table 5.6.

	Control Factors	Low (-1)	High (+1)
A	1 Injection Time	50	80
B	2 Injection Time	50	80
C	1 Injection Pressure	20	50
D	2 Injection Pressure	20	50
E	2 Injection Speed	30	80
F	Nozzle and Barrel Temperature	200	240

Table 5.6 Six chosen factors and their input levels

5.4.2 Conducting two level factorial design

An experiment using two-level, full factorial design for six factors ($k = 6$) with two replicates, totalling 128 runs, was performed. The duration of the experiments was 2 days.

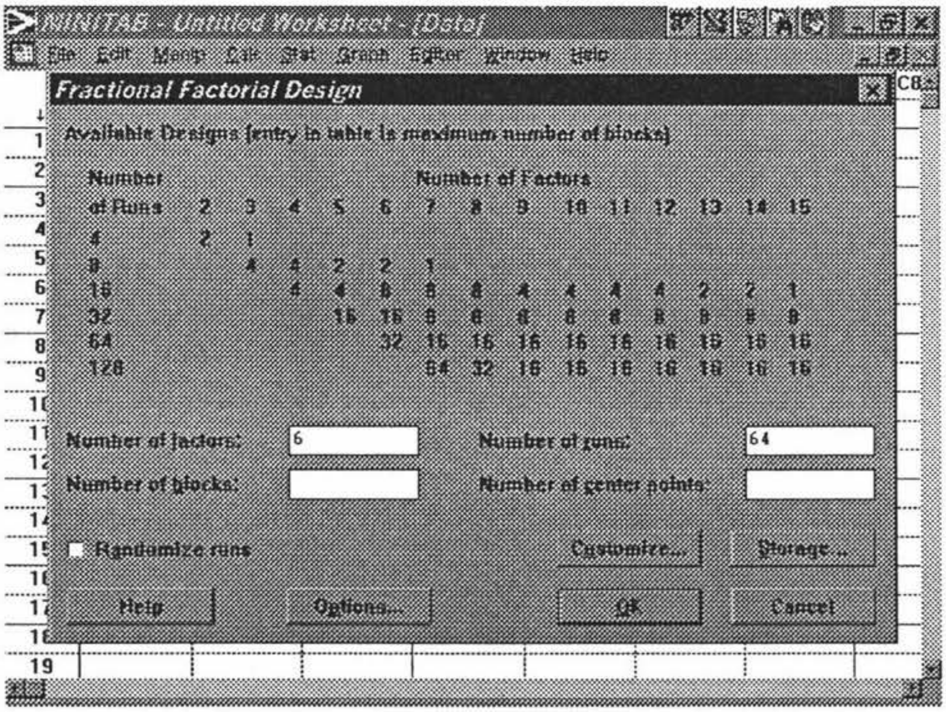
$$t_c = 2^k = 2^6 = 64,$$

$$Run = t_c \times r = 64 \times 2 = 128 \quad (r: \text{replicates})$$

Five products were produced from the each treatment combination, and 640 products were made from this experiment in total. The average from the five products from each treatment combination was used for analysis.

From the previous Plackett-Burman designed experiments, it was found that the nozzle temperature and the four separate stages of the barrel temperatures affect each of the other temperatures. Therefore the barrel temperatures were not considered as independent controllable input factors. Also, the nozzle temperature does not have a significant effect on the product quality (refer to the Plackett-Burman experimental results). For the factorial experiments, the nozzle temperature and barrel temperatures were considered as one input factor.

Randomisation was not considered due to the difficulties and time-lag involved with changing the nozzle and barrel temperatures. However, the data was checked for time dependencies and none were evident. The experiment followed the typical two-level factorial design table developed using the Minitab fractional factorial design function program (Figure 5.3).



Fractional Factorial Design

Available Designs (entry in table is maximum number of blocks)

Number of Runs	Number of Factors 2	3	4	5	6	7	8	9	10	11	12	13	14	15
4	2	1												
8		4	4	2	2	1								
16			4	4	8	8	8	4	4	4	4	2	2	1
32				16	16	8	8	8	8	8	8	8	8	8
64					32	16	16	16	16	16	16	16	16	16
128						64	32	16	16	16	16	16	16	16

Number of factors: 6

Number of runs: 64

Number of blocks:

Number of center points:

☐ Randomize runs

Figure 5.3 Fractional factorial design in the Minitab program

5.4.3 Centre point shrinkage

The centre point thickness of the product surface was measured to check the shrinkage effects. Figure 5.4 and Table 5.7 shows the significance order of the effects for the centre point thickness from the first to the ninth. The full analysis result is shown in the Appendix E (Analysis results from Minitab).

From this effects analysis, it was found that the effects of the main factors and the two factor interactions were significant, whereas, three or more factor interactions had a very limited effect on the centre point thickness.

Therefore, it was only necessary to analyse the main factors and the two factor interactions to determine the optimum input levels required to maximise the centre point thickness and minimise the centre point shrinkage.

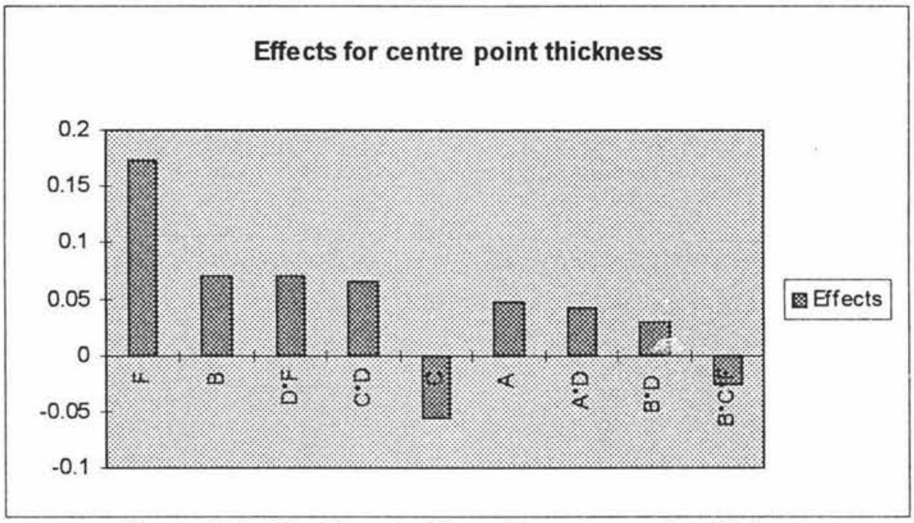


Figure 5.4 Significant effects for centre point thickness

	Factors and interactions	Effects	Abs(eff)	P values
F	Nozzle and Barrel Temperature	0.17331	0.17331	0.000
B	2 Injection Time	0.07038	0.07038	0.000
D*F	2 Injection Pressure & Nozzle/Barrel Temperature Interaction	0.07030	0.07030	0.000
C*D	1 Injection Pressure & 2 Injection Pressure Interaction	0.06515	0.06515	0.000
C	1 Injection Pressure	-0.05510	0.05510	0.000
A	1 Injection Time	0.04784	0.04784	0.000
A*D	1 Injection Time & 2 Injection Pressure Interaction	0.04282	0.04282	0.000
B*D	2 Injection Time & 2 Injection Pressure Interaction	0.03033	0.03033	0.000
B*C*F	2 Injection Time, 1 Injection Pressure & Nozzle/Barrel Temperature Interaction	-0.02471	0.02471	0.000

Table 5.7 Significant effect order and their absolute effect value

5.4.3.1 Main factor effects for centre point shrinkage

The average centre point thickness from each factor's low and high input level is shown on the Table 5.8. Figure 5.5 shows the graphical analysis result for the centre point shrinkage using these shrinkage data.

As minimising the centre point shrinkage is the object of this experimental analysis, the input levels to obtain the highest centre point thickness in the range used for the two level factorial experiments would be as shown in Table 5.9. To determine the optimum settings, a multilevel experiment such as Central Composite Design (CCD) would need to be used.

	Input Factors	Low (-1)	High (+1)
A	1 Injection Time	5.32	5.37
B	2 Injection Time	5.31	5.38
C	1 Injection Pressure	5.37	5.32
D	2 Injection Pressure	5.34	5.35
E	2 Injection Speed	5.35	5.34
F	Nozzle and Barrel Temperature	5.26	5.43

Table 5.8 Average thickness from different input levels

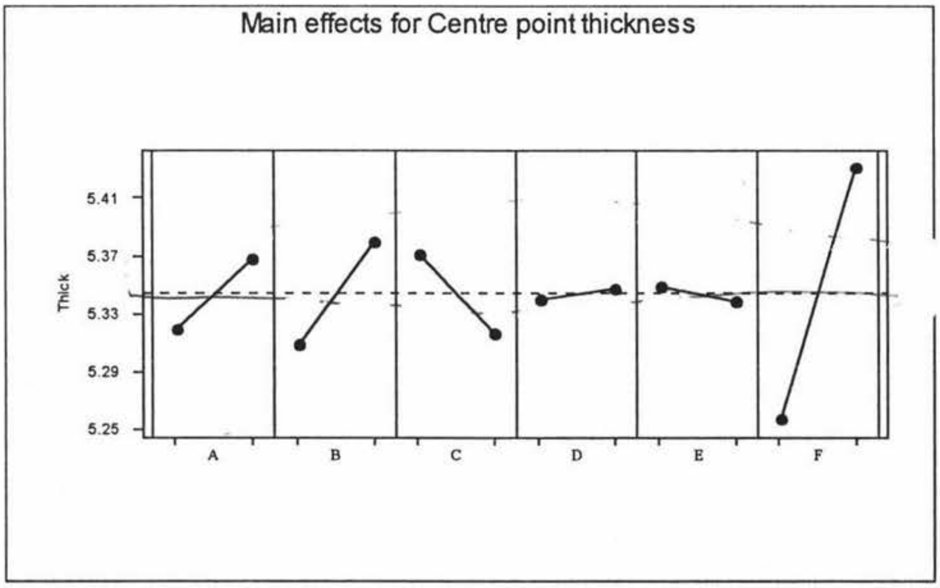


Figure 5.5 Graphical analysis for centre point thickness

	Control Factors	Low (-1)	High (+1)
A	1 Injection Time	50	**80**
B	2 Injection Time	50	**80**
C	1 Injection Pressure	**20**	50
D	2 Injection Pressure	20	**50**
E	2 Injection Speed	**30**	80
F	Nozzle and Barrel Temperature	200	**240**

Table 5.9 Main factor effect analysis results for centre point shrinkage

5.4.3.2 Two factor interactions for centre point shrinkage

The figure 5.6 shows that there are four significant two factor interactions which affect the centre point thickness. Therefore interaction analysis was necessary to define the main factor's relationship and to determine the best input levels for the highest centre point thickness.

The significant two-factor interactions are:

Temperature (F) * 2 Injection Pressure (D) DF
1 Injection Pressure (C) * 2 Injection Pressure (D) CD
1 Injection Time (A) * 2 Injection Pressure (D) AD
2 Injection Time (B) * 2 Injection Pressure (D) BD.

The second injection pressure (D) which involves all the significant interactions, acts as an important factor for the interaction effects. The detailed analysis results for two factor interactions are shown in Appendix E (Analysis results from Minitab), and these four significant interactions are plotted as isoplots in Figure 5.6.

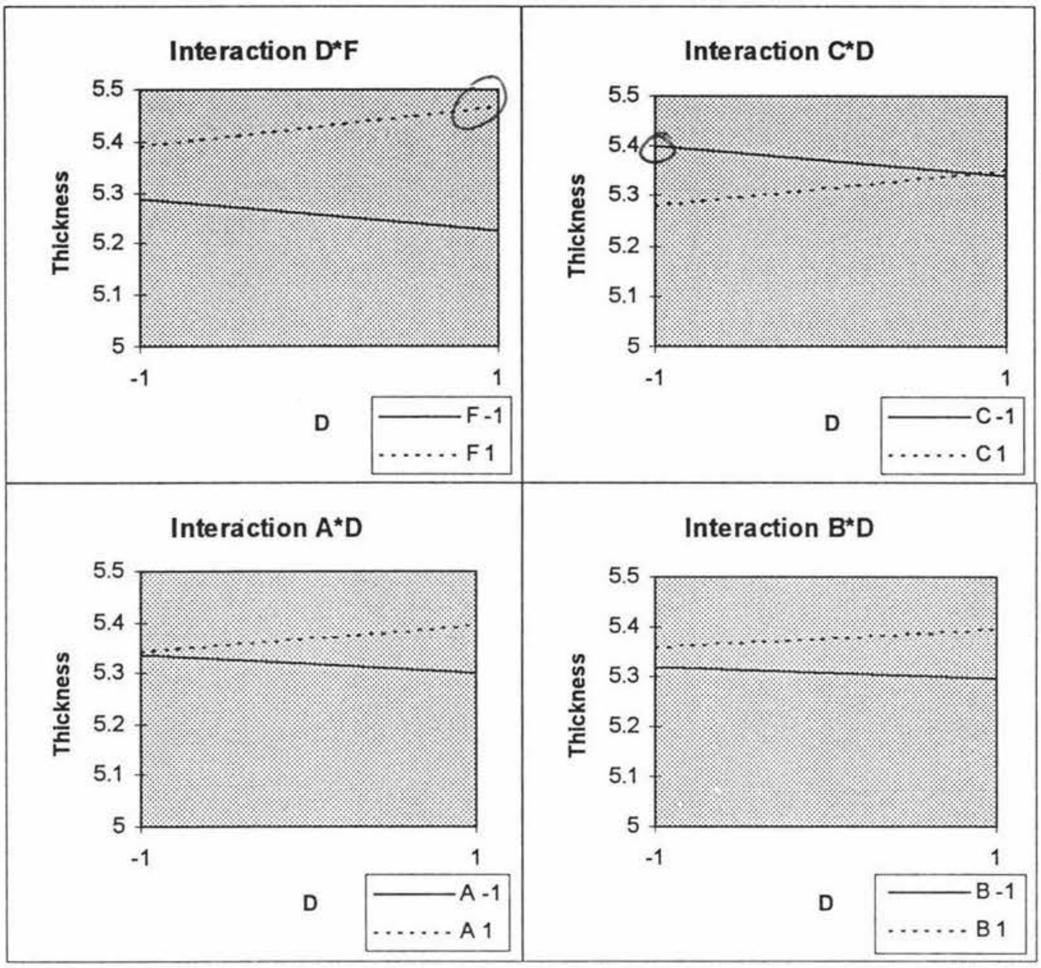


Figure 5.6 Isoplots for centre point thickness

- Nozzle / barrel temperature (F) and 2 Injection pressure (D) interaction

The nozzle / barrel temperature has a little difference when the second injection pressure is low. However, it has a significant difference when the second injection pressure is high (Figure 5.6).

The best input levels for the highest centre point thickness are:

	Control Factors	Level	2 Inj Pres (D)	Remarks
F	Nozzle / Barrel Temperature	+	+	Mean: 5.470

- 1 Injection Pressure (C) and 2 Injection pressure (D) interaction

Figure 5.6 shows that the highest centre point thickness can be obtained from the low level of the first injection pressure and the low level of the second injection pressure as follows:

	Control Factors	Level	2 Inj Pres (D)	Remarks
C	1 Injection Pressure	-	-	Mean: 5.400

As the second injection pressure is increased, the effect of the first injection pressure is reduced and may even be reversed.

- 1 Injection Time (A) and 2 Injection pressure (D) interaction

Figure 5.6 shows that the highest centre point thickness was produced from the high level of the first injection time and the high level of the second injection pressure as follows:

	Control Factors	Level	2 Inj Pres (D)	Remarks
A	1 Injection Time	+	+	Mean: 5.393

At the second injection pressure is low, the effect of the first injection time is reduced to approximately zero.

- 2 Injection Time (B) and 2 Injection pressure (D) interaction

The highest centre point thickness was produced from the high level of the second injection time and the high level of the second injection pressure.

	Control Factors	Level	2 Inj Pres (D)	Remarks
B	2 Injection Time	+	+	Mean: 5.398

Figure 5.6 shows that at the low level of the second injection pressure, the second injection time has a little effect on the centre point thickness.

5.4.3.3 Input levels to obtain the lowest centre point shrinkage

The treatment combination of the run # 44 produced the highest centre point thickness as follows:

Run	A	B	C	D	E	F	Thickness
# 44	+	+	-	+	-	+	5.5884

Therefore, the best process input levels to obtain the highest centre point thickness from the given two input levels are shown in the Table 5.10. As the main factors have more significant effect than the two and more factor interactions, the treatment combination for the highest centre point thickness is same as the main factor effect analysis results.

	Control Factors	Low (-)	High (+1)
A	1 Injection Time	50	**80**
B	2 Injection Time	50	**80**
C	1 Injection Pressure	**20**	50
D	2 Injection Pressure	20	**50**
E	2 Injection Speed	**30**	80
F	Nozzle and Barrel Temperature	200	**240**

Table 5.10 The best input levels for the highest thickness

5.4.4 Product length

Minimising the product shrinkage to obtain the designed product length is another important characteristic for product quality. The object of product length analysis was to determine the factors which have the major effect on product length.

An order of significance of the first 9 effects for the product length is shown in the Figure 5.7 and Table 5.11, and the detail analysis results are shown in the Appendix E (Analysis results from Minitab).

This analysis shows that the main factors and the two factor interactions influence the product length significantly, whereas three or more factor interactions have a very limited effect which is similar to the centre point shrinkage (thickness) analysis.

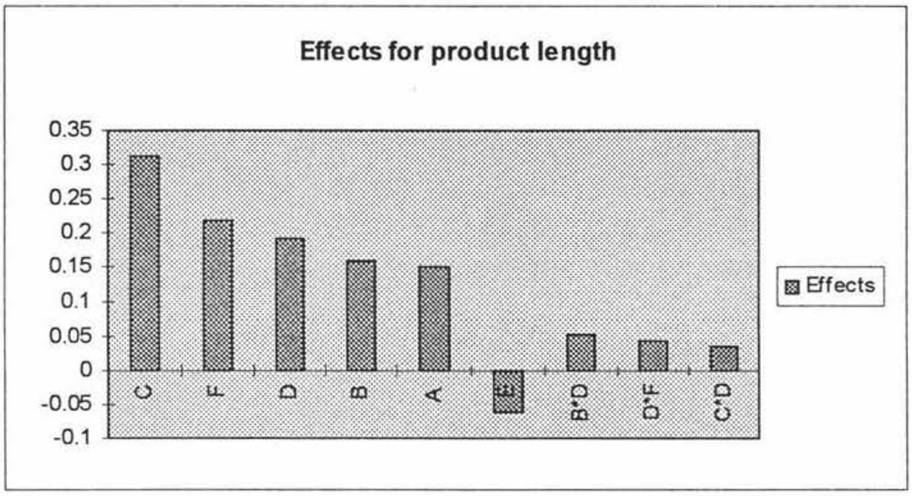


Figure 5.7 Significant effects for product length

	Factors and interactions	Effects	Abs(eff)	P values
C	1 Injection Pressure	0.3128	0.3128	0.000
F	Nozzle and Barrel Temperature	0.2183	0.2183	0.000
D	2 Injection Pressure	0.1926	0.1926	0.000
B	2 Injection Time	0.1606	0.1606	0.000
A	1 Injection Time	0.1503	0.1503	0.000
E	2 Injection Speed	-0.0625	0.0625	0.000
B*D	2 Injection Time & 2 Injection Pressure interaction	0.0514	0.0514	0.000
D*F	2 Injection Pressure & Temperature	0.0431	0.0431	0.000
C*D	1 Injection Pressure & 2 Injection Pressure Interaction	0.0340	0.0340	0.000

Table 5.11 Significant effect order and their absolute effect value

5.4.4.1 Main factor effects for product length

The average product length for each factor's two level is shown on the Table 5.12. Figure 5.8 shows the graphical analysis for the product length from the main 6 factors low and high input levels.

Minimum shrinkage and maximum product length can be obtained when input levels are set at the high input levels, except for the second injection speed. The optimum input levels which produce the least product length shrinkage are shown on the Table 5.13.

	Control Factors	Low (-1)	High (+1)
A	1 Injection Time	98.34	98.49
B	2 Injection Time	98.33	98.49
C	1 Injection Pressure	98.25	98.57
D	2 Injection Pressure	98.31	98.51
E	2 Injection Speed	98.44	98.38
F	Nozzle and Barrel Temperature	98.30	98.52

Table 5.12 Average product length from different input levels

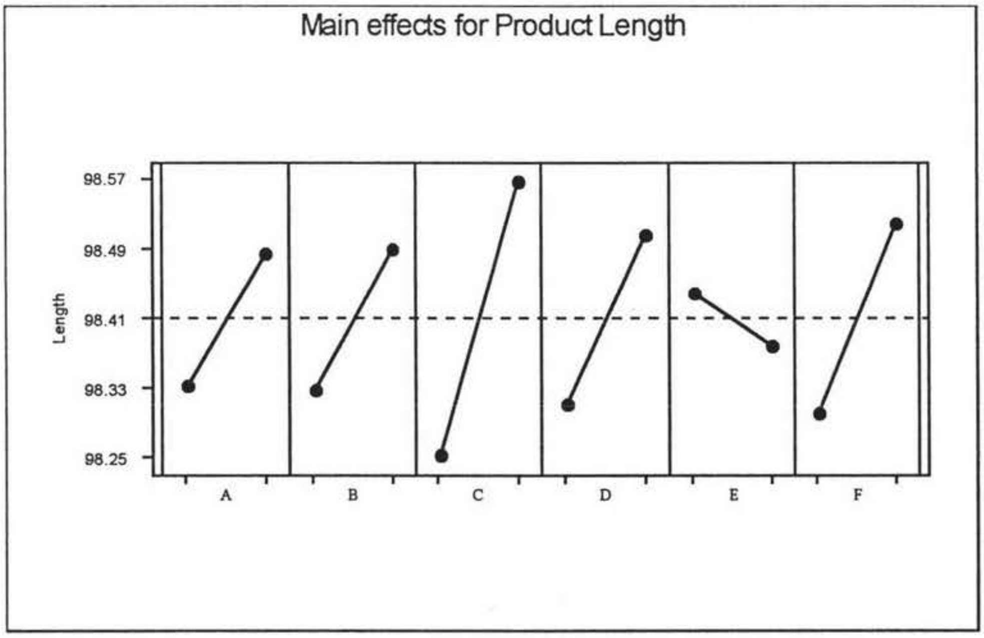


Figure 5.8 Graphical analysis for product length

	Control Factors	Low (-1)	High (+1)
A	1 Injection Time	50	**80**
B	2 Injection Time	50	**80**
C	1 Injection Pressure	20	**50**
D	2 Injection Pressure	20	**50**
E	2 Injection Speed	**30**	80
F	Nozzle and Barrel Temperature	200	**240**

Table 5.13 Main factor effect analysis results for product length

5.4.4.2 Two factor interactions for product length

The figure 5.9 shows that there are three significant two-factor interactions which affect the product length significantly.
These interactions are:

2 Injection Time (B) * 2 Injection Pressure (D)
Temperature (F) * 2 Injection Pressure (D)
1 Injection Pressure (C) * 2 Injection Pressure (D)

The second injection pressure which is involved in these three interactions, acts as an important factor for interactions. The detailed analysis results for two factor interactions are shown in Appendix E (Analysis results from Minitab), and these three significant interactions are plotted as isoplots in Figure 5.9.

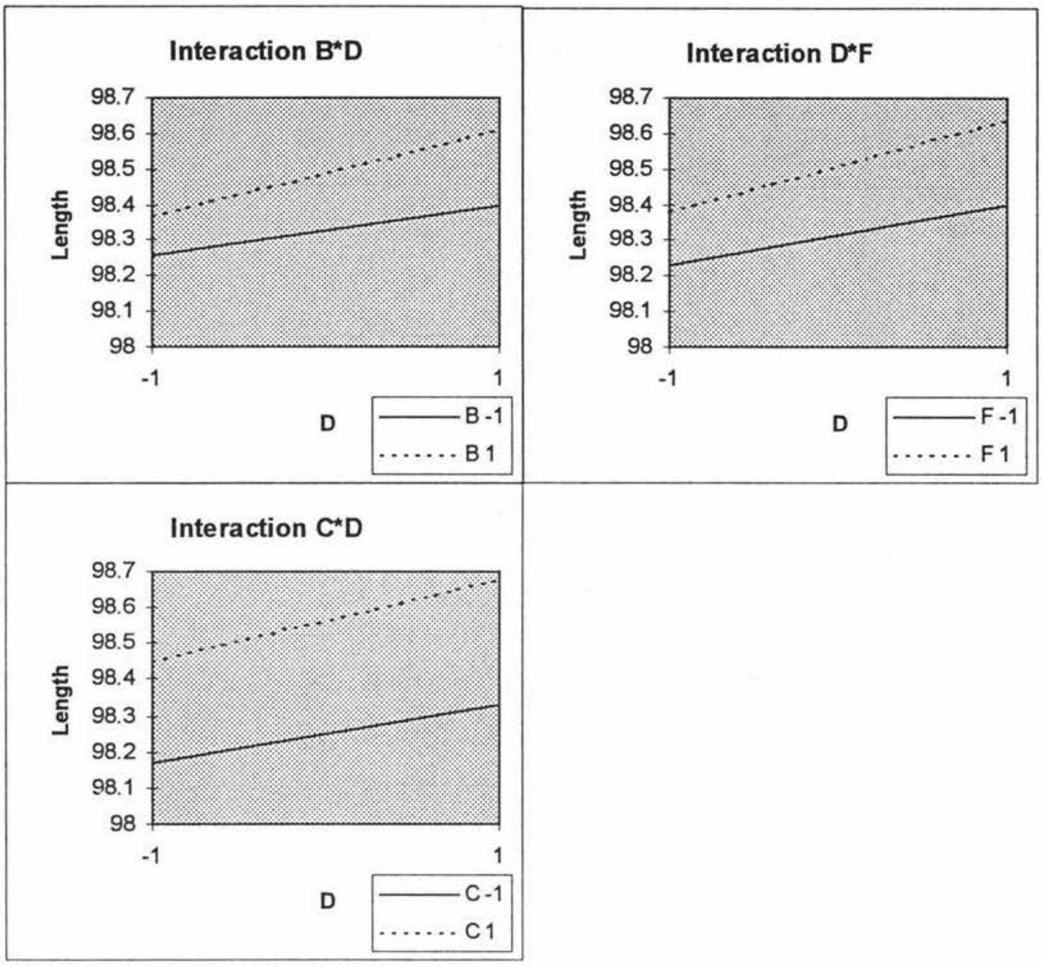


Figure 5.9 Isoplots for product length

- 2 Injection Time (B) and 2 Injection Pressure (D) interaction

The greatest product length is produced from the high level of the second injection time and the high level of the second injection pressure.

The best input levels for the maximum product length are:

	Control Factors	Level	2 Inj Pres (D)	Remarks
B	2 Injection Time	+	+	Mean: 98.61

As the second injection pressure is increased, the effect of the second injection time is increased.

- Nozzle / barrel temperature (F) and 2 Injection pressure (D) interaction

The greatest product length (i.e least shrinkage for the range of treatment combination s used) is produced from the high level of the nozzle/barrel temperature and the high level of the second injection pressure (Figure 5.9).

The best input levels for the maximum product length are:

	Control Factors	Level	2 Inj Pres (D)	Remarks
F	Nozzle / Barrel Temperature	+	+	Mean: 98.64

Again, as the second injection pressure is increased, the effect of the temperature is increased.

- 1 Injection pressure (C) and 2 Injection pressure (D) interaction

The greatest product length is produced from the high level of the first injection pressure and high level of the second injection pressure. The best input levels for the maximum product length are:

	Control Factors	Level	2 Inj Pres (D)	Remarks
C	1 Injection Pressure	+	+	Mean: 98.68

The figure 5.9 shows that as the second injection pressure is increased, the effect of the first injection pressure is increased.

5.4.4.3 Input levels to obtain the lowest length shrinkage

The treatment combination of the run # 48 produced the greatest product length as follows:

Run	A	B	C	D	E	F	Length
# 48	+	+	+	+	-	+	98.946

Therefore, the best process input levels to obtain the lowest product length shrinkage from the given two input levels are shown in the Table 5.14. Again, as the main factors have more significant effect than the two and more factor interactions, the treatment combination for the greatest product length is same as the main factor effect analysis results.

	Control Factors	Low (-)	High (+1)
A	1 Injection Time	50	**80**
B	2 Injection Time	50	**80**
C	1 Injection Pressure	20	**50**
D	2 Injection Pressure	20	**50**
E	2 Injection Speed	**30**	80
F	Nozzle and Barrel Temperature	200	**240**

Table 5.14 Input levels for the lowest length shrinkage

5.4.5 Product weight

The product weight has a strong relationship with the product shrinkage, because the more polymer material is used the weight increases and this reduces dimensional shrinkage. Whereas, using less polymer material can save the raw polymer material, but the shrinkage rate will be increased. For this experimental designed analysis, the maximum product weight was chosen as the product quality characteristic.

Figure 5.10 shows significance order for the factors affecting the product weight from the first to the ninth in order of significance, and the effects are displayed on Table 5.15.

The effects of main factors and the two factor interactions are considered significant, however, three or more factors interactions are not considered significant. The detail analysis result is shown in Appendix E (Analysis results from Minitab).

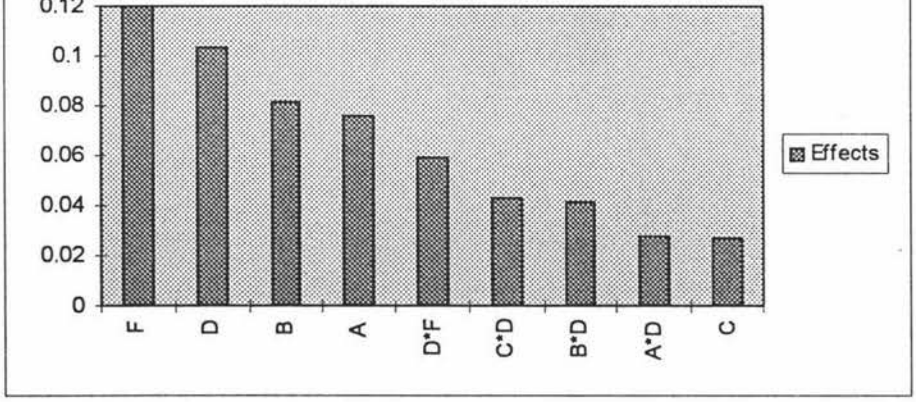


Figure 5.10 Significant effects for product weight

	Factors and interactions	Effects	Abs(eff)	P value
F	Nozzle / Barrel Temperature	0.11977	0.11977	0.000
D	2 Injection Pressure	0.10334	0.10334	0.000
B	2 Injection Time	0.08155	0.08155	0.000
A	1 Injection Time	0.07608	0.07608	0.000
D*F	2 Injection Pressure & Temperature Interaction	0.05898	0.05898	0.000
C*D	1 & 2 Injection Pressure Interaction	0.04291	0.04291	0.000
B*D	2 Injection Time & 2 Injection Pressure Interaction	0.04133	0.04133	0.000
A*D	1 Injection Time & 2 Injection Pressure Interaction	0.02817	0.02817	0.000
C	1 Injection Pressure	0.02750	0.02750	0.000

Table 5.15 Significant effect order and their absolute effect value

5.4.5.1 Main factor effects for product weight

For the main factor effect analysis, the average product weight from low input level and high input level is shown on the Table 5.16.

The figure 5.11 shows that the second injection pressure and the nozzle and barrel temperature have a relatively large effect for the product weight. Whereas, the second injection speed has a very small effect compared with the other six main factors. The optimum input levels to obtain maximum product weight are shown on the Table 5.17.

	Control Factors	Low (-1)	High (+1)
A	1 Injection Time	9.2625	9.3385
B	2 Injection Time	9.2600	9.3410
C	1 Injection Pressure	9.2865	9.3140
D	2 Injection Pressure	9.2485	9.3520
E	2 Injection Speed	9.3110	9.2900
F	Nozzle and Barrel Temperature	9.2405	9.3605

Table 5.16 Average product weight from different input levels

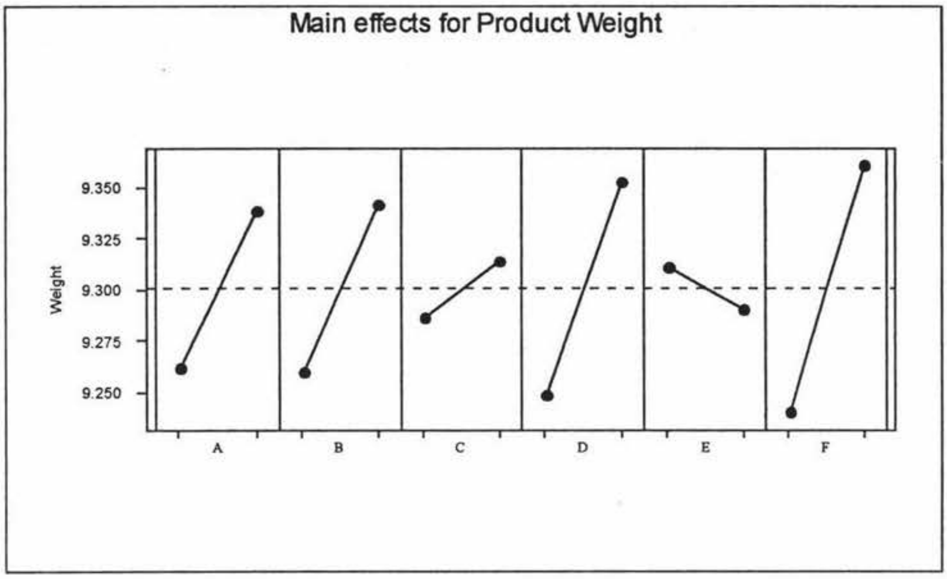


Figure 5.11 Graphical analysis for product weight

	Control Factors	Low (-1)	High (+1)
A	1 Injection Time	50	80
B	2 Injection Time	50	80
C	1 Injection Pressure	20	50
D	2 Injection Pressure	20	50
E	2 Injection Speed	30	80
F	Nozzle and Barrel Temperature	200	240

Table 5.17 Main factor effect analysis results for product weight

5.4.5.2 Two factor interactions for product weight

The figure 5.10 shows that there are four two-factor interactions which affect the product weight significantly. Therefore, the two-factor interaction analysis was necessary to define the main factor's relationship and to determine the best input levels for the greatest product weight.

The significant two-factor interactions are:

Temperature (F) * 2 Injection Pressure (D)
1 Injection Pressure (C) * 2 Injection Pressure (D)
2 Injection Time (B) * 2 Injection Pressure (D)
1 Injection Time (A) * 2 Injection Pressure (D)

The second injection pressure (D) which involves all the significant interactions, acts as an important factor for the interaction effects. The detailed analysis results for two factor interactions are shown in Appendix E (Analysis results from Minitab), and the four significant interactions are plotted as isoplots in Figure 5.12.

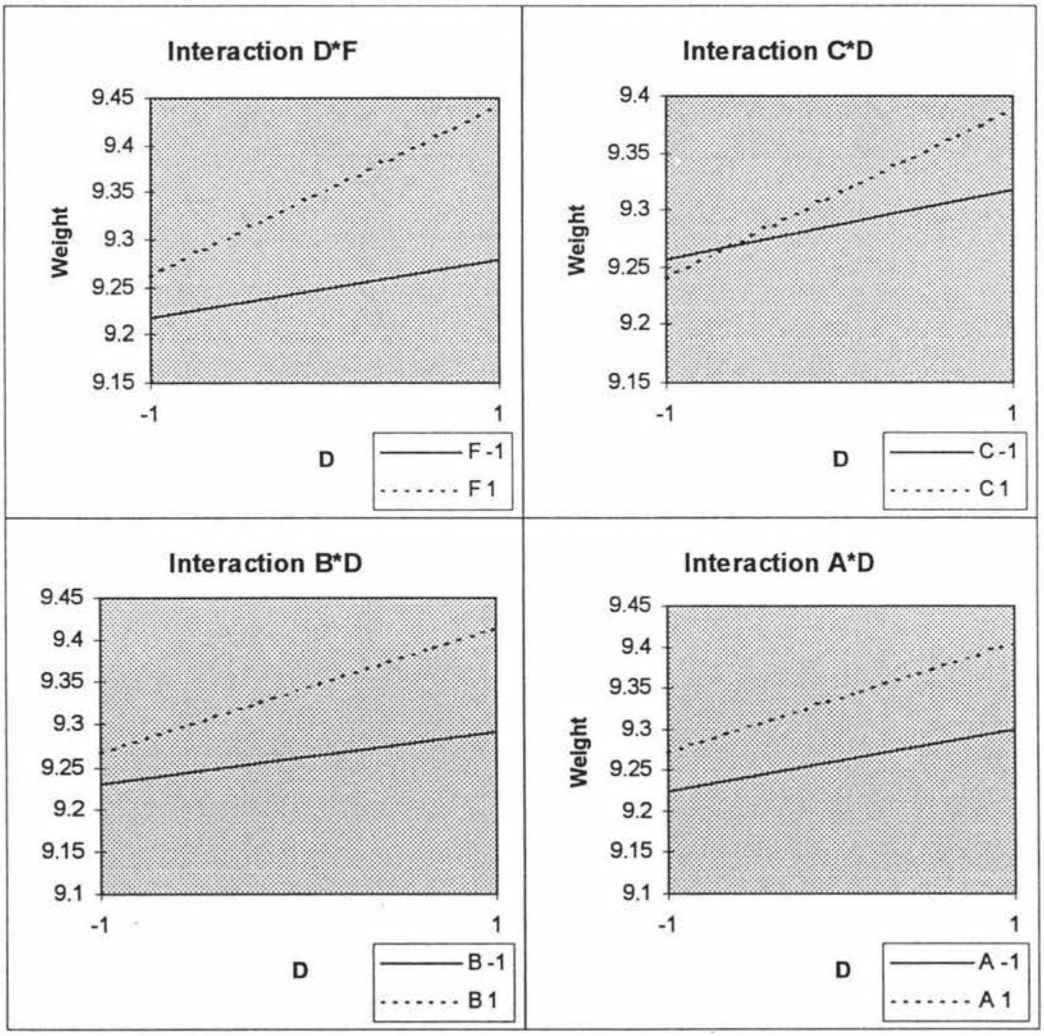


Figure 5.12 Isoplots for product weight

- Nozzle / barrel temperature (F) and 2 Injection pressure (D) interaction

The nozzle / barrel temperature has relatively little effect when the second injection pressure is low. Whereas, it has a significant effect when the second injection pressure is high.

The best input levels to obtain the greatest product weight are:

	Control Factors	Level	2 Inj Pres (D)	Remarks
F	Nozzle / Barrel Temperature	+	+	Mean: 9.441

- 1 Injection Pressure (C) and 2 Injection pressure (D) interaction

The greatest product weight was produced from the high level of the first injection pressure and the high level of the second injection pressure.

The best input levels for the maximum product weight are:

	Control Factors	Level	2 Inj Pres (D)	Remarks
C	1 Injection Pressure	+	+	Mean: 9.387

As the second injection pressure is increased, the effect of the first injection pressure has a higher effect on the product weight.

- 2 Injection Time (B) and 2 Injection pressure (D) interaction

The greatest product weight was produced from the high level of the second injection time and the high level of the second injection pressure.

The best input levels for the maximum product weight are:

	Control Factors	Level	2 Inj Pres (D)	Remarks
B	2 Injection Time	+	+	Mean: 9.414

Again, as the second injection pressure is increased, the effect of the second injection time has a higher effect on the product weight.

- 1 Injection Time (A) and 2 Injection pressure (D) interaction

The greatest product weight was produced from the high level of the first injection time and the high level of the second injection pressure. The best input levels for the greatest product weight are as follows:

	Control Factors	Level	2 Inj Pres (D)	Remarks
A	1 Injection Time	+	+	Mean: 9.404

5.4.5.3 Best input levels to produce the highest product weight.

The treatment combination of the run # 48 produced the greatest product weight as follows:

Run	A	B	C	D	E	F	Length
# 48	+	+	+	+	-	+	98.541

Therefore, the best process input levels to obtain the greatest product weight from the given two input levels are shown in the Table 5.18. Again, as the main factors have more significant effect than the two and more factor interactions, the treatment combination for the greatest product weight is same as the main factor effect analysis results.

	Control Factors	Low (-)	High (+1)
A	1 Injection Time	50	**80**
B	2 Injection Time	50	**80**
C	1 Injection Pressure	20	**50**
D	2 Injection Pressure	20	**50**
E	2 Injection Speed	**30**	80
F	Nozzle and Barrel Temperature	200	**240**

Table 5.18 Input levels for the greatest product weight

5.5 Summary and conclusions

A Plackett-Burman design was used for screening the input factors, and Full Factorial design was used to define and analyse the chosen factors' effects and their interactions. From the results, the main factors and the two-factor interactions are more significant than the three or more factor interactions. The second injection pressure acts as an important factor for all two-factor interactions connected with centre point shrinkage, product length and product weight.

From the given high and low input levels, the best machine input levels to obtain the lowest centre point shrinkage, the greatest product length and the greatest product weight are summarised on the Table 5.10, 5.14 and 5.18.

The results of this experimental design can be explained, in that, higher nozzle and barrel temperatures loosen the molecular bonding of the polymer material, and a higher injection pressure forces or packs the material into the cavity, which reduces the dimensional shrinkage rate, but requires more polymer material.

Chapter 6

Discussion and Conclusions

This chapter discusses the achievements from this research project and makes recommendations for further studies.

6.1 Introduction

Computer based quality control methods are widely used in manufacturing industry with the spread of low-cost personal computers and the availability of spreadsheets and statistical software packages. In spite of this, most quality data is still being collected manually by the operator or inspector, and statistical quality control methods are limited in use.

This research project has been focused on developing two advanced quality control methods; computer-based on-line quality data acquisition, integrated with Design of experiments (DOE) for product quality improvement. A low cost quality data acquisition system was developed for process and product data collection from injection moulding. The collected data was then analysed using Minitab to implement the experimental design methods.

In this chapter, general discussions and conclusions resulting from this research project are identified and developed. For further studies, recommendations for useful future work will be identified.

6.2 On-line quality data acquisition

Many different kinds of sensing devices and data acquisition systems are available on the instrumentation market. Unfortunately, most of the systems require significant amount of initial investments to apply to particular plant or machinery.

This research concentrated on developing a low cost quality data acquisition system which can be adapted easily to all plastic injection moulding machines without sacrificing the operating speed and data accuracy.

The Automatic Quality Data Acquisition System (AQDAS) which is a computer based on-line quality data acquisition system, was successfully developed and implemented on an injection moulding machine. The process and the product quality information were displayed in real-time on the data collection computer, enabling the operator to react, if necessary to any problem detected in the process. In addition, significant time reduction was achieved from the automation of this data collection and analysis for quality improvement. The manually measured quality data concerning the product was automatically collected through the serial communication ports, and analysed by the statistical software packages in conjunction with the process data from sensors.

6.3 'Design of experiments' for quality improvement

'Design of experiments (DOE)', the methods known as the hidden tools of Japanese economic success, are increasingly used in manufacturing industry. In spite of its great possibilities for quality improvement, DOE has been used only in a limited number of plants. The main reason maybe that this method requires a strong background of applied statistics. As most of the operators or engineers in industry are not familiar with this advanced statistical method, its limited implementation is unavoidable.

With a help of many software packages which have been developed for statistical quality control activities, DOE can be implemented with basic training in the package usage.

Two methods were used for this research, Plackett-Burman design and Factorial two-level design, for screening and analysis respectively. The Plackett-Burman design screened the key factors from the many input process parameters. The key factors effects were then analysed using the Factorial two-level design. From this analysis, the relationship between process parameters and the product quality characteristics was explained and understood in scientific terms.

The two methods used for this research were relatively simple compared with other methods, such as response surface methods. There are currently efforts to develop relatively simple 'design of experiments' methodologies which can be easily implemented in the industry. 'Taguchi methods' which were developed by Dr. Taguchi (1986), can be viewed as perhaps the most significant development. It has been more than a decade since Taguchi's experimental design methods were introduced to industry. His methods to reduce the variation in products and processes have generated a great deal of interest among both quality practitioners and statisticians. Also, it has been on the topic of discussions for many quality "gurus," especially the Signal-to-Noise ratio (S/N) concept which is central Taguchi methods.

Hunter (1987) insists that S/N ratio, $\log(\bar{Y}/s^2)$, "should not be used", and explains that "the S/N is the log of the square of the estimate of the reciprocal of the coefficient of variation." On the other hand, Barker (1989) strongly suggests learning Taguchi methods to improve the product quality, and explains that "the S/N ratio is a transform of the fundamental basis of the Taguchi's philosophy of quality....not the inverse of the coefficient of variation." Both are in their own way correct, but the Taguchi methodology gives a number of advantages in its approach to the management of variation.

Initially, the research project was planned to compare traditional experimental design methods with Taguchi methods. However, a significant amount of time was spent to develop the on-line quality data acquisition system. Therefore, the initial project plan was changed to use only the traditional experimental design methods, factorial two-level design. The Minitab program had several kinds of experimental design functions including Factorial two-factor design, and executing the design of experiments methods in the Minitab environment was very simple.

6.4 Recommendations for further studies

The sensors used for this research were simple and low cost instruments were used to keep the total cost of data collection system down. A mechanical pressure measuring instrumentation was devised for this research. This maybe difficult to use in the plastic industry as it requires relatively large space on the mould. Using the advanced pressure sensors, such as a diaphragm pressure transducer, would be more suitable both to researchers and the plastic industry. Collecting the cavity injecting temperature from the melt thermocouple was not successful as its steel sheath had considerable thermal 'inertia' and a relatively low thermal conductivity. The best place for this type of thermocouple is the injection barrel which keeps a relatively consistent temperature.

A simple flat plastic product was produced for this research project to study dimensional shrinkage. Factors for minimising of shrinkage were successfully obtained by the experimental design analysis. For further studies, a more complex product is recommended to be used. This design should also be related to analysis using the 'Moldflow', a polymer flow simulation software.

The mould temperature control is considered as one of the most significant input factors which affect the plastic product quality characteristics. It is recommended to use a water cooled mould for further experiments and consider the mould temperature as another key input factor.

On the experimental analysis phases, the collected quality data on the shop floor computer was analysed on the supervisory computer without connection to the Massey network due to a lack networking facilities in the Industrial Engineering Laboratory at that time. A suitable networking system is essential for the practical use of this data collection and analysis system.

Useful direction would be the development of a closed-loop control system for product quality improvement. The previous generation of quality control activities were done manually, with manual data collection and analysis. Now, parts of these activities are being implemented using computers, for example, the automatic data acquisition and statistical analysis is now implemented but at this stage the process does not have an automatic control feedback function. This open-loop control concept was applied to this research project. The process and product quality data were collected automatically on the shop floor computer and analysed by the 'Minitab' program. Then, the machine adjustment was done by manually according to the analysed results.

The next generation should use closed-loop quality control methods which collect the required quality data automatically, analyse the data by sophisticated statistical software packages, and feed back the analysed result to the process.

The current trends of quality improvement lay more stress on the quality management concepts than on quality measurement and analysis technology, such as the computer-oriented quality automation and statistical quality improvement methods. The quality management concepts stress the human and management aspects. On the other hand, the quality technology concepts stress the computerised automation. When these two concepts are developed and applied together for quality improvement activities in industry, better results should be achieved.

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Appendix A

Injection Moulding Machine Specification

1. Injection Unit

Injection volumn (theoretical)		
	Ordinal Screw	171 cm^3
	Enlarged Screw	219 cm^3
	Diminished Screw	129 cm^3
Injection capacity (theoretical)		
	Ordinal Screw	180 *g*
	Enlarged Screw	230 *g*
	Diminished Screw	135 *g*
Screw diameter		
	Ordinal Screw	38 *mm*
	Enlarged Screw	43 *mm*
	Diminished Screw	33 *mm*
Screw L/D ratio		18 : 1
Screw speed range		20 - 175 *rpm*
Injection pressure (theoretical)		
	Ordinal Screw	1950 $kgf\ /\ cm^2$
	Enlarged Screw	1500 $kgf\ /\ cm^2$
	Diminished Screw	2590 $kgf\ /\ cm^2$
Injection speed		70 *mm/sec*
Plasticising capacity		50 *kg/hr*
Hopper capacity		35 *litre*
Nozzle stroke		20 *mm*
Nozzle contact force		3.6 *ton*

2. Clamping Unit

Clamping force	100 *ton*
Clamping stroke	300 *mm*
Tie bar diameter	60 *mm*
Distance between tie bar	355x355 *mm*
Platen size	535x535 *mm*

Mould thickness range	10 - 310 *mm*
Clamping speed	550 *mm/sec*
Opening speed	460 *mm/sec*
Ejector force	2.7 *ton*
Ejector stroke	75 *mm*
Ejector pin number	1 pc

3. Power Unit

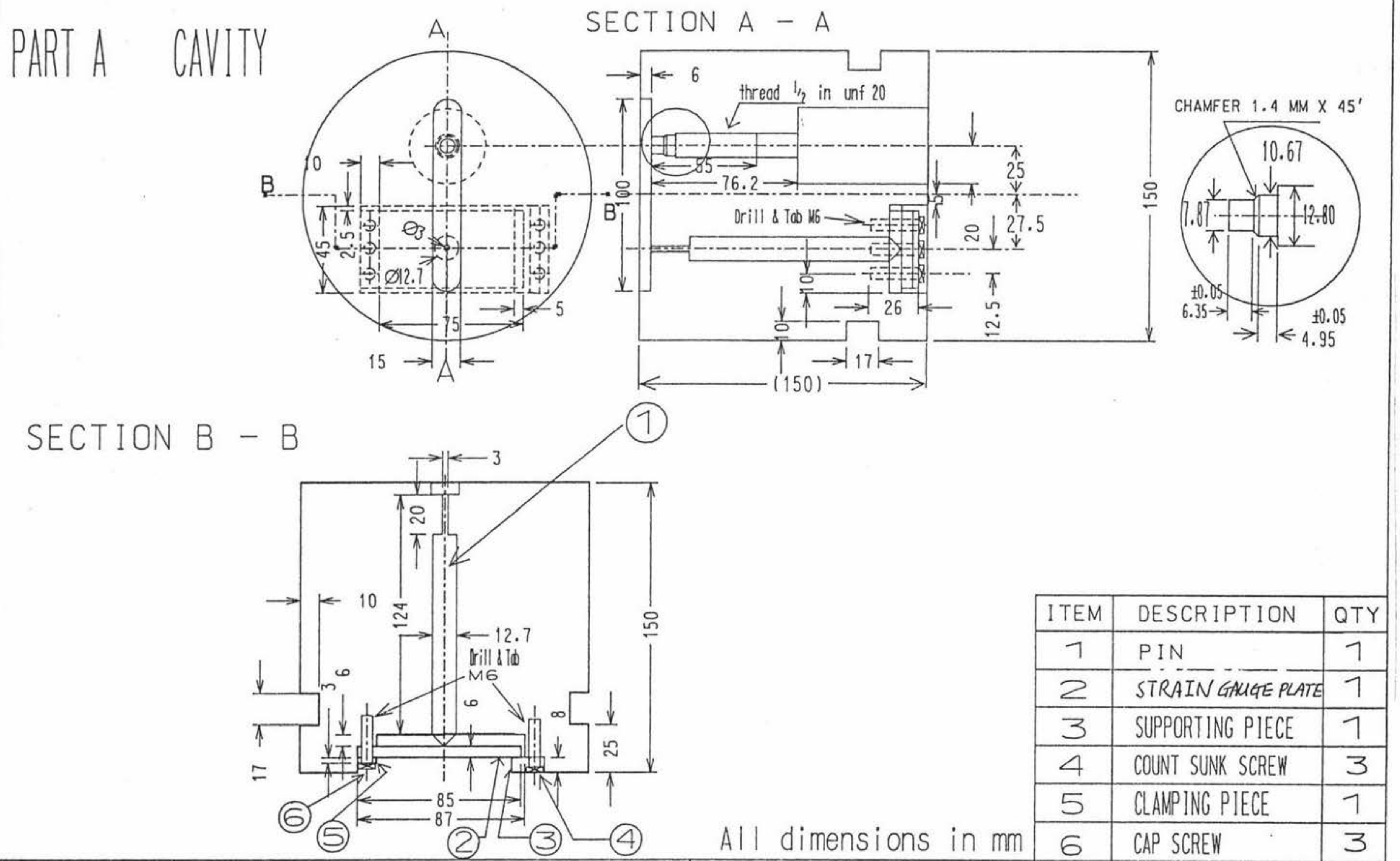
Control system voltage	DC 24 V
Electrical motor power	11 kw/4p
Motor speed range	1440 rpm
Pump capacity	76 lit/min
Heater input power	7.5 kw
Current requirement	41 A

4. General

Oil tank capacity	170 littre
Floor space	324x84 cm
Gross weight	2.7 ton

Appendix B

Mould Design Drawings



ITEM	DESCRIPTION	QTY
1	PIN	1
2	STRAIN GAUGE PLATE	1
3	SUPPORTING PIECE	1
4	COUNT SUNK SCREW	3
5	CLAMPING PIECE	1
6	CAP SCREW	3

All dimensions in mm

Title :
EXPERIMENTAL BLOCK MOULD PART A -CAVITY

General tolerance : ± 0.1 mm

DEPARTMENT OF PRODUCTION TECHNOLOGY
MASSEY UNIVERSITY

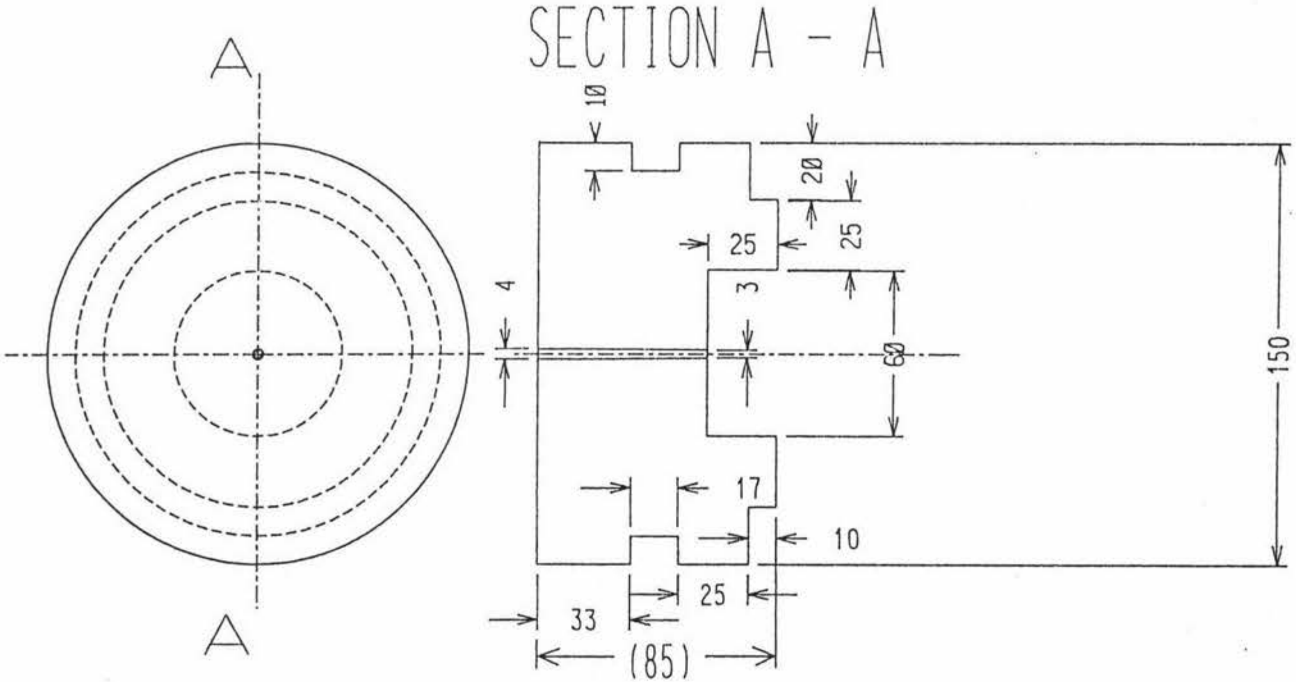
Material specification
PART A: STEEL

DRAWN BY: T. E. KIM

CHECKED BY:

DATE : MAR '95

PART B SPRUE



All dimensions in mm

TITLE
EXPERIMENTAL BLOCK MOULD PART B - SPRUE

GENERAL TOLERANCE ±0.1 MM

DEPARTMENT OF PRODUCTION TECHNOLOGY
MASSEY UNIVERSITY

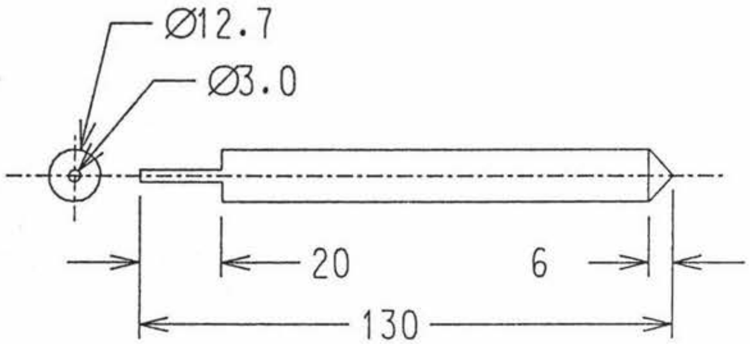
MATERIAL SPECIFICATION PART B: STEEL

DRAWN BY: T. E. KIM

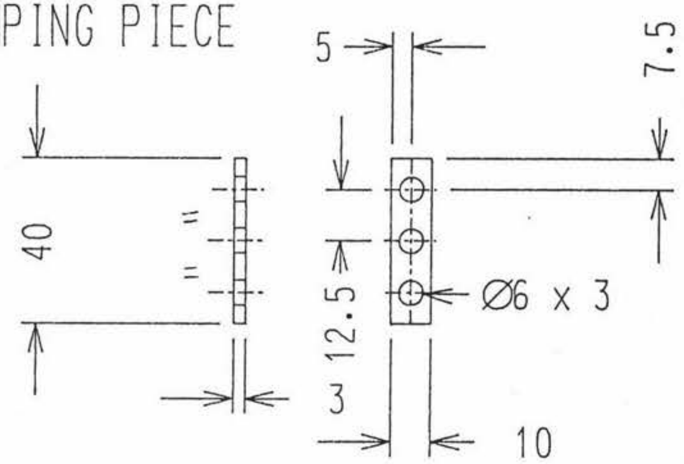
CHECKED BY :

DATE : MAR '95

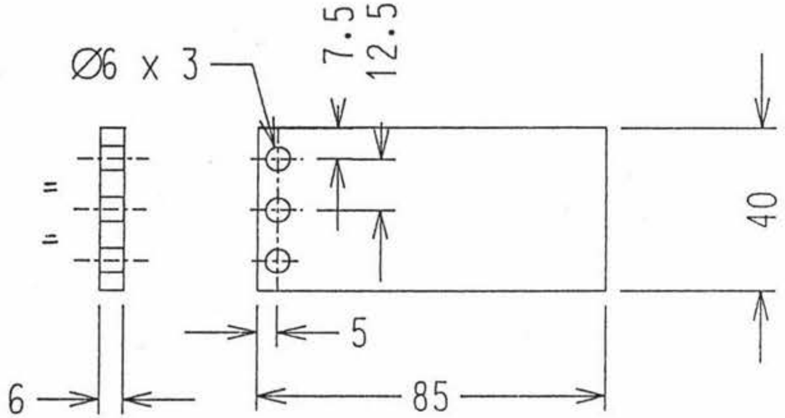
PRESSURE PIN



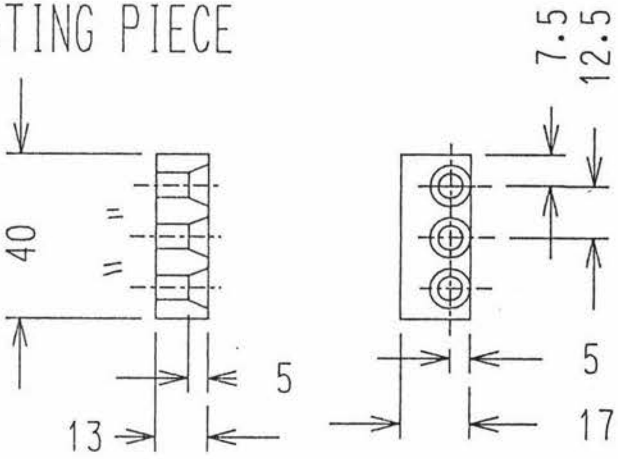
CLAMPING PIECE



STRAIN GAUGE PLATE



SUPPORTING PIECE



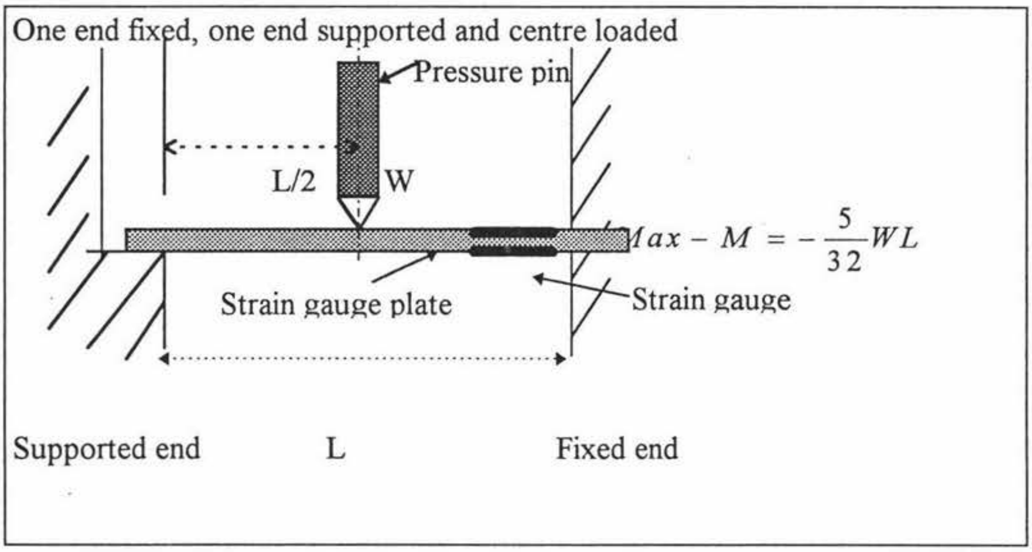
All dimensions in mm

Title : MOULD ASSEMBLY PARTS	General tolerance : ± 0.1 mm	DEPARTMENT OF PRODUCTION TECHNOLOGY MASSEY UNIVERSITY
Material specification : STEEL	DRAWN BY: T. E. KIM	CHECKED BY:
		DATE: APR. '95

Appendix C

Design calculations for strain gauges

As the pressure pin method was chosen to collect the injection pressure data (see Chapter 3), the design specifications for the strain gauge plate and the pressure pin were important considerations. The spring steel and the silver steel were chosen for the strain gauge plate and the pressure pin respectively.



A certain size of spring steel, 6 mm thickness and 40 mm width, was available in the Department of Production Technology. Therefore, this size of spring steel was decided to be used for the experiments.

To decide the length of the strain gauge plate and the diameter of the pressure pin, the used formulas and calculations are as follows:

$$\sigma = E \times \varepsilon$$

$$\sigma = \frac{M \times y}{I}$$

$$M = \frac{5}{32} W L$$

$$I = \frac{b d^3}{12}$$

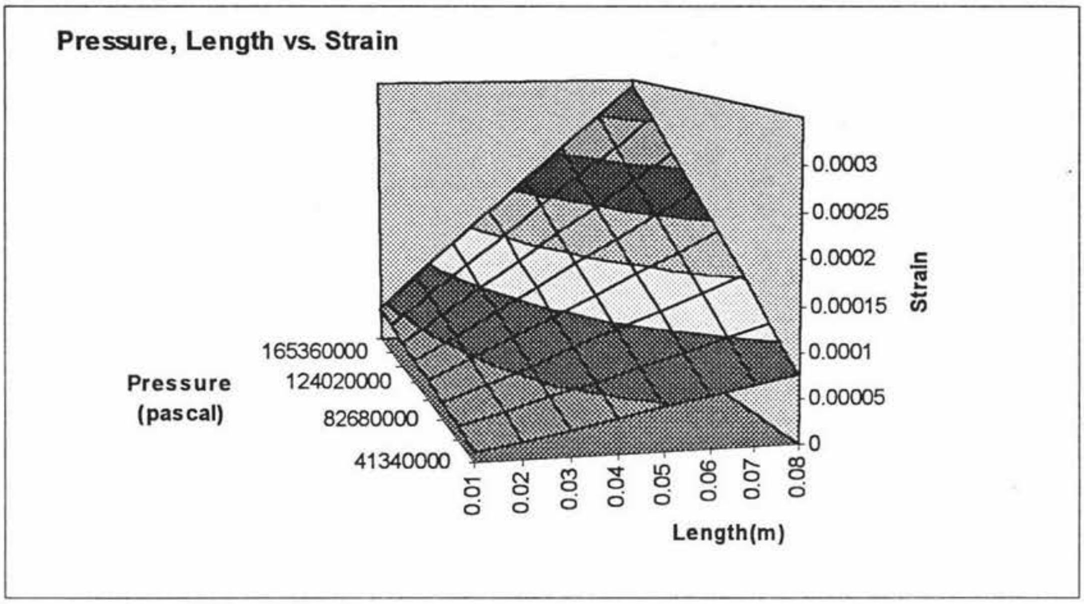
where, σ : Stress
E : Young's modular
ε : Strain
M : Bending moment
I : Second bending moment
y : Bending distance ($d / 2$ was chosen)
W : Force
b : Width of the strain gauge plate
d : Thickness of the strain gauge plate

The desirable strain (ε) from the strain gauge was recommended as 300με when the safety of the strain gauge circuit was considered. Also, the Young's modular for the steel (E) is 200 GN/m².

The following data was calculated with the consideration of the spring steel specification (6 mm thickness, and 40 mm width).

	Length (m)							
Press(pa)	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08
41340000	9.51E-06	1.9E-05	2.85E-05	3.8E-05	4.76E-05	5.71E-05	6.66E-05	7.61E-05
62010000	1.43E-05	2.85E-05	4.28E-05	5.71E-05	7.13E-05	8.56E-05	9.99E-05	0.000114
82680000	1.9E-05	3.8E-05	5.71E-05	7.61E-05	9.51E-05	0.000114	0.000133	0.000152
1.03E+08	2.38E-05	4.76E-05	7.13E-05	9.51E-05	0.000119	0.000143	0.000166	0.00019
1.24E+08	2.85E-05	5.71E-05	8.56E-05	0.000114	0.000143	0.000171	0.0002	0.000228
1.45E+08	3.33E-05	6.66E-05	9.99E-05	0.000133	0.000166	0.0002	0.000233	0.000266
1.65E+08	3.8E-05	7.61E-05	0.000114	0.000152	0.00019	0.000228	0.000266	0.000304
1.86E+08	4.28E-05	8.56E-05	0.000128	0.000171	0.000214	0.000257	0.0003	0.000342

*** Pressure from 6000PSI to 27000PSI.**



Therefore the specifications of the strain gauge plate and the pressure pin were decided as follows:

1. Pin diameter : 5 mm
2. Spring steel thickness : 6 mm
3. Spring steel width : 40 mm
4. Spring steel length : 70 mm

Appendix D

AQDAS Main Program

```
{***************************************************************************
 *Revised
 *      5 June 1995 - Strain gauge calibration program
 *      6 June 1995 - Vernier calliper data receiving program
 *     14 June 1995 - Seperate, i) Process, ii) Product data program
 *     15 June 1995 - Redesign monitoring screen
 *     27 June 1995 - Changed the strain gauge data conversion equation
 ***************************************************************************}

Program DAQ16;

uses  daq_6_b, async4ub, gamefoot, crt, dos;

var
  ch          : char;
  f_ch        : char;
  done        : boolean;
  channel     : integer;
  resolution  : integer;
  resolution_new: integer;
  c           : integer;
  ok          : boolean;

  data_no     : integer;
  avg_data_no  : integer;
  result_1     : longint;
  result_1_1   : longint;
  result_2     : longint;
  result_3     : longint;
  result_4     : longint;
  total_2      : real;
  total_3      : real;
  total_4      : real;
  pressure     : real;
  average_pressure : real;
  original_pressure: real;
  compensation  : real;
  pressure_final: real;
  cavitytemp    : real;
  cavity_final  : real;
  nozzletemp    : real;
  nozzle_final  : real;
  average_no    : integer;
  first_pressure: real;
  last_pressure : real;
```

```
 area        : real;
 range       : longint;
 adc_com     : integer;
 scale_com   : integer;
 vernier_com : integer;

 YorN        : char;
 address_process      : string[64];
 address_process_new  : string[64];
 address_sub          : string[64];
 address_sub_new      :string[64];
 address_product      : string[64];
 address_product_new  : string[64];
 outfile_process      : text;
 outfile_sub          : text;
 outfile_product      : text;
 inchar      : char;
 outchar     : char;
 cr          : char;
 count       : integer;
 length      : char;
 width       : char;
 thickness   : char;

(***************************************************************************
         Injection Process Data Receiving
         Strain Gauge:  Data14=6509+13.2*Weight14
                        Data12=1643+3.22*Weight12
***************************************************************************)

Procedure ProcessData;

label  400;

begin

  assign (outfile_process,address_process);
  assign (outfile_sub, address_sub);
  rewrite (outfile_process);
  rewrite (outfile_sub);

  average_no := 0;

  {open up for business}
  ok := adc16_driver_open (adc_com);

  clrscr;

  writeln ('******** ******** ******** ******** ');
  writeln ('  Data   Cavity P  Cavity T  Nozzle T ');
  writeln ('  No.     (MPa)     ("C)      ("C) ');
  writeln ('******** ******** ******** ******** ');

  repeat
```

```
result_1  := 0;
result_2  := 0;
result_3  := 0;
result_4  := 0;
data_no   := 0;
total_2   := 0;
total_3   := 0;
total_4   := 0;

{open channel 1 for trigger monitor, when switch is on, out this repeat}

  repeat
    repeat
    ok:= adc16_get_value (result_1, 1, resolution, TRUE);
    until result_1 <> 0;

    if result_1 > range then begin
      window (1,22,80,25);
      clrscr;
      gotoxy (1,22);
      writeln ('>>>> Moulder is open.');
    end

  until result_1 < range;

clrscr;
gotoxy (1,22);

writeln ('>>>>>>>>>>      Instruction Message       <<<<<<<<<<<');
writeln ('Receiving data now....');

window (1,5,80,21);
gotoxy (1,5);
clrscr;

400:

repeat

  {Data Number}

  inc (data_no);
  write (data_no:8);
  write (outfile_sub,data_no:8);
  {receive Cavity Pressure data from channel 4}

  ok:=adc16_get_value (result_4, 4, resolution, TRUE);

  if ok then begin
      pressure:=result_4 - compensation;

      if resolution =14 then
        pressure := ((pressure-6509)/13.2)
```

```
            /(0.0025*0.0025*3.141592)*9.80665/1000000;

  if resolution =12 then
    pressure := ((pressure-1643)/3.22)
            /(0.0025*0.0025*3.141592)*9.80665/1000000;

  write (pressure:10:0);
  write (outfile_sub, pressure:10:0);
  if data_no > avg_data_no then total_4:=total_4+pressure;
  end

else begin
    write (' No data');
    write (outfile_sub, ' No data');
    data_no:=data_no-1;
    goto 400
end;

if data_no=avg_data_no + 1 then first_pressure:=pressure;

{receive cavity temperature data from channel 2}
ok:=adc16_get_value (result_2, 2, resolution, TRUE);

if ok then begin
  cavitytemp:=result_2;
  if resolution =14 then cavitytemp:=(cavitytemp-308.963)/44.1355;
  if resolution =12 then cavitytemp:=(cavitytemp-80.05)/10.8152;
  write (cavitytemp:10:0);
  write (outfile_sub, cavitytemp:10:0);
  if data_no > avg_data_no then total_2:=total_2+cavitytemp;
  end

else begin
    write (' No data');
    write (outfile_sub,' No data');
    data_no:=data_no-1;
    total_2:= total_2-cavitytemp;
    total_4:= total_4-pressure;
    goto 400
end;

{receive Nozzle temperature data from channel 3}
ok:=adc16_get_value (result_3, 3, resolution, TRUE);

if ok then begin
  nozzletemp:=result_3;
  if resolution =14 then nozzletemp:=(nozzletemp-543.286)/34.3143;
  if resolution =12 then nozzletemp:=(nozzletemp-136.143)/8.55714;

  writeln (nozzletemp:10:0);
  writeln (outfile_sub,nozzletemp:10:0);
  if data_no > avg_data_no then total_3:=total_3+nozzletemp;
  end
```

```
     else begin
        writeln (' No data');
        writeln (outfile_sub,' No data');
        data_no:=data_no-1;
        total_2:= total_2-cavitytemp;
        total_3:= total_3-nozzletemp;
        total_4:= total_4-pressure;
        goto 400
     end;

     {receive data from channel 1 for the following until condition}
     repeat
     ok:=adc16_get_value (result_1, 1, resolution, TRUE);
     until result_1 <> 0;

  until result_1 > range;

 {average Data }
 inc (average_no);
 write       ('AVG ',average_no:4);
 write       (outfile_process,'AVG ',average_no:4);
 write        (total_4/(data_no-avg_data_no):10:2);
 write (outfile_process, total_4/(data_no-avg_data_no):10:2);
 write        (total_2/(data_no-avg_data_no):10:2);
 write (outfile_process, total_2/(data_no-avg_data_no):10:2);
 write        (total_3/(data_no-avg_data_no):10:2);
 write (outfile_process, total_3/(data_no-avg_data_no):10:2);

 {Message for Continue or Finish}
 window (1,22,80,25);
 clrscr;
 gotoxy (1,22);
 writeln ('>>>>>>>>>>      Instruction Message      <<<<<<<<<<<');
 writeln ('Select - <F> for finish,  <C> for continue...');

 f_ch:=readkey;
 until (f_ch = 'F') or (f_ch = 'f');

 adc16_close ;
 close (outfile_process);
 close (outfile_sub);

end;

(*************************************************************************
             Strain Gauge Calibration
 *************************************************************************)

 Procedure Calibration;

 begin

 ok := adc16_driver_open (adc_com);
  clrscr;
```

```
 writeln ( '************ Strain Gauge calibration data ******************');
 case resolution of
    14 : original_pressure:= 6.175;
    12 : original_pressure:= 0.0263;
    end;

 data_no:=0;
 total_4:=0;
{open channel 1 for trigger monitor, when switch is on, out this repeat}
 repeat
     repeat
     ok:= adc16_get_value (result_1, 1, resolution, TRUE);
     until result_1 <> 0;

 until result_1 < range;
 repeat
     inc (data_no);
     ok:=adc16_get_value (result_4, 4, resolution, true);
     write (data_no:8);
     writeln (result_4:8);
     if data_no > avg_data_no then total_4:= total_4 + result_4;
     repeat
     ok:=adc16_get_value (result_1, 1, resolution, true);
     until result_1 <> 0;
 until result_1 > range;

 average_pressure:=total_4/ (data_no-avg_data_no);
 writeln ('Average Pressure Data = ',average_pressure:10:0);
 compensation:= average_pressure - original_pressure;
 writeln ('Compensation = ', compensation:10:0);
 writeln;
 writeln (' Press <Enter> to finish.');
 adc16_close;
 readln;
 end;

(****************************************************************************
                Product Data Receiving
 ****************************************************************************)

Procedure ProductData;

Label 300;

begin

 assign (outfile_product,address_product);
 rewrite (outfile_product);

 data_no := 0;

 window (1,1,80,25);
 clrscr;
```

```
writeln ('******** ******** ******** ******** ********');
writeln ('Data no.  Weight   Length   Width    Thick ');
writeln ('          (gram)    (mm)     (mm)     (mm)');
writeln ('******** ******** ******** ******** ********');

{Message for Continue or Finish}
window (1,21,80,25);
clrscr;
gotoxy (1,21);
writeln ('>>>>>>>>>>       Instruction Message       <<<<<<<<<<<');
writeln ('1. Press <ENTER> after measure one WEIGHT.');
writeln ('2. Press <ENTER> after measure three DIMENSIONS.');
writeln ('3. <F> for FINISH, <SPACEBAR> to CONTINUE...');

window (1,5,80,20);
clrscr;
gotoxy (1,1);

300:

     inc (data_no);
     write (data_no:8);
     write (outfile_product, data_no:8);

     (* Weight data *)
     Async_Init;
     ok:=Async_Open(Scale_com,2400,'E',7,1);
     outchar:=' ';
     cr:=#13;

     repeat
     if Async_Buffer_Check(inchar) then
       if inchar = cr then begin
         write('   ');
         write (outfile_product,'    ');
         count := 0;
       end
       else begin
          count := count + 1;
          if (count > 2) and (count < 14) then begin
          write (inchar);
          write (outfile_product,inchar);
       end;
     end;

     if keypressed then begin
       outchar:=Readkey;
       Async_send(outchar);
     end;

     until outchar=#13;

     Async_Close;
```

```
 (* dimension data *)
 async_init;
 ok:=async_open (vernier_com,9600,'n',8,1);
 outchar:=' ';
 cr:=#13;

 repeat
     if Async_Buffer_Check(inchar) then
       if inchar=cr then begin
         write ('   ');
         write (outfile_product,'   ');
         count:=0;
       end
       else begin
          count:=count+1;
          if (count>4) and (count<12) then begin
            write (inchar);
            write (outfile_product, inchar);
          end;
       end;

     if footswitchpressed then begin
       async_send('1');
       async_send(#13);
       resetfootswitch;
     end;

     if keypressed then begin
       outchar:=readkey;
       async_send(outchar);
     end;

 until outchar=#13;

 Async_Close;
 writeln;
 writeln (outfile_product);
 f_ch := readkey;
 if (f_ch='F') or (f_ch='f') then close (outfile_product)
 else goto 300;
end;


(****************************************************************************
                    Main Program
 ****************************************************************************)
label 100;

begin

 clrscr;
 window (1, 1, 80, 25);
 writeln;
```

```
writeln;
writeln;
writeln;
writeln;
writeln ('********************************************************************');
writeln ('*                                                                  *');
writeln ('*    #        ####     #####       #       #####                   *');
writeln ('*   # #      #     #   #     #    # #     #                        *');
writeln ('*   #  #     #     #   #     #    #  #    #                        *');
writeln ('*  #    #    #     #   #     #   #    #   #####                    *');
writeln ('* ######     #     #   #     #  ######          #                  *');
writeln ('* #      #   #    ##   #     #  #      #   #     #                 *');
writeln ('* #       #    ### #   #####    #       #  #####                   *');
writeln ('*                                                                  *');
writeln ('*          Supervisor    : Dr. James JDT Tannock                   *');
writeln ('*          Programmed by : Tae Eub, Kim                            *');
writeln ('*               Date : June 1995                                   *');
writeln ('*                                                                  *');
writeln ('************************INSTRUCTION***************************');
writeln (' Connection : Micro switch (ch 1), Melt thermocouple (ch 2), ');
writeln ('            Wire Thermocouple (Ch 3), Strain gage (ch 4)   ');
writeln;
writeln ('>>>> Press <Enter> ');
readln;

{Pre-setting for comport, resolution, data store file}
adc_com         := 1;
Scale_com       := 2;
Vernier_com     := 3;
resolution      :=14;
address_process := 'C:\PROCESS.TXT';
address_sub     := 'C:\ProcSub.TXT';
address_product := 'C:\PRODUCT.TXT';


{menu design}
100:

if resolution =12 then begin
  range :=1000;
  avg_data_no :=10;
  end;
if resolution =14 then begin
  range :=500;
  avg_data_no :=5;
  end;

repeat
window (1,1,80,25);
clrscr;
gotoxy (1, 5);
writeln;
writeln;
writeln (' Step 1. Resolution and data saving file were selected as >>');
```

```
writeln ('                    <R>esolution >> ',resolution,' Bits');
writeln;
writeln ('                     Data File');
writeln ('                      <1> Process Data File      >> ',address_process);
writeln ('                      <2> Process SubData File  >> ',address_sub);
writeln ('                      <3> Product Data File      >> ',address_product);
writeln;
writeln (' Step 2. Strain gauge calibration >>');
writeln ('                    <C>alibrate the strain gauge ');
writeln;
writeln (' Step 3. Select data receiving program >>');
writeln ('                    <I>njection process data');
writeln ('                    <P>roduct data');
writeln;
writeln ('                     E<x>it this program');
writeln;
writeln (' >>>> Press the character or number in < >.');
writeln;
writeln;
writeln;

{readkey for menu change}

ch := readkey;

if (ch='R') or (ch='r') then begin
clrscr;
writeln;
writeln ('Select resolution >> ( 12, 14 bits)');
readln (resolution_new);
     if (resolution_new <> 12) and (resolution_new <> 14) then goto 100;
resolution := resolution_new;
goto 100;
end

else if (ch = '1') then begin
clrscr;
writeln;
writeln ('Select drive and file name to save the data. (ex, C:\PROCESS.TXT)');
Writeln ('* Hint: Save the data in C drive is recommendable to increase speed.');
readln (address_process_new);
address_process := address_process_new;
goto 100;
end

else if ch = '2' then begin
clrscr;
writeln;
writeln ('Select drive and file name to save the data. (ex, C:\PROCSUB.TXT)');
Writeln ('* Hint: Save the data in C drive is recommendable to increase speed.');
readln (address_sub_new);
address_sub := address_sub_new;
goto 100;
end
```

```
 else if ch = '3' then begin
 clrscr;
 writeln;
 writeln ('Select drive and file name to save the data. (ex, C:\PRODUCT.TXT)');
 Writeln ('* Hint: Save the data in C drive is recommendable to increase speed.');
 readln (address_product_new);
 address_product := address_product_new;
 goto 100;
 end

 else if (ch = 'C') or (ch = 'c') then begin
 Calibration;
 goto 100;
 end

 else if (ch ='I') or (ch='i') then begin
 ProcessData;
 goto 100;
 end

 else if (ch='P') or (ch='p') then begin
 ProductData;
 goto 100;
 end

 until (ch = 'X') or (ch = 'x') ;

end.
```

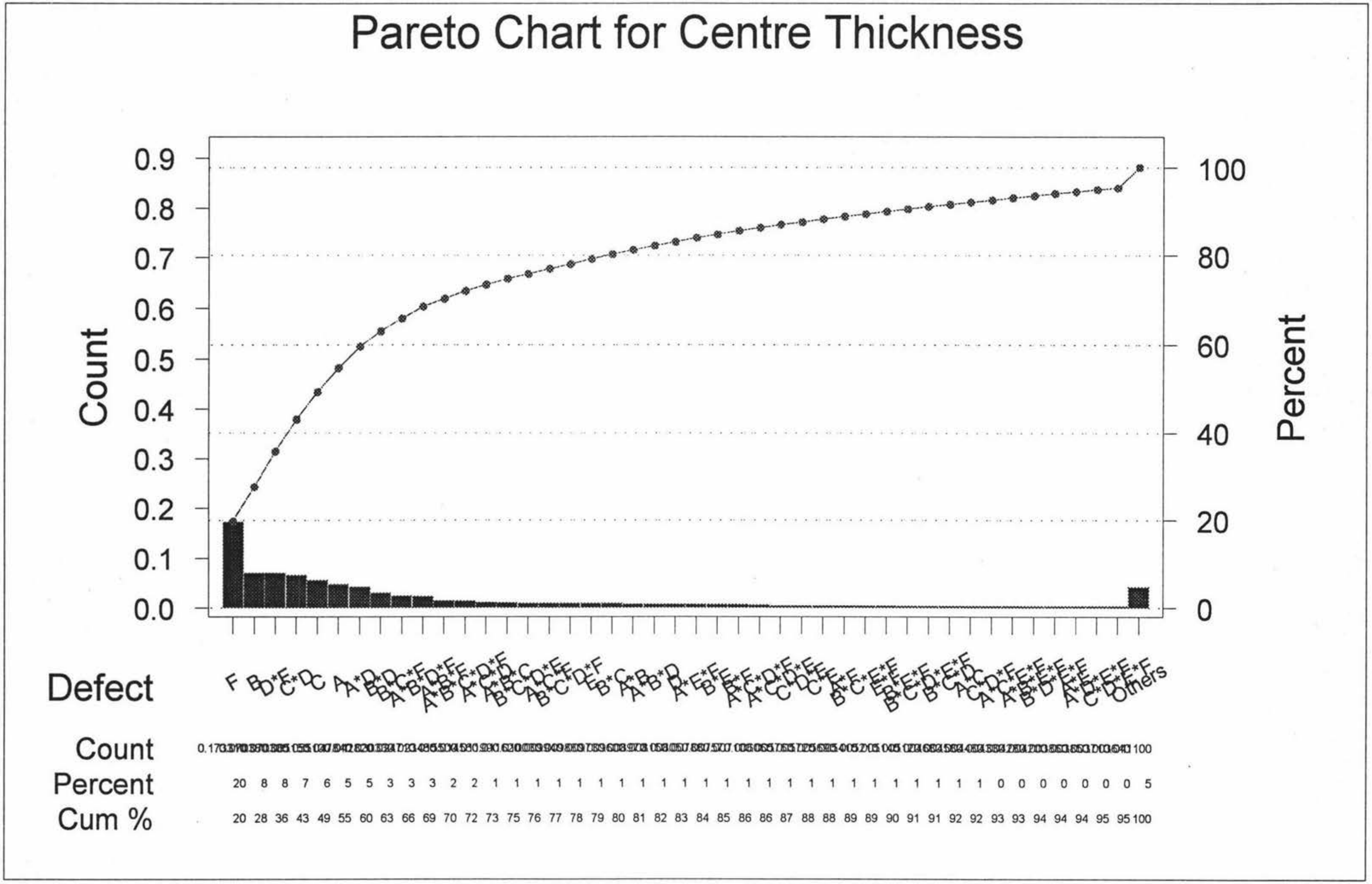
Appendix E. Analysis results from Minitab

1. Centre Point Thickness

```
Fractional Factorial Fit

Estimated Effects and Coefficients for Thick

Term            Effect       Coef  Std Coef t-value      P
Constant                  5.34380  0.002178 2453.67  0.000
A              0.04784    0.02392  0.002178   10.98  0.000
B              0.07038    0.03519  0.002178   16.16  0.000
C             -0.05510   -0.02755  0.002178  -12.65  0.000
D              0.00805    0.00403  0.002178    1.85  0.069
E             -0.00973   -0.00486  0.002178   -2.23  0.029
F              0.17331    0.08666  0.002178   39.79  0.000
A*B            0.00897    0.00448  0.002178    2.06  0.044
A*C           -0.00448   -0.00224  0.002178   -1.03  0.307
A*D            0.04282    0.02141  0.002178    9.83  0.000
A*E           -0.00385   -0.00193  0.002178   -0.88  0.380
A*F            0.00541    0.00271  0.002178    1.24  0.219
B*C            0.00960    0.00480  0.002178    2.21  0.031
B*D            0.03033    0.01517  0.002178    6.96  0.000
B*E           -0.00757   -0.00379  0.002178   -1.74  0.087
B*F            0.00710    0.00355  0.002178    1.63  0.108
C*D            0.06515    0.03257  0.002178   14.96  0.000
C*E            0.00569    0.00284  0.002178    1.31  0.196
C*F           -0.00063   -0.00031  0.002178   -0.14  0.886
D*E           -0.00277   -0.00139  0.002178   -0.64  0.527
D*F            0.07030    0.03515  0.002178   16.14  0.000
E*F            0.00514    0.00257  0.002178    1.18  0.242
A*B*C         -0.01162   -0.00581  0.002178   -2.67  0.010
A*B*D          0.00815    0.00407  0.002178    1.87  0.066
A*B*E         -0.00140   -0.00070  0.002178   -0.32  0.749
A*B*F         -0.01550   -0.00775  0.002178   -3.56  0.001
A*C*D          0.01199    0.00600  0.002178    2.75  0.008
A*C*E          0.00295    0.00147  0.002178    0.68  0.501
A*C*F         -0.00994   -0.00497  0.002178   -2.28  0.026
A*D*E         -0.00272   -0.00136  0.002178   -0.62  0.534
A*D*F         -0.00062   -0.00031  0.002178   -0.14  0.886
A*E*F          0.00788    0.00394  0.002178    1.81  0.075
B*C*D         -0.00458   -0.00229  0.002178   -1.05  0.297
B*C*E          0.00361    0.00180  0.002178    0.83  0.410
B*C*F         -0.02471   -0.01236  0.002178   -5.67  0.000
B*D*E         -0.00011   -0.00006  0.002178   -0.03  0.980
B*D*F          0.00350    0.00175  0.002178    0.80  0.424
B*E*F          0.00512    0.00256  0.002178    1.18  0.244
C*D*E         -0.00572   -0.00286  0.002178   -1.31  0.193
C*D*F          0.00433    0.00216  0.002178    0.99  0.324
C*E*F         -0.00205   -0.00103  0.002178   -0.47  0.639
D*E*F          0.00349    0.00175  0.002178    0.80  0.426
A*B*C*D       -0.00263   -0.00132  0.002178   -0.60  0.548
A*B*C*E        0.00008    0.00004  0.002178    0.02  0.986
A*B*C*F        0.00058    0.00029  0.002178    0.13  0.895
A*B*D*E       -0.00142   -0.00071  0.002178   -0.33  0.746
A*B*D*F       -0.02348   -0.01174  0.002178   -5.39  0.000
A*B*E*F       -0.00420   -0.00210  0.002178   -0.96  0.339
A*C*D*E        0.00576    0.00288  0.002178    1.32  0.191
A*C*D*F       -0.00606   -0.00303  0.002178   -1.39  0.169
A*C*E*F       -0.00428   -0.00214  0.002178   -0.98  0.329
A*D*E*F        0.00371    0.00185  0.002178    0.85  0.398
```

```
B*C*D*E          0.01003    0.00502  0.002178     2.30  0.024
B*C*D*F         -0.00988   -0.00494  0.002178    -2.27  0.027
B*C*E*F         -0.00521   -0.00260  0.002178    -1.20  0.236
B*D*E*F          0.00386    0.00193  0.002178     0.89  0.379
C*D*E*F         -0.00364   -0.00182  0.002178    -0.84  0.406
A*B*C*D*E       -0.00337   -0.00169  0.002178    -0.77  0.442
A*B*C*D*F       -0.01456   -0.00728  0.002178    -3.34  0.001
A*B*C*E*F       -0.00288   -0.00144  0.002178    -0.66  0.511
A*B*D*E*F        0.00352    0.00176  0.002178     0.81  0.422
A*C*D*E*F        0.00080    0.00040  0.002178     0.18  0.854
B*C*D*E*F       -0.00468   -0.00234  0.002178    -1.07  0.287
A*B*C*D*E*F      0.00197    0.00099  0.002178     0.45  0.652

Analysis of Variance for Thick

Source                DF      Seq SS      Adj SS      Adj MS       F       P
Main Effects           6     1.29518     1.29518    0.215864  355.55   0.000
2-Way Interactions    15     0.39523     0.39523    0.026349   43.40   0.000
3-Way Interactions    20     0.04851     0.04851    0.002426    4.00   0.000
4-Way Interactions    15     0.02988     0.02988    0.001992    3.28   0.000
5-Way Interactions     6     0.00853     0.00853    0.001422    2.34   0.042
6-Way Interactions     1     0.00012     0.00012    0.000124    0.20   0.652
Residual Error        64     0.03886     0.03886    0.000607
  Pure Error          64     0.03886     0.03886    0.000607
Total                127     1.81631

Unusual Observations for Thick

Obs.     Thick        Fit Stdev.Fit   Residual    St.Resid
  1    5.30100    5.34920   0.01742   -0.04820      -2.77R
  7    5.23400    5.29900   0.01742   -0.06500      -3.73R
 65    5.39740    5.34920   0.01742    0.04820       2.77R
 71    5.36400    5.29900   0.01742    0.06500       3.73R

R denotes an obs. with a large st. resid.

  Nscores -                                            *    F
          -                           *    B
          -                           *    DF
       1.5+                       *  *   A,CD
          -                 2  * *    ACD,BCDE,BD,AD
          -                4*    D,AB,ABD,AEF,BC
          -                6   AF,BF,CE,EF,BEF,ACDE
          -               *7   ACE,BCE,BDF,CDF,DEF,ADEF,BDEF,...
       0.0+               7   CF,ADF,BDE,ABCE,ABCF,ACDEF,ABCDEF
          -              *7   ABCDE,DE,ABE,ADE,CEF,ABCD,ABDE,...
          -              6   AC,AE,BCD,ABEF,ACEF,CDEF
          -              5   BE,CDE,ACDF,BCEF,BCDEF
          -             4   E,ABC,ACF,BCDF
      -1.5+            **   ABF,ABCDF
          -           *    ABDF
          -           *    BCF
          -      *    C
            ----+---------+---------+---------+---------+--Effects
           -0.060     0.000     0.060     0.120     0.180

A = 1 Injection Time             B = 2 Injection Time
C = 1 Injection Pressure         D = 2 Injection Pressure
E = 2 Injection Speed            F = Nozzle/barrel Temperature
```

```
Means for Thick

                  Mean      Stdev
 A* D
-1 -1            5.337   0.004356
 1 -1            5.342   0.004356
-1  1            5.302   0.004356
 1  1            5.393   0.004356
 B* D
-1 -1            5.320   0.004356
 1 -1            5.360   0.004356
-1  1            5.297   0.004356
 1  1            5.398   0.004356
 C* D
-1 -1            5.400   0.004356
 1 -1            5.280   0.004356
-1  1            5.343   0.004356
 1  1            5.353   0.004356
 D* F
-1 -1            5.288   0.004356
 1 -1            5.226   0.004356
-1  1            5.391   0.004356
 1  1            5.470   0.004356

CUBE B*C*F

               5.371400________5.433775
                 /|               /|
                / |              / |
               /  |             /  |
              /   |            /   |
    +1   5.181103________5.278700  |
            |     |          |     |
            |     |          |     |
            |  5.412022______|_5.504612   +1
     C      |    /           |    /
            |   /            |   /      F
            |  /             |  /
            | /              | /
    -1   5.269900________5.298862   -1

           -1       B       +1
MTB >
```


Pareto Chart for Centre Thickness

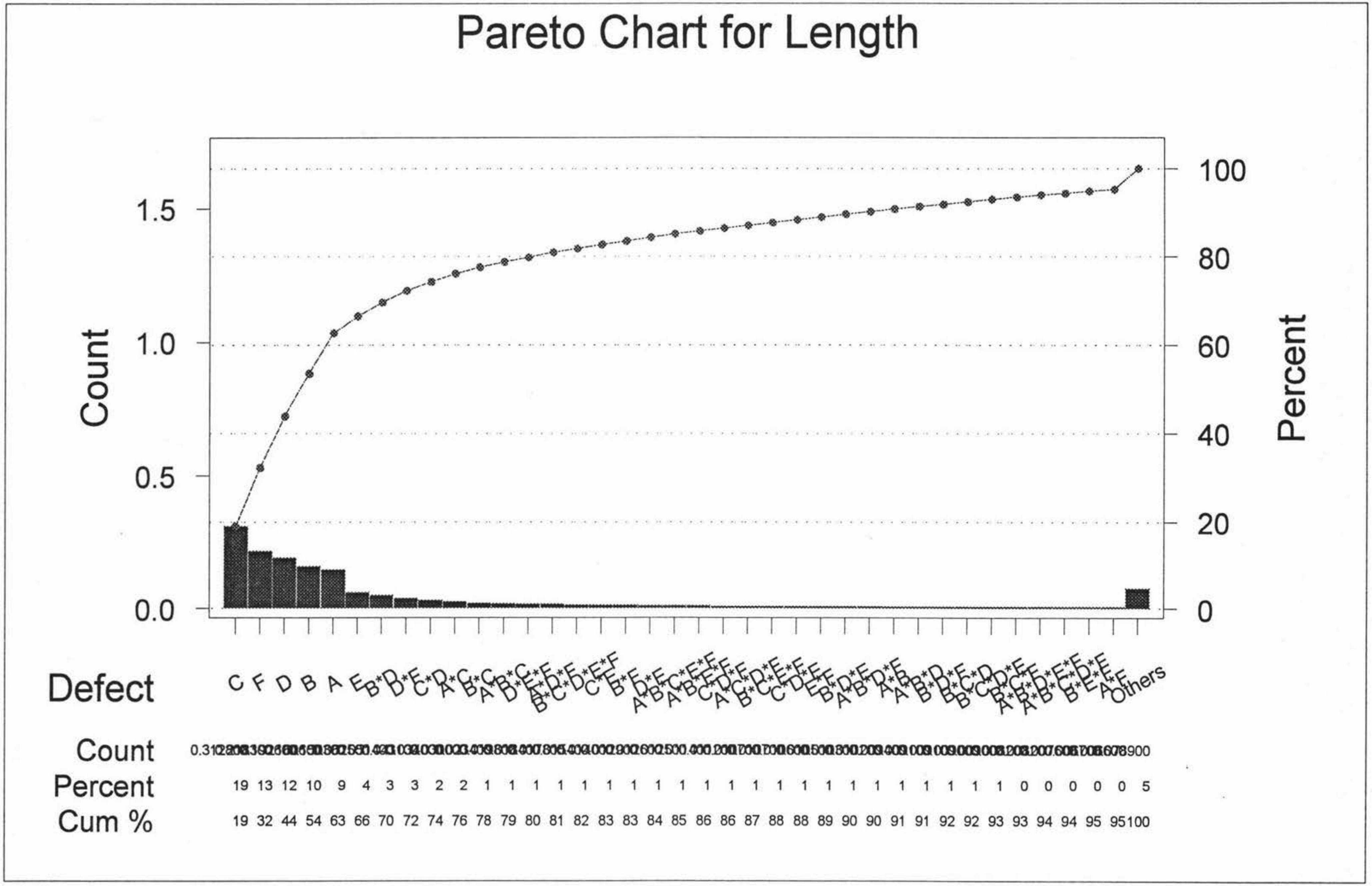
Appendix E. Analysis results from Minitab

2. Product Length

```
Fractional Factorial Fit

Estimated Effects and Coefficients for Length

Term            Effect      Coef  Std Coef t-value      P
Constant                 98.4094  0.003949 2.5E+04  0.000
A               0.1503    0.0751  0.003949   19.03  0.000
B               0.1606    0.0803  0.003949   20.33  0.000
C               0.3128    0.1564  0.003949   39.61  0.000
D               0.1926    0.0963  0.003949   24.39  0.000
E              -0.0625   -0.0313  0.003949   -7.92  0.000
F               0.2183    0.1091  0.003949   27.63  0.000
A*B            -0.0094   -0.0047  0.003949   -1.19  0.237
A*C             0.0300    0.0150  0.003949    3.79  0.000
A*D            -0.0029   -0.0014  0.003949   -0.36  0.717
A*E             0.0054    0.0027  0.003949    0.69  0.494
A*F            -0.0066   -0.0033  0.003949   -0.84  0.404
B*C            -0.0234   -0.0117  0.003949   -2.97  0.004
B*D             0.0514    0.0257  0.003949    6.50  0.000
B*E             0.0025    0.0013  0.003949    0.32  0.748
B*F            -0.0129   -0.0064  0.003949   -1.63  0.108
C*D             0.0340    0.0170  0.003949    4.30  0.000
C*E             0.0140    0.0070  0.003949    1.78  0.080
C*F             0.0051    0.0026  0.003949    0.65  0.519
D*E             0.0126    0.0063  0.003949    1.60  0.115
D*F             0.0431    0.0215  0.003949    5.45  0.000
E*F             0.0105    0.0053  0.003949    1.33  0.188
A*B*C          -0.0198   -0.0099  0.003949   -2.51  0.015
A*B*D          -0.0091   -0.0046  0.003949   -1.16  0.252
A*B*E          -0.0007   -0.0003  0.003949   -0.09  0.931
A*B*F          -0.0045   -0.0022  0.003949   -0.57  0.572
A*C*D          -0.0009   -0.0004  0.003949   -0.11  0.912
A*C*E          -0.0051   -0.0025  0.003949   -0.64  0.524
A*C*F           0.0001    0.0001  0.003949    0.02  0.986
A*D*E          -0.0034   -0.0017  0.003949   -0.43  0.669
A*D*F          -0.0178   -0.0089  0.003949   -2.26  0.028
A*E*F           0.0056    0.0028  0.003949    0.71  0.479
B*C*D          -0.0090   -0.0045  0.003949   -1.14  0.260
B*C*E          -0.0005   -0.0003  0.003949   -0.07  0.945
B*C*F          -0.0082   -0.0041  0.003949   -1.04  0.300
B*D*E          -0.0103   -0.0051  0.003949   -1.30  0.199
B*D*F          -0.0091   -0.0045  0.003949   -1.15  0.255
B*E*F           0.0067    0.0034  0.003949    0.85  0.397
C*D*E          -0.0106   -0.0053  0.003949   -1.35  0.183
C*D*F          -0.0112   -0.0056  0.003949   -1.42  0.161
C*E*F          -0.0050   -0.0025  0.003949   -0.64  0.528
D*E*F           0.0184    0.0092  0.003949    2.33  0.023
A*B*C*D         0.0031    0.0016  0.003949    0.40  0.694
A*B*C*E         0.0031    0.0015  0.003949    0.39  0.699
A*B*C*F        -0.0065   -0.0033  0.003949   -0.82  0.412
A*B*D*E        -0.0045   -0.0022  0.003949   -0.57  0.572
A*B*D*F        -0.0102   -0.0051  0.003949   -1.29  0.202
A*B*E*F         0.0114    0.0057  0.003949    1.44  0.155
A*C*D*E         0.0033    0.0016  0.003949    0.41  0.681
A*C*D*F        -0.0107   -0.0053  0.003949   -1.35  0.181
A*C*E*F        -0.0047   -0.0024  0.003949   -0.60  0.550
A*D*E*F         0.0005    0.0003  0.003949    0.07  0.945
```

```
B*C*D*E          0.0090     0.0045  0.003949     1.14  0.259
B*C*D*F         -0.0023    -0.0011  0.003949    -0.29  0.772
B*C*E*F         -0.0107    -0.0054  0.003949    -1.36  0.179
B*D*E*F          0.0022     0.0011  0.003949     0.28  0.783
C*D*E*F          0.0006     0.0003  0.003949     0.07  0.943
A*B*C*D*E       -0.0044    -0.0022  0.003949    -0.56  0.580
A*B*C*D*F       -0.0076    -0.0038  0.003949    -0.96  0.342
A*B*C*E*F       -0.0125    -0.0063  0.003949    -1.58  0.118
A*B*D*E*F       -0.0082    -0.0041  0.003949    -1.03  0.305
A*C*D*E*F       -0.0017    -0.0008  0.003949    -0.21  0.833
B*C*D*E*F       -0.0154    -0.0077  0.003949    -1.95  0.055
A*B*C*D*E*F      0.0003     0.0001  0.003949     0.04  0.970

Analysis of Variance for Length

Source              DF      Seq SS      Adj SS      Adj MS       F       P
Main Effects         6     7.51606     7.51606     1.25268  627.53   0.000
2-Way Interactions  15     0.25380     0.25380     0.01692    8.48   0.000
3-Way Interactions  20     0.05982     0.05982     0.00299    1.50   0.113
4-Way Interactions  15     0.02142     0.02142     0.00143    0.72   0.760
5-Way Interactions   6     0.01730     0.01730     0.00288    1.44   0.212
6-Way Interactions   1     0.00000     0.00000     0.00000    0.00   0.970
Residual Error      64     0.12776     0.12776     0.00200
  Pure Error        64     0.12776     0.12776     0.00200
Total              127     7.99615

Unusual Observations for Length

Obs.   Length       Fit Stdev.Fit   Residual    St.Resid
 11   98.3860   98.3160    0.0316     0.0700       2.22R
 33   98.0880   98.2030    0.0316    -0.1150      -3.64R
 75   98.2460   98.3160    0.0316    -0.0700      -2.22R
 97   98.3180   98.2030    0.0316     0.1150       3.64R

R denotes an obs. with a large st. resid.

 Nscores -                                            *    C
         -                                   *    F
         -                                *    D
      1.5+                               **    A,B
         -                   2**    AC,CD,DF,BD
         -                 4*    CE,DE,EF,ABEF,DEF
         -                *5    ACDE,AE,CF,AEF,BEF,BCDE
         -                 8   BE,ACF,ABCD,ABCE,ADEF,BDEF,CDEF,...
      0.0+                 7   AD,ABE,ACD,ADE,BCE,BCDF,ACDEF
         -               44    AF,ACE,CEF,ABCF,ABF,ABDE,ACEF,ABCDE
         -                6   ABD,BCD,BCF,BDF,ABCDF,ABDEF
         -                5   AB,BDE,CDE,ABDF,ACDF
         -                4   BF,CDF,BCEF,ABCEF
     -1.5+               2   ADF,BCDEF
         -               *   ABC
         -               *   BC
         -           *    E
          --+---------+---------+---------+---------+----Effects
          -0.10     0.00      0.10      0.20      0.30

A = 1 Injection Time              B = 2 Injection Time
C = 1 Injection Pressure          D = 2 Injection Pressure
E = 2 Injection Speed             F = Nozzle/barrel Temperature
```

```
Means for Length

                      Mean      Stdev
 B* D
-1 -1                98.26   0.007898
 1 -1                98.37   0.007898
-1  1                98.40   0.007898
 1  1                98.61   0.007898
 C* D
-1 -1                98.17   0.007898
 1 -1                98.45   0.007898
-1  1                98.33   0.007898
 1  1                98.68   0.007898
 D* F
-1 -1                98.23   0.007898
 1 -1                98.38   0.007898
-1  1                98.40   0.007898
 1  1                98.64   0.007898
MTB >
```


Pareto Chart for Length
Count
0.0
0.5
1.0
1.5
Percent
0
20
40
60
80
100
Defect
C
F
D
B
A
E
B*D
D*E
C*D
A*C
B*C
A*B*C
Others
Count
0.31
Percent
19 13 12 10 9 4 3 3 2 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 5
Cum %
19 32 44 54 63 66 70 72 74 76 78 79 80 81 82 83 83 84 85 86 86 87 88 88 89 90 90 91 91 92 92 93 93 94 94 95 95 100

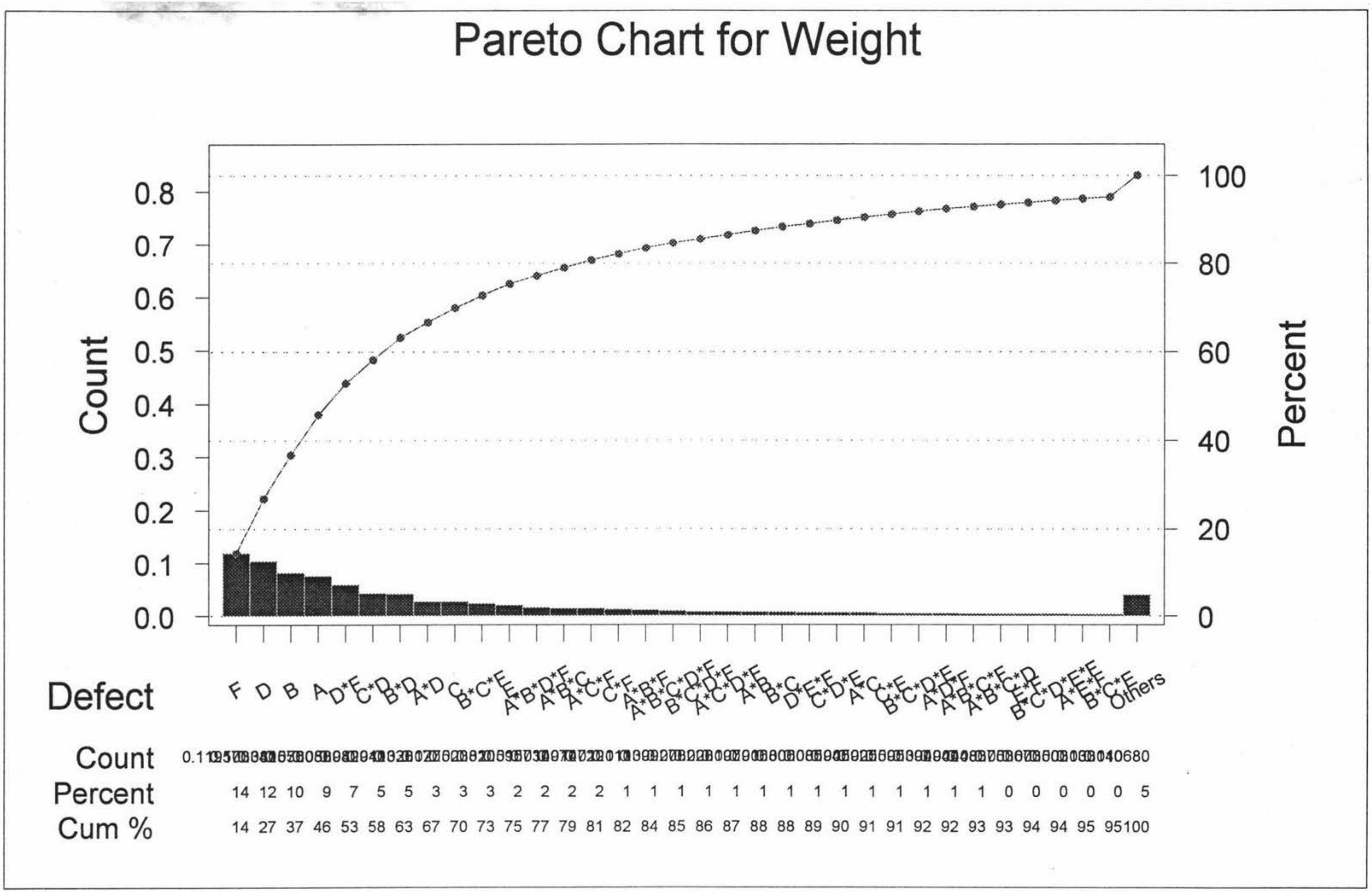
Appendix E. Analysis results from Minitab

3. Product Weight

```
Fractional Factorial Fit

Estimated Effects and Coefficients for Weight
Term              Effect        Coef  Std Coef t-value      P
Constant                     9.30044  0.001596 5828.75  0.000
A                0.07608     0.03804  0.001596   23.84  0.000
B                0.08155     0.04077  0.001596   25.55  0.000
C                0.02750     0.01375  0.001596    8.62  0.000
D                0.10334     0.05167  0.001596   32.38  0.000
E               -0.02059    -0.01030  0.001596   -6.45  0.000
F                0.11977     0.05988  0.001596   37.53  0.000
A*B             -0.00791    -0.00395  0.001596   -2.48  0.016
A*C              0.00592     0.00296  0.001596    1.86  0.068
A*D              0.02817     0.01409  0.001596    8.83  0.000
A*E             -0.00014    -0.00007  0.001596   -0.04  0.965
A*F             -0.00053    -0.00027  0.001596   -0.17  0.868
B*C             -0.00680    -0.00340  0.001596   -2.13  0.037
B*D              0.04133     0.02066  0.001596   12.95  0.000
B*E              0.00002     0.00001  0.001596    0.00  0.996
B*F             -0.00019    -0.00009  0.001596   -0.06  0.953
C*D              0.04291     0.02145  0.001596   13.45  0.000
C*E              0.00559     0.00280  0.001596    1.75  0.084
C*F              0.01211     0.00605  0.001596    3.79  0.000
D*E              0.00106     0.00053  0.001596    0.33  0.740
D*F              0.05898     0.02949  0.001596   18.48  0.000
E*F              0.00367     0.00184  0.001596    1.15  0.254
A*B*C           -0.01497    -0.00748  0.001596   -4.69  0.000
A*B*D           -0.00175    -0.00087  0.001596   -0.55  0.585
A*B*E           -0.00119    -0.00059  0.001596   -0.37  0.711
A*B*F           -0.01139    -0.00570  0.001596   -3.57  0.001
A*C*D           -0.00005    -0.00002  0.001596   -0.01  0.988
A*C*E            0.00077     0.00038  0.001596    0.24  0.811
A*C*F           -0.01472    -0.00736  0.001596   -4.61  0.000
A*D*E           -0.00261    -0.00130  0.001596   -0.82  0.417
A*D*F           -0.00494    -0.00247  0.001596   -1.55  0.127
A*E*F            0.00313     0.00156  0.001596    0.98  0.331
B*C*D           -0.00245    -0.00123  0.001596   -0.77  0.445
B*C*E            0.00311     0.00155  0.001596    0.97  0.334
B*C*F           -0.02381    -0.01191  0.001596   -7.46  0.000
B*D*E           -0.00239    -0.00120  0.001596   -0.75  0.457
B*D*F            0.00084     0.00042  0.001596    0.26  0.792
B*E*F            0.00241     0.00120  0.001596    0.75  0.454
C*D*E           -0.00594    -0.00297  0.001596   -1.86  0.067
C*D*F           -0.00023    -0.00012  0.001596   -0.07  0.942
C*E*F           -0.00167    -0.00084  0.001596   -0.52  0.602
D*E*F            0.00608     0.00304  0.001596    1.90  0.061
A*B*C*D         -0.00375    -0.00188  0.001596   -1.18  0.244
A*B*C*E          0.00069     0.00034  0.001596    0.22  0.830
A*B*C*F         -0.00448    -0.00224  0.001596   -1.41  0.165
A*B*D*E          0.00153     0.00077  0.001596    0.48  0.633
A*B*D*F         -0.01573    -0.00787  0.001596   -4.93  0.000
A*B*E*F         -0.00055    -0.00027  0.001596   -0.17  0.864
A*C*D*E          0.00311     0.00155  0.001596    0.97  0.334
A*C*D*F         -0.00819    -0.00409  0.001596   -2.57  0.013
A*C*E*F         -0.00075    -0.00037  0.001596   -0.24  0.815
A*D*E*F          0.00216     0.00108  0.001596    0.68  0.502
B*C*D*E          0.00539     0.00270  0.001596    1.69  0.096
B*C*D*F         -0.00822    -0.00411  0.001596   -2.58  0.012
```

```
B*C*E*F       -0.00303  -0.00152  0.001596   -0.95  0.346
B*D*E*F        0.00225   0.00112  0.001596    0.71  0.483
C*D*E*F        0.00105   0.00052  0.001596    0.33  0.744
A*B*C*D*E     -0.00241  -0.00120  0.001596   -0.75  0.454
A*B*C*D*F     -0.00927  -0.00463  0.001596   -2.90  0.005
A*B*C*E*F     -0.00245  -0.00123  0.001596   -0.77  0.445
A*B*D*E*F      0.00067   0.00034  0.001596    0.21  0.834
A*C*D*E*F      0.00109   0.00055  0.001596    0.34  0.733
B*C*D*E*F     -0.00350  -0.00175  0.001596   -1.10  0.277
A*B*C*D*E*F   -0.00055  -0.00027  0.001596   -0.17  0.864

Analysis of Variance for Weight
Source                  DF      Seq SS      Adj SS      Adj MS       F      P
Main Effects             6     1.23654     1.23654    0.206090  632.40  0.000
2-Way Interactions      15     0.26107     0.26107    0.017405   53.41  0.000
3-Way Interactions      20     0.04117     0.04117    0.002058    6.32  0.000
4-Way Interactions      15     0.01532     0.01532    0.001021    3.13  0.001
5-Way Interactions       6     0.00357     0.00357    0.000595    1.83  0.108
6-Way Interactions       1     0.00001     0.00001    0.000010    0.03  0.864
Residual Error          64     0.02086     0.02086    0.000326
  Pure Error            64     0.02086     0.02086    0.000326
Total                  127     1.57853

Unusual Observations for Weight
Obs.   Weight        Fit Stdev.Fit   Residual    St.Resid
 33   9.22000    9.25200   0.01276   -0.03200      -2.51R
 35   9.26400    9.29700   0.01276   -0.03300      -2.59R
 42   9.35800    9.38600   0.01276   -0.02800      -2.19R
 43   9.40200    9.43300   0.01276   -0.03100      -2.43R
 97   9.28400    9.25200   0.01276    0.03200       2.51R
 99   9.33000    9.29700   0.01276    0.03300       2.59R
106   9.41400    9.38600   0.01276    0.02800       2.19R
107   9.46400    9.43300   0.01276    0.03100       2.43R

R denotes an obs. with a large st. resid.
 Nscores -                                             *   F
         -                                         *    D
         -                                  *    B
      1.5+                            *    *    DF,A
         -                    2   2   C,AD,BD,CD
         -             4*    AC,CE,DEF,BCDE,CF
         -             6   EF,AEF,BCE,BEF,ACDE,BDEF
         -           7*    DE,ACE,BDF,ABCE,ABDE,CDEF,ACDEF,ADEF
      0.0+           7    AE,AF,BE,BF,ACD,CDF,ABDEF
         -          26    BDE,ABCDE,ABD,ABE,CEF,ABEF,ACEF,ABCDEF
         -          6    ADE,BCD,ABCD,BCEF,ABCEF,BCDEF
         -         32    AB,BC,CDE,ADF,ABCF
         -        22    ABF,ABCDF,ACDF,BCDF
     -1.5+       2    ABC,ACF
         -       *    ABDF
         -     *    E
         -    *    BCF
           +---------+---------+---------+---------+---------+------Effects
      -0.035    0.000     0.035     0.070     0.105

A = 1 Injection Time           B = 2 Injection Time
C = 1 Injection Pressure       D = 2 Injection Pressure
E = 2 Injection Speed          F = Temperature
```

```
Means for Weight

                        Mean      Stdev
 A* D
-1 -1                  9.225   0.003191
 1 -1                  9.273   0.003191
-1  1                  9.300   0.003191
 1  1                  9.404   0.003191
 B* D
-1 -1                  9.229   0.003191
 1 -1                  9.269   0.003191
-1  1                  9.291   0.003191
 1  1                  9.414   0.003191
 C* D
-1 -1                  9.256   0.003191
 1 -1                  9.241   0.003191
-1  1                  9.317   0.003191
 1  1                  9.387   0.003191
 D* F
-1 -1                  9.218   0.003191
 1 -1                  9.263   0.003191
-1  1                  9.279   0.003191
 1  1                  9.441   0.003191
MTB >
```


Pareto Chart for Weight
Count
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Percent
0
20
40
60
80
100
Defect
F
D
B
A
D*E
C*D
B*D
A*D
C
B*C*E
E
A*B*D*F
A*B*C
A*C*F
C*F
A*B*F
A*B*C*D*F
B*C*D*E
A*C*D*E
A*B*C
B*C
D*E*F
C*D*E
A*C
C*E
B*C*D*E
A*D*F
A*B*C*F
A*B*C*D
E*F
B*C*D*E*F
A*E*F
B*E*F
B*C*E
Others
Count
Percent 14 12 10 9 7 5 5 3 3 3 2 2 2 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 5
Cum % 14 27 37 46 53 58 63 67 70 73 75 77 79 81 82 84 85 86 87 88 88 89 90 91 91 92 92 93 93 94 94 95 95 100