Electrical Discharge Machining and Rapid Manufacture of Injection Moulding Tools

A Thesis presented in partial fulfilment of the
requirements for the degree
of Master of Technology in
Manufacturing and Industrial Technology at
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To

Percy Jayasuriya

with greatest gratitude

Abstract

This thesis presents how rapid manufacture of injection moulding tools could be adopted in the New Zealand manufacturing environment.

The approach is to study about the conventional methods, machinery and the materials of moulding tools and their limitations, application of modern machinery, NC programming, CNC programming using commercially available software to generate NC codes, use of high level programming language to generate NC codes. Futher practical difficulties and limitations of modern methods of design and manufacture will be discussed. Finally, the application of electrical discharge machine in rapid manufacture of moulding tools will be studied as an alternative solution to overcome the difficulties in modern methods.

A study of an alternative moulding tool materials and EDM tool materials will be carried out.

Since there is no guidance in predicting the machining speed and the surface finish of the EDM process in most available manuals a special study has been carried out, to determine both machining speed and surface finish in terms of available EDM process variables.

Experimental design technique was used to collect data and graphical and statistical analysis has been used to identify significant factors. By collecting data after further experimentation and regression analysis using statistical software package called MINITAB release 10, relationships for machining speed, surface finish with available process variables have been established.

Finally some conclusions in rapid manufacture of injection moulding tools appropriate to New Zealand environment will be discussed in the last chapter of this thesis.

Acknowledgements

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Also Author expresses his special thanks to Mr Merv Foot and Mr. Leith Baker for providing him frequent assistance and advises in using machinery and equipment, computers and software in the departmental industrial engineering laboratory.

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Chapter 1

Introduction and Overview of Thesis

Objectives of the research work and Summary of each chapter is described in this chapter.

1.1 Foreword

This research thesis describes the concept of Rapid Manufacture of Injection Moulding Tools. Various methods of rapid manufacture of moulds are described and the impact of Electrical Discharge Machining on rapid manufacture of injection Moulding tools.

Initially conventional methods and materials of design and manufacture of injection moulding tools and their limitations were investigated. Then NC programming was carried out using the departmental CNC milling machine for manufacture of moulds. Also the application of CAD/CAM software in mould manufacture was studied by using Mastercam Ver. 4.11 and downloading to the Heidenhein TNC 145 controller of the departmental CNC milling machine.

Since the machining of free form curves and surfaces is not possible by using manual NC programming and CAD/CAM software, the author studied the possibility of using high level computer programming language to generate NC code for machining free form curves.

A special study has been carried out about the application of Electrical Discharge Machines on rapid mould manufacture, to overcome the difficulties found in both conventional and modern machinery. Currently, there is no guidance for predicting machining speed and surface finish using available EDM literature. Therefore experimental design methods have been used to predict machining speed (rate of penetration) and surface finish against available process variables, using the departmental Electrical Discharge Machine.

Collected data were analysed using both graphical and statistical methods and screened to reveal significant variables. A statistical software package called Minitab 10 has been for further analysis and two separate relationships were obtained for rate of penetration and surface roughness with important process variables.

Further experiments were carried out to verify these relationships to find out whether these could be used in the real situation by comparing predicted results against actual results.
The bulk of the experiments were done using Zinc as the mould material, since this is the proposed material for short run moulding tools, as most often used by the department. Also, copper electrodes were most often used. However, some were done using Aluminium electrodes, since these are much cheaper than copper.

Finally, the author makes some important conclusions regarding rapid manufacture of injection moulding tools in the New Zealand environment.

1.2 Objective of the Research Work

The rate of penetration and the surface roughness of the EDM process can not be predetermined neither by mould maker nor by machinist. These are determined by using trial and error methods which is totally depends on the experience of the machinist. Since there is no theoretical background, this is an inaccurate method.
Initially conventional methods and materials of design and manufacture of injection moulding tools and their limitations were investigated. Then NC programming (using the departmental CNC milling machine) for manufacture of moulds. Software

Therefore the main objective of this research is,

- To established a relationship in EDM process for Rate of Penetration against other process variables.
- To established a relationship for Surface Roughness in EDM operation against process variables.

In addition to these, other objective is to find out how easily modern machinery, software, CAD/CAM techniques, high level languages could be used practically in injection moulding tool manufacture and to examine the difficulties if any.

1.3 Summary of Contents

Chapter 2 describes the injection moulding process, injection moulding machines, its various types and its important sections.

Chapter 3 describes about injection moulding tools, various designs, materials used to manufacture injection moulding tools, the effect of mould on the quality of the product.

Chapter 4 describes applications and limitations of conventional machinery in manufacture of injection moulding tools.

Chapter 5 describes the concept of rapid tool manufacture, disadvantages of using conventional machine tools in rapid tool manufacture, the impact of modern machinery on rapid tool manufacture and finally the impact of EDM on rapid tool manufacture.

Chapter 6 describes experimental design, collection data, analysis, establishment of relationships of P_R, S_R against other process variables.

Chapter 7 describes verification of relationships already established by comparing estimated and actual values of P_R and S_R.

Chapter 8 makes some conclusions for rapid injection moulding tool manufacture appropriate to the New Zealand environment.

1.4 General References

The following general references had been used by the author for this research.

Operation manual - Bridge port two and half axis CNC milling machine

Operation manual - Electrical Discharge Machine, Model DT-168

(ALIC-1)

Minitab reference manual release 10 for windows.

Mastercam mill version 5 user and design guide, 1994 CNC software, Inc.

Operation manual - Injection Moulding Machine, Welltec TTI-330/100

Other scientific references from scientific literature

Chapter 2

Injection Moulding Process

Topics related to Injection Moulding Machine and Injection Moulding process are discussed in this chapter.

2.1 Injection Moulding

2.1.1 Introduction

Injection moulding is one of major processes by which thermoplastics are converted to products for consumer and industrial use. The process consists of feeding granular or powdered thermoplastics are melted by external heating elements, mixed, transported and injected through an aperture of a nozzle and forced in to a metal mould. Injected plastics already in the mould are allowed to cool and solidify as per the shape of the mould cavity. Mould opens and the solidified plastic product is ejected out. This process is continued as a cycle according to the quantity of the end product required.

2.1.2 Advantages

Injection moulding is an efficient, economical and quick process. Also from this cleaned, excellent surface quality plastic products can be manufactured in large quantities. Further, plastic products with any colour, any design, surface quality, any other features such as lettering, fine details, fillets, etc. can be produced as the customer required.

2.1.3 Injection Moulding Process

Plasticizing

Heating and melting of thermoplastic granules and venting of the melt.

Injection

Melt under pressure injects into the relatively cold mould when it is closed. Solidification of the plastic material begins during this injection, first at the cavity walls.

After filling

Maintaining the injected material under pressure for sometime to compensate for decrease in volume due to solidification. It should be noted that, during injection and after filling stages, there is an oppressive force from the mould opening side in mould opening side in order to keep the mould close. This is known as clamping force.

Cooling

Cooling the moulded part until it is sufficiently rigid to be ejected.

Mould Release

Opening the mould, ejection of the product with out deformation, closing of the mould again and ready for the next cycle.

2.2 Injection Moulding Machine

The equipment which is designed to facilitate the above process and manufacture large quantities of plastic products is known as Injection Moulding Machine. Conventional injection moulding machine consists of two major sections.

a. Injection section

b. Mould closing section

The injection section comprises the injection cylinder equipped with screw or plunger which serves to plasticize the material and till the mould. Also injection section consists of a stationary machine platen on which the cavity plate or stationary side of the mould is fixed.

The mould closing section operates the opening and closing movement of the mould and handles the ejection of the plastic product. Also this section develops a sufficient clamping force to keep the mould closed during injection and after filling. Movable machine platen is fitted with an opening and closing mechanism and a central ejector mechanism. These are operated either hydraulically, mechanically or by combination of the two.

2.3 Types of Injection Moulding Machines

2.3.1 Plunger Type

Plunger type injection moulding machine consists of two reciprocating hydraulic plungers. The first one which is a smaller one close to the hopper forces the plastic granules feed from hopper through the narrow passage way to the main injection cylinder. Plastic granules are melted in the injection cylinder before they reach the injection nozzle. Due to the movement of main hydraulic plunger platicized granules injected and forced into the cavity of the mould. After return the main plunger to its original position, plastic granules are sent by the top small plunger and the cycle operates again. This type of machine is not often used nowadays due to the quality of the product is not so good. Because for coloured products, colouring agents (Master

Batches) are not properly mixed with plastic granules in the cylinder. Therefore appearance of the finish is not satisfactory

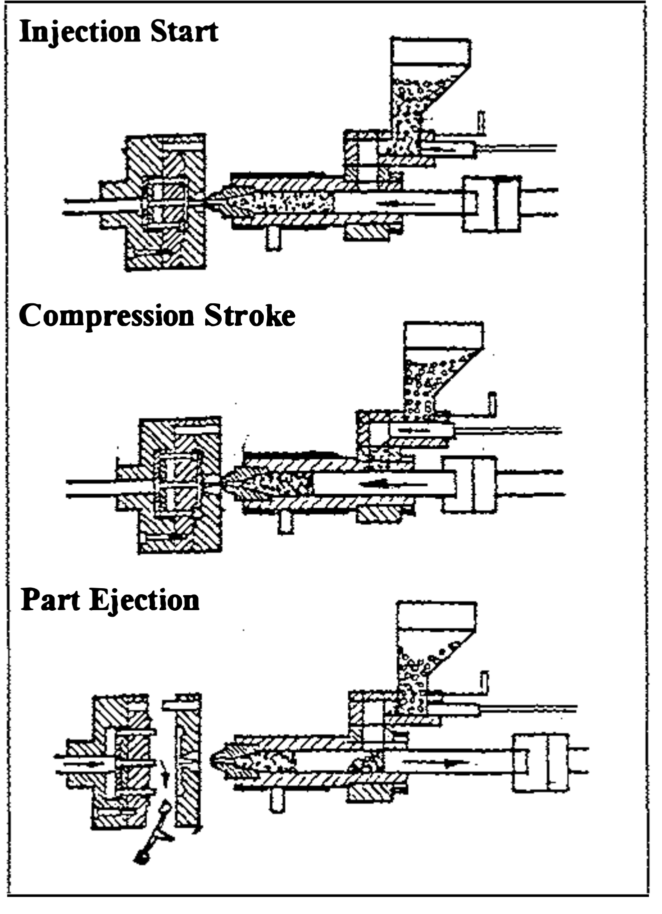


Figure 2.1 Principle of Plunger type moulding machine

2.3.2 Screw Type

Screw type injection moulding consists of an injection cylinder in which plastic granules are heating and mixed by means of a rotating screw.

The sequence of operation is as follows.

- The rotating screw transports the plastic granules from the hopper into the injection cylinder where they are heated, plasticized and vented.
- The screw deposits the melt in front of itself moving backward to accommodate the material as it build up. To ensure optimum plasticization, this backward movement is usually slowed down by a counter pressure exerted on the screw.

- As soon as plastic granules has been plasticized for one shot, the screw stops rotating, acts as a plunger and moves forward, forces the melt flow into the mould.

The system ensures maximum melt homogeneity, shorter cylinder dwell time and in many cases, a shorter moulding cycle. The appearance of the finish product using this type of machine is very good.

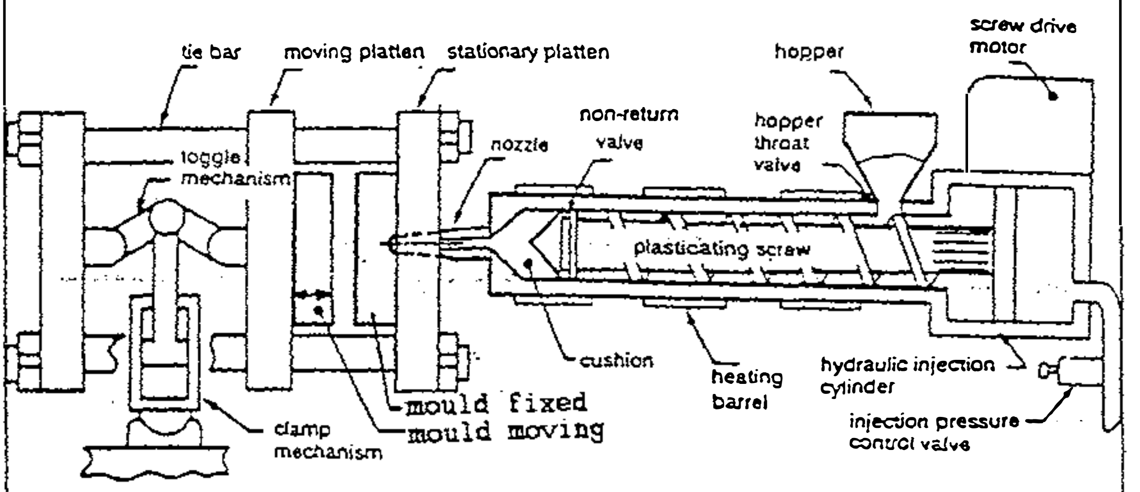


Figure 2.2 Parts of Screw type moulding machine

2.3.3 Manual Type

This type of machines are used by manufactures who want to have prototypes of the end product. Normally it is vertical and portable. Plastic granules are directly put into the injection cylinder through its funnel opening and plunger is pushed down by the hand wheel or cross bars through the mechanism of the rack and pinion. Plastic granules are heated by heating elements around the cylinder. Heated granules are injected and forced into the mould. Mould is also opened by screws connected to two hand wheels. Finish product is removed manually by unscrewing hand wheels. This machine can be only for products which can be moulded by standard simple moulds. Also there machines up to 4 oz injection shot weight.

This machine can be made locally with very low cost and it is very useful for domestic self employed personnel.

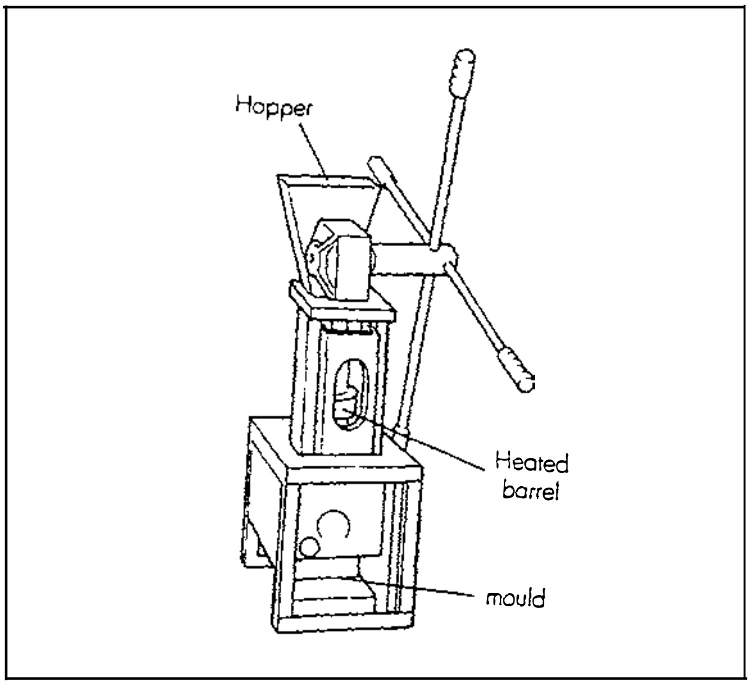


Figure 2.3 Manual type moulding machine

2.4 Important Parts of the Conventional Injection Moulding Machine

2.4.1 Injection System

In conventional machines, injection system consists of a screw which reciprocates with in the cylinder. The screw is typically rotated by a hydraulic motor. In the forward position after the injection, the screw is energised to rotate. Plastic granules fed by gravity from an over head hopper, are moved forward along the flights of the screw in the heated cylinder are melted. Because of the injection which was blocked by the previous shot in to the mould, causes the screw to move itself backward into the cylinder. A supply of plastic is built up in front of the screw, which is sufficient for next cycle. To control the volume of the shot, there is a limit switch to shut off the screw when it has reached its required stroke. When the pressure locks up screw comes forward acts as plunger. The non return valve closes the escape passages in the screw and acts as a solid plunger to the melt and injects in to the mould. At the completion of the injection of the injection cycle, it holds some times and is energised to return. During the return, non return valve moves open and allows plastic material to flow forward from the screw again

2.4.2 Clamping System

The purpose of the clamping system,

1. Support the stationary and movable halves of the mould.
2. Transport the movable half of the mould open to shut, for mould filling.
3. Open the mould again for ejection of the completed product.

Due to the very large force exerted to the core side (stationary side) of the mould due to injection and holding pressures; there is a tendency to open the mould. To prevent that, the clamping pressure which acts against through the core plate should be equal or more than injection or holding pressure. This is achieved by ether hydraulic or mechanical toggle mechanism or combination of both hydraulic and mechanical toggle mechanism.

2.4.3 Hydraulic System

In conventional injection moulding machine there are there two hydraulic pumps driven by an electric motor, which pumps hydraulic fluid to injection system in order to drive the hydraulic motor to either rotate or move the screw. On the other hand pressurised hydraulic fluid supplies to clamping side to clamp the stationary side of the mould against the injection and holding pressure. Hydraulic circuit is opened and closed by series of directional valves driven by programmable logic controllers (PLC), conventional electro-magnetic relays, electronic PCB cards. Hydraulic system is very essential for the operation of injection moulding machine.

2.4.4 Mould

Mould is an assembly of metal components which is being used to produce plastic products. Molten plastic fluid is injected in to the mould cavity which is a mirror image of the plastic product and is cooled. In order to do this, mould basically consists of a cavity plate which is the female portion and a core plate which is the male portion. Cavity plate is normally attached to the stationary side of the machine and core plate is attached to the movable side. Mould is the most important part in the injection moulding machine.

2.4.5 The effect of specification of injection moulding machine in basic mould design

Example

Suppose the weight of the plastic product to be produced is 10g

Injection capacity - 180g/shot

Therefore 18 cavities can be made.

The projected diameter of the cavity - 40 mm

Projected area - $\pi * 20^2 = 12.56\ cm^2$

Injection pressure - 1950 kgf/cm^2 (For the machine at the departments industrial engineering laboratory)

The force exerted on one cavity- 24.57 tons

For 18 Nos. cavities the force . 442.26 tons

The machine required 442 tons of clamping force. But available clamping force is 100 tons. In addition to this, after consideration of areas runners, gates and sprue puller of the mould, 18 Nos. items can not be moulded. Maximum No. of item can be produced is just about four.

Further, the distance between the tie bars and the distance between the stationary and movable platens when the machine is fully opened should be taken into account before making a decisions about the outside dimensions of the mould.

2.5 Description of the Injection Moulding Machine at the Production Technology, Industrial Engineering laboratory.

The make and model of the injection moulding machine is Cosmo, TTI 330/100 HI manufactured by Welltec Industrial equipment Ltd., Hong-Kong. Injection capacity is 180g. The clamping force 100 tons.

Distances between tie bars- 355 mm.

Distance between platen when they are fully opened- 310 mm

Full specifications of this machine is attached in Appendix A.

The machine consists of reciprocating screw injection system. The screw is driven by rotating type hydraulic motor. Clamping system is a new hydro-mechanical to toggle design which employs a hydraulic cylinder for the traversing of the movable mould plate. The cylinder is connected between the movable platen and the back plate. The traditional toggle system is still retained. But the cross head is controlled by one cylinders anchored to the movable platen rather than the back paten. All controls can be adjusted through a digital display. There are 04 four of heaters around the injection barrel. The machine can be run fully automatic. Relatively this is a modern type of injection moulding machine. This machine is always busy and is used for academic purposes by both undergraduates and post graduate students as well as commercial purposes by the department.

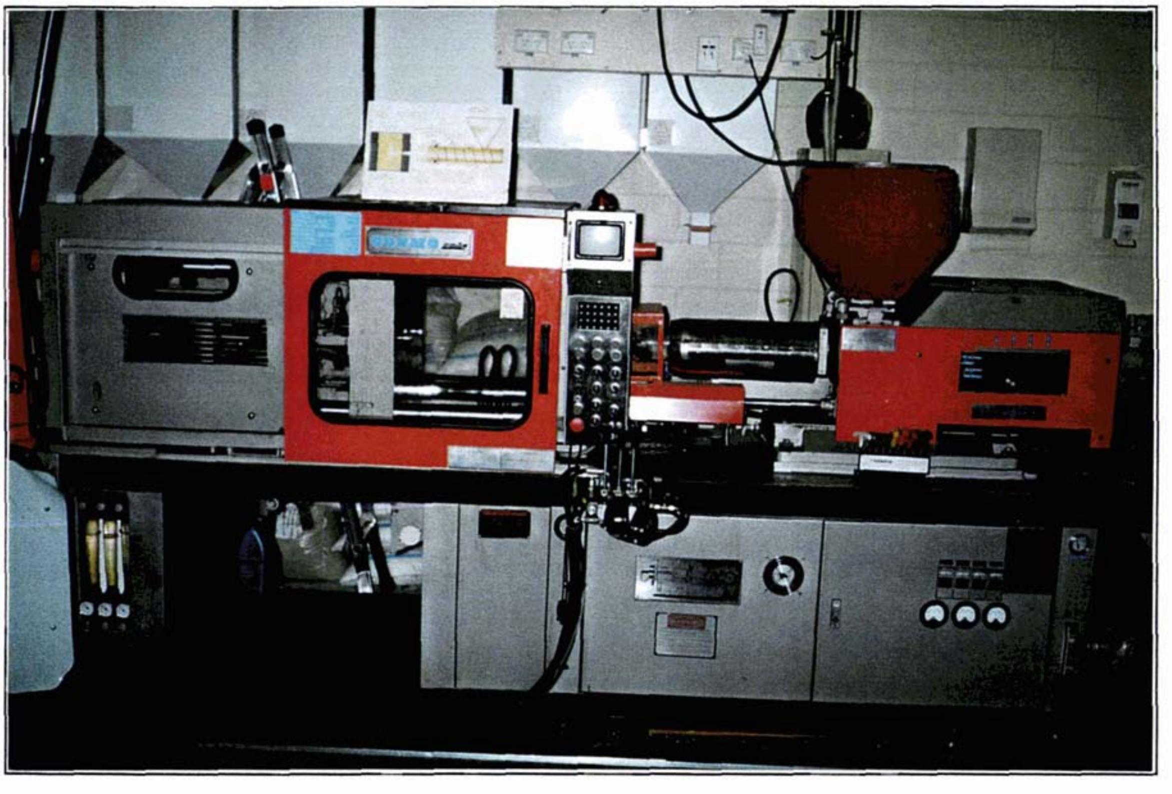


Figure 2.4 Departmental Injection Moulding Machine

Chapter 3

Description of Injection Moulding Tool

This chapter describes about the injection mould design and manufacture difficulties, various designs, material selection and effect of mould on the finish plastic product.

3.1 Difficulties in Moulding

The objective of whole plastic injection moulding is to produce specified plastic product in a large quantities, with excellent quality, without damaging either to the machine or to the mould. Therefore following difficulties will have to be overcome by the designer during mould manufacturing.

1. Obtaining the correct shape of the mould cavity according to the end product.
2. Transportation of high temperature molten plastics from the injection nozzle to the cavity of the mould.
3. Automatic ejection of moulded end product at the end of each injection cycle.

Normal injection moulding operation conditions;

- Cavity pressure - 300 bar to 1500 bar (700 bar is typical)
- Mould temperature during operation 40^0C - 70^0C (50^0C is typical)
- Plastic injection temperature 140^0C- 280^0C (200^0C is typical

3.2Overcoming Difficulties Through Quality of Design and Manufacture.

3.2.1 Basic parts of conventional two plate mould

- Cavity plate - The half of the mould containing mould cavity.
- Core plate - The other half of the mould. Cores are generally on the movable half of the mould to made part ejection easier.
- Sprue bushing - Tapered insert in the mould which allows plastic flow from the nozzle to the runner.
- Ejector pins - Movable pins that eject the part and runner out of the sprue bushing when the mould opens.
- Sprue puller pin - Designed to pull the plastic sprue out of the sprue bushing when the mould opens.
- Support plates (optional) - Makes the mould more rigid to resist deflection.
- Support pillars - Placed behind support plates to resist deflection.
- Ejector and retainer plate - Holds the heads of the ejector pins and the sprue puller

pin.

- Guide pins - Used to exactly locate the position of two mould halves in relation to each other.
- Clamp plate - The plate that is clamped or bolted on to the machine platen.
- Cooling lines - Either in the support plates or the cavity and the core plates. Use to take heat away from the plastic.

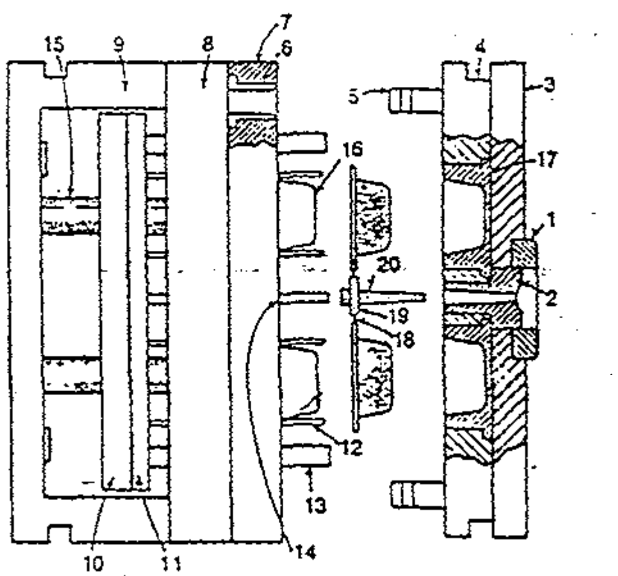


Figure 3.1 Parts of conventional moulding tool

3.2.2 Obtaining the Correct shape

The cavity is machined on the cavity plate of the mould. The core in most cases projects from the core plate and forms the inside shape of the moulding. This is illustrated in fig. 3.2. Machine of cavities can be carried out using conventional as well as modern machinery. When the mould is closed, the two plates come together forming a space between the cavity and core plates of the mould is known as parting line. Some times to simplify the process of mould manufacture local inserts are used either in the cavity or core plates. Some examples are shown in fig.3.3. On the other hand it is not economical all the time to attempt to machine the cavity and core plates from single blocks of material, because the machining sequences and operation would be too complicated and expensive. Therefore a small piece of material part is machined. After machining the one which forms male part is termed as the core insert and conversely the one which forms the female part is termed as the cavity insert. The block or plate of mould material on which cavity/core insert are fitted is called the bolster.

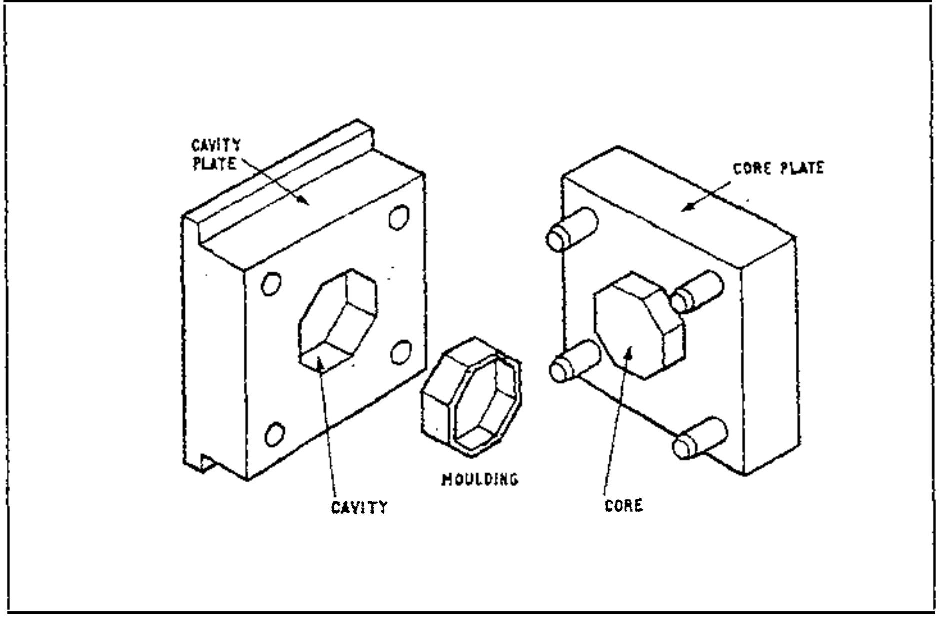


Figure 3.2 Basic mould configuration

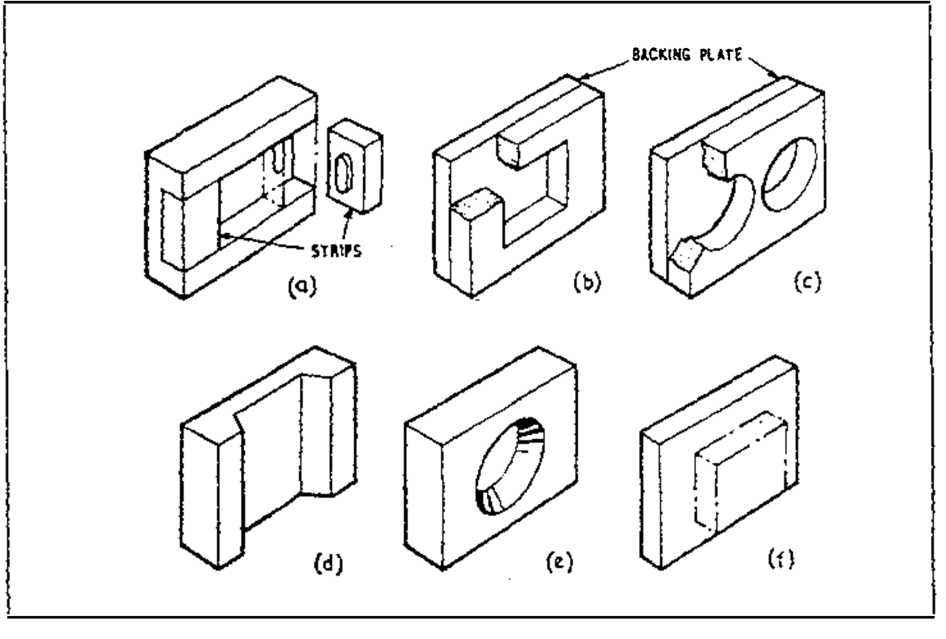


Figure 3.3 Inserts and bolsters

3.2.3 Transportation of molten plastic into the mould cavity

3.2.3.1 Sprue bush

During injection moulding process moulted liquid plastic material from the injection nozzle to the mould cavity is delivered through a passage. This passage is a tapered hole and termed as Sprue. Some manufacturers makes this hole directly on mould. cavity plate. But most manufacturers design and make this passage in a separate stepped bush as shown in the diagram 3.4.

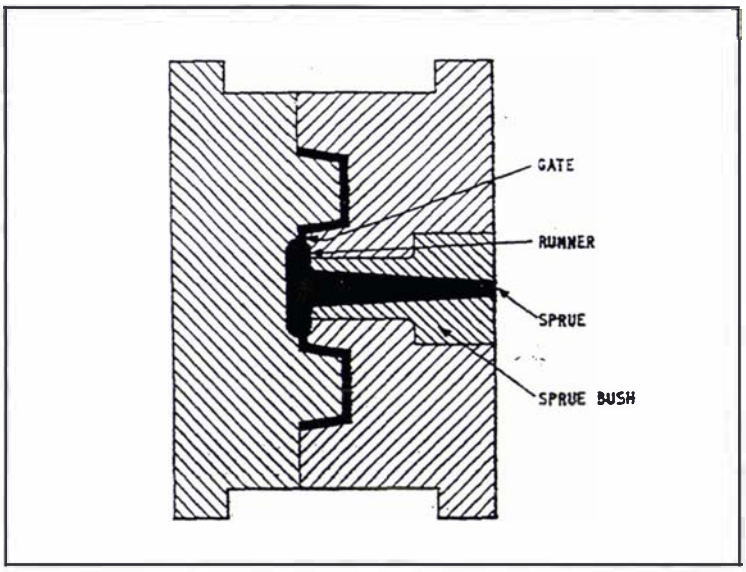


Figure 3.4 Sprue and sprue bush

This is fixed to the cavity plate as an insert and can be replaced with any other sprue bush with different sizes of sprues. Sprue may have the taper from 3^0 to 5^0. Sprue bush may be designed either with a spherical front ended injection nozzle or flat nozzle as shown in fig.3.5. It should be noted that the radius on the nozzle is slightly less than the bush. This ensures both parts are in physical contact at the apertures. Also centrelines of nozzle and the bush should be aligned to make sure leak free joint is achieved.

During the use of flat conjunction of nozzle and bush leakage does not occur even if there is a slight misalignment.

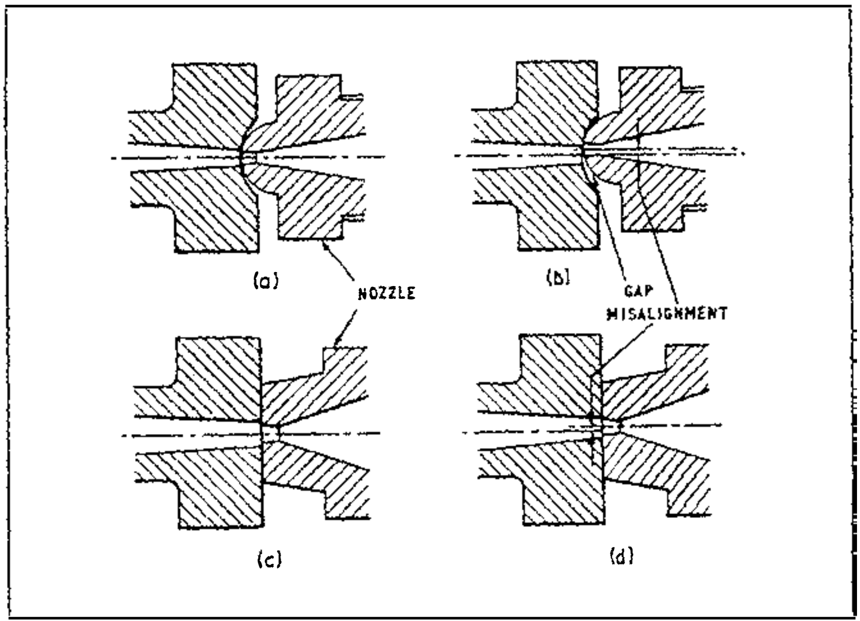


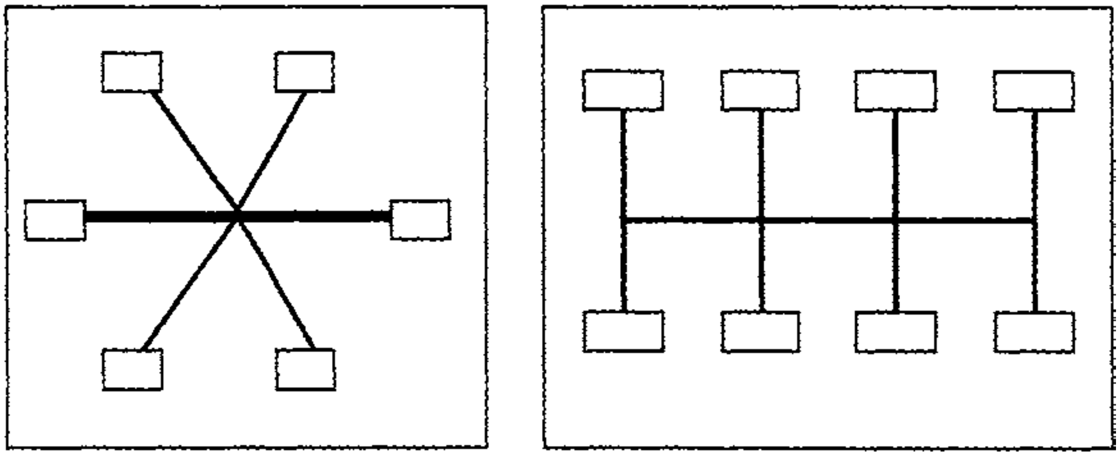
Figure 3.5 Effect of misalignment between sprue bush and injection nozzle

3.2.3.2 Runner system

The runner system accommodates molten plastics material coming through the sprue and guides it in to the mould cavity. Its configuration, dimensions and connection with the moulding affect the mould filling process and therefore largely the quality of the end product. It may be round, half round, parabolic or trapezoidal. During the design of runner system, the designer should

- Select the shortest way in order to convey the melt rapidly in to the cavity with a minimum heat and pressure loss.
- Ensure that the material must enter cavity (or cavities) at all gates at the same time under same pressure with same temperature.
- Keep optimum cavity area in order to save material as well as optimum cavity filling.
- Keeping surface over volume ratio as small as feasible.

Runner system can be designed as ring shaped, star shapes (fig.3.6 a) which offer the advantage of identical and shortest possible flow paths. Also In line runner (fig. 3.6 b) are useful but have the disadvantage of unequal flow path lengths.



(a) Radial runners and gates (b) In line runners and gates

Figure 3.6 Different runner systems

3.2.3.3 Gates

Gates separate the runner and the part. Gate is defined as the cross section of the runner system at the location where it feeds into the mould cavity. The type and location of both runner/gate are important because they affect economical production, properties, tolerances, weld lines etc., of the end product. Different types of gates and guidelines for gate design are shown in Appendix L

3.2.4 Ejection

As all thermoplastic materials contracts as they solidify, moulding will shrink either in the cavity or on the core which forms it. This shrinkage makes the moulding difficult to remove. The mechanism of removing the end product is known as ejection. In order to facilitate automatic ejection there are some basic designed features in the mould. Sprue is designed as tapered by keeping the aperture size of the nozzle mating surface is smaller and at the end of the sprue, Sprue puller is provided as shown in figure 3.7. These facilitates the sprue remove from the cavity plate easily with minimum friction and comes with the core plate when mould is opened. Also walls of cavities and cores are designed to machine with a small taper inward and outward (as shown in the figure 3.9) in order to facilitate easy removal of the moulded part. Ejector mechanism is provided behind the core plate (moving side) which activates when the mould is opened due to the direct push by the ejector or knockout bar provided in the injection moulding machine. Due to this, ejector pins and the

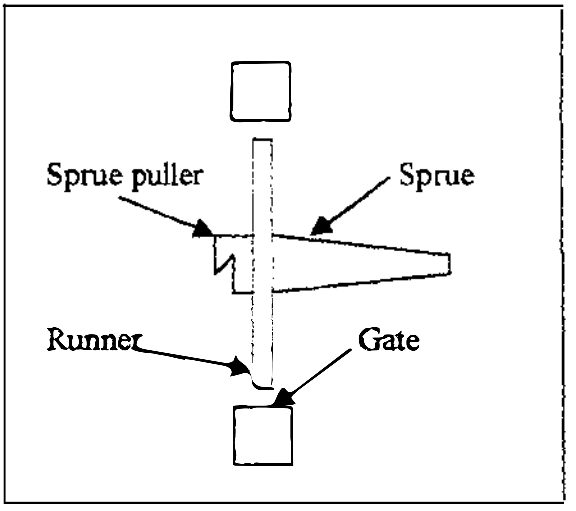


Figure 3.7 Sprue and sprue puller

puller pin fitted to the ejector plate moves towards the stationary side of the mould and pushes the moulded part, runner system and the sprue puller already attached to the core side. Hence moulded parts ejects outside from the mould.

There are various designs of ejection pins such as circular pin. D-pin, sleeve, blade. Valve headed type, bar type, etc. as shown in figure 3.8. Typical ejection action is shown in figure 3.9. For parts with under cuts, external threads, internal threads mould is designed with more complicated ejector systems in order to make sure of automatic ejection. These will be described in the next section. The designer should have a through understanding about the ejector system on rapid manufacture of moulds.

3.3 Various Mould Designs

3.3.1 Parts with out undercut - Standard mould

3.3.1.1 Major components

- Clamping plate for movable side
- Ejector system
- Cavity plate and sprue
- Core plate for stationary side

3.3.1.2 Characteristics

- Most simple design
- Two mould halves

- One part line
- Opening in one direction
- Ejection by gravity, ejector pins or sleeve

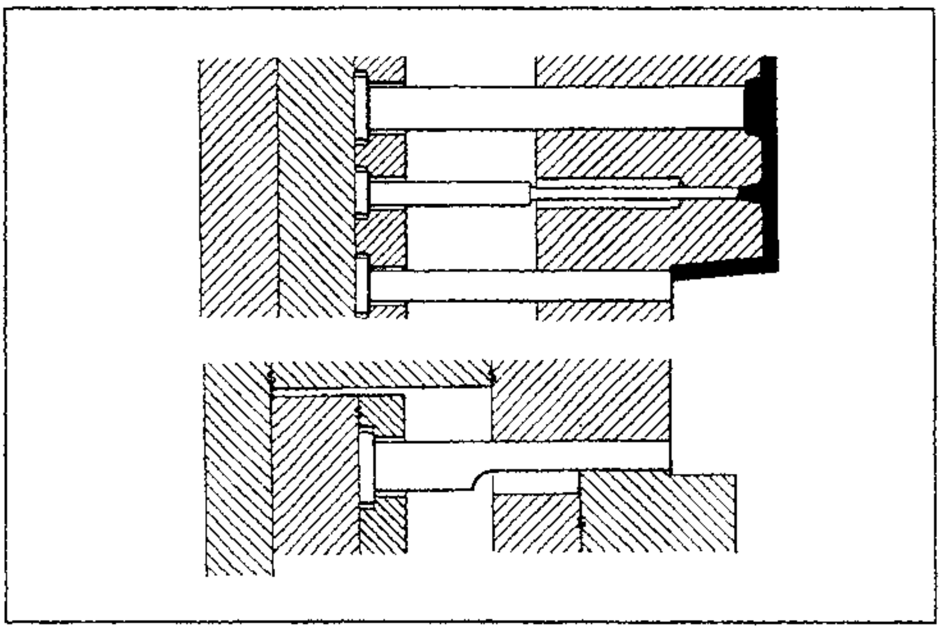


Figure 3.8 Various designs of ejection pins

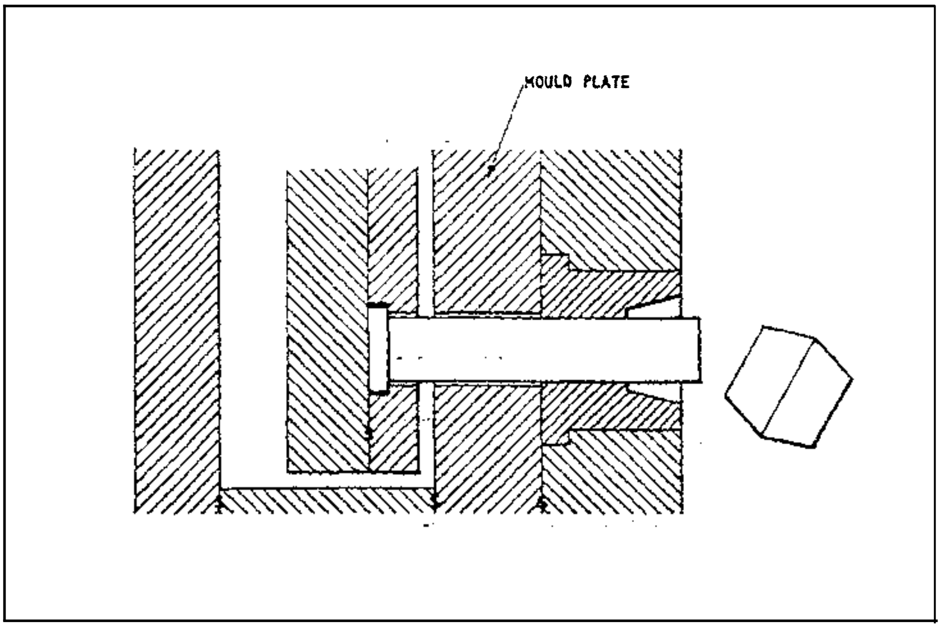


Figure 3.9 Typical ejection action

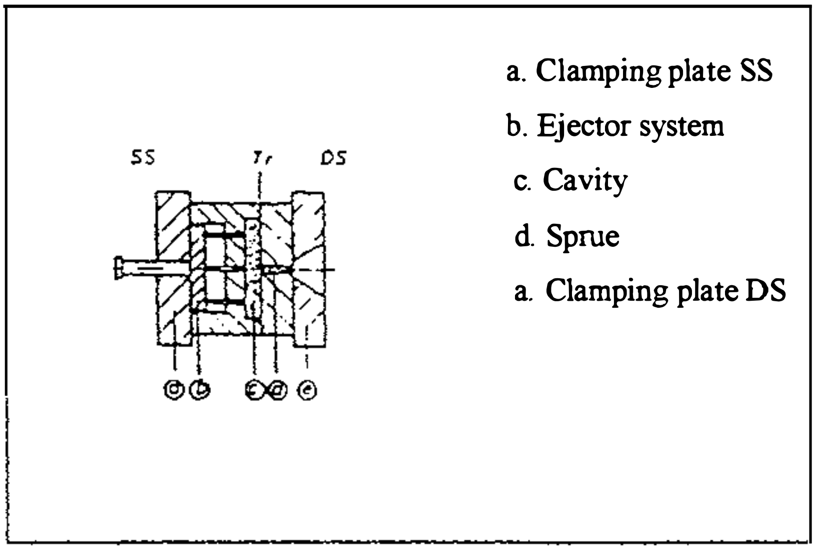


Figure 3.10 Standard mould

3.3.1.3 End products

- Simple rectangular containers
- Container lids
- Flower made by the author
- Plastic plates and dishes

3.3.2 Mould with stripper plate

3.3.2.1 Major components

- Clamping plate for movable side
- Stripper plate
- Cavity
- Sprue
- Clamping plate for stationary side

3.3.2.2 Characteristics

- Design is similar to standard mould but with stripper plate for ejection

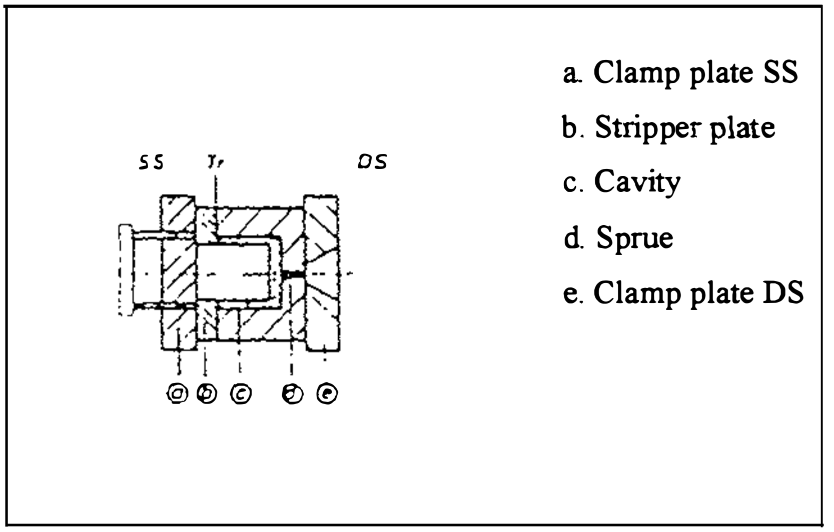


Figure 3.11 Moulds with stripper plates

3.3.2.3 End products

- For cup shape moulding with out undercut

3.3.3 Slide moulds

3.3.3.1 Major components

- Ejector system
- Cam pin
- Cavity
- Slide
- Sprue

3.3.3.2 Characteristics

- Design similar to standard mould but with slides and cam pins for additional lateral movement.

3.3.3.3 End products

- Transformer bobbins
- TV aerial dipole bases with external threads
- TV aerial dipole tops with internal threads

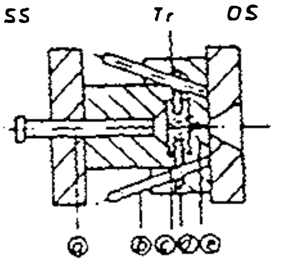


Figure 3.12 Slide mould

3.3.4 Split cavity mould

3.3.4.1 Major components

- Ejector system
- Retainer block
- Split cavity block
- Cavity
- Sprue

3.3.4.2 Characteristics

- Design similar to standard mould but with split cavity block for mouldings with under cuts or external threads.

3.3.4.4 End products

- Oblongs with undercuts or threads

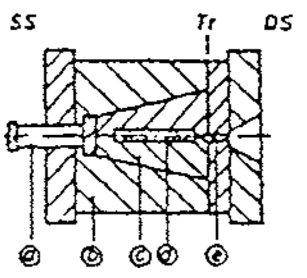


Figure 3.13 Split cavity mould

3.3.5 Mould with unscrewing device

3.3.5.1 Major components

- Ejection system
- Lead screw
- Gear
- Core
- Cavity

3.3.5.2 Characteristics

- Thread forming core is rotated by built in and mechanically activated drive

3.3.5.3 End product

- products with internal or external threads such as tooth paste tube lid, lids of small bottles, small threaded plugs

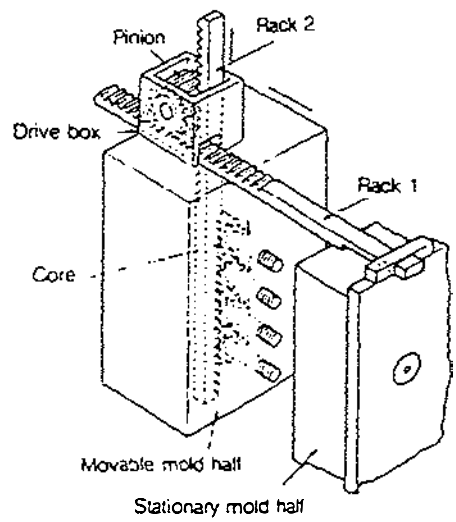


Figure 3.14 Moulds with unscrewing device

3.4 Moulding Tool Materials

3.4.1 Mould steel

3.4.1.1 Introduction

Moulding tool materials should be carefully selected for products with very high quality and large quantities. The mould maker is interested in the machinability of the steels, its polishability, heat treatment and surface treatment property and good thermal conductivity. The moulder who works with the moulding tool will be looking for a tool with good wear, corrosion resistance and high compressive strength etc.. Therefore mould steel is being used to manufacture moulding tools which require good wear, high strength, corrosion resistance properties. Therefore in many cases the choice of steel grade becomes a compromise, but always aiming for the best tooling and production economy.

3.4.1.2 Commonly used steel types

- Pre hardened mould steels: IMPAX SUPREM
- Through hardening mould steel: GRANE, ORVARM SUPREME
- Corrosion resistant mould steel: STAVAX ESR

- Bolster steels
  - Pre hardened: HOLDAX
  - Medium carbon: UHB
- For best tooling economy, "Think standard"
  - Standard steel grades
  - Standard steel sizes
  - Standard machined plates
  - Standard mould sets and accessories.

    (Some specifications are attached in Appendix M)

3.4.2 Mild steel

Mild steel is used to manufacture moulds for plastic products with moderate quality and quantities. It is cheaper and easier to machine and polish than tool steel Its compressive strength is also high. It has a good thermal conductivity. In order to economise the tooling manufacture Mild steel can be used for clamping plates, space block and ejector plates of the mould. Further, mild steel can be used for both cavity and core plates with mould steel inserts. Mould steel inserts are placed in locations where cavities and runners exist.

3.4.3 Aluminium alloys

3.4.3.1 Introduction

The mould manufacturing industry is constantly looking for alternative methods, processes and materials to maintain economic production levels. After research and development, the aluminium industry has developed a wrought aluminium plate specially designed for plastic injection moulding tools. This plate has been used with great success in western countries. Wrought plate is made by hot rolling a cast slab and it becomes homogeneous, free from porosity with no inclusion or casting defects.

3.4.3.2 General characteristics

- Machinability of Aluminium alloy is considerably higher than steel. Therefore higher cutting speeds can be selected with less tool edge wear. Production time is shorter and better utilisation of the machine tool is possible. Since machining time is less than 50% of that is required for steel, it is very useful in rapid mould manufacture.

- Thermal conductivity of Aluminium is very much higher than steel. This affects the performance of the tool. Better heat transfer, faster heating and cooling the moulding tool influence the injection cycle time and quality of the end product.
- Corrosion resistance of Al alloy is higher than steel. No protection such as chromium plating or application of hydro-cabonic ingredients such as grease, oil etc. in order to prevent natural corrosion. During Injection moulding process with PVC material due to heavy corrosion, it is economical to use moulding tools made with Al alloys.
- The density of Aluminium is normally one third of steel. Hence it is very easy to handle during moulding tool manufacture. No extra personnel or lifting appliances are required. Reduces accidents due to easy handling.

3.4.3.3 Commonly used Aluminium alloys

AlZnMgCu alloy is very much popular in tool making industry in western countries. Fatigue properties are very good. Suitable for machining on standard machine tools such as milling, grinding, lathe, pantograph etc.. Fine machining, punching, engraving can be achieved high degree of accuracy and fine contours or embossing can be carried by using EDM. A highly polished surface of excellent quality can be obtained either by manually or polishing tools. Repairs can be carried out in the event of machining errors. Welding may be done by using MIG or TIG. Surface treatment also can be improved by hard anodising or chromium plating which results higher hardness and less tool wear.

3.4.4 Zinc alloys

Zinc alloys are relatively cheaper than other alloys. Also they have a very good mouldability. They are used in injection moulding not only for preproduction trial run tools but also for production run tools for small quantities of products. Manufacturing time is less due to easy machinability. Clamping and transverse forces can be absorbed either by appropriately dimensioning wall thickness or by using steel bushings, pins, steel pressure pads, steel edge strips etc.. Tool temperature can be controlled by cooling without interfering with the strength. This can be carried out by using copper pipes around the mould. Abrasion stresses and chemical reactions can be controlled by surface protection. Zinc moulds are easily re-cast when obsolete.

Moulds with larger dimensions and deeper cavities can be easily made by using Zn alloy castings and hence a considerable machining savings is possible. In manufacturing, plastic parts that are subjected to fashionable influences, a rapid reaction to the trends of the market is frequently essential. Cast Zn mould with surface finishing operation are the best answer in such situations. Zn alloys can easily be machined by using both traditional as well as modern machinery. Also these can be subjected to EDM operations in comparatively lesser time with appropriate surface quality. Surface finishing can be carried out by grinding with a 400 or 600 abrasive grain. If a high gloss polish is required, the tool must be protected against chemical reactions or if the surface must be hardened, it is possible to Nickel plate the Zn moulding tool chemically.

Moulding tools made of Zn alloys can be repaired easily either by gas welding, arc welding, soft soldering or by TIG welding process. Zn alloy is a very useful material in rapid manufacture of injection moulding tools.

3.5Common moulding problems and their causes

3.5.1 Short shots

- Too small runners
- Gate too small
- Aperture of sprue near the nozzle too small
- Improper gate location
- Insufficient number of gates
- Cold slug well too small
- Insufficient venting

3.5.2 Flashing

- Cavities and cores are not sealing
- Cavities and cores out of line
- Mould plates not parallel
- Mould not sealing off

- Obstructed guiding pins or bushings
- Insufficient venting
- Vents too large
- Land area round the cavity too large, reduces the sealing pressure.

3.5.3 Sink marks- voids

- Insufficient gate, runner, sprue or nozzle sizes
- Insufficient vent
- Unequal filling rate of cavity
- Interrupted flow into the cavity
- No gates in thick sections
- Uneven wall thickness

3.5.4 Flow marks

- Insufficient venting at the weld line of the moulding
- Runner system, gate system, sprue opening or nozzle opening too small
- Gate too far from the weld
- Wall section too thin causing premature freezing
- Part is too thin at the weld
- Unequal filling rate
- Interrupted filling

3.5.5 Material discoloration

- Insufficient vent
- Gate size too small
- Runner, sprue, nozzle too small
- In appropriate gating pattern
- Lubricant or oil in the mould
- Incorrect mould lubricant
- Mould or plastic temperature too high

3.5.6 Surface defects

- Mould surface is not polished
- Mould surface dirty
- Excess lubricants
- Runner too small
- Cold slug well too small
- Sprue, runner and gate are not polished

3.5.7 Warpage and shrinkage

- Improper location of gate
- Insufficient gates
- Gate size not correct
- Ejection area small
- Ejection not even
- Wrong mould dimensions
- Insufficient cooling
- Wrong part design
- Insufficient wall thicknesses

3.5.8 Surface disturbances at the gate

- Mould temperature too low
- Gate size too small
- Gate shape not correct
- Cold slug well too small
- Runner size too small
- Incorrect gate location
- Venting not sufficient

Chapter 4

Use and effect of Conventional Machinery In Rapid Mould Manufacture

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This chapter describes the effect of conventional machinery on rapid injection moulding tool manufacture

4.1 Centre Lathe

4.1.1 Applications

The centre lathe is the oldest machine in the family of workshop equipment and is a very useful machine in manufacture of moulding tool. Turning of guiding pins, ejector pins, circular cavities in moulds, sprue bushes, guide pin bushes, threading operations in different components, finishing operations in moulding plates are carried out by using centre lathe. Further boring and drilling operations also can be commenced by the centre lathe. This can easily be used to find and locate the exact centre point of circular mould plates before they are fixed on to other machines such as milling for a certain job.

4.1.2 Limitations

Lathe can not be used in machining pockets with any shapes other than circular. Operations such as gear cutting, long slot cutting which we come across in moulding tool manufacture can not be carried out by the lathe.

4.2 Milling Machine

4.2.1 Applications

Milling includes a number of versatile operations which are capable of producing a variety of configurations. There are three types of milling machines available known as Vertical, Horizontal and Universal. Milling cutter is a multi tooth tool that produces a number of chips in one revolution. There are three basic types of milling cutters and operations, known as slab milling, face milling and end milling. Using these basic milling cutters and operations, various operations that we come across in moulding tool manufacture, can be carried out. In addition to these it is possible to carriy out operations such as gear cutting using both simple and differential indexing, helical gear cutting, spiral making etc..

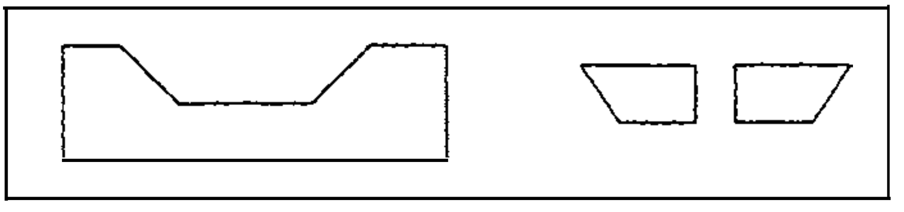
4.2.2 Limitations

Special tooling is required to machine cavities combining circular arcs and polygons. Difficult to machine cavities with free form curves and surfaces. It is not possible to machine cavities with complex surfaces. High skilled machinist is required to operate the machine during mould machining. Also he must have experience, care, patience and common sense. Process very slow and takes more machining time.

4.3 Shaping Machine

4.3.1 Applications

- Shaping all sides of mould plates, ejector plates, spacer blocks to required dimensions.
- Trapezoidal cavity and splits as shown in figure 4.1a and 4.1b in split mould manufacture can be machined by using the shaping machine.



(a) (b)

Figure 4.1

4.3.2 Limitations

- Can only be used for shaping operation of mould plates
- Relatively a slow process. Machine time is high.

4.4 Drilling Machine

4.4.1 Applications

- Drilling guide pin holes, ejector pin holes, holes before boring operations of cavities.
- Drilling holes to provide fixing Allen screws for assembling mould components such as core plate, cores, spacer blocks, clamping plates etc. together.
- Boring holes

Making holes for cooling water circulation in cavity and core plates.

4.4.2 Limitations

- Can only be used for drilling and boring operations.
- Skilled personnel required

4.5 Surface Grinder

4.5.1 Applications

- Surface grinder is used to surface finish of all parts of moulding tool such as clamping plates, spacer bars, base plates, main mould plates etc. in order to obtain smooth surfaces. This makes sure that all surfaces are parallel to each other and make accurate fitting all parts together.
- Also this make sure prevent splashing of plastics through mating surfaces of cavity and core plates.

4.5.2 Limitations

- Can be used only for surface grinding, ie. Flat surfaces
- Skilled machinists are required to operate the machine

4.6 Concept of Rapid Manufacture of Moulds

There are number of interdependent factors to be considered in mould design and manufacture as shown in figure 4.2. Since all these factors are interdependence, mould designer and maker have to consider all information from each factor. When using conventional machine tools, these information are taken either by the operator to set all necessary machine parameters immediately at the equipment, or by the designer at the design and drawing stage. Instead of prepare drawing, some conventional mould manufactures give the sample or the pattern of the end product to the mould maker.

Conventional sequence in mould manufacture is shown in figure 4.3. According to this method, final quality of the mould after making depends on adjustment of production and part testing. Frequently the mould has to be modified three or four times. This leads to waste of time, materials, labour and machinery. Some times entire mould itself may have to be discarded. Usually many manufactures pass losses due to all above factors to the customer by billing higher charges, taking long duration for completion. Because neither the supervisor nor the mould maker is able to plan the job in advance, predict the end quality of the job and the time required to complete the job correctly. This practice is not economically viable under competitive environment. Therefore in order to find a solution to these problems and eliminate difficulties the concept of rapid mould manufacture is introduced.

In rapid mould making manager or supervisor will be able to plan the job in advance and predict the time required to complete the job, select the correct type of machinery to be used for each sub job, proper allocation of personnel and finally able to predict the end quality of the job and make a realistic estimate. This leads to a saving of time and money of the customer. On the other hand, by completing jobs as quickly as possible with good quality, realistic price, manufacture's market share can be increased. Further, manufacturer can provide various motivational strategies for his or her employees in order to keep industrial harmony in the workplace.

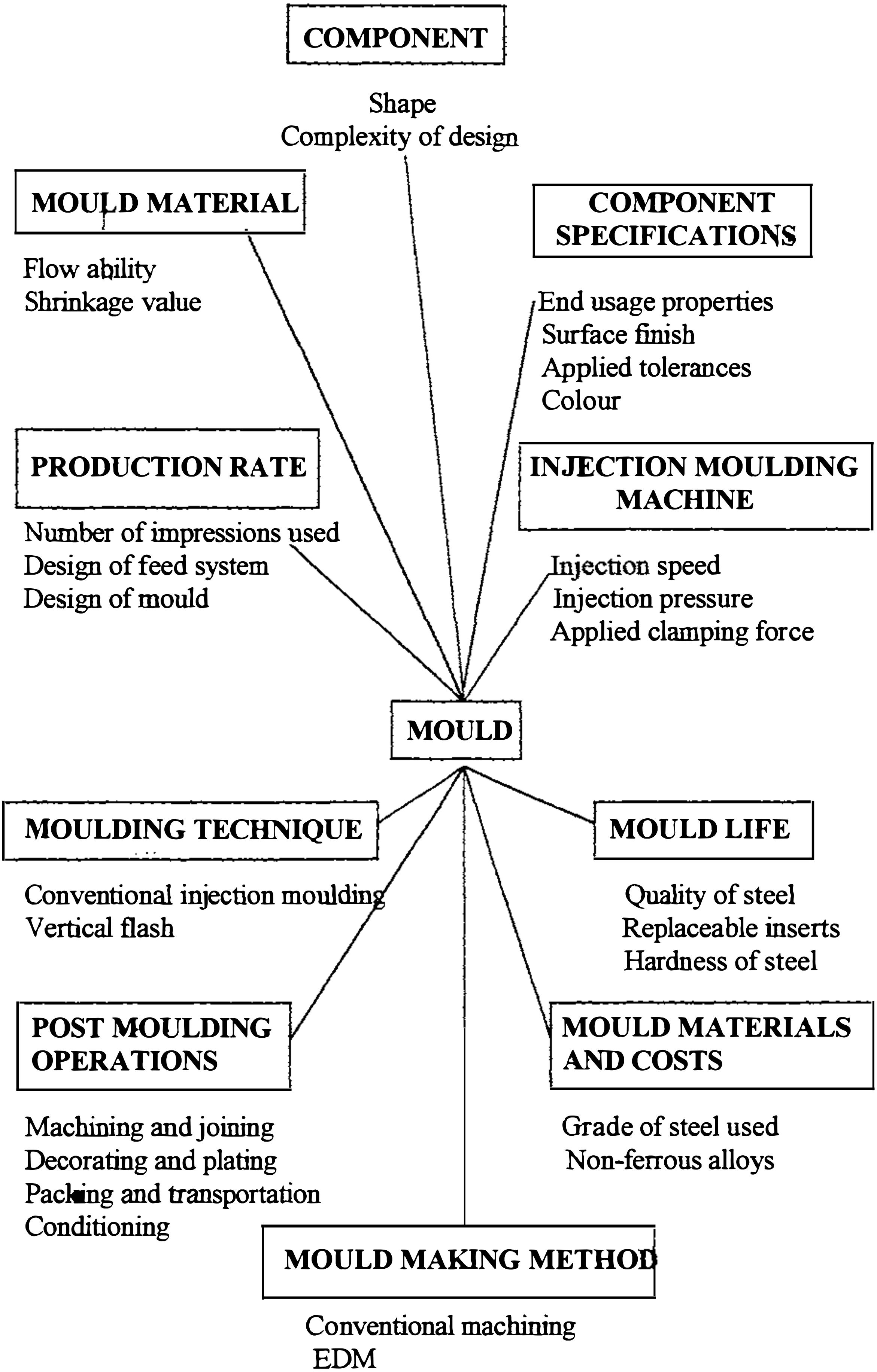


Figure 4.2 Interdependence factors in mould design and manufacture

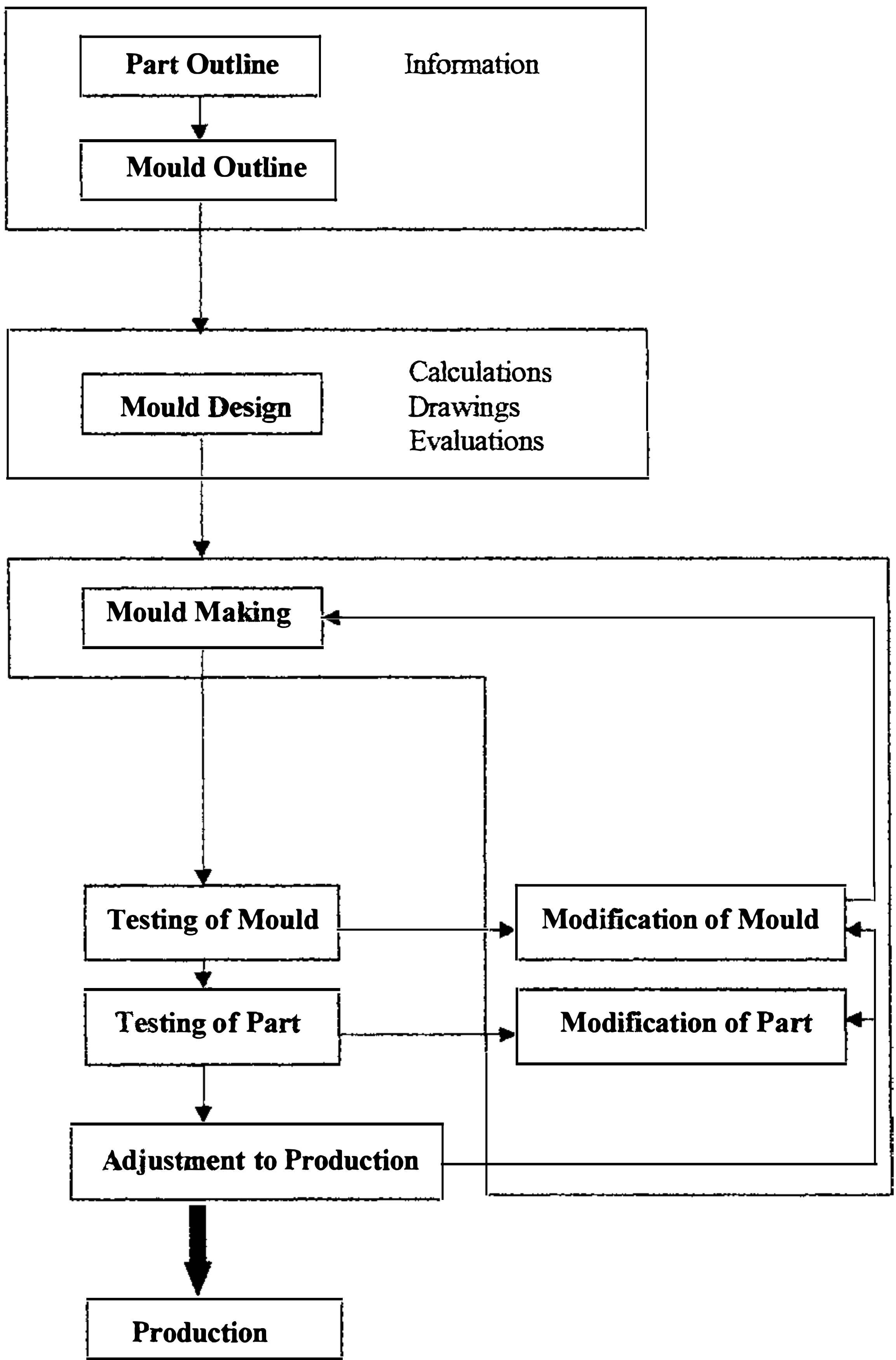
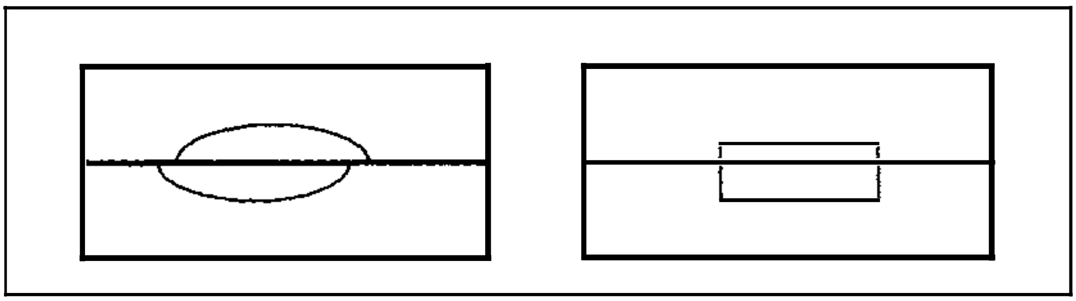


Figure 4.3 Conventional Sequence in Mould Manufacture

4.7 Effect of Conventional Machinery on Rapid Mould Manufacture

4.7.1 Locating errors in mating surfaces

It is difficult to locate symmetrically either cavities of both plates or cavity and core of cavity and core plates respectively by using conventional machinery. Some times even end product is not symmetrical along the parting line. This frequently happens for uneven cavities. The mould maker should have skills, patients and carefulness to do this accurately. Also it takes lots of time if he uses conventional methods



(a) (b)

Figure 4.4 Non-symmetrical cavities.

4.7.2 Non alignments of guiding pin holes

Due to inaccuracies of the machine or the operator, non-alignment of guiding pinholes for two plates of the mould may occur as shown in the figure 4.5.

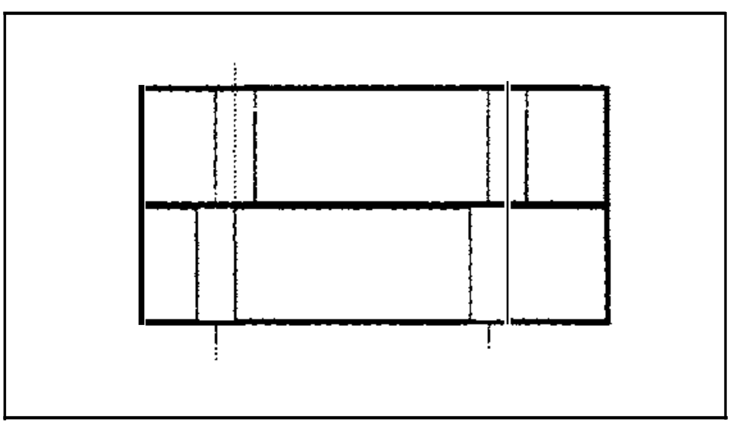


Figure 4.5 Non alignment of guiding pin holes.

Since centre points for drilling are measured and marked in both plates by persons, it may leads for inaccuracies. In addition to that, the may happens due to improper clamping, inaccuracies of the machine.

4.7.3 Non uniform thickness in the finished product

Since all measurement are carried out manually either by the mould maker or by the machinist when using conventional machinery, it is difficult to keep uniform or required thickness between the cavity and core as shown in the figure 4.6. This will affect the thickness of the finished product.

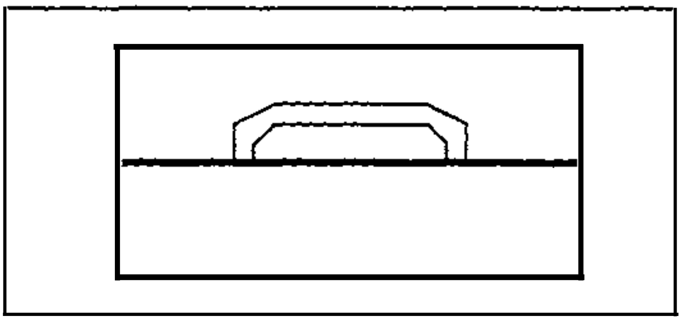


Figure 4.6 Non uniform thickness between the cavity and core.

4.7.4 Non identical cavities in multi-cavity moulds

During the manufacture of multi cavity moulds using conventional machinery, non-symmetry of mating surfaces and non-identical among the cavities or cores may occur. If this happens, finished products are not identical to each other. This is entirely depends on the machine accuracy and the operator. Some times mould makers mark or engrave cavity number on each cavity to identify possible manufacturing defects in the mould.

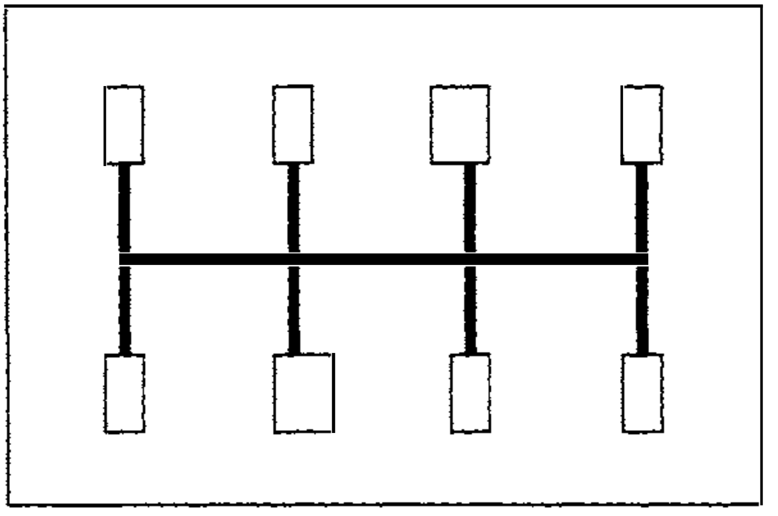
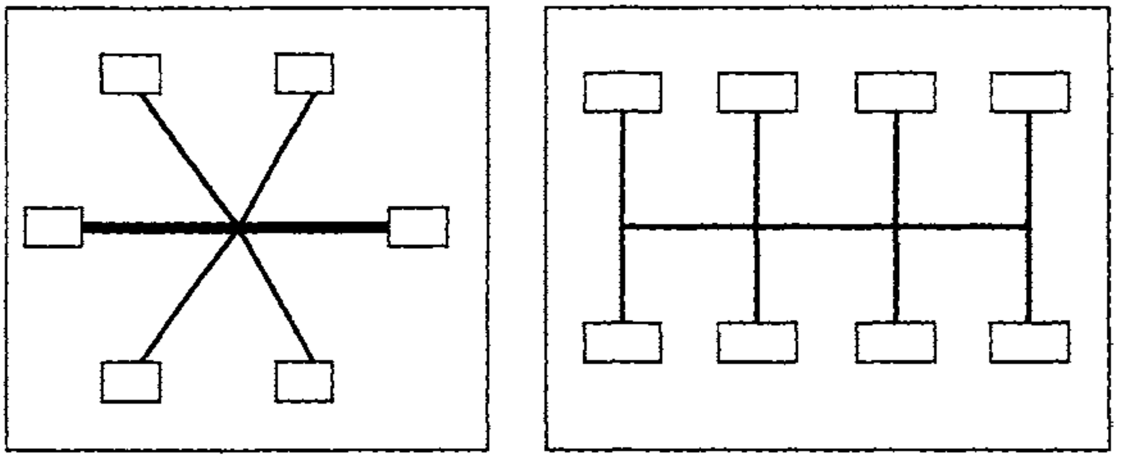


Figure 4.7 Non identical cavities.

4.7.5 In accuracy in machining radial types of runners and gates

It is a difficult and time consuming task to machine runners and gates symmetrically and accurately. Specially radial types of runners and gates as shown in the figure 4.8 a. The design of this type of runners and gates has to be machined manually by the machinist. Again this requires time, patients and skills. Even skilled machinists may make this type of mistakes while on machining.



(a) Radial runners and gates (b) In line runners and gates

Figure 4.8 Basic designs of runner and gate systems

Manufactures who are equipped with conventional machinery may select inline runner and gate system as shown in figure 4.8 b. in order to avoid radial type of designs. But in this design, plastic material does not reach to all cavities at once in the same time. Therefore filling defects in the finished product may occur.

4.7.6 Requirement of special tooling for circular complex shapes

During mould manufacture, mould maker may come across products with shapes as shown in figure 4.9.

Mould maker need to use templates and an additional tooling in order to machine such cavities.

For example, mould maker might use boring bars with ply cutters. Copy turning attachment use in centre lathe is another example additional tooling which helps to machine irregular shapes. Even for copy turning attachment a template is required.

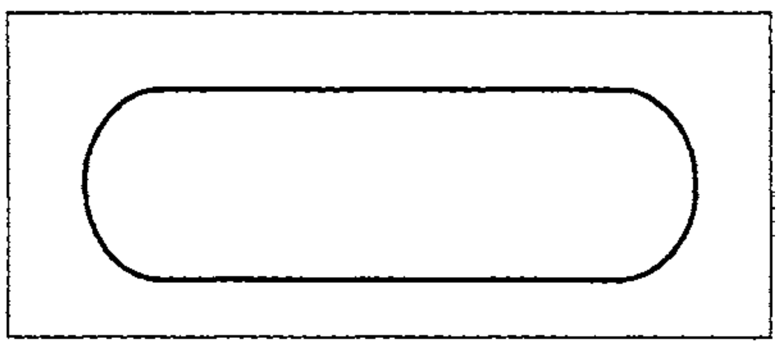


Figure 4.9 An example for a shape of mould cavity

4.7.7 Waste of time

According to the discussion about problems using conventional machinery, it is obvious that it is taken lot of time during manufacture of injection moulding parts. In addition to that, the mould maker and the machinist should have patient to do an accurate job. Also both mould maker and machinist should have knowledge to use all types measuring gauges. In addition to these measuring gauges must be accurate or should be properly calibrated periodically. This leads to wastage of time. No body can predict when the mould will be ready for delivery. Manager or Supervisor is unable to plan the job in advance due to these problems unless he is not thorough in mould making process.

4.7.8 Waste of material

Most times, due to inaccuracies described in above sections materials throw away and new materials will have to be used. Some times inaccurate cavities are machined and those are replaced by inserts. Author has observed several occasions, some mould makers use welding to refill inaccurate cavities.

This leads to both wastage of materials and time.

4.7.9 Dependency of highly skilled personnel

In order to eliminate all problems discussed above, mould manufacturer has to recruit skilled personnel from the manager, mould designer to machinists. Every body in the tool room must have skills, thorough knowledge of the moulding process. Management has to motivate their employees to maintain required quality of the job as well as to keep industrial harmony. This means dependency of skilled personnel has unnecessarily become a critical factor. Also manufacture has to spend more to recruit , train and keep personnel. This means usage of conventional machinery leads to wastage of time, material and dependency of personnel and mould manufacture becomes an expensive process.

Chapter 5

Modern Manufacture of Injection Moulding Tools

This chapter describes modern techniques of manufacture of moulding tools

5.1 Copy Milling Machine/ Pantograph

5.1.1 Applications

This machine can be used to overcome most problems described in sections from 4.7.1 to 4.7.5. This can even be used mill machine multiple cavities identical to each other with complex shapes. A tracing finger is being used to reproduce the cavity, runner or the part from a master model. Cavity can be machined from 1:1 to 1:2 proportions as well as mirror image of the master. Although this machine is well established not fall in to category of conventional machinery. Operation and maintenance of this machine is very easy. Further, it is not expensive.

5.1.2 Limitations

This requires to make a master equivalent to the shape of the cavity either manually or by casting. For multiple cavity moulding tools, machining is possible only one at a time. Tools for these machine is simple but expensive.

5.2 Numerical Control Machines

5.2.1 Introduction

The discussion in section 4.7 make it clear that conventional machine tool can not fulfil the need for rapid tool manufacture. In 1952, a three axis Cincinnati Hydrotel milling machine with digital technology was developed by Massachusetts Institute of Technology. This digital technology was termed Numerical Control (NC). The machines run by numerical controllers are termed as numerical control machines. Although the first NC controllers used in the 1950's were extremely large, due to the revolution of transistor, these controllers were possible to made relatively smaller with more reliable and cheaper.

In these controllers, the coded instructions consisting of letters of alphabet, numbers and symbols can be understand by the controller. These instructions are converted in to electrical pulses of current which the machine's motor and controls follow to carry out machining operation on a work piece. The numbers, letters and symbols are coded instructions which refers to specific distances, positions, functions or motions which the machine tool can understand as it machines the work piece.

5.2.2 Types

In 1970's the control hardware mounted on the NC machine was converted to local computer control with software. Two types of computerised systems are currently used namely Computer Numerical Control (CNC) and Direct Numerical Control (DNC).

CNC is a self contained NC system for a single machine tool including a dedicated computer controlled by stored instructions to perform some or all of the basic NC functions. In these machines the program for the part to be machined can be prepared at remote site by the programmer. Also the machinist can either prepare the same program or modify manually with the onboard computer.

- With DNC, several machine tools are directly controlled by a central computer. However, DNC had the crucial disadvantage that if the computer went down, all the machines become inoperative. Therefore a more recent definition of DNC (Distributed Numerical Control) includes the use of a central computer serving as the control system over a number of individual computer numerical control machines with onboard computers. This system provides large memory, computational capabilities with offering flexibility while overcoming previous disadvantages of DNC.
- Numerical control has been successfully implemented for turning, milling, drilling, grinding, boring and electrical discharge machines. In addition to these, it is interesting to note that numerical control has made possible the development of machines with basic capabilities that for surpass those conventional machines. For example, sophisticated NC milling machines maintain control over five axes of motion and literally sculpt complex surfaces.

A new breed of NC machine tool is the machining and turning centre which incorporates the functions of many machines in to a single device. A machining centre can access multiple tools to perform such operations as milling, drilling, boring and tapping. A turning centre is a powerful lathe equipped with an automatic tool changer. Other types of NC machines include welding machines, drafting machines and coil winding machines in the electronic industry.

5.2.3 General principle

The basic elements and operation of a typical NC machine are outlined in figure 5.1.

The functional elements in numerical control and components involved are:

- Data input. Numerical information is read by a tape reader stored in computer memory. A typical punch tape and standard Electronic Industries Association tape coding are shown in figure 5.2a and figure 5.2b. Paper tape is very nearly totally obsolete.

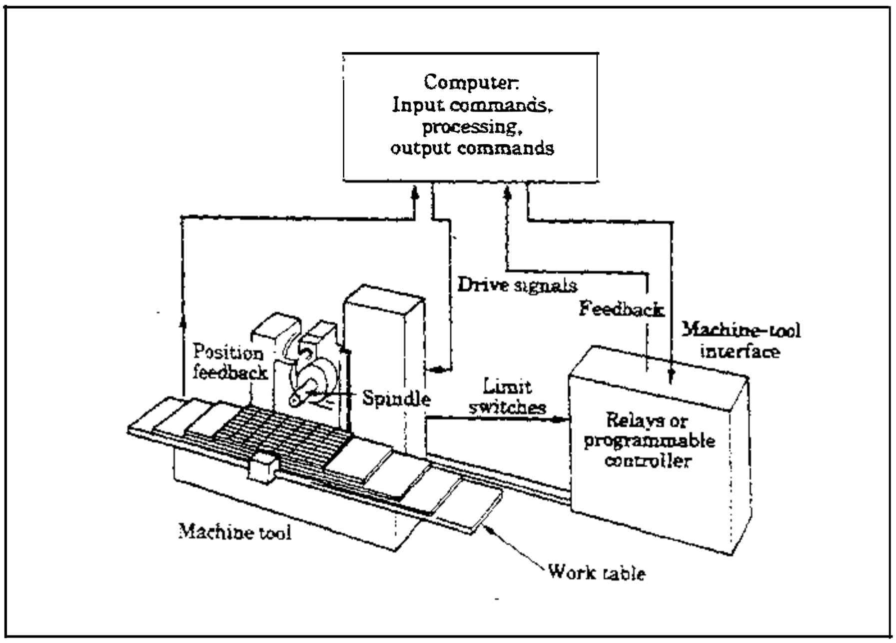


Figure 5.1 A Typical NC machine

- Data processing. The programs are read into the machine control unit for processing.
- Data output: This information is translated into commands, typically pulsed commands to a servomotor which is connected to the table. The servomotor moves the table on which the work piece is placed to specific positions through linear or rotary movements by means of stepping motors, lead screws and other devices.

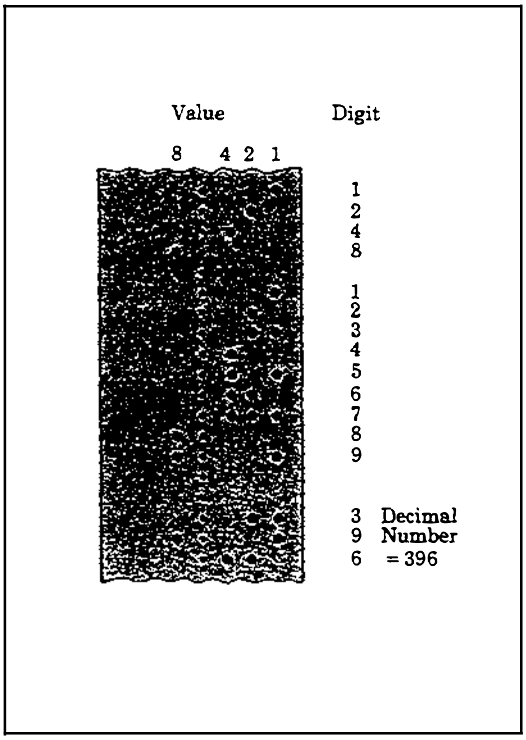


Figure 5.2a Typical punch tape

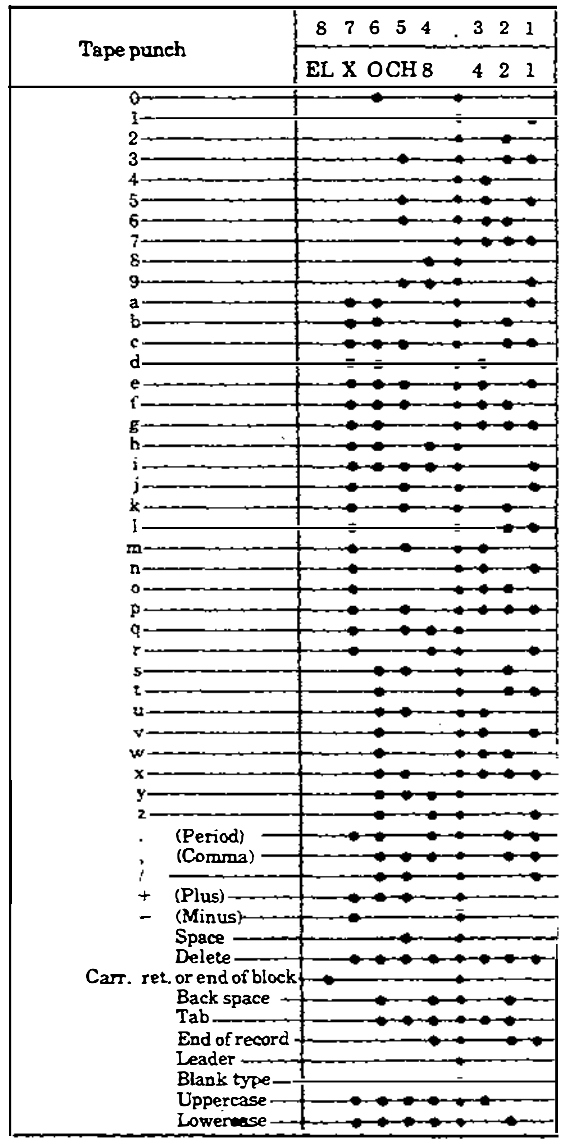


Figure 5.2b EIA tape code

NC machines can be controlled through two types of circuits namely Open loop and Closed loop system as shown in figure 5.2a and 5.2b. In the open loop system the signals are given to the servomotor by the processor and the movements and final destinations of the work table are not checked for accuracy. The loop system is equipped with various transducers, sensors and counters that measure the position of the table accurately. The position of the table is compared against the signal through feed back control. Table movements terminated when the proper co-ordinates are reached.

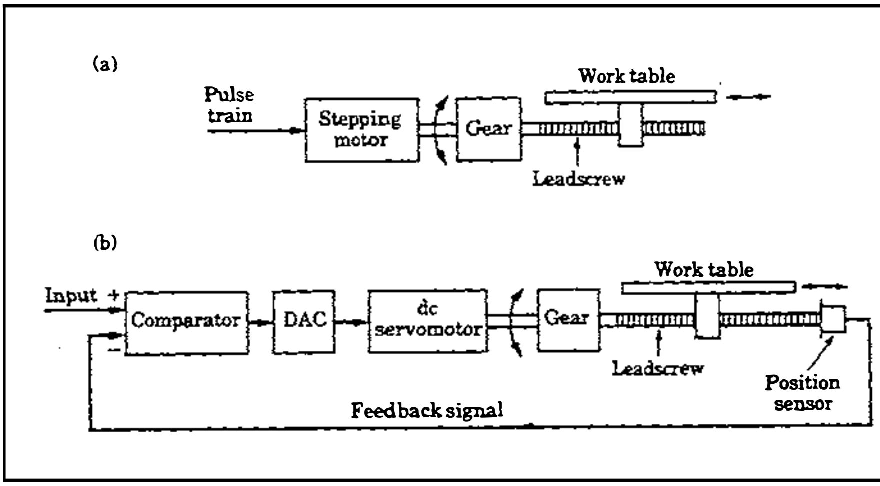


Figure 5.3 (a) Open loop and (b) Closed loop systems.

5.3 CNC Milling Machine at the Departmental Industrial Engineering Laboratory

5.3.1 Introduction

The CNC milling machine at the industrial engineering laboratory is a two and half axis Bridgeport Series 1 Interact fitted with Heidenhain TNC 145 controller. (figure 5.4) This machine has the additional capability for 2 axis simultaneous linear movement and circular contouring (e.g. Rectangular and Circular pockets) plus drilling, tapping, slot cutting, mirror image, datum shift and 3 axis positioning. It provides the simplest form of CNC control and minimal training is required to enable operators to use the machine with very little adjustment to their traditional method of operation. Machining can be carried out through a program using question and answer techniques. Also program can be edited in a particular file of a PC and transferred to the machine and vice-versa. Programming code of the controller is simple to understand and easier to keep in memory. The Heidenhain code is, however, not used on any other controller, unlike G codes, which are widespread. An electronic hand wheel permits full manual operation in all three axes using digital read out on the controller. All components of the machine have been designed for rigidity, accuracy and repeatability, essential for operation under automatic control. The machine is always busy and a very useful machine which is being used for both academic and commercial purposes.

Figure 5.4 Departmental CNC milling machine

5.3.2 Brief description of control

The interactive CNC control provides direct programming on the machine by the machinist. Simple operation and a clear arrangement of the control panel are provided in order to be understand easily. This includes separate displays for plain language dialogue and program block position values on key board for programming and other functions.

Programming can be performed

- With Stationary machine in accordance with a work piece drawing or program sheet.
- By 'Keying-in' values prior to automatic machining of the work piece.
- External programming via V24 interface. This interface enables the connection of a magnetic tape, storage unit or a tape punch unit.

5.4 Effect of NC Machining for Rapid Manufacture of Moulds

- Easily able to produce shapes such as circular, oval, rectangular etc. or combination of these. Runners and gates can be machined very easily within a very short time. Even cavities with complex shapes can be machined after programming. Operations can be carried out with very good dimensional accuracy, repeatability, high productivity.
- Quality of machining is very high.
- Cavities, runners, gates and other drilling holes can be machined in one program. It is possible to test the program by machining a prototype using less expensive materials such as timber. Therefore no material wastage occurs.
- If there is a problem after machining the prototype, design changes, program changes can be carried out very easily with in a very short time.
- No need to use extra tooling such as templates, copy turning attachments etc..
- Machine adjustments are easy to make with computers.
- Programs can be prepared rapidly and can be recalled at any time using microprocessors. Less paper work is involved.
- Required machinist skill is less and the machinist has more time to attend other tasks of mould making.

5.5 CNC Programming in G Code and Heidenhain Code

5.5.1 Co-ordinate systems

A right hand rectangular co-ordinate system is used to describe the position and motion of the tool or work piece.

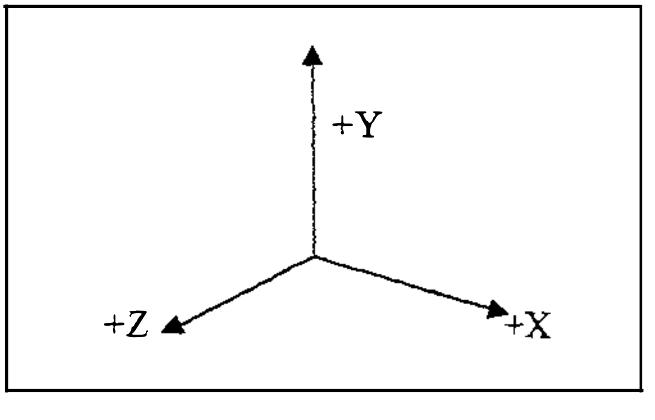
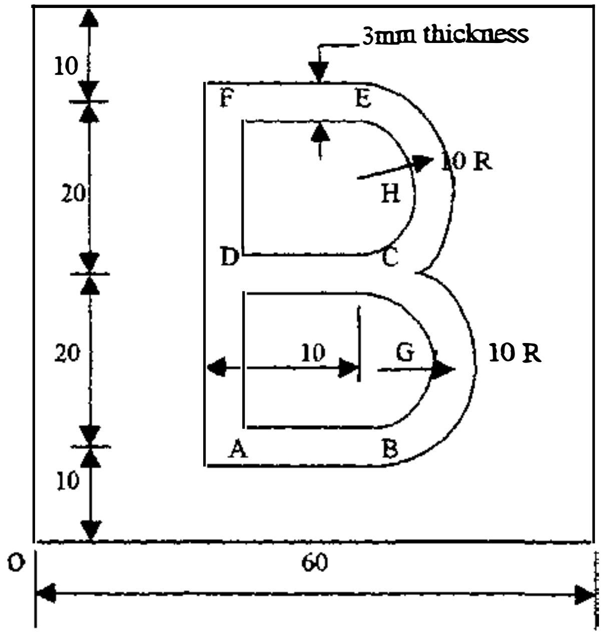


Figure 5.5 Right Hand Cartesian co-ordinate system

5.5.2 Example



ALL DIMENSIONS ARE IN MILLIMETERS

Figure 5.6 An example profile

Suppose it is required to cut a cavity 3mm deep as shown in figure 5.6. The diameter of the cutter is 3 mm. Machining operation is carried out in XY plane.
Co-ordinates of points are shown below.

Point	O	A	B	C	D	E	F	G	H
X	0	20	30	30	20	30	20	30	30
Y	0	10	10	30	30	50	50	20	40

Table 5.1 Co-ordinates of points in the example.

5.5.3 Description of cutter path for the example

- Cutter comes to point 'O' which is part zero, Spindle starts. The speed is 1500 rev/min.
- Cutter goes to on a straight line to A.
- Cutter moves down until Z= 2 mm on the display with feed rate 400.

- Moves down to touch the top surface of the work with feed rate 50.
- Penetrate 3 mm into the work with feed rate 50.
- Goes to point B on a straight line
- Moves to point C on a curve of radius 10 mm, centre G.
- Moves to point D on a straight line.
- Moves to back to point C on a straight line.
- Goes to point E on a curve radius 10 mm, centre H.
- Goes to point F on a straight line.
- Moves back to point A on a straight line.
- Cutter goes upward till Z=50 mm with a feed rate 400.
- Cutter comes to point 'O' on a straight line.
- Spindle rotation stops.
- End of the rotation.

5.5.4 Program in G code (Fanuc F10 controller)

0001 {Program Number}

N1 G40 G49 G80 {Cancel compensation already saved previously in the machine. Radius, Length, Canned cycle respectively}

N2 G91 G28 G0 X0 Y0 Z0 {Tool comes to home position with rapid traverse}

N3 G17 G21 {Cutter work on XY plane, Metric input}

N4 G92 X0 Y0 Z0 {Pre-set 'O' as part zero}

N5 G90 G55 X20 Y 10 Z 50 {Position A}

N6 G91 Z2 M03 S 1500 F400 {Spindle starts, Speed 1500 rev/ min, Feed rate 400}

N7 Z0 F200

N8 Z-2 F50

N9 G1 G40 T19 X10

N10 G3 X10 Y20 I0 J10

N11 G1 X0

N12 X10

N13 G3 X10 Y40 I0 J10

N14 G1 X0

N15 Y0

N15 Y0

N16 Z50 F400

N17 G0 X-20 Y-10

N18 G92 X0 Y0

N19 M05 M30

5.5.5 Program in Heidenhain TNC 145 code

0. Begin program
1. Tool Def.1 L 0.000 R 1.5 {Cutter Number 1, Zero length compensation, Radius 1.5 mm}
2. Tool Call 1 Z S1500 {Cutter moves on Z axis, Spindle speed 1500rev/min}
3. L X 20.000 Y 10.000 R0 F400 M03 {Zero radius compensation, Feed rate 400, Spindle starts}
4. Z 2.000 R0 F400 M
5. Z 0.000 R0 F200 M
6. Z -2.000 R0 F50 M
7. L X 30.000 Y 10.000 R0 F50 M
8. CC X 30.000 Y 20.000
9. C X 30.000 Y 30.000 DR(+) R0 F50 M {Direction of movement of the cutter- Anti clockwise (+) ve}
10. L X 20.000 Y 30.000 R0 F50 M
11. L X 30.000 Y 30.000 R0 F50 M
12. CC X 30.000 Y 40.000 R0 F50 M
13. C X 30.000 Y 50.000 DR(+) R0 F50 M
14. L X 20.000 Y 10.000 R0 F50 M
15. Z 50.000 R0 F400 M
16. L X 0.000 Y 0.000 R0 F400 M05 {Spindle stops}
17. STOP M02 { Program end goes to '0'}

5.5.6 Comparison of G code with Heidenhain code

Both codes described above are for the same job. By careful observation, it is possible to decide that the G code is more complex and more difficult to understand at once. Also G codes for each function has to be keep in memory. Only experience machinists are able to keep G codes in memory. The program length is also longer. In addition to these, at the beginning of the program, cancellation command should be written for tool radius, tool length and canned cycle already saved previously. But after consideration of Heidenhain code it is clear that it is simple and easy to understand, easier to keep in memory. It is not necessary to issue cancellation command for compensation at the beginning, like in the G code. Program is shorter compared with G code. It makes more sense to the average machinist.

5.6 Problems in NC Machines

The machinist has to undergo training before he can operate the machine. In particular he should be familiar with standard codes which are used by the controller of the machine he is using. Otherwise either he may end up with an accident or machine will get damaged or the job may have to be discarded due to inaccurate machining. However, for the same amount of training, much more complex and accurate work can be done. Further it is not possible to machine free form curves or surfaces directly by using standard G code or Heidenhain code, because there is no such facility available in these controllers. Finally, NC machines are more expensive than conventional types of machinery and hence the initial investment is higher.

5.7 Computer Programming for Free form Curves and Surfaces

As it is not possible to machine a cavity of shape as shown in figure 5.7, it is required to find the co-ordinates of points which are on the curve. If the curve segment AB can be approximated by a large number of straight lines, after finding the end points of these straight lines, an NC program can be written to carry out the machining operations. This is possible by using Ferguson or Non-parametric spline equations. In order to calculate points between each segment, spline equations are used. Spline equations are solved by using mathematical software packages such as MATLAB and high level programming languages such as C, C^{++}, PASCAL, FORTRAN, BASIC etc..

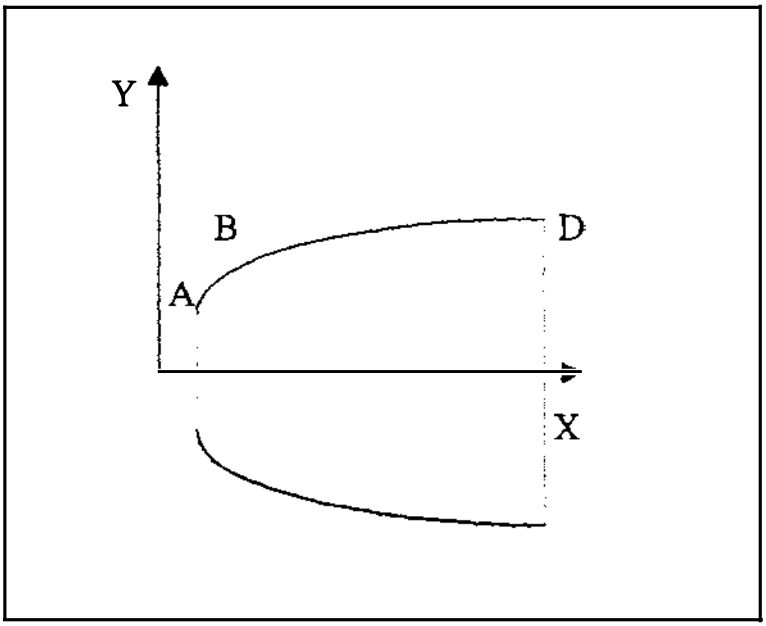


Figure 5.7 Free form curves

Also it is possible to use high level programming languages to generate automatically the required NC code. The resulting NC program can be transferred from the PC to the controller.

An NC program generated using Pascal language to make the shape of an Aerofoil which was written and tested by the author is attached in the Appendix G

Further, if the curve AD in figure 5.7 is rotated 180^0 degrees along the X axis, a surface can be obtained. By modification of the program it is possible to machine the cavity equivalent to the mirror image. In addition to these, by advance mathematical concepts and computer programming languages NC programs can be automatically generated.

5.8 Automatic CNC Programming using CAD/CAM

5.8.1 CAD

Computer Aided Design (CAD) involves the use of computers to create design drawings. Computer aided design is usually associated with interactive computer graphics known as a CAD system. CAD systems are powerful tools and are used in mechanical design and geometric modelling of injection moulding tools and its parts.

Using CAD systems, it is possible to carry out engineering design analysis and identify potential problems such as plastic flow, cooling, excessive loads and hence

- Generate drawing of mould and components quickly and accurately
- Determine and optimise the tool path during machining.

5.8.2 CAM

Computer Aided Manufacturing (CAM) is the use of computers and computer technology to assist in all phases of manufacturing a product including planning, machining, scheduling management and quality control.

5.8.3 CAD/CAM

The combination of CAD/CAM allows the transfer from design into the planning for manufacture of a mould. The data base developed in CAD is stored and processed further by CAM to generate NC code, that can be understand by the machine controller. From CAD/CAM system, it is possible to design and manufacture injection moulds and modify parts, complex electrode shapes for EDM. Various ready made CAD/CAM system software are commercially available in the market such as CATIA (Italy), Pro Engineer (USA), DUCT (British), Mastercam, Surfcam etc.. Geometrical models created by CAD packages can be imported by CAD/CAM packages. But some occasions there may be slight changes in the model after transferring into the CAD package for 3D models.

In addition to these, an original computer assisted method of part program language known as Automatically Programmed Tools (APT) can be used define complex geometrical shapes and control CNC machines. APT is a high level NC language which uses an English like language statement to define part shape and tool motion as well as machine tool dependent data such as feed rates and spindle speeds etc..

5.8.4 Automatic CNC program generation

The principle of automatic generation of NC code by using commercially available CAD/CAM software and APT language is shown in figure 5.8.

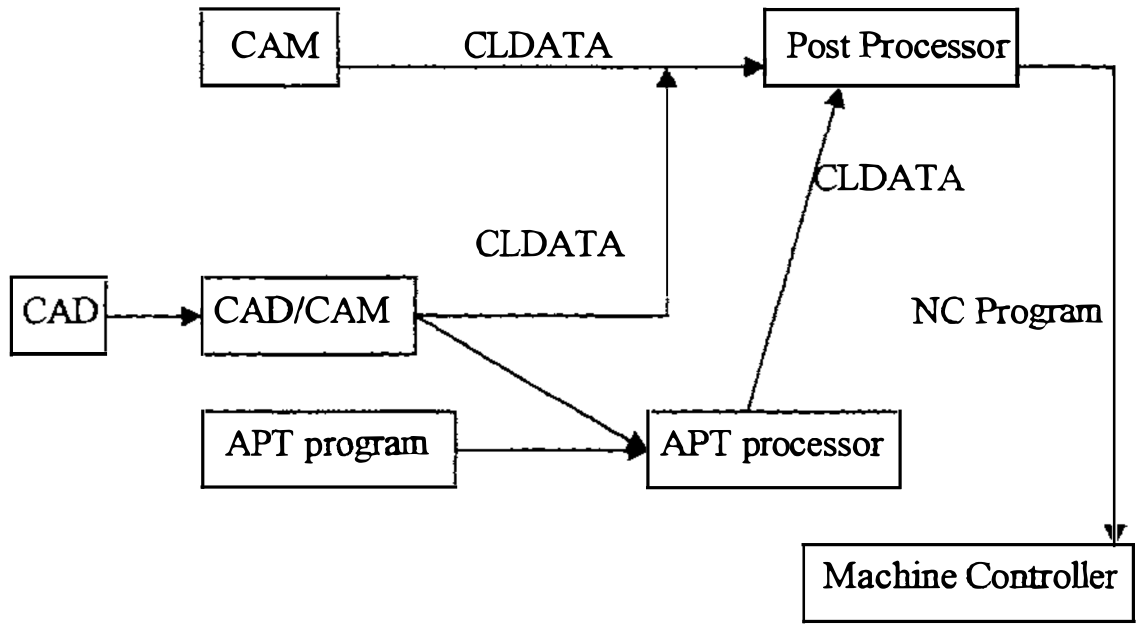


Figure 5.8 Automatic CNC program generation

The calculated results and statement regarding part specifications are output in a form known as cutter centre line data or cutter location data (CLDATA). This is a standard or common interface code. APT processor or IBM APT-NC processor is a program that accepts a user written APT program as input, processes it and transforms the processed results into CLDATA. The NC processor which processes and translates cutter location data (CLDATA) into the format required by machine controller is known as a post processor. This is a small program designed specifically for the given machine, It is comparatively easier to design and implement.

All CAD/CAM packages available in the market such as Pro-engineer, Mastercam etc., generate CLDATA in order to send to the post processor. But CATIA can generate CLDATA for the post processor as well as APT program for APT post processor.

An automatic CNC program generated in Heidenhain code using Mastercam Version 5 for an injection moulding tool, which was made and tested by the author is attached in Appendix F.

5.9 Problems in using CAD/CAM Software and Computer Programming in Rapid Manufacture of Moulds

The average cost of CAD/CAM software is between $ 20,000 - $ 30,000. Even after purchase and installation of a CAD/CAM package, it is necessary to train personnel how to use it. Packages such as CATIA, Mastercam, Pro-engineer etc. are powerful and take sometime to learn. Therefore the person who studies these systems should have a knowledge of mould design and manufacture as well as machining. Also there should be a close co-ordination between the programmer, mould designer and the machinist.

During mould manufacture, there are sometimes requirements , to machine very complex shapes which can not be handled by CAD/CAM packages. These can be resolved by using spline techniques as discussed in section 5.5. This involves a knowledge of Advanced mathematics and high level computer programming. In addition it takes so much time.

Further there are machines to make rapid prototypes of various complex shapes which are very expensive. In a real situation it is very difficult to find personnel who understand of computer programming, mathematics, mould manufacture and machining. There are occasions when the mould materials can not be machined by using CNC machines due to its extreme hardness. During such occasions, it is not possible to use conventional machines already described in chapter 4. Therefore it is necessary to consider other cheaper means of machining very complex shapes and very hard materials.

In the next section author will describe how these problems could be tackled.

5.10 Introduction to the Electrical Discharge Machine (EDM)

Electrical Discharge Machining sometimes is referred to as spark erosion machining and it is a non-traditional method of removing metal. It is a thermal process which uses a series of rapidly recurring electrical discharges between an electrode (cutting tool) and the work piece. Both the electrode and the work piece must be electrically conductive materials. Electrical sparks travels in the presence of a dielectric fluid. Due to the spark energy material removes and a cavity is formed in the work piece which matches the shape of the electrode (tool). Electrical discharge machining is a relatively simple manufacturing process to set up and perform. After positioning the work piece on the machine, is connected to one pole of a pulsed power supply. An electrode, shaped to the desired cavity to be machined, is connected to the remaining pole of the power supply. The electrode and the work piece are then positioned in such a way that a small gap is maintained between the two. Dielectric fluid is flooded between the electrode and work piece and provides a controlled amount of electrical resistance in the gap and continuously helps to flush the process residues from the gap.

There are many types of electrical discharge machines. The first one is cavity type EDM which was studied by the author. The second one is electrical discharge wire cutting and some times refers to as travelling wire EDM. In this process, a thin brass wire acts as the electrode. The third one is electrical discharge grinding (EDG) and the final one is electrical discharge machines using orbital electrodes. Also some EDM are capable of movement in several axes.

5.11 Important parts in EDM Systems

5.11.1 Servo mechanism

The first type, the cavity type with vertical axis only under servo-control is best for illustration as shown in figure 5.9. Positive polarity indicates that the electrode is positive and also negative polarity can be used. If the ram is allowed to move forward unchecked there would be a direct contact between the electrode and the work piece causing an electrical short circuit. This is prevented by a servo mechanism in which the potential is monitored and compared with a reference. If the potential is greater than the reference ram advances. If it is less, the ram retracts. The movement of the ram may be accomplished either by a direct drive servo motor or by hydraulic cylinder.

During the machining, the distance between electrode and work piece increases. Then the potential goes up and the ram advances until the potential matches the reference. By this, servo mechanism maintains a constant gap. Machining continues until the pre-set depth is reached. At this point, the spark stops and in most machines the electrode retracts from the work piece.

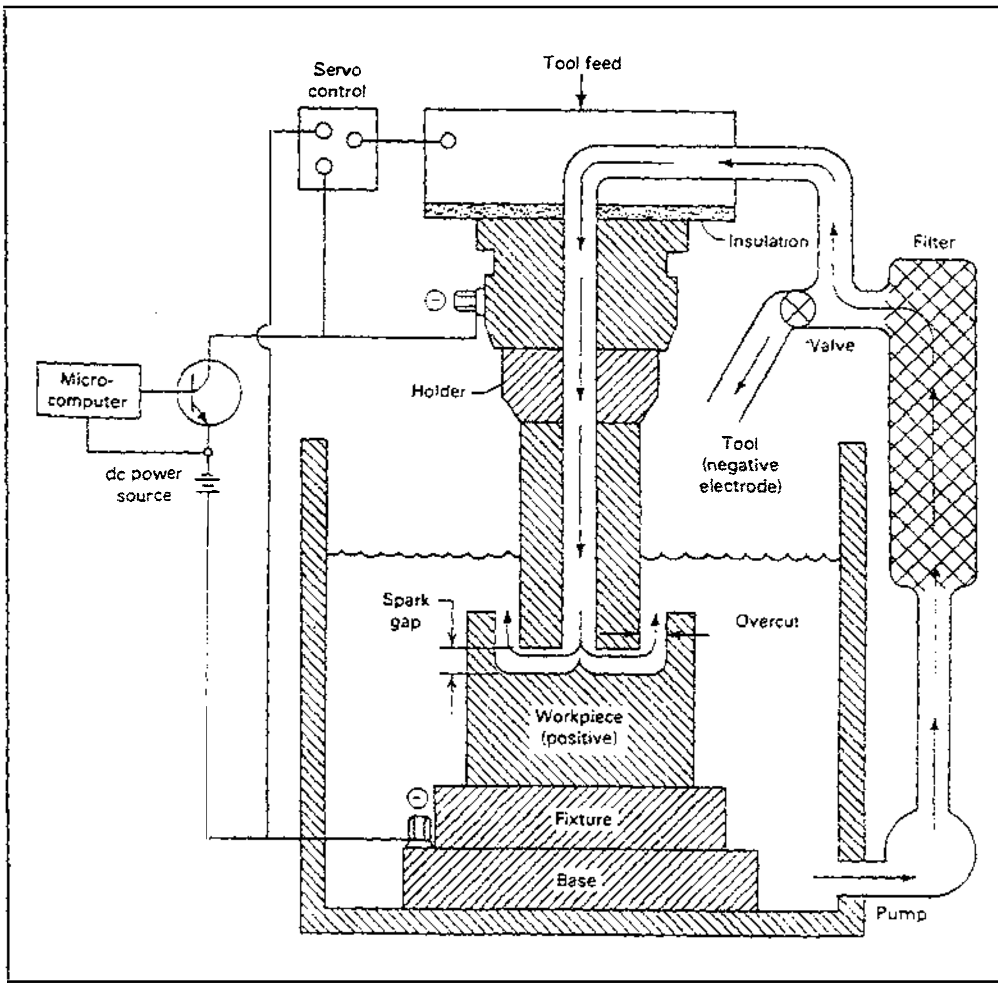


Figure 5.9 Schematic diagram of EDM

5.11.2 Power supply

Power supply is an important part of the EDM system. It transforms alternating current (ac) from mains supply into direct current (dc) pulses which are required to produce spark discharges for machining. Sensing the potential between the electrode and the work piece is an additional function of the EDM power supply, because a direct relationship exists between the potential voltage and the electrode-work piece gap. This signal is used to control the servo system, enabling it to maintain a constant gap. On the other hand, the power supply helps to facilitates the selection of the optimum parameter for a wide range of cutting conditions by controlling pulse voltage, current, pulse frequency and pulse duration etc.. Finally the EDM power supply helps to terminates power if an over voltage, over current or dc arc occur as a result of a short circuit between the electrode and the work piece it then alerts the operator.

5.11.3 Dielectric system

The EDM dielectric system consists of the dielectric fluid, delivery devices, pumps and fitters. Requisite properties of the fluid are high viscosity and high electric resistance. Hydro-carbon fluids such as Kerosene etc., are most commonly used. There are three functions of the dielectric fluid. It acts as an insulator between the electrode and work piece, as a coolant to draw away the heat generated by the spark and as a flushing medium to remove the metal by products from the cutting gap. As shown in figure 5.10 there are methods available for flushing the dielectric fluid through the cutting zone. Any of these flushing techniques can be performed exactly as illustrated in figure 5.10 with or without the work piece submerged in a tank of dielectric fluid. Whenever flammable dielectric fluids such as kerosene, lamp oil etc. are being used, submersion of the work piece is recommended to reduce the chances of accidental fires.

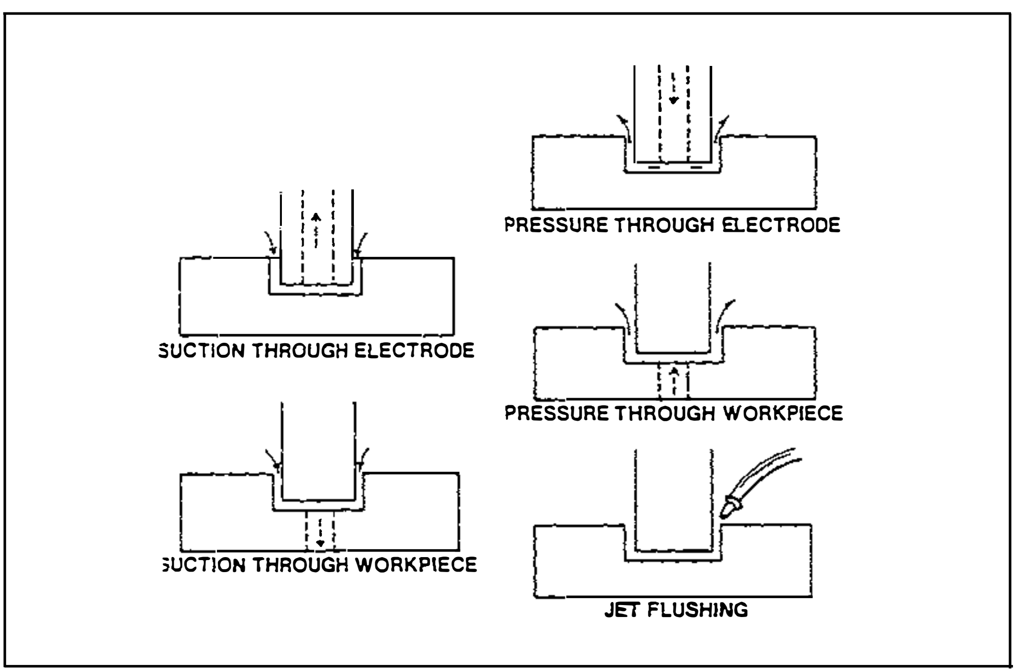


Figure 5.10 Various flushing techniques

5.12 Principle of Operation

Experimental evidence suggests that metal removal in EDM operation take place as a result of the generation of extremely high temperatures generated by the high intensity of the discharge current. The discharge mechanism can be explained by division of the whole process in to phases and stages. A model representation of the electrical discharge for all three phases and stages are shown in figure 5.11 a to 5.11 i.

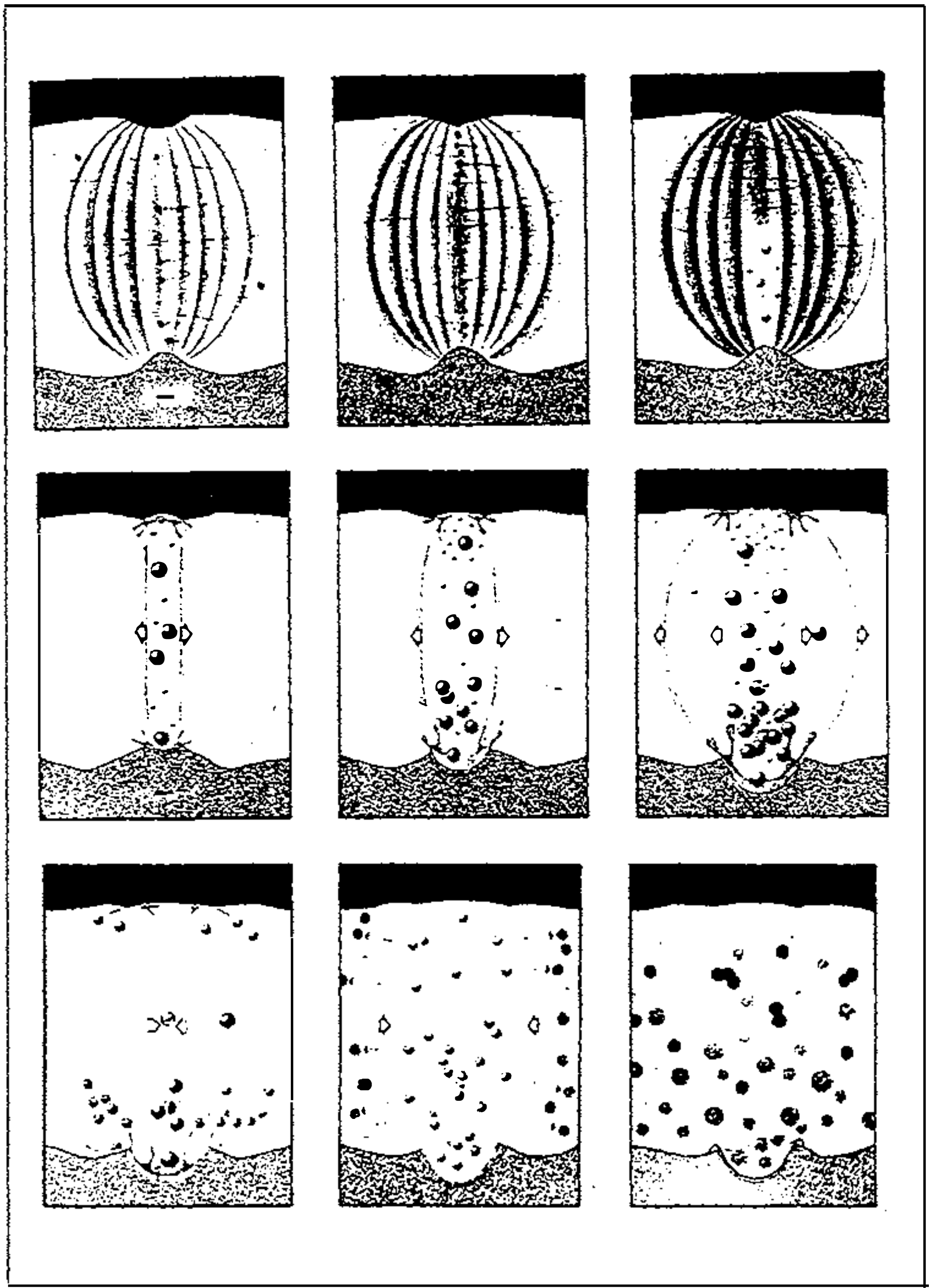


Figure 5.11 Principle of Operation

The tool electrode is marked with (+)ve sign and the work piece is marked with (-)ve sign. Variation in voltage and current over the duration of the discharge is shown schematically on the screen of oscilloscope.

Phase 1: Preparatory phase

Formation of a high conductivity channel due to ionisation of the dielectric medium due to the powerful electric field, which lasts only a very limited time.

Stage 1: Application of a voltage to machining site by the spark generator used.

Stage 2: Polarisation and orientation of the molecules and ions of the dielectric medium

Stage 3: Negative and positive streamers organise and a current flow begins to occur when polarisation reaches a certain point.

Phase2: Formation of a heavy current similar to an avalanche of electrons due to the discharge. Ejection and erosion of metals in the work piece begins.

Stage1: Resistance of the dielectric medium drops to very low value. Current intensity rises to a very high value and voltage drops. The ionised channel consists of positive ions, free electrons, vapour metal of both electrodes, gases due to chemical decomposition of dielectric.

Stage 2: Discharge channel is ionised by the flow of high intensity current. Formation of strong magnetic field occurs which may attracts the ions towards the axis of the discharge channel.

Stage 3: As a result of compressed current beam due to ions, channel is greater than 10000^0C. A certain volume of electrodes, metal melts and evaporation occurs.

Phase 3: Ejection of eroded metal in the work piece may continue further even after the end of discharge.

Stage 1: Ejection and evaporation of metal leaves a specific mark on the edges of the crater both in anode and cathode.

Stage 2: Vapour bubbles collapses.

Stage 3: Cycle completes as soon as the energy of the discharge is over.

5.13 Selection of Electrodes

Graphite

The EDM electrode is the tool by which electric current is transported to the work piece. It determines the shape of the hole or cavity ultimately generated. Important criteria pertaining to selection of electrode is material and the application. During selection of electrode materials, the designer of operator should consider about the easy availability, machinability, electrical conductivity and low wear during the process.

Graphite is easily available, having good machinability and the wear rate of graphite is extremely low for low grain sizes. Surface finish of the work is high. Metal removal rate also high. It is dirty to machine; vacuum system is needed. Also it is a brittle material. The cost increases with decreasing grain sizes.

Copper graphite

An alloy of copper and graphite 5 to 10 times more expensive than copper. Due to higher flexural strengths, thin cross sections can be used. Electrical conductivity is greatly improved. Corner wear is not so good when compared with graphite. Works well when machining Tungsten Carbide.

Copper

Copper has good EDM wear, good electrical conductivity and is cheap when compared with other materials. It is possible to machined easily as well as to hot or cold forge. Casting is easy for uneven shapes. When a smooth surface finish is required copper can be polished with out concern for the structure of the material.

Copper Tungsten

Recommended for fine detail, high precision EDM work. It has good thermal and electrical conductivity. It is capable of producing smooth surface finish. Due to the composition of tungsten as high as 70% some manufactures recommend the use of tungsten carbide tool for machining this material. Grinding wheel manufactures should be contacted for proper wheel recommendations as some problems may be encountered in grinding if loading occurs. An expensive material.

Silver Tungsten

Similar to copper tungsten. However, corner wear of this material is less than copper tungsten.

Brass

Brass is inexpensive and easy to machine, but shows high wear rate. It is frequently used for small hole EDM drilling machines where high wear is acceptable.

Steel

Steel is not a satisfactory electrode material, but it is useful to match the parting planes of moulds in which half of the mould is used as electrode and the other half is used as the work piece.

Other materials

Tellurium copper, titanium, tungsten carbide are used for high precision jobs where electrode wear is low, but all are very expensive.

5.14 Applications, Advantages and Health and Safety

5.14.1 Applications

Electrical discharge machining is applied to plastic injection moulding tools, extrusion dies, forging dies, die casting dies etc.. Application examples are shown in the figure 5.12. Also EDM wire cut is used to make press tools.

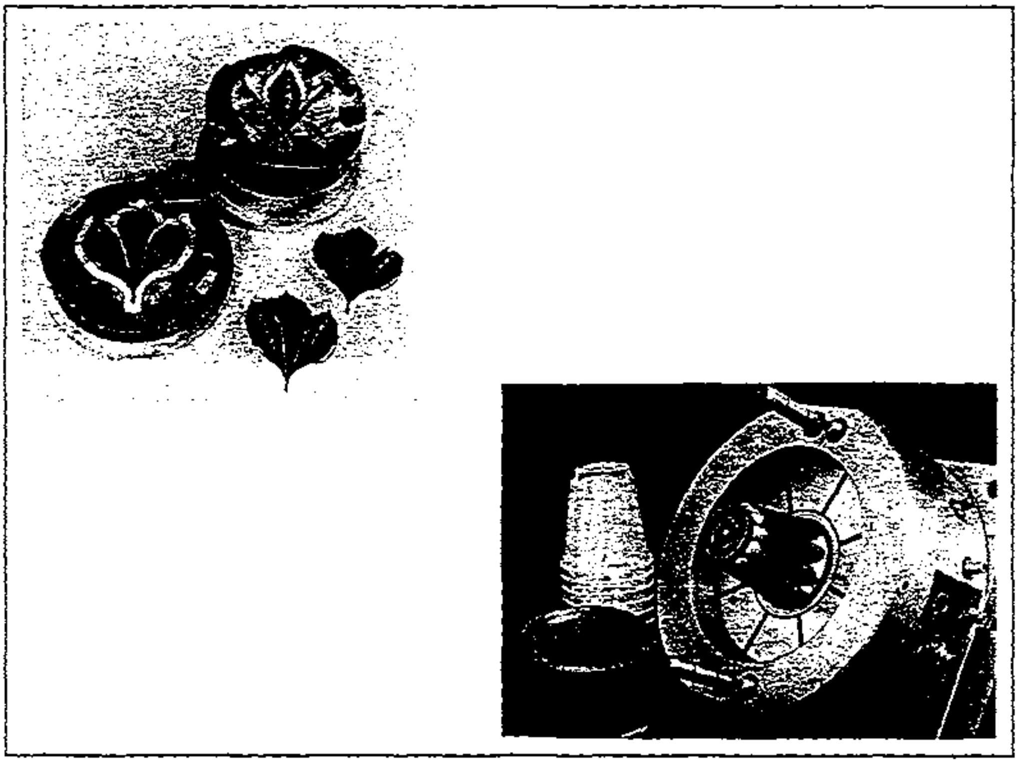


Figure 5.12 Application examples of EDM

5.14.2 Advantages

During rapid manufacture of injection moulding tools, it is advantages to use EDM and this considerably facilitates the operation at various stages of production.

Manufacturing process

- Freedom of choice in combining motions of the machine tool.
- Production of cavities in one machining procedure through combination of electrode geometry.
- Electrode tool can be made using easily machinable materials with any manufacturing process.
- Tool exerts no force on work piece.

Design and layout

- Material with poor machinability such as cemented tungsten carbide and hardened tool steel can be machined freely.
- Design freedom with respect to materials and geometry.
- Compact mould design

Production

- Cavities with thin walls and fine features are possible to machine.
- Possibility of producing complex geometry in one machining step
- Electrical discharge machining is burr free
- Machining geometry can be checked in advance by measurement of tool electrode dimensions.
- Easier planning and organisation of the job due to fewer processing steps and less monitoring of intermediate stages.
- Process is automatic because of automatic controls
- Ability to machine deep, very small holes.

Personnel

- Process can be carried out by semiskilled personnel.
- Limited set up times
- Less operator attention during the operation except set up and adjustment.

Economics

- Less machining time due to fewer operations, but essentially a slow process.

- Full utilisation of the machine due to automatic operation during breaks such as night time operations

5.14.3 Health and safety

- Fire risks occurs for unattended machines. Automatic fire extinguishers should be mounted on any unattended machines.
- Health problems such as skin irritation due to contamination by dielectric fluid and throat irritation due to smoke may occur. Good ventilation or vent device should be provided.
- Since this machine is an electronic and is processed by a pulse of electricity, electrodes should not be touched during the operation to prevent electric shock.

5.15 Process Parameters Available in EDM

The cutting operation of EDM is carried out due to the energy contained in the electrical spark. Therefore the power supply circuit must provide the most efficient cutting spark possible. For this, there are several basic types of circuits available to provide pulsating direct current.

A typical EDM pulse train is shown in figure 5.13.

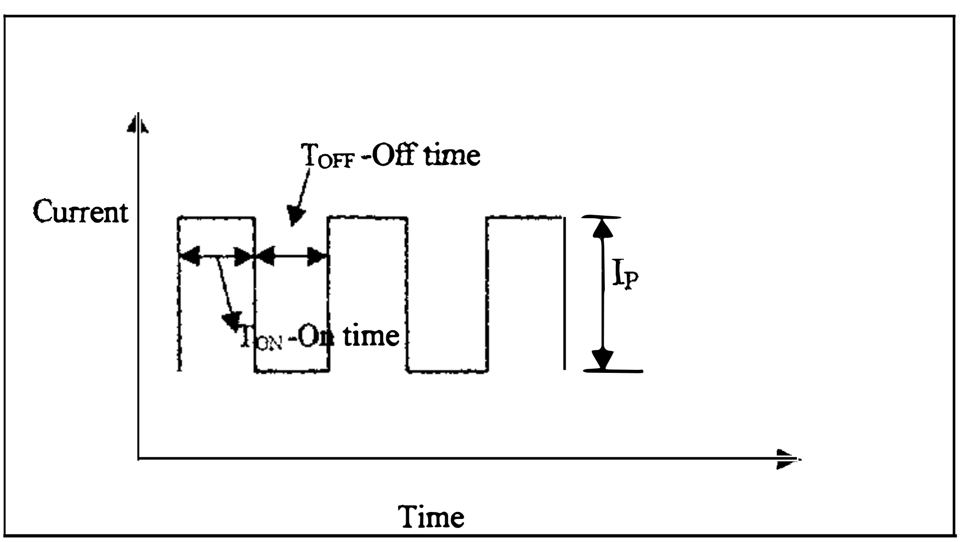


Figure 5.13 Typical pulse train in EDM operation

Parameters available in EDM are:

T_{ON}- Pulse on time

T_{OFF}- Pulse off time

I_P- Peak current selector knob in the pulse train

G_V-Spark voltage

There are controls on the EDM to vary these parameters at the operator's wish.

Also there is a knob to vary the jumping time of the electrode. Jumping time is the time takes to move the tool electrode up and return back to its original position while the machine is on operation. From this, operation time and jumping time of the electrode can be varied. Jumping operation helps to flush metal residues forming during the process.

In addition to these, in some machines, there are separate knobs to vary the polarity of the electrode and the work piece, spark voltage (high and low range) and sensitivity control.

5.16 Description of the EDM at the Industrial Engineering Laboratory in the Department

The departmental EDM consists of 80 L dielectric fluid tank, power supply unit, fluid return plate and a working head. The fluid return plate was developed into a fluid tank and both this tank and the working head were mounted on a three axis mill-drill assembly. The work piece can be mounted in the fluid tank and it is possible to move the work in X, Y and Z directions manually by hand wheels. There are two push buttons on the working head to move the tool electrode up or down as required. Tool electrode stem (holder) diameter is 10 mm. All the usual controls are available in the power supply unit. From the electronic display in the power supply unit, final depth of cut to be machined, jumping distance, real distance, absolute distances can be set as required by the operator.

Jumping distance- The upward moving distance of the tool electrode during jumping operation. This can be adjusted as required and normally is kept at constant as required.

Real distance- The penetration of the tool electrode into the work piece during machining.

Absolute distance- The total distance travel by the electrode from the top position of the stroke.

All flushing techniques can be applied with out submerge the work piece in dielectric fluid medium.

This machine is capable for cutting an injection moulding tool up to the size of 250mm * 200 mm * 60mm due to the limited space in the fluid tank. Initially the machine was not well used to the non availability of a proper operation manual. It was started and put for operation by the author and now it is possible to use this machine for both academic and commercial purposes. Starting, Operation procedure of this machine is attached in the Appendix D.

List of parameters available on this machine;

T_{ON}- Pulse on time

T_{OFF}- Pulse off time

I_P- Peak current selector of the pulse train

G_V- Gap voltage

Working time selector (W_{TC})-Jumping time control

Servo speed control (S_{PC})-Maintain the discharge spark stable

Jump set- Jumping distance adjustment

Polarity Knobs- Change the polarity of electrodes

5.17 Problems in EDM during Rapid Manufacture of Moulding Tools

- Since EDM operation is non traditional machining process, it is relatively new and quite different from other traditional machinery. Therefore, familiarisation of the process is required before operation of EDM.
- Work must be planned in advance to meet the process requirements.
- Initial setting time may be higher.
- Process variables should be considered before carrying out the job.
- The operating manuals supplied with most Electrical Discharge Machines contain no clear information relating the many process variables to the two main items of interest to the tool maker. i.e.

Metal Removal Rate

Surface Finish

The establishment of such relationships was a major part of the work done in this project.

Prior to EDM operation for rapid mould manufacture, it is required to train the operator and given him a thorough understanding about the process, initial setting of the work, selection of electrode material, selection of appropriate values and combinations of process variables. Also he must know the effects of process variables on the rate of machining and the surface quality. Further, he should be able to diagnosed faults, to carry out preventive maintenance of the machine. Finally, he must know about health and safety aspects of the EDM operation. For this, it takes some time and initial cost.

Since there is no relationship for rate of machining and surface quality with other process variables, it is difficult to calculate the time required for a given cavity with a specified surface finish. Due to this, time is wasted during the process unnecessarily. Also, it is difficult to do exact costing, planning the job.

5.18 Identification of Important Process Parameters

During the EDM operation, the machining rate (rate of penetration) depends on the energy of the spark produced by the machine. Spark energy depends on following parameters.

- On and Off times
- Gap voltage
- Gap current

By using the EDM which is in the department, several trial experiments have been carried out by the author in order to study the process. Copper electrode with (+)ve polarity and Zinc work piece with (-)ve polarity have been used. From these trial operations, it has been observed that rate of machining (rate of penetration) depends on T_{ON}, T_{OFF}, I_P and G_V values. Also surface quality depends on T_{ON}, T_{OFF}, I_P and G_V values.

5.19 The Necessity of Establishment of Relationships

As explained in section 5.15, for rapid tool manufacture, the designer should consider the time taken for the EDM process for a required surface roughness given by the customer. Since there are no established relationships, designers and operators use process variables found by trial and error methods. In most cases, surface quality is too good and it takes too long and high tool electrode wear results. Also in other cases operators use variables for high cutting speeds with high electrode wear. During finishing stages, many operators use another tool electrode in order to obtain a good surface finish.

This means there is no optimum selection of process variables. Also this leads to high cost of machine operation due to excessive operation time, excessive tool electrode wear, making another tool electrode and inaccuracies of the cavity. Further, this method leads to need for skilled operators because the selection of optimum values of parameters entirely depends on his or her experience. Finally, the mould manufacturer should be able to give a realistic cost and the date of delivery of the completed mould to his customer in advance. For this, current prediction of time and estimation may lead to a financial loss either to the manufacturer or to the customer. Hence, after consideration of above facts, it is clear that it is required to establish relationships for rate of penetration and surface quality with process variables.

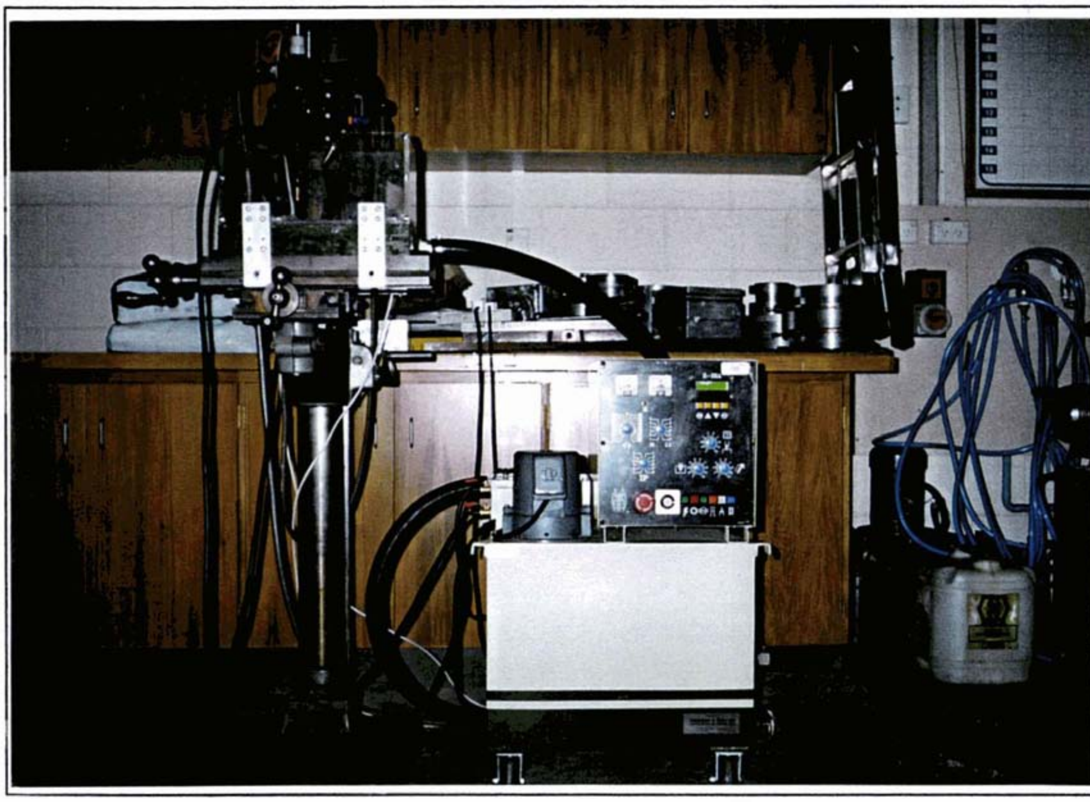


Figure 5.14 The Departmental EDM

Chapter 6

Design of Experiment and Analysis of Results

This chapter describes experimental design and analysis process in establishment of relationship for rate of penetration, surface roughness with EDM process variables.

6.1 Introduction

The main reason for current scientific achievements and developments is the principle of experimentation. Experimentation is a way to scientific approach. Scientific approach involves the definition of truth. Historical use of one factor at a time experimentation has resulted in very inefficient and often ineffective attempts to understand the process. Therefore to solve problems and to understand various industrial processes experimental design technique is used by most engineers and technologists. Experimental design consists of purposeful changes of inputs or factors to a process to observe the corresponding changes in the outputs or responses. It is a scientific approach which allows the researcher to better understand a process and determine how the inputs affect the response.

Although experimental design was originally used for agricultural researches, now it is widely used in manufacturing processes and quality engineering. According to Montgomery, experimental design is the primary function of modern quality engineering followed by SPC and acceptance sampling.

As discussed in the last chapter, in order to establish relationships for penetration rate and surface quality of the job with other process variables, experimental design technique were selected by the author. Because, after gathering knowledge about the process, response variables and having clear goals and objective, it is easier to understand the factors which are critical while relaxing non-critical factors.

Hence, the author uses experimental design method;

- To gain better understanding of the relationship between the input factors available in the machine with responses P_R and S_R
- Determine the settings of input factors which optimise the results
- Establish a mathematical relationship relating the results (P_R and S_R) to the input factors

6.2 Experimental Design

6.2.1 Preliminary Experiments

All controlling process parameters available in the machine such as T_{ON}, T_{OFF}, I_P, G_V, Working time selector (W_{TC}), Servo speed selector (S_{PC}), Jump set etc. were considered to find out their effects on rate of penetration (P_R) and surface roughness (S_R). From this, it is possible to screen the factors having significant effects on P_R and S_R respectively.

Plackett-Burman two level experimental design matrix was used for initial screening experiments where a large number of factors need to be screened.

Number of factors selected = All controlling factors available

= 07

Number of runs were taken = 08

The design matrix was taken by using Minitab 10 as shown in table 6.1.

6.2.2 Plackett – Burman Experiment

Run No	I_P	G_V	T_{ON} (u Sec)	T_{OFF} (u Sec)	W_{TC}	W_{PC}	Jump set (mm)
1	+	-	-	+	-	+	+
2	+	+	-	-	+	-	+
3	+	+	+	-	-	+	-
4	-	+	+	+	-	-	+
5	+	-	+	+	+	-	-
6	-	+	-	+	+	+	-
7	-	-	+	-	+	+	+
8	-	-	-	-	-	-	-

(+) - High Level (-) - Low Level

Table 6.1 Placket Berman two level design matrix

Factors	High Level (+)	Low Level (-)
T_{ON} (u.sec)	600	10
T_{OFF} (u.sec)	10	3
I_P*	10	3
G_V*	9	2
W_{TC}*	9	2
S_{PC}*	9	2
Jump set (mm)**	3	1

*Factors represent no dimensions, Only positions on the machine switches/controls.

Table 6.2 Factors for Placket-Burman experiment.

Run No	I_P	G_V	T_{ON} (u.sec)	T_{OFF} (u.sec)	W_{TC}	S_{PC}	Jump set (mm)
1	10	2	10	10	2	9	3
2	10	9	10	3	9	2	3
3	10	9	600	3	2	9	1
4	3	9	600	10	2	2	3
5	10	2	600	10	9	2	1
6	3	9	10	10	9	9	1
7	3	2	600	3	9	9	3
8	3	2	10	3	2	2	1

Table 6.3 Treatment table for Placket-Burman experiment

6.2.3 Rate of Penetration (P_R)

Cross sectional area of the copper electrode tool = 1 cm^2

Work piece- Zinc

Polarity of the tool electrode (+) ve

Polarity of the work piece (-) ve

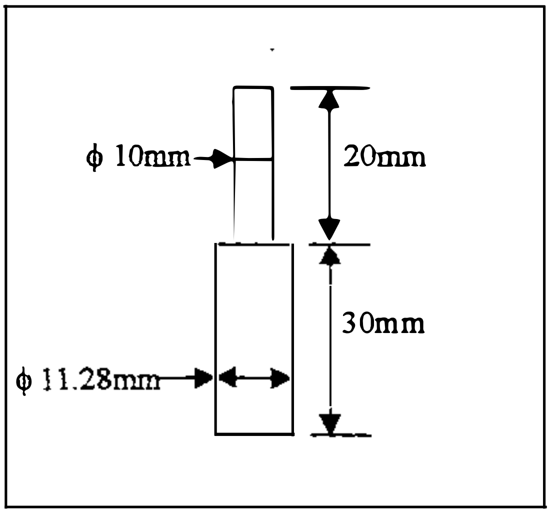


Figure 6.1 Copper Electrode 1 cm^2

6.2.3.1 Experimental Observations

Run No.	Time (Min)	Penetration (mm)	P_R (mm/min)	Amp meter Reading – I (Amps)
1	10	1.05	0.105	2.00
2	5	1.37	0.274	2.50
3	3	2.90	0.967	6.00
4	7	0.77	0.110	1.50
5	2	2.04	1.02	5.00
6	10	0.60	0.06	0.50
7	5	1.78	0.356	3.00
8	10	0.77	0.077	1.00

Table 6.4 Rate of penetration - Placket Burman design

6.2.4 Surface Roughness (S_R)

Cross sectional area of the copper electrode = 2cm^2

(The reason for selecting 2 cm^2 cross sectional area for the copper electrode will be discussed in the section 6. 6)

Work piece- Zinc

Polarity- Tool electrode (+)ve

-work piece (-)ve

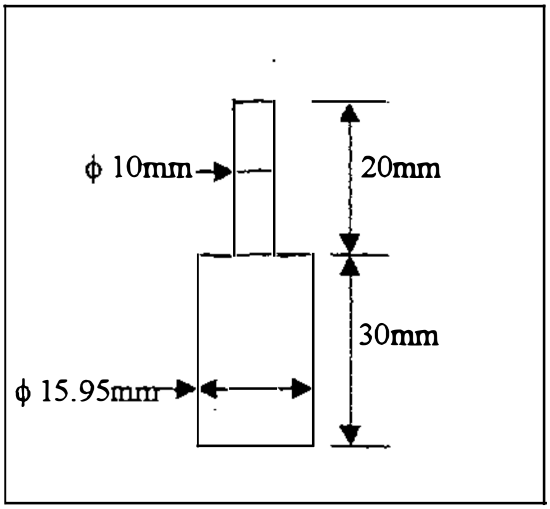


Figure 6.2 Copper Electrode 2 cm^2

6.2.4.1 Experimental Observations

Run No.	S_R (umRs)	I (Amps)
1	5.25	2.0
2	4.65	2.0
3	19.00	6.0
4	11.00	1.5
5	18.00	5.0
6	2.75	0.5
7	11.00	3.0
8	2.75	1.0

Table 6.5 Surface Roughness – Placket Burman design

6.2.5 Effect Analysis

6.2.5.1 Rate of Penetration (P_R)

Run No.	P_R (mm/min)	I_P	G_V	T_{ON} (u.sec)	T_{OFF} (u.sec)	W_{TC}	S_{PC}	Jump set (mm)
1	0.105	0.105	-0.0105	-0.105	0.105	-0.105	0.105	0.105
2	0.274	0.274	0.274	-0.274	-0.274	0.274	-0.274	0.274
3	0.967	0.967	0.967	0.967	-0.967	-0.967	0.967	-0.967
4	0.110	-0.110	0.110	0.110	0.110	-0.110	-0.110	0.110
5	1.020	1.020	-1.020	1.020	1.020	1.020	-1.020	-1.020
6	0.060	-0.060	0.060	-0.060	0.060	0.060	0.060	-0.060
7	0.356	-0.356	-0.356	0.356	-0.356	0.356	0.356	0.356
8	0.077	-0.077	-0.077	-0.077	-0.077	-0.077	-0.077	-0.077
	Sum	1.763	-0.147	1.937	-0.367	0.451	0.007	-1.279
	Effect	0.4408	-0.0368	0.4843	-0.0948	0.1128	0.0018	-0.3198

Table 6.6 Effect analysis for P_R

6.2.5.2 Surface Roughness (S_R)

Run No.	S_R (umRs)	I_P	G_V	T_{ON} (u.sec)	T_{OFF} (u.sec)	W_{TC}	S_{PC}	Jump set (mm)
1	5.25	5.25	-5.25	-5.25	5.25	-5.25	5.25	5.25
2	4.65	4.65	4.65	-4.65	-4.65	4.65	-4.65	4.65
3	19.00	19.00	19.00	19.00	-19.00	-19.00	19.00	-19.00
4	11.00	-11.00	11.00	11.00	11.00	11.00	-11.00	11.00
5	18.00	18.00	-18.00	18.00	18.00	18.00	-18.00	-18.00
6	2.75	-2.75	2.75	-2.75	2.75	2.75	2.75	-2.75
7	11.00	-11.00	-11.00	11.00	-11.00	11.00	11.00	11.00
8	2.75	-2.75	2.75	-2.75	-2.75	-2.75	-2.75	-2.75
	Sum	19.40	0.40	43.60	-0.40	-1.60	1.60	-10.60
	Effect	4.85	0.10	10.90	-0.10	-0.40	0.40	-2.65

Table 6.7 Effect analysis for S_R

6.2.6 Selection of important factors

According to the effect analysis in the section 6.2.5.1, it is clear that the effects of I_P and jump set are significant. Effects of T_{OFF}, G_V and working time selector are medium. The effect of servo speed control is very small and hence it was not considered for further experimentation.

On the other hand, the analysis in the section 6.2.5.2 for S_R shows that the effects of I_P, T_{ON} and jump set are significant. Further, the effects of G_V, T_{OFF}, Working time selector and Servo speed control are small.

During the experiment jumping distance and working time selector were adjusted to make sure an adequate sludge removal would be taken place. Experiment shown that allowing sludge to accumulate reduces P_R and worsen the surface finish (increasing S_R). In industry when machining deep cavities, it would be essential to set working time selector and jump set to ensure sludge removal. This would reduced the effective machining time and hence job will take longer. This is equivalent to reduce average P_R. The author has not attempted to incorporate this allowance in relationship between P_R, S_R and major process variables.

After consideration above facts, in order to obtain appropriate relationships for both PR and SR with process variables which could be used in the real situation, jump set was kept constant at 1.50mm and working time selector kept at its middle position (5.5).

Factors T_{ON}, T_{OFF}, I_P and G_V were taken for further experimentation for both P_R and S_R.

6.2.7 Further experimental observations

Although peak current selector IP was set in low and high positions 10 and 3 as shown in table 6.3, corresponding current flow readings shown in the ampere meter (table 6.4 and 6.5) were different. This means current flow itself varies with all other factors. Therefore same Placket- Burman design matrix was used to find out the significant effects on the current flow (I)

Run No.	I (Amps)	I_P	G_V	T_{ON} (u.sec)	T_{OFF} (u.sec)	W_{TC}	S_{PC}	Jump set (mm)
1	2.0	2.0	-2.0	-2.0	2.0	-2.0	2.0	2.0
2	2.5	2.5	2.5	-2.5	-2.5	2.5	-2.5	2.5
3	6.0	6.0	6.0	6.0	-6.0	-6.0	6.0	-6.0
4	1.5	-1.5	1.5	1.5	1.5	-1.5	-1.5	1.5
5	5.0	5.0	-5.0	5.0	5.0	5.0	-5.0	-5.0
6	0.5	-0.5	0.5	-0.5	0.5	0.5	0.5	-0.5
7	3.0	-3.0	-3.0	3.0	-3.0	3.0	3.0	3.0
8	1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
	Sum	9.5	-0.5	9.5	-3.5	0.5	1.5	-3.5
	Effects	2.375	-0.125	2.375	-0.875	0.125	0.375	-0.875

Table 6.8 Effect analysis for I

6.2.8 Screening significant factors on current flow (I)

According to the effect analysis in table 6.8, significant factors are I_P, T_{ON}, T_{OFF} and jump set. It is obvious that, increasing the jump set means, that there is no current flow between the copper electrode and the work piece. The effect of jump set on I is just a mechanical effect. Therefore I_P, T_{ON} and T_{OFF} were considered as significant effects.

6.3 Further experimental design

6.3.1 Description

As discussed in section 6.2 by using Placket-Burman experimental design matrix, input factors which governs the current flow (I), rate of penetration (P_R) and surface roughness (S_R) were taken as T_{ON}, T_{OFF}, I_P and G_V positions. Because T_{ON}, T_{OFF} and I_P had been shown to be important ones. G_V was considered even though it had shown little effects on I, P_R and S_R since it was an important parameter which could affect on the pulse train between the tool and the work piece. Other variables were set at their mid-points during the rest of the experiments. Jump set was adjusted to 1.50 mm. Copper electrode tool and Zinc work piece have been used. Electrode tool was kept as (+)ve polarity and the Zn work piece was kept as (-)ve polarity. Electrode cross sectional area was taken as 100 mm^2 (1 cm^2) and 200 mm^2 (2 cm^2) for rate of penetration and surface roughness respectively.

6.3.2 Full factorial experiment

A two level full factorial design was selected. The number of observations in such an experiment is given by taking the number of levels to the power of the number of factors.

$$t_c = n^k$$

Where k = Number of factors = 4, n = 2 since this is a two level experiment.

Hence, t_c (Number of observations) = 16

The orthogonal design matrix shown in table 6.1 has been used for the experiment.

Runs	I_P	G_V	T_{ON}	T_{OFF}
1	+	+	+	+
2	+	+	+	-
3	+	+	-	+
4	+	+	-	-
5	+	-	+	+
6	+	-	+	-
7	+	-	-	+
8	+	-	-	-
9	-	+	+	+
10	-	+	+	-
11	-	+	-	+
12	-	+	-	-
13	-	-	+	+
14	-	-	+	-
15	-	-	-	+
16	-	-	-	-

(+) - High Level (-) - Low Level

Table 6.9 Two level full factorial design matrix

Factors	High Level (+)	Low Level (-)
T_{ON} (u.sec)	600	10
T_{OFF} (u.sec)	10	3
I_P *	10	3
G_V *	9	2

* Factors represent no dimensions, only positions on the machine/ switches/ controls

Table 6.10 High and low values for factors.

Run No	I_P	G_V	T_{ON}	T_{OFF}
1	10	9	600	10
2	10	9	600	3
3	10	9	10	10
4	10	9	10	3
5	10	2	600	10
6	10	2	600	3
7	10	2	10	10
8	10	2	10	3
9	3	9	600	10
10	3	9	600	3
11	3	9	10	10
12	3	9	10	3
13	3	2	600	10
14	3	2	600	3
15	3	2	10	10
16	3	2	10	3

Table 6.11 Treatment table for two level full factorial design

6.4 Current Flow (I)

6.4.1 Observations of two level factorial experiment

Cross sectional area of the copper electrode was 1 cm^2 as shown in the figure 6.1. The treatment table 6.11 was used.

Run No.	Current (Amps)
1	4.50
2	6.00-6.50
3	2.00
4	2.50
5	5.00
6	10.00
7	1.80-2.00
8	3.50
9	1.00
10	1.20
11	0.50
12	0.80
13	1.20
14	1.75
15	0.50
16	0.80

Table 6.12 Observations for current flow

6.4.2 Graphical Analysis

6.4.2.1 The effect of change of T_{OFF}

T_{OFF} (u.sec)	I (Amps)								Ave.I (Amps)
3	6.25	2.50	10.00	3.50	1.20	0.80	1.75	0.80	3.350
10	4.50	2.00	5.00	1.90	1.00	0.50	1.20	0.50	2.075

Table 6.13 (I) vs (T_{OFF})

The effect of change of T_{OFF} to I is –1.275.

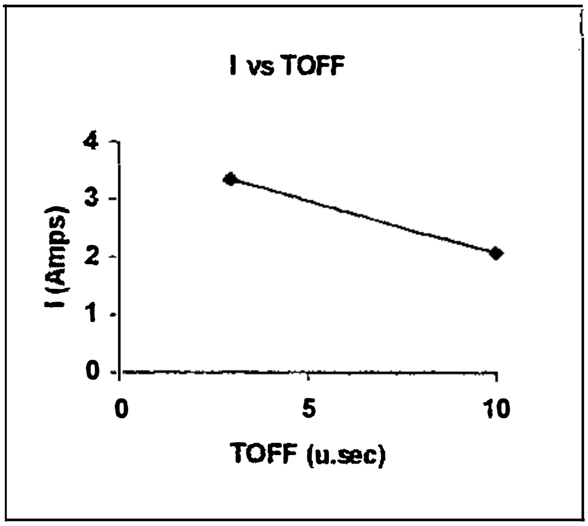


Figure 6.3 I vs T_{OFF}

6.4.2.2 The effect of change of G_V

G_V	I (Amps)								Ave.I (Amps)
2	5.00	10.00	1.90	3.50	1.20	1.75	0.50	0.80	2.3438
9	4.50	6.25	2.00	2.50	1.00	1.20	0.50	0.80	3.0813

Table 6.14 (I) vs (G_V)

The effect of change of G_V to I is 0.7375.

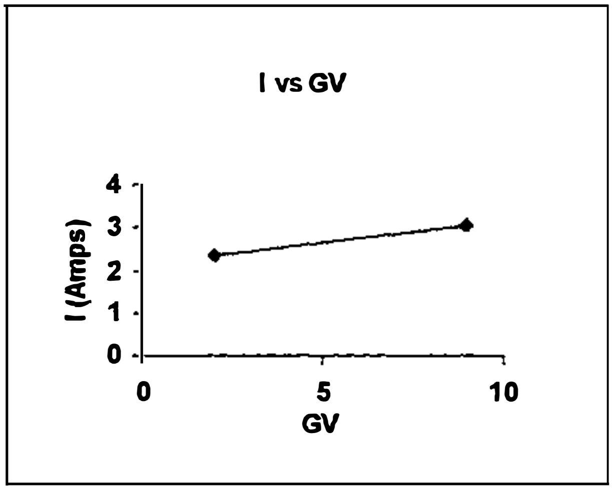


Figure 6.4 I vs G_V

6.4.2.3 The effect of change of T_{ON}

T_{ON} (u.sec)	I (Amps)								Ave.I (Amps)
10	2.00	2.50	1.90	3.50	0.50	0.80	0.50	0.80	1.5625
600	4.50	6.25	5.00	10.00	1.00	1.20	1.20	1.75	3.8625

Table 6.15 (I) vs (T_{ON})

The effect of change of T_{ON} to I is 2.300.

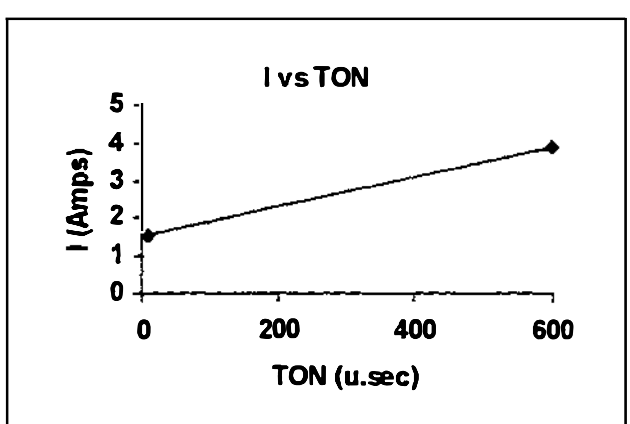


Figure 6.5 I vs T_{ON}

6.4.2.4 The effect of change I_P

IP	I (Amps)								Ave.I (Amps)
3	1.00	1.20	0.50	0.80	1.20	1.75	0.50	0.80	0.9688
10	4.50	6.25	2.00	2.50	5.00	10.00	1.90	3.50	4.4563

Table 6.16 (I) vs (I_P)

The effect of change of T_{ON} to I is 3.4875.

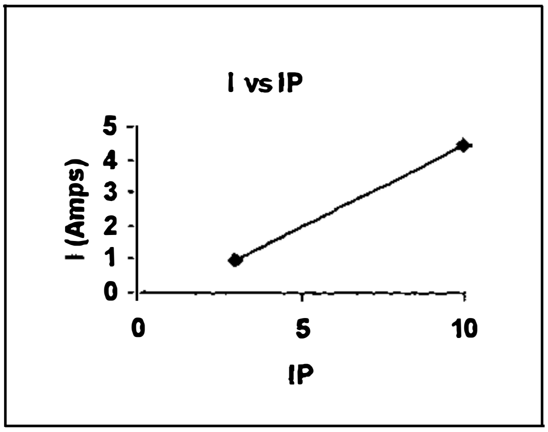


Figure 6.6 I vs I_P

6.4.3 Yates Analysis

According to the Yates analysis shown in table 6.17,

Significant effects for I are:

I_P = 3.4875

T_{ON} = 2.3000

I_P T_{ON} = 1.6625

T_{OFF} = -1.2750

I_P T_{OFF} = -0.9375

		1	2	3	4	5	Average
- - - -	I	0.80	4.30	7.60	26.80	43.40	5.4250
+ - - -	I_P	3.50	3.30	19.20	16.60	27.90	3.4875
- + - -	G_V	0.80	11.75	4.90	17.70	-5.90	-0.7375
+ + - -	I_PG_V	2.50	7.45	11.70	10.20	-4.40	-0.5500
- - + -	T_{ON}	1.75	2.40	4.40	-5.30	18.40	2.3000
+ - + -	I_PT_{ON}	10.00	2.50	13.30	-0.60	13.30	1.6625
- + + -	G_VT_{ON}	1.20	6.20	2.90	-4.20	-4.10	-0.5125
+ + + -	$I_PG_VT_{ON}$	6.25	5.50	7.30	-0.20	-2.60	-0.3250
- - - +	T_{OFF}	0.50	2.70	-1.00	11.60	-10.20	-1.2750
+ - - +	I_PT_{OFF}	1.90	1.70	-4.30	6.80	-7.50	-0.9375
- + - +	G_VT_{OFF}	0.50	8.25	0.10	8.90	4.70	0.5875
+ + - +	$I_PG_VT_{OFF}$	2.00	5.05	-0.70	4.40	4.00	0.5000
- - + +	$T_{ON}T_{OFF}$	1.20	1.40	-1.00	-3.30	-4.80	-0.6000
+ - + +	$I_PT_{ON}T_{OFF}$	5.00	1.50	-3.20	-0.80	-4.50	-0.5625
- + + +	$G_VT_{ON}T_{OFF}$	1.00	3.80	0.10	-2.20	2.50	0.3125
+ + + +	$I_PG_VT_{ON}T_{OFF}$	4.50	3.50	-0.30	-0.40	1.80	0.2250
		43.40					

Table 6.17 Yates Analysis for I

6.4.4 ANOVA using MINTAB

Full analysis of results is shown in Appendix I. From the effect analysis, it is clear that effects of following main factors and interactions are significant.

Factors/ Interactions	Effects	T value	P value
I_P	3.4875	8.610	0.000
T_{ON}	2.3000	5.680	0.002
T_{OFF}	-1.2750	-3.150	0.025
I_PT_{ON}	1.6625	4.100	0.009

Table 6.18 Significant effects for I

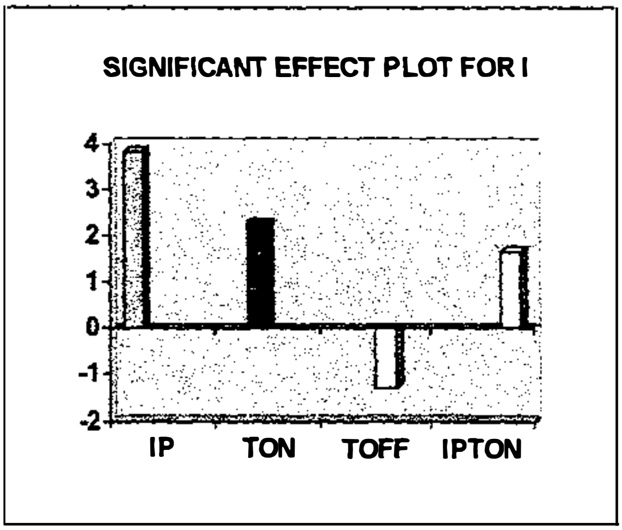


Figure 6.7 Significant effect plot for I

6.4.5 Discussion for selection of important factors and interactions for I

After consideration of evaluation of effects using graphical analysis, Yates analysis and factorial fit using Minitab significant effects for I are I_P, T_{ON}, T_{OFF} and I_PT_{ON}. Other factors and interactions were not considered further as the effects are very small and hence insignificant. Low p value and high t value of ANOVA, further strengthens and helps to select significant factors and interactions.

6.4.6 Further experimentation and analysis

6.4.6.1 Preliminaries

Tool electrode- Copper

Work piece - Zinc

Working time selector at its mid position (5.5)

Jump set – 1.50mm

Servo speed control at its mid position (5.5)

Copper electrodes with cross sectional areas 1.00cm2, 1.25cm2, 2cm2 and 3cm2 were used.

6.4.6.2 Experimental observations

I (Amps)	I_P	T_{ON} (u.sec)	T_{OFF} (u.sec)
2.00	6	100	10
2.00	6	200	10
2.80	6	300	10
2.80	6	500	10
2.50	6	700	10
2.50	6	800	10
2.50	6	1000	10
2.50	6	100	1
4.10	6	200	1
4.20	6	300	1
4.50	6	500	1
4.80	6	700	1
4.90	6	800	1
6.00	6	1000	1
3.75	10	50	3
5.00	10	100	3
5.00	10	200	3
5.50	10	300	3
5.50	10	400	3
5.50	10	500	3
6.50	10	800	3
7.00	10	1000	3
1.00	3	50	3
1.20	3	100	3
1.30	3	200	3
1.50	3	300	3
1.50	3	400	3
1.50	3	500	3
1.50	3	800	3
1.65	3	1000	3

0.70	5	10	10
2.00	5	600	10
1.20	8	10	10
4.20	8	600	10
5.00	9	100	3
5.00	9	100	3
5.00	9	100	3
2.00	5	100	3
4.00	8	100	3
4.00	8	100	3
6.00	11	100	3
2.00	5	100	3
4.00	7	100	3
6.00	11	100	3
1.00	3	100	3

Table 6.19 I vs I_P, T_{ON} and T_{OFF}

6.4.6.3 Regression analysis using MINITAB

Full analytical results using MINTAB is attached in Appendix I

The regression equation is;

$Log_e (I) = -1.88 + 1.20\ Log_e (I_P) + 0.210\ Log_e (T_{ON}) - 0.302\ Log_e (T_{OFF})$

This can be written in the form;

$I = 0.1526\ (I_P)^{1.2}(T_{ON})^{0.210}/(T_{OFF})^{0.302}$ ....(6.4.1)

The regression output shows low p values (0.000) and high t ratios. P value is zero and F statistics is larger in ANOVA. R squared and adjusted R squared are over 94%. Hence, the equation adequately describes a relationship between I, I_P, T_{ON} and T_{OFF}.

6.5 Rate of Penetration

6.5.1 Observations of two level factorial experiment

Cross sectional area of Cu electrode tool 1 cm^2 as shown in figure 6.1.

Run No.	Time (min)	Penetration (mm)	P_R (mm/ min)
1	40	24.31	0.608
2	30	27.33	0.911
3	30	5.66	0.189
4	35	7.42	0.212
5	30	22.44	0.748
6	12	16.43	1.369
7	30	5.14	0.171
8	30	5.87	0.196
9	30	4.56	0.152
10	30	5.94	0.198
11	30	1.67	0.056
12	40	3.81	0.095
13	30	5.45	0.182
14	30	8.15	0.272
15	30	1.03	0.034
16	30	2.34	0.078

Table 6.20 Observations for penetration

6.5.2 Graphical Analysis

6.5.2.1 Calculation the effect of change of T_{OFF}

T_{OFF} (u.sec)	P_R (mm/min)								Ave. P_R (mm/min)
3	0.911	0.212	1.369	0.196	1.198	0.095	0.272	0.078	0.416
10	0.608	0.189	0.748	0.171	0.152	0.056	0.182	0.034	0.268

Table 6.21 P_R vs T_{OFF}

The effect of change of T_{OFF} to P_R is -0.148.

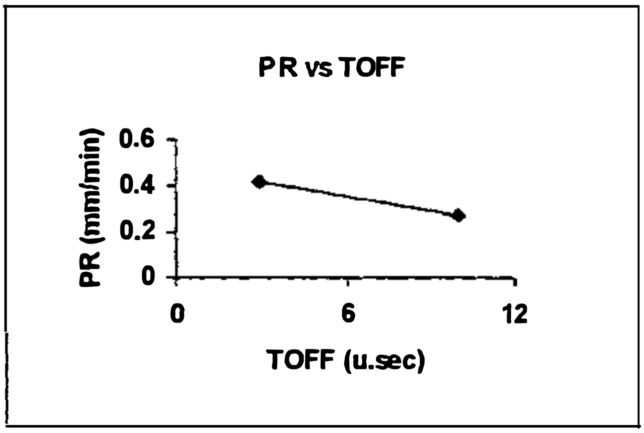


Figure 6.8 P_R vs T_{OFF}

6.5.2.2. The effect of change of G_V

G_V	P_R (mm/min)								Ave. P_R (mm/min)
2	0.748	1.369	0.171	0.196	0.182	0.272	0.034	0.078	0.381
9	0.608	0.911	0.189	0.212	0.152	0.198	0.056	0.095	0.303

Table 6.22 P_R vs G_V

Hence the effect of change of G_V to P_R is -0.078.

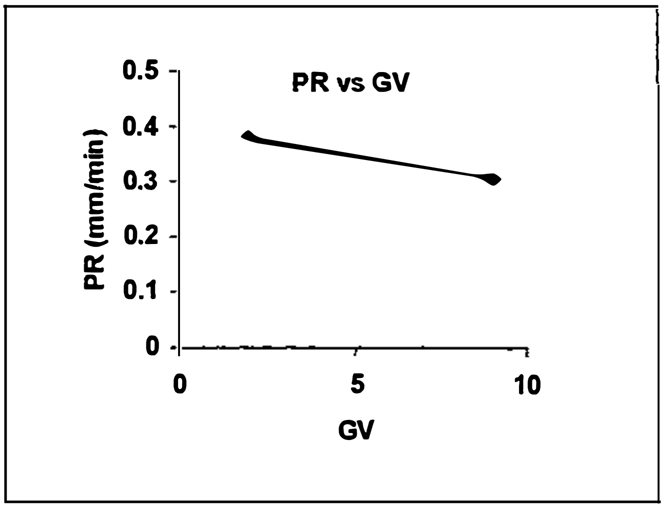


Figure 6.9 P_R vs G_V

6.5.2.3 The effect of change of T_{ON}

T_{ON} (u.sec)	P_R (mm/min)								Ave. P_R (mm/min)
10	0.189	0.212	0.171	0.196	0.056	0.095	0.034	0.078	0.129
600	0.608	0.911	0.748	1.369	0.152	0.198	0.182	0.272	0.555

Table 6.23 P_R vs T_{ON}

The effect of change of T_{ON} to P_R is 0.426

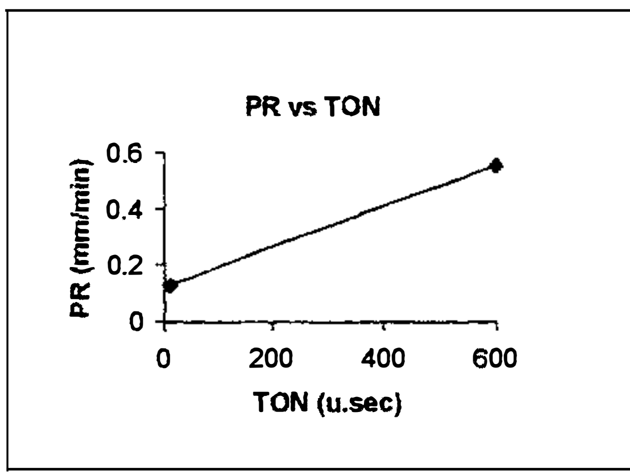


Figure 6.10 P_R vs T_{ON}

6.5.2.4 The effect of change of I_P

I_P	P_R (mm/min)								Ave. P_R (mm/min)
3	0.152	0.198	0.056	0.095	0.182	0.272	0.034	0.078	0.133
10	0.608	0.911	0.189	0.212	0.748	1.369	0.171	0.196	0.551

Table 6.24 P_R vs I_P

The effect of change of I_P to P_R is 0.418

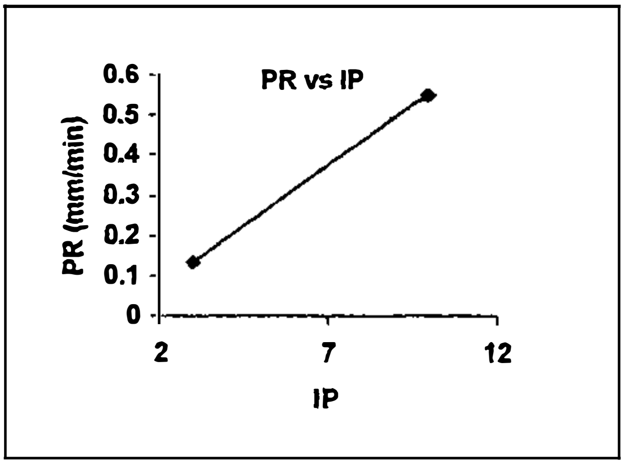


Figure 6.11 P_R vs I_P

6.5.3 Yates analysis

		1	2	3	4	5	Average
- - - -	I	0.078	0.274	0.581	3.331	5.471	0.6839
+ - - -	I_P	0.196	0.307	2.750	2.140	3.337	0.4171
- + - -	G_V	0.095	1.641	0.450	2.045	-0.629	-0.0786
+ + - -	I_PG_V	0.212	1.109	1.690	1.292	-0.499	-0.0624
- - + -	T_{ON}	0.272	0.205	0.235	-0.499	3.409	0.4261
+ - + -	I_PT_{ON}	1.369	0.245	1.810	-0.130	2.327	0.2909
- + + -	G_VT_{ON}	0.198	0.930	0.270	-0.385	-0.775	-0.0969
+ + + -	$I_PG_VT_{ON}$	0.911	0.760	1.022	-0.114	-0.489	-0.0611
- - - +	T_{OFF}	0.034	0.118	0.033	2.169	-1.191	-0.1489
+ - - +	I_PT_{OFF}	0.171	0.117	-0.532	1.240	-0.753	-0.0941
- + - +	G_VT_{OFF}	0.056	1.097	0.040	1.575	0.369	0.0461
+ + - +	$I_PG_VT_{OFF}$	0.189	0.713	-0.170	0.752	0.271	0.0339
- - + +	$T_{ON}T_{OFF}$	0.182	0.137	-0.001	-0.565	-0.929	-0.1161
+ - + +	$T_{ON}T_{OFF}$	0.748	0.133	-0.384	-0.210	-0.823	-0.1029
- + + +	$I_PT_{ON}T_{OFF}$	0.152	0.566	-0.004	-0.383	0.355	0.0444
+ + + +	$G_VT_{ON}T_{OFF}$	0.608	0.456	-0.110	-0.106	0.277	0.0346
	$I_PG_VT_{ON}T_{OFF}$	5.471					

Table 6.25 Yates Analysis for P_R

Significant effects for P_R are;

I_P = 0.4171

T_{ON} = 0.4261

I_PT_{ON} = 0.2909

T_{OFF} = -0.1489

$T_{ON}T_{OFF}$ = -0.1161

6.5.4 ANOVA using MINITAB

Full analysis of results is shown in the Appendix I. From this effect analysis, it is clear that, following main factors and interactions are having significant effects.

Factors/Interactions	Effects	t- value	P- value
I_P	0.41712	6.83	0.001
T_{ON}	0.42612	6.98	0.001
T_{OFF}	-0.14887	-2.44	0.059
I_PT_{ON}	0.29087	4.76	0.005
$T_{ON}T_{OFF}$	-0.11613	-1.90	0.116

Table 6.2 6 Significant effects for P_R

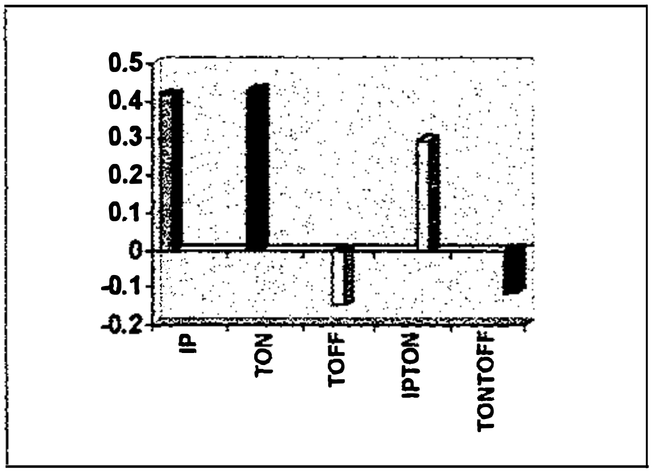


Figure 6.12 Significant effect plot for P_R

6.5.5 Discussion for selection of important factors and interactions

After consideration of evaluations of effects using graphical analysis, Yates analysis balance ANOVA and factorial fit using MINITAB it is clear that T_{ON}, I_P and T_{ON} I_P affects positively for P_R. There is a negative effect to P_R from T_{OFF}. G_V and other interactions are not considered further as the effects are very small and insignificant. In order to find a relationship between I_P and P_R further experiments have been carried out. Since I_P is just a position in the machine, there is insufficient meaning. Therefore the corresponding current flow reading of the Ampere meter in the machine was taken for each I_P position as shown in table 6.27.

6.5.6 Further experimentation and analysis to find out the relationship between P_R, I_P, T_{ON} and T_{OFF}.

6.5.6.1 Preliminaries

Cu electrode tool (+) ve, Zinc work piece (-) ve, Working time selector kept constant at 5.5.

Jump set for 1.60 mm, $G_V = 9$, $T_{ON} = 100$, $T_{OFF} = 3$

Cu electrodes with 1.00 cm^2, 1.25 cm^2, 2.00 cm^2 and 3 cm^2 have been

6.5.6.2 Experimental observations

I_P	Current (Amps)	Electrode area (cm^2)	Time (min)	Penetration (mm)	(I/A) Amp/cm^2	P_R (mm/min)
9	5.0	1.25	15	8.995	4.000	0.600
10	5.5	1.25	10	6.930	4.400	0.693
9	5.0	3.00	32	7.620	1.667	0.238
9	5.0	3.00	30	7.300	1.667	0.243
9	5.0	2.00	30	9.440	2.500	0.315
9	5.0	2.00	30	10.190	2.500	0.340
9	5.0	1.00	25	17.350	5.000	0.694
9	5.0	1.00	13	9.860	5.000	0.758
9	5.0	1.00	10	7.820	5.000	0.782
5	2.0	1.00	16	4.730	2.000	0.296
8	4.0	1.00	19	12.720	4.000	0.669
8	4.0	1.00	20	12.600	4.000	0.630
11	6.0	1.00	12	10.750	6.000	0.896
5	2.0	2.00	25	3.770	1.000	0.151
7	4.0	2.00	20	6.410	2.000	0.321
11	6.0	2.00	15	6.780	3.000	0.452
3	1.0	2.00	25	2.360	0.500	0.094

Table 6.27 P_R vs Current Density

6.5.6.3 Regression analysis using MINITAB

Full analytical results using MINITAB is attached in Appendix J.

The regression equation is;

P_R = -0.0055 + 0.152 (I/A) ....(6.5.1)

Where P_R is in mm/min and (I/A) is in Amp/cm^2.

According to the regression analysis, p value is for constant –0.0055 is very large (0.766) and the t value is small (0.30). This explains that there is no constant in the equation.

Therefore the equation (6.5.1) can be written in the form

$P_R = 0.152\ (I/A)$ ....(6.5.2)

Plot is shown below.

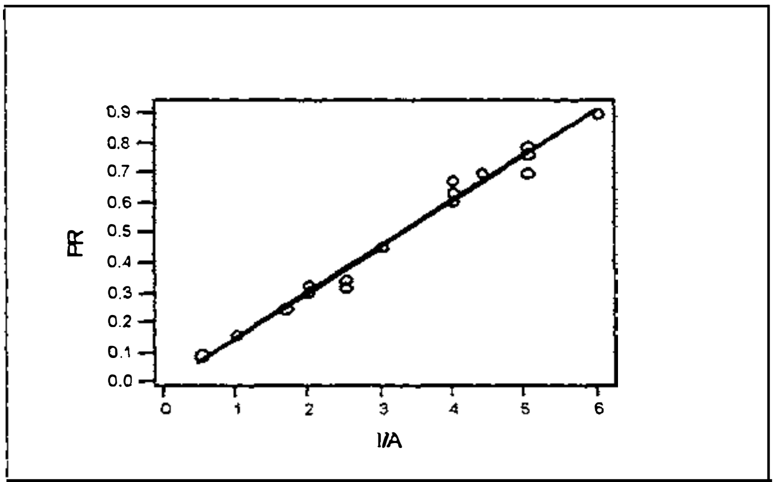


Figure 6.13 Plot for P_R vs (I/A)

6.5.7 Establishment of Relationship Between P_R and Process Variables

Since the main objective is to find a relationship with P_R, T_{ON}, T_{OFF} and current, further analysis has been carried out by using MINITAB.

As I_P shows only positions which does not have much meaning, corresponding current reading by the ampere meter in the machine for each I_P was taken for analytical purposes.

T_{ON}, I_P have (+)ve effect on P_R

T_{OFF} has (-)ve effect on P_R

$T_{ON}.I_P$ has (+) effect on P_R

$T_{ON}.T_{OFF}$ has (-) on P_R

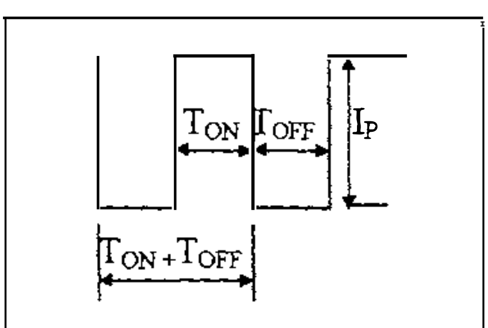


Figure 6.14 Wave form of dc electrical pulse

When considering the wave form of the electrical pulse; reduction of T_{OFF} means the increasing frequency of T_{ON}. This is why effects of T_{OFF} and $T_{ON}.T_{OFF}$ are negative. Therefore $[(T_{ON})/(T_{ON}+T_{OFF})]$ and $[(T_{ON})/(T_{OFF})\}$ were taken for further analysis.
Since several electrodes with different cross sectional areas have been used for the experiment, the current density (I/A) has been selected as in the previous section for analysis.

MINTAB release 10 has been used to examine whether is there any relationship between P_R, (I/A) and $[(T_{ON})/(T_{ON}+T_{OFF})]$ or $[(T_{ON}/T_{OFF})]$.
Full analytical results using MINITAB 10 is shown in Appendix J.

Model 1.1

Regression equation is,

$Log_e(P_R) = -1.85 + 0.944\ Log_e(I/A) + 0.976\ Log_e[(T_{ON})/(T_{ON}+T_{OFF})]$

This can be written in the form;

$P_R = 0.157\ (I/A)^{0.944}[(T_{ON})/(T_{ON}+T_{OFF})]^{0.976}$ ....(6.5.3)

After substitution $I = 0.1526\ (I_P)^{1.2}(T_{ON})^{0.210}/(T_{OFF})^{0.302}$ from equation (6.4.1), this can be written in the form;

$P_R = 0.02661[(I_P)^{1.1328}/(A)^{0.944}] * [(T_{ON})^{1.1742}/(T_{OFF})^{0.285}(T_{ON}+T_{OFF})^{0.976}]$ ......(6.5.4)

Regression output for model 1.1 shows low p values and high ratios.

R squared and adjusted R squared are over 95%. Low p value and high F statistics in ANOVA. This means the equation in model 1.1 adequately describe a relationship between P_R, (I/A) and $[(T_{ON})/(T_{ON}+T_{OFF})]$.

Model 1.2

Regression equation is,

$Log_e(P_R) = -2.43 + 0.937\ Log_e(I/A) + 0.148\ Log_e[(T_{ON}/T_{OFF})]$

This can be written in the form;

$P_R = 0.088\ (I/A)^{0.937}[(T_{ON}/T_{OFF})]^{0.148}$ ....(6.5.5)

After substituting equation (6.4.1), (6.4.4) can be rewritten as shown below.

$P_R = 0.01512\ [(I_P)^{1.1244}/(A)^{0.937}]*[(T_{ON})^{0.3448}/(T_{OFF})^{0.431}]$.......(6.5.6)

In this model, all p values are zero and t values are higher than model 1.1.

R squared value is higher than 96% and adjusted R squared value is 96.4%. Both these values are higher than model 1.1. Also p value is zero and F statistics is larger in ANOVA when compared to model 1.1.

Therefore it seems that model 1.2 describes a better relationship for P_R than model 1.1.

After careful study of both model 1.1 and model 1.2, high t ratio and low p value in the table of coefficients indicate evidence a relationship between P_R, (I/A), T_{ON} and T_{OFF}. High F statistics and low p value in the table quantify this relationship in different way. The R squared and adjusted R squared values are greater than 95%. This further reinforce that there is a relationship. When comparison between model 1.1 and model 1.2, it is clear that the model 1.2 describes a better relationship.

Before making a final conclusion, author suggests to try both model in actual situation and to see which relationship better predicts the actual rate of penetration.
Therefore in Chapter 7, is shown the comparison between actual values and estimated values for both models.

6.6 Surface Roughness (S_R)

6.6.1 Two level factorial experiment

For surface roughness experiments, the author has used the same two level full factorial orthogonal design matrix shown in table 6.9 with same variables. The cross sectional area of the Copper electrode tool is 2 cm^2. An instrument called surface profilometer was used to measure and record surface roughness of machined surfaces. This consists of a diamond stylus travelling along a straight line over the surface to be measured. The distance that the stylus travels, which can be varied is called the cut-off. The principle of measuring surface roughness using this equipment is attached in appendix K. Copper electrode with 2 cm^2 cross sectional area was used to provide adequate stylus travel over machined surfaces and hence to obtain accurate readings. Access to this type of equipment was limited and after many enquires from various research institutions it was possible to find from the Metrology Calibration Services Ltd, Hamilton. The author had to send machined work pieces to Hamilton to measure surface roughness on several occasions. This was and expensive and time consuming process due to the limited access to these type of equipment.

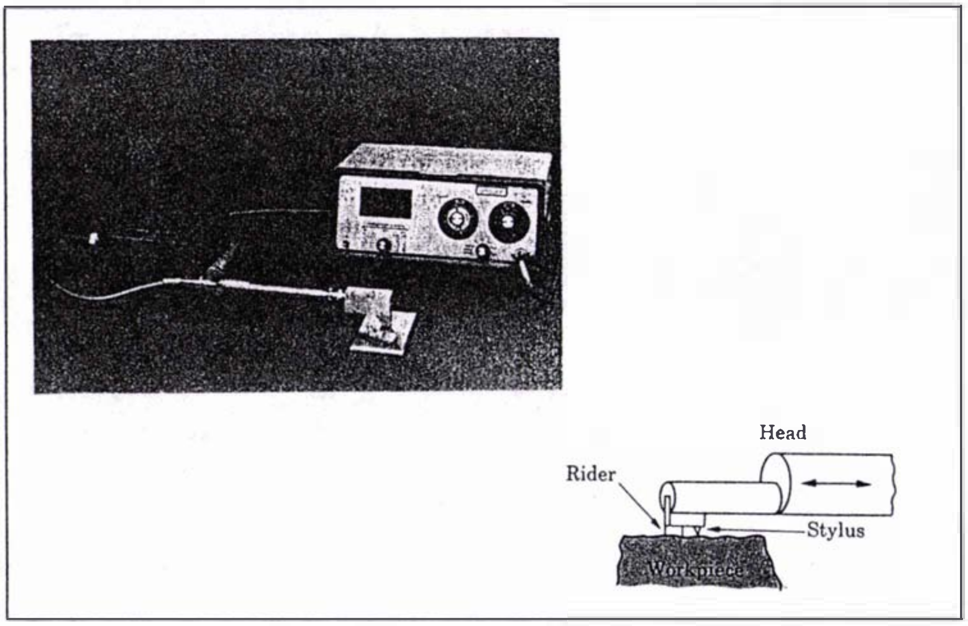


Figure 6.15 Surface Profilometer

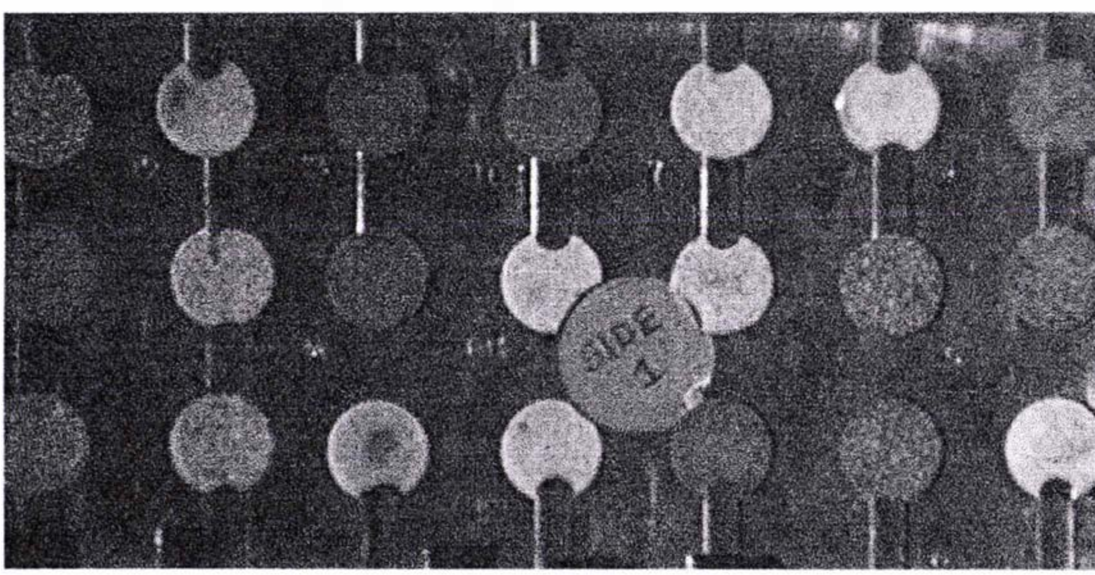


Figure 6.16 Corresponding surface roughness of values in the table 6.12

6.6.2 Experimental Observations- Surface Roughness

Run No.	Current (Amp)	Voltage (Volts)	S_R (umRs)	Average S_R (umRs)
1	4.5	50	18-20	19.00
2	7.0	60	12-13	12.50
3	2.0	60	4.3-4.5	4.40
4	2.5	60	4.3-5.0	4.65
5	5.0	35	17-19	18.00
6	10.0	30	17-21	19.00
7	2.0	45	5.0-5.5	5.25
8	5.0	35	4.8-5.2	5.00
9	1.2	60	10-11	10.50
10	1.3	65	12-14	13.00
11	0.5	60	3.3-3.8	3.55
12	1.0	60	2.6-2.9	2.75
13	1.2	35	9-10	10.00
14	3.0	35	10.5-12	11.25
15	0.5-0.8	50	2.7-3.0	2.85
16	1.0	50	2.6-2.9	2.75

Table 6.28 Observations for surface roughness

6.6.3 Graphical Analysis

6.6.3.1 The effect of change of T_{OFF} on S_R

T_{OFF} (u.sec)	S_R (umRs)								Ave. S_R (umRs)
3	12.5	4.65	19.0	5.00	13.0	2.75	11.25	2.75	8.8625
10	19.0	4.40	18.0	5.25	10.5	3.55	10.00	2.85	9.1938

Table 6.29 S_R vs T_{OFF}

The average effect of change of T_{OFF} to S_R is +0.3313.

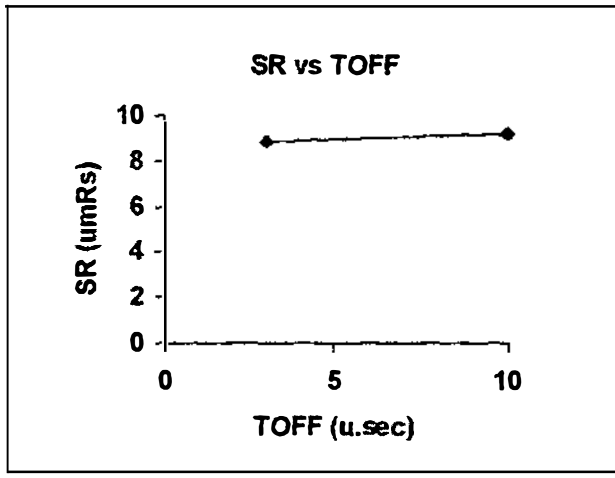


Figure 6.17 S_R vs T_{OFF}

6.6.3.2 The effect of change on G_V

G_V	S_R (umRs)								Ave. S_R (umRs)
2	18.0	19.0	5.25	5.00	10.0	11.25	2.85	2.75	9.2625
9	19.0	12.5	4.40	4.65	10.5	13.00	3.55	2.75	8.7938

Table 6.30 S_R vs G_V

The average effect of change of G_V to S_R is -0.4687.

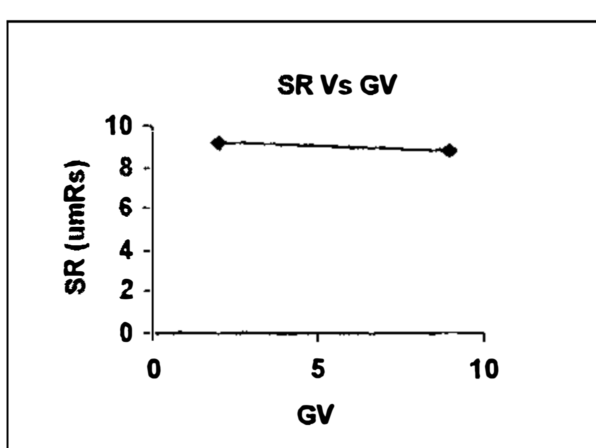


Figure 6.18 S_R vs G_V

6.6.3.3 The effect of change of T_{ON}

6.6.3.3 The effect of change of T_{ON}

T_{ON} (u.sec)	S_R (umRs)								Ave. S_R (umRs)
10	4.4	4.65	5.25	5.0	3.55	2.75	2.85	2.75	3.900
600	19.0	12.50	18.0	19.0	10.50	13.0	10.0	11.25	14.156

Table 6.31 S_R vs T_{ON}

The average effect of change of T_{ON} to S_R is 10.2563.

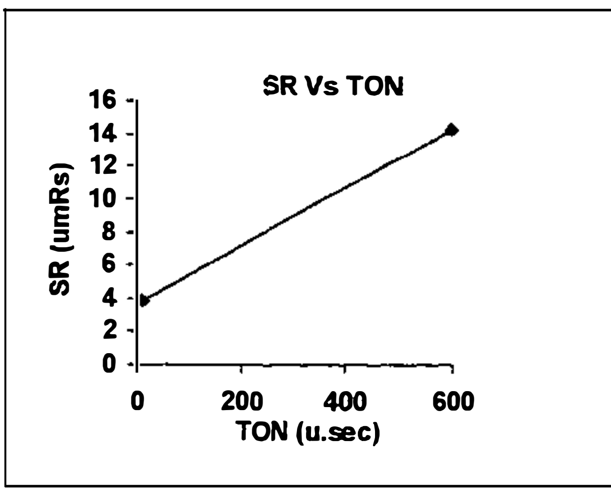


Figure 6.19 S_R vs T_{ON}

6.6.3.4 The effect of change on I_P

I_P	S_R (umRs)								Ave. S_R (umRs)
3	10.5	13.0	3.55	2.75	10.0	11.25	2.85	2.75	7.0813
10	19.0	12.5	4.40	4.65	18.0	19.00	5.25	5.00	10.975

Table 6.32 S_R vs I_P

The average effect of change of I_P to S_R is 3.893

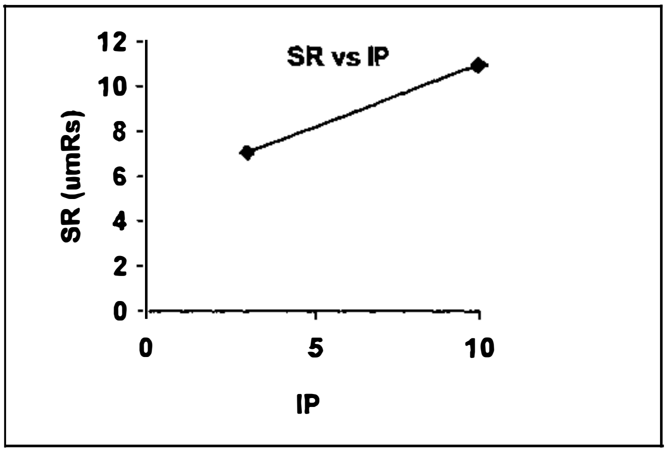


Figure 6.20 Ave. S_R vs I_P

6.6.4 Yates analysis

		1	2	3	4	5	Average
- - - -	I	2.75	7.75	15.15	70.90	144.45	18.056
+ - - -	I_P	5.00	7.4	55.75	73.55	31.15	3.8938
- + - -	G_V	2.75	30.25	16.05	11.40	-3.75	0.4688
+ + - -	I_PG_V	4.65	25.50	57.50	19.75	-9.65	-1.2063
- - + -	T_{ON}	11.25	8.10	4.15	-5.10	82.05	10.2563
+ - + -	I_PT_{ON}	19.00	7.95	7.25	1.35	16.35	2.0438
- + + -	G_VT_{ON}	13.00	28.00	3.25	-8.60	-2.75	-0.3438
+ + + -	$I_PG_VT_{ON}$	12.50	29.50	16.25	-1.05	-5.85	-0.7313
- - - +	T_{OFF}	2.85	2.25	-0.35	40.60	2.65	0.3313
+ - - +	I_PT_{OFF}	5.25	1.90	-4.75	41.45	8.35	1.0438
- + - +	G_VT_{OFF}	3.55	7.75	-0.15	3.10	6.45	0.8063
+ + - +	$I_PG_VT_{OFF}$	4.4	0.50	1.50	13.25	7.55	0.9438
- - + +	$T_{ON}T_{OFF}$	10.00	2.40	-0.35	-4.40	0.85	0.1063
+ - + +	$I_PT_{ON}T_{OFF}$	18.00	0.85	-8.25	1.65	10.15	1.2688
- + + +	$G_VT_{ON}T_{OFF}$	10.50	8.00	-1.55	-7.90	6.05	0.7563
+ + + +	$I_PG_VT_{ON}T_{OFF}$	19.00	8.50	0.50	2.05	9.95	1.2438
		144.45					

Table 6.33 Yates analysis for surface roughness

According to the results of Yates analysis shown in table 6.17, significant effects of factors and interactions are as follows.

I_P = 4.019

T_{ON} = 10.256

$I_P T_{ON}$ = 2.169

6.6.5 Analysis using MINITAB

Full analysis is shown in the Appendix I. After a careful study of estimated effects and coefficients for S_R and ANOVA for S_R and effect plot of the results, following effects and interactions can be identified as significant.

Factors	Effects	t- value	P- value
I_P	3.8937	3.84	0.120
T_{ON}	10.2563	10.10	0.000
$I_P T_{ON}$	2.0438	2.01	0.100

Table 6.34 Significant effects for S_R

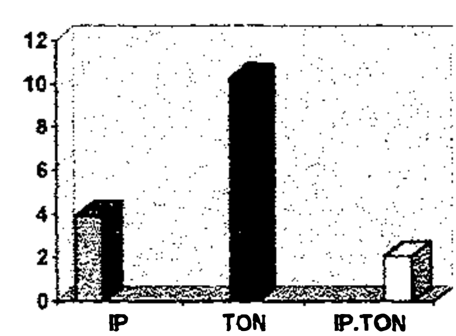


Figure 6.21 Significant effect plot for S_R

6.6.6 Selection of important factors

According to the effects using graphical analysis, Yates analysis and estimated effects and coefficients for S_R, analysis of variance for S_R using MINITAB; T_{ON}, I_P and $T_{ON}.I_P$ affects positively for S_R. These effects are significant. According to the results effects of other factors and interactions are very small compared to the factors describe above. Therefore these effects are not considered for further experiments and analysis.

6.6.7 Further experimentation and analysis to find out relationship between S_R, I_P, T_{ON} and T_{OFF}.

6.6.7.1 Preliminaries

Since I_P is just a position, corresponding current reading of the Ampere meter in the machine was taken for each I_P position. Further experiments were carried out by keeping G_V at 5.5, working time selector at 5.5, Servo speed selector at 5.5, jumping time at 1.6 mm.

Cu tool electrode kept at (+)ve polarity and the Zn work piece at (-)ve polarity. Cross sectional area of the Cu electrode taken as 2 cm^2 for further experiments.

6.6.7.2 Experimental observations and analysis with changing T_{ON} and T_{OFF}

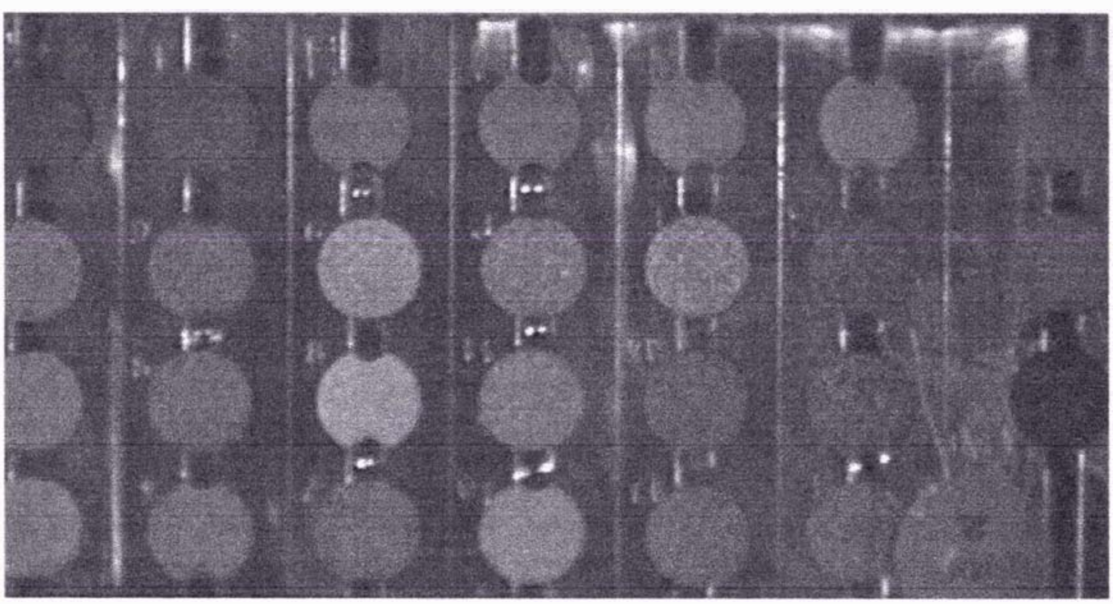


Figure 6.22 Different surface roughness values of side 2 of the work piece

Pad No	T_{OFF}	T_{ON}	I_P	Current (Amps)	S_R (umRs)	Average S_R (umRs)
1	10	100	06	2.0	7.0-8.0	7.50
2	10	200	06	2.0	9.0-10.5	9.75
3	10	300	06	2.8	11.0-13.0	12.00
4	10	500	06	2.8	16.0-17.5	16.75
5	10	700	06	2.5	11.0-13.0	12.00
6	10	800	06	2.5	15.0-16.5	15.75
7	10	1000	06	2.5	17.5-18.5	18.00
8	01	100	06	4.0	6.5-7.5	7.00
9	01	200	06	4.2	7.5-9.0	8.25
10	01	300	06	4.5	8.5-9.5	9.00
11	01	500	06	4.8	12.5-14.0	13.25
12	01	700	06	4.9	12.0-14.0	13.00
13	01	800	06	5	10.5-11.5	11.00
14	01	1000	06	6.5-5.5	13.0-14.5	13.75

Table 6.35 S_R with changing T_{ON}

S_R vs T_{ON} for different T_{OFF} values;

Regression analysis using MINITAB is attached in the Appendix K.

The regression equation for S_R at T_{OFF} 10;

$\text{Log}_e\, S_R = 0.585 + 0.294\, \text{Log}_e\,(T_{ON})$ ....(6.6.1)

Regression out put shows low p values. R squared and adjusted R squared are over 80%. Low p value and high F statistics can be seen in ANOVA.

The regression equation for S_R at T_{OFF} 1;

$\text{Log}_e\, S_R = 0.477 + 0.343\, \text{Log}_e\,(T_{ON})$ ....(6.6.2)

Regression out put shows low p values. R squared and adjusted R squared are over 78%. Low p value and high F statistics can be seen in ANOVA.

This means, both models (6.6.1) and (6.6.2) are adequately describe relationships between S_R and T_{ON}.

Further, by careful observations it is clear that both model (6.6.1) and (6.6.2) equations are same although under different T_{OFF} values. In other words, there is no effect of T_{OFF} on S_R.

6.6.7.3 Further experimentation and analysis with changing T_{ON} and I_P

T_{ON} (u.sec)	I_P	T_{OFF} (u.sec)	Current (Amps)	Pad No.	S_R (umRs)
50	10	03	3.5-4.0	B	7.5-8.5
100	10	03	5.0	C	10.5-12.0
200	10	03	5.0	D	9.5-11.5
300	10	03	5.5	A	12.0-13.0
400	10	03	5.5	E	13.0-15.5
500	10	03	5.5	F	14.0-16.0
800	10	03	6.5	G	18.0-21.0
1000	10	03	7.0	H	15.0-19.0
50	03	03	1.0	J	4.25-5.00
100	03	03	1.2	K	3.50-4.00
200	03	03	1.3	L	5.50-6.50
300	03	03	1.5	I	8.50-10.00
400	03	03	1.5	M	9.00-10.00
500	03	03	1.5	N	8.00-9.25
800	03	03	1.5	O	10.50-11.50
1000	03	03	1.6-1.7	P	12.00-15.00
10	05	03	0.70	1	2.50-3.25
600	05	03	2.00	2	12.00-14.00
10	08	03	1.20	3	4.50-5.00
600	08	03	4.20	4	15.00-16.00

Table 6.36 S_R values with changing T_{ON} and I_P

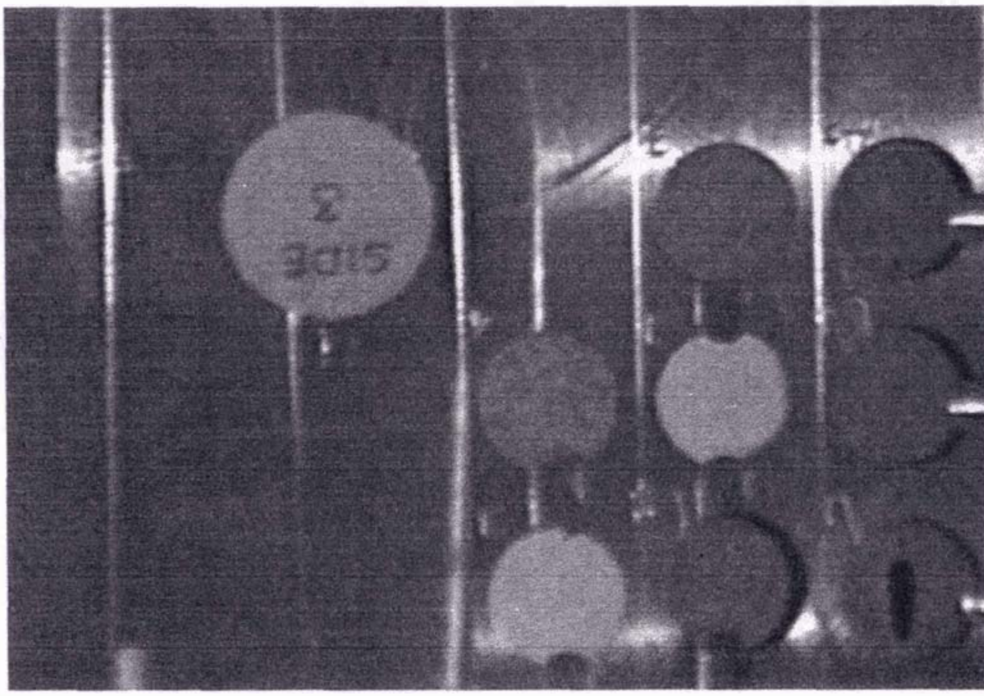


Figure 6.23 Corresponding S_R side 3 of Zn work piece

S_R vs T_{ON} for different I_P values;

Analysis using MINITAB is attached in the appendix K.

The regression equation for S_R when $I_P = 10$,

$Log_e\ S_R = 0.900 + 0.296\ Log_e\ (T_{ON})$ ....(6.6.3)

The regression equation for S_R when $I_P = 3$,

$Log_e\ S_R = 0.286 + 0.321\ Log_e\ (T_{ON})$ ....(6.6.4)

Regression out put for both these models shows low p values. Adjusted R squared and R squared are over 92%. A high F statistics value can be seen in ANOVA for both models. Therefore both models (6.6.3) and (6.6.4) are adequately describe a relationship between S_R and T_{ON}.

In both models, 0.296 and 0.321 can be approximated to 0.300. Also these models are in the form of Y= mX + C. This means both models can be represented by straight lines with same gradient with different interceptions in $Log_e\ (S_R)$ vs $Log_e\ (T_{ON})$ graph for different I_P positions as shown in figure 6.24.

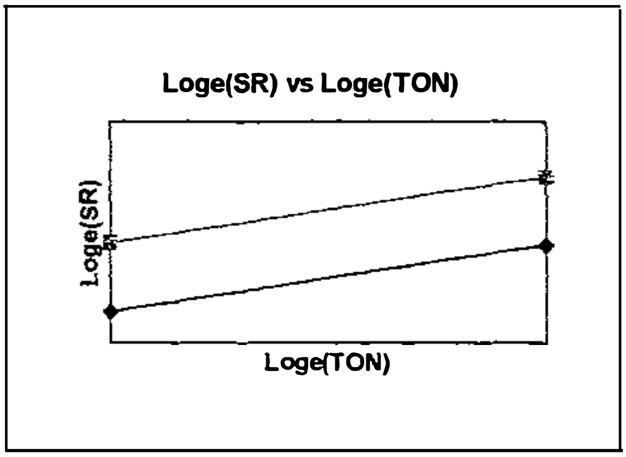


Figure 6.24 $Log_e(S_R)$ vs $Log_e(T_{ON})$

6.6.8 Establishment of relationships between S_R and process variables

Since the main objective is to establish a relationship for S_R with T_{ON}, T_{OFF} and current, further analysis has been carried out by using MINITAB. Corresponding ampere meter reading of the machine were taken for each I_P position.

Regression analysis has been used to see whether there is any relationship between S_R, (I/A) and $[(T_{ON})/(T_{ON}+T_{OFF})]$.

Full analysis is attached in the Appendix K.

Model 1

Regression equation is;

$Log_e S_R = 2.30 + 1.24 Log_e [(T_{ON})/(T_{ON}+T_{OFF})] + 0.344 Log_e (I/A)$

This can be written in the form;

$S_R = 9.974 (I/A)^{0.344} [(T_{ON})/(T_{ON}+T_{OFF})]^{1.24}$ ....(6.6.5)

After substituting $I= 0.1526(I_P)^{1.2} [(T_{ON})^{0.216}/(T_{OFF})^{0.302}]$

$S_R= [5.244(I_P)^{0.4128}/(A)^{0.344}][(T_{ON})^{1.3122}/(T_{OFF})^{0.1039}(T_{ON}+T_{OFF})^{1.24}]$...........(6.6.6)

Regression analysis was used for the model S_R, (I/A) and T_{ON} to see whether there is any correlation.

Regression output is attached in the Appendix K.

Model 2

Regression equation for this model is;

$Loge S_R = 0.834 + 0.254 Log_e (T_{ON}) + 0.254 Log_e (I/A)$

This can be written in the form;

$S_R = 2.303(T_{ON})^{0.254}\ (I/A)^{0.254}$ ....(6.6.7)

After substituting $I = 0.1526(I_P)^{1.2}[(T_{ON})^{0.210}/(T_{OFF})^{0.302}]$

$S_R=[1.4286(I_P)^{0.3048}(T_{ON})^{0.3074}]/[(A)^{0.254}(T_{OFF})^{0.0767}]$.................(6.6.8)

6.7 Comparison between Copper and Aluminium electrodes on surface quality

6.7.1 Introduction

Making tool electrode for electrical discharge machine is an important factor in rapid mould manufacture. The mould maker should be able to make the electrode as quickly as possible while maintaining the surface finish of work after electrical discharge machining. At the same time electrode material should be cheaper, easily available, easily machinable and handled. Advantages and limitations of electrode materials currently available has already been discussed in chapter 5.

Since Aluminium is cheaper, easily available, easily machinable and easily handled, it is very useful to find out the possibility of using Aluminium as an EDM tool electrode. Further, it is possible to cast Aluminium more easily and economically than Copper. Therefore Aluminium is more competitive tool electrode material than Copper.

Hence, experiment described in section 6.7.2 was carried out by the author in order to compare the performance of Aluminium and Copper.

6.7.2 Experimental Observations

In this experiment, G_V was kept constant at 5.5. Servo speed selector, working time selector and Jumping set were kept at constant values as described in earlier experiments. Cross sectional area of both Cu and Al electrode were 2 cm^2. Both electrodes are dimensionally identical as shown below.

Surface roughness using both Cu and Al electrodes was measured subjected to conditions as shown in the table 6.37.

T_{ON}	I_P	T_{OFF}	Current (Amps)	Electrode	Pad No.	S_R (umRs)	Ave. S_R (umRs)
600	6	10	2.5	Cu	C1	15.00-17.00	16.00
600	6	10	2.5	Cu	C2	13.00-14.50	13.75
600	6	10	2.5	Al	A1	9.00-10.00	9.50
600	6	10	2.5	Al	A2	11.00-12.00	11.50

Table 6.37 Effect of electrode material on surface quality

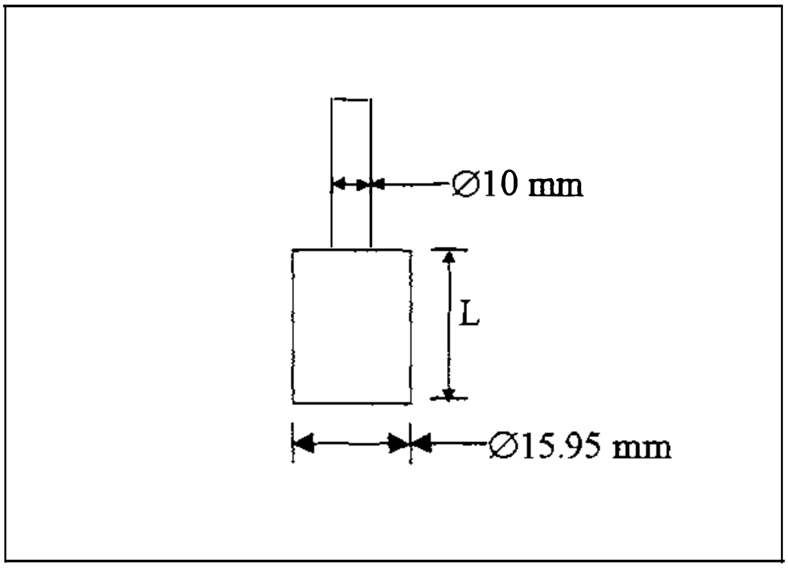


Figure 6.25 Tool electrode with 2 cm^2 cross sectional area

Further, in order to find the wear rate of both electrodes lengths (L) of both tools were measured before and after 10 min of EDM operations.

Pad No.	Electrode	Initial 'L' (mm)	Final 'L' (mm)	% Wear
C1	Cu	25.83	25.79	0.155
C2	Cu	25.70	25.65	0.195
A1	Al	27.63	27.35	1.013
A2	Al	26.90	26.35	2.045

Table 6.38 Wear rates of Cu and Al electrode tools

According to the observations in table 6.35 and 6.36, it is clear that the surface finish improves when Al electrode was used. But the percentage wear rate of Al is higher than the Cu electrode for Zn work piece.

Percentage average improvement of surface finish with Al electrode
29.40%.

For 10 min interval;
Percentage average electrode wear of Cu electrode is 0.175%
Percentage average electrode wear of Al electrode is 1.529%

In addition to these, it was observed that the risk of fire hazard when using Al electrode was higher than Cu. Therefore to prevent such hazards, it is suggested to use Al electrode only if the work is submerged by the dielectric fluid.

6.8 Discussion

6.8.1 The effect of I_P on P_R

According to graphical analysis, Yates table and the analysis using MINITAB, the effect of I_P on P_R is significant. In the section 6.5.6.3 to find out a relationship between P_R and current density the regression analysis has been used. Low p values, high t values and high t value in the table of coefficients indicates that there is a strong correlation between P_R and (I/A). This further reinforces due to high percentage values for R squared (94.7%) and adjusted R squared value (94.6 %). This can be seen in the regression plot. Further, from the model equation (6.5.1) in the regression output, it is clear that the Rate of penetration (P_R) is directly proportional to the current density (I/A).

6.8.2 The relationship between P_R, I_P, T_{ON} and T_{OFF}

In the section 6.5.7 two model equations (6.5.3) and (6.5.5) have been discussed. According to the discussion in this section about the regression output model equation (6.5.5) is slightly better than (6.5.3). After substitution of equation (6.4.1) to (6.5.3) and (6.5.5) model equations (6.5.4) and (6.5.6) were obtained. Before making a final conclusion author already has suggested that all models be tested in the real situation. This will be described in chapter 7.

6.8.3 The effect of I_P, T_{ON} and T_{OFF} on S_R

In addition to analysis using graphical analysis, Yates table and the analysis using MINITAB release 10, the model equations (6.6.1) and (6.6.2) shows evidence that there is a relationship between S_R and T_{ON}, as low p values and high t value occur in the table of coefficients. As R squared and adjusted R squared values are over 80%,low p value and high F statistics in ANOVA, this reinforces the evidence.

By careful observations, it is clear that both of these equations are almost same even though these equations were obtained with same I_P position and different T_{OFF} positions.

This further shows that the surface finish is independent of the main factor T_{OFF}.

Also by looking at model equations (6.6.3) and (6.6.4) it is clear that there is a relationship between S_R and T_{ON}. These equations are different to each other and have been obtained under different I_P positions. This further shows that S_R is depended on the main factor I_P and there is a linear relationship between $Log_e(S_R)$ and $Log_e(T_{ON})$.

6.8.4 Relationship between S_R, I_P, T_{ON} and T_{OFF}

The regression output for model equation (6.6.5) shows a low p value and high t value in the table of coefficients. This indicates evidence of relationship between S_R, (I/A) and $[(T_{ON})/(T_{ON}+T_{OFF})]$. R squared and adjusted R squared values are just over 60%. Although p value is low in ANOVA, F statistic shows a medium value. In addition to these, there are some unusual observations in the regression output.

But from the regression output for the model equation (6.6.7), p values are low as well as t values being high. R squared and adjusted R squared are over 88%. On the other hand there is a low p value and a high F statistics in ANOVA. Also there is only one unusual observations.

This means the model equation (6.6.7) adequately describes a relationship. After substituting equation (6.4.1) to (6.6.5) and (6.6.7) model equations (6.6.6) and (6.6.8) were obtained. Before making a final conclusion for correct model equations to be used, author suggests to try all models in actual situations and to see which relationship is better at predicting actual performance.

In chapter 7, it is possible to see the comparison between actual and estimated values for both models.

6.8.5 Comparison of electrode materials

Section 6.4.6.5 indicates that when Aluminium was being used as an electrode material, surface quality of the job improves about 30% than in the case of Copper. But the wear rate of Aluminium is very much higher than the Copper. Also jet flush system without submerged electrode was not suitable for Aluminium because author has observed a fire hazard while using Aluminium. But Aluminium is good in submerged work pieces.

Since Aluminium is cheaper, easily available, easily machinable and easily handled author suggests to commence further studies on how Aluminium electrodes can be used in rapid mould manufacture.

6.8.6 Further studies

Since working time selector and jump set were kept at constant when determining relationships for P_R and S_R, it would be beneficial to carry out further studies to find out relationships for P_R and S_R including working time selector and jump set.

Chapter7

Verifications of Relationships

This chapter compares the actual and estimated values calculated from established relationships for both P_R and S_R and concludes which relationship is more appropriate.

7.1 Current Flow (I)

7.1.1 The experimental observations

The cross sectional area of the Cu electrode tool is 1 cm^2. G_V, working time selector and servo sensitivity control were kept constant at 5.5. Jumping set was adjusted to 1.50 mm. Electrode was (+)ve and the Zinc work piece was (-)ve polarities.

No.	I_P	T_{ON} (u.sec)	T_{OFF} (u.sec)	Time (min)	Depth (mm)	Current (Amp)
1	10	600	10	7	5.20	5.0
2	7	100	7	8	3.09	3.0
3	3	10	3	7	0.67	1.0
4	5	200	5	7	2.58	2.5

Table 7.1 Experimental observations for P_R

7.1.2 Analysis, comparison between actual and estimated values

Equation derived for current flow;

$I=0.1526(I_P)^{1.2}[(T_{ON})^{0.210}/(T_{OFF})^{0.302}]$..(6.3.1)

Actual Current (Amps)	Estimated Value (Amps)
5.0	4.5117
3.0	2.3038
1.0	0.6638
2.5	1.9699

Table 7.2 Actual current flow vs Estimated current

Since the graph shown in figure 7.1 is a straight line, Actual current flow is directly proportional to the estimated value.

Therefore for an estimated current value using the formula (6.3.1), corresponding actual current flow between the gap could be determined. Further current flow can be checked from the ampere meter connected to the EDM. Actual current value can be used to find out P_R and S_R in model (6.5.3) and (6.5.5)

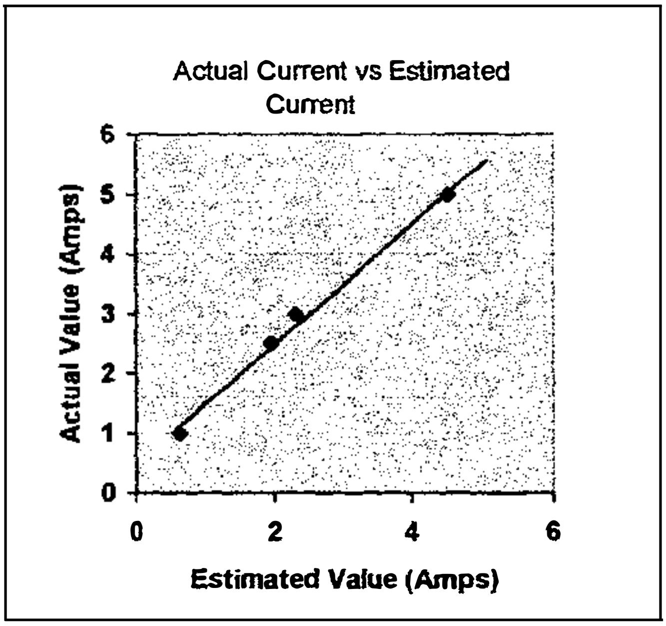


Figure 7.1 Current Flow- Actual vs Estimated

7.2 Rate of Penetration (P_R)

7.2.1 Experimental Observations

Same Observations shown in Table 7.1 in section 7.1.1, was used.

7.2.2 Analysis, comparison between actual and estimated values

Model 1:

$P_R = 0.157\ (I/A)^{0.944}\ [(T_{ON})/(T_{ON}+T_{OFF})]^{0.976}$ ....(6.5.3)

$P_R = [0.02661(I_P)^{1.1328}/(A)^{0.944}][(T_{ON})^{1.1742}/(T_{OFF})^{0.285}(T_{ON}+T_{OFF})^{0.976}]$.........(6.5.4)

Model 2:

$P_R = 0.088\ (I/A)^{0.937}\ (T_{ON}/T_{OFF})^{0.148}$ ....(6.5.5)

$P_R=[0.01512(I_P)^{1.1244}/(A)^{0.937}][(T_{ON})^{0.3448}/(T_{OFF})^{0.431}]$............................(6.5.6)

Estimated P_R Model1 (mm/min)		Estimated P_R Model 2 (mm/min)		Actual P_R (mm/min)	% Variation Model1		% Variation Model 2	
(6.5.3)	(6.5.4)	(6.5.5)	(6.5.6)		(6.5.3)	(6.5.4)	(6.5.5)	(6.5.6)
0.7058	0.6554	0.7288	0.6774	0.7429	+4.99	11.78	+1.89	8.82
0.4146	0.3231	0.3651	0.2852	0.3863	-7.33	16.36	+5.49	26.17
0.1215	0.0826	0.1052	0.0717	0.1092	-11.26	24.36	+3.66	34.34
0.3640	0.2906	0.3585	0.2868	0.3686	+1.25	21.16	+2.74	22.19
% Variation RMS value					7.19	19.02	3.443	24.67

Table 7.3 Actual vs Estimated P_R

7.3 Surface Roughness (S_R)

7.3.1 Experimental observations

The cross sectional area of the Cu electrode tool was 2 cm^2. Other parameters were kept at constant similar to the section 7.1.2.

No.	I_P	T_{ON} (u.sec)	T_{OFF} (u.sec)	S_R (umRs)
1	10	600	10	13.00-15.50
2	7	100	7	7.50-9.00
3	3	10	3	3.30-3.80
4	5	200	5	9.00-10.00

Table 7.4 Experimental observations for S_R

7.3.2 Analysis, comparison between actual and estimated values

Model 1

$S_R = 9.974\ (I/A)^{0.344}\ [(T_{ON})/(T_{ON}+T_{OFF})]^{1.24}$ ....(6.6.5)

$S_R = [5.224(I_P)^{0.4128}/(A)^{0.344}][(T_{ON})^{1.3122}/(T_{OFF})^{0.1039}(T_{ON}+T_{OFF})^{1.24}$ ....(6.6.6)

Model 2

$S_R = 2.303\ (I/A)^{0.254}\ (T_{ON})^{0.254}$ ....(6.6.7)

$$S_R = [1.4286(I_P)^{0.3048}(T_{ON})^{0.3074}]/[(A)^{0.254}(T_{OFF})^{0.0767}] \ldots\ldots (6.6.8)$$

Estimated S_R Model 1		Estimated S_R Model 2		Actual S_R (umRs)	% Variation Model 1		% Variation Model 2	
(6.6.5)	(6.6.6)	(6.6.7)	(6.6.8)		(6.6.5)	(6.6.6)	(6.6.7)	(6.6.8)
13.45	13.04	14.76	14.47	13.00-15.50	5.61	8.49	-3.58	-1.54
10.54	9.63	8.22	7.69	7.50-9.00	-27.76	-16.73	0.36	6.79
5.868	4.92	3.47	3.13	3.30-3.80	-60.00	-38.59	2.25	11.83
10.45	9.62	9.36	8.82	9.00-10.00	-10.00	-1.26	1.47	7.16
% Variation RMS value					33.55	21.46	2.246	7.741

Table 7.4 Actual vs estimated S_R

7.4 Conclusions

7.4.1 Rate of Penetration (P_R)

According to the actual vs estimated results, it is clear that model 2 is better than model 1 in describing the relationship for P_R. Also statistical analysis suggests that the model 2 is better than model 1.

Therefore after careful consideration of both analytical and experimental results, the author suggests model 2 for determination of the rate of penetration (P_R). Equations either (6.5.5) or (6.5.6) can be used to determined P_R. According to results it is clear that the equation (6.5.5) is more accurate. As discussed in section 7.1.2, using equation (6.3.1) estimated current flow can be determined. Actual current can be find out using figure 7.1. Finally, the value of current can be substitute to the equation (6.5.5) and possible to calculate P_R. Further, after considering % variation between the estimated and actual values, author suggests to add 3.5% of the estimated value to the estimated P_R in order to compensate for experimental errors.

7.4.2 Surface Roughness

According to experimental and statistical analytical results, the author suggests that the model 2 is more suitable in determining surface roughness. Equations either (6.6.7) or (6.6.8) can be used to determined S_R. According to results it is clear that the equation (6.6.7) is more accurate. For calculated current flow using (6.3.1), actual current can be determined in advance. After substituting actual current value with other process variables, to equation (6.6.7) it is possible to calculate S_R.

After considering the % variation between the actual and experimental values, author suggests to add 2.26% of the estimated S_R to the estimated S_R to compensate experimental and measurement errors.

Chapter 8

Conclusions for the Development of Rapid tool Manufacture Appropriate to the New Zealand Manufacturing Environment

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This chapter describes the author's conclusions for the development of rapid tool manufacture appropriate to the New Zealand environment.

8.1 Introduction

According to 1995/1996 Statistics published by the Economist intelligence unit, the manufacturing sector contributed 18.6% of the total real GDP to the NZ economy. Also it gained 62.5% of the total export market of the country. Under these circumstances according to the strength, weakness, opportunities and threats (SWOT) analysis which was carried out by the manufacturing advisory group, there are some important points for manufacturing technologists should look at. Inadequate knowledge and resources for global market development is one of our weaknesses among others. Widening education gap between New Zealand and competitors is also a serious threat. Therefore it is very necessary to train and educate manufacturers in order to meet these challenges. In selecting manufacturers, it is vital to identify the importance of small and medium scale manufacturers. They are a source of renewal and future growth, generally highly motivated and innovative and finally make a particular contribution to employment.

Most of the plastic injection moulding tool makers and plastic manufacturers here in New Zealand are small or medium scale manufacturers. However they encounter specific difficulties in maintaining the funding for further improvements, information on market opportunities, technology and other key business matters which are essential for them to achieve a satisfactory growth.

Hence based on studies and experiments already discussed in earlier chapters, the author makes following conclusions in order to improve the quality and effectiveness of injection moulding tool manufacturers.

8.2 Conclusions

8.2.1 Identification of the customer needs

Tool makers are usually involved before the product suits the market, so those factors are less important. Usually it is just tight deadlines that is the problem. Tool makers need and usually get, very good information from the customer. After consideration about the quality, quantity, how quickly the customer needs the said item manufacturer can decide the design, choose the material and the method of manufacture of the injection moulding tool.

8.2.2 Design

Before manufacturing the mould, plastic part has to be designed. Depending on the plastic material which is used to produce the part, thickness of various sections, height and other dimensions can be determined using modern commercially available software such as Cad mould, Mould flow, Cad form etc.. In addition to determination of part dimensions, it is possible to determine optimum dimensions of runners, gates, sprues etc., and the location of the sprue. Also using these software packages, the mould can be designed for optimum cooling, moulding filling without weld lines etc.. Further, the mould has to be designed to withstand forces such as compression, tensile etc. while it is in operation. This can be carried out by using commercially available software such as 'Mystro', a finite element analysis programme.

Usually most manufactures do not carry out either flow or force analysis. They over design and select higher dimensions than required. This means waste of money, time and skills. By implementing a proper design procedure using modern software material, money and time can be saved. Also this improves the quality of the end product greatly.

8.2.3 Selection of material

As discussed in the section 8.2.1, if the plastic manufacturer want to produce large quantities over a very long duration, material such as mould steel can be selected. Alternatively Mild Steel can be used with tool steel inserts. Aluminium is a very good material for manufacture of moulds. Use of Aluminium must be encouraged for injection moulding tools. As per discussion about mould materials, Zinc is an another important alternative material for rapid manufacture of moulding tools. All these materials except mould steels are easily machinable and easy to handle. Hence according to the required quality, quantity, the urgency of the requirement of the finished tool, correct mould material must be selected and used. Relative cost of these materials is attached in Appendix M.

In addition to that, selection of pre manufactured mould component such as mould bases, guiding pins and bushes, ejector pins etc. is an another possibility.

8.2.4 Integration between conventional and modern machinery

As conventional machinery such as centre lathes, drilling machines, surface grinders etc., still plays a vital roll in mould tool manufacture, these cannot be discarded. Also, it is not possible for every manufacturer to use modern machinery due to heavy capital investment, lack of trained personnel etc.. Therefore it is necessary to have integration between conventional and modern machinery.

8.2.5 Use of established formulae for P_R and S_R

Since formulae, have already been established for rate of penetration and surface quality in EDM operation, these can be used in rapid manufacture of injection moulding tools in order to increase productivity and quality.

After determining the final surface roughness required, values for T_{ON} and I can be decided. Since there is a relationship for I and T_{ON}, T_{OFF} and I_P values for T_{OFF} and I_P can be decided to suit the formula. For accurate calculations, estimated I should be used by using graph actual I vs estimated I in figure 7.1. Since values of I,T_{ON} and T_{OFF} have been decided, P_R can be determined.

Therefore, for required depth of cut the machining time can be determined. Hence, proper costing procedure and planning all jobs in the tool room for required time frame.

Further, according to the experimental findings, surface finish can be further improved by increasing the jump set and reducing T_{ON} and I_P. Therefore when the tool reaches to the final depth of cut, the machinist can change parameters in order to increase the surface finish. By this, surface quality can be further improved with out affecting the P_R. Also this reduces the final mould polishing time.

8.2.6 Co-ordination between the manufactures and academic institutions

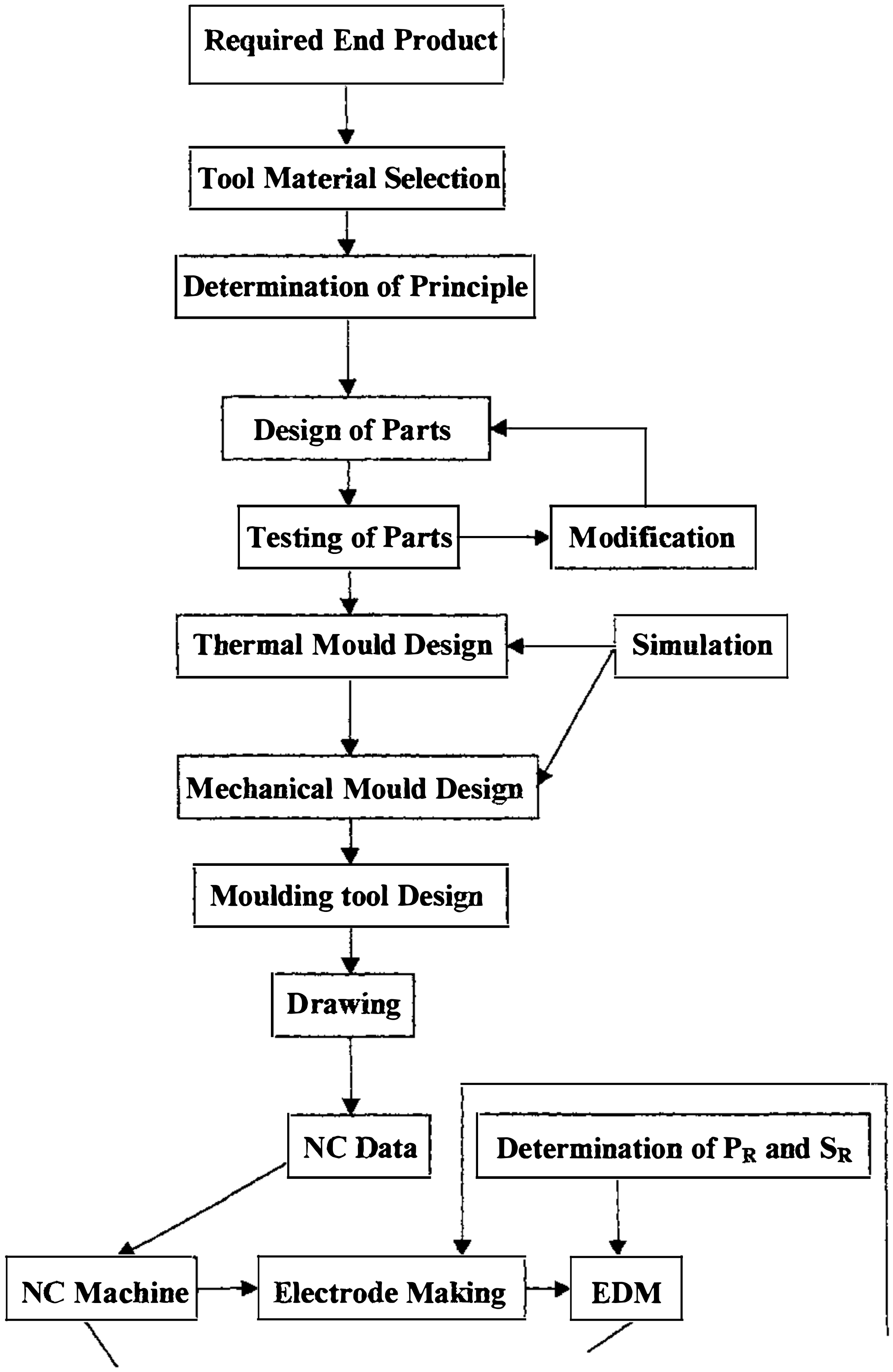
As mentioned in the section 8.2.3, since the capital investment for CNC machinery and CAD/CAM software is high, small and medium manufacturers should be encouraged to get the help from universities and polytechnics throughout the country. Since the universities and technical colleges have machinery, software packages and personnel who are knowledgeable about the use of software packages, programming etc., it is easier and cheaper for manufacturer to use these facilities. In addition to that, Author concludes that, it would be beneficial if the universities can organise short courses in rapid injection mould tool manufacture for small and medium scale manufacturers who are in the industry. Further according to the author's thinking, these short courses, workshops and seminars can be organised by universities funded by the business development board, New Zealand.

8.2.7 Establishment of Industrial development organisation

Further, author thinks that, it is advantageous to establish an organisation for industrial development by the government of New Zealand which may have branches through out the country in order to help all small and medium scale manufacturers. This will help all manufacturers who are engaged in the plastics as well as other industries.

8.2.8 Encouragement of joint venture collaborations

Finally manufacturers engaged in moulding tool manufacture, (as well as other sectors in manufacturing) must be encouraged to have joint venture collaborations with manufacturers both in New Zealand and other industrially developed countries in order to learn technical know-how.



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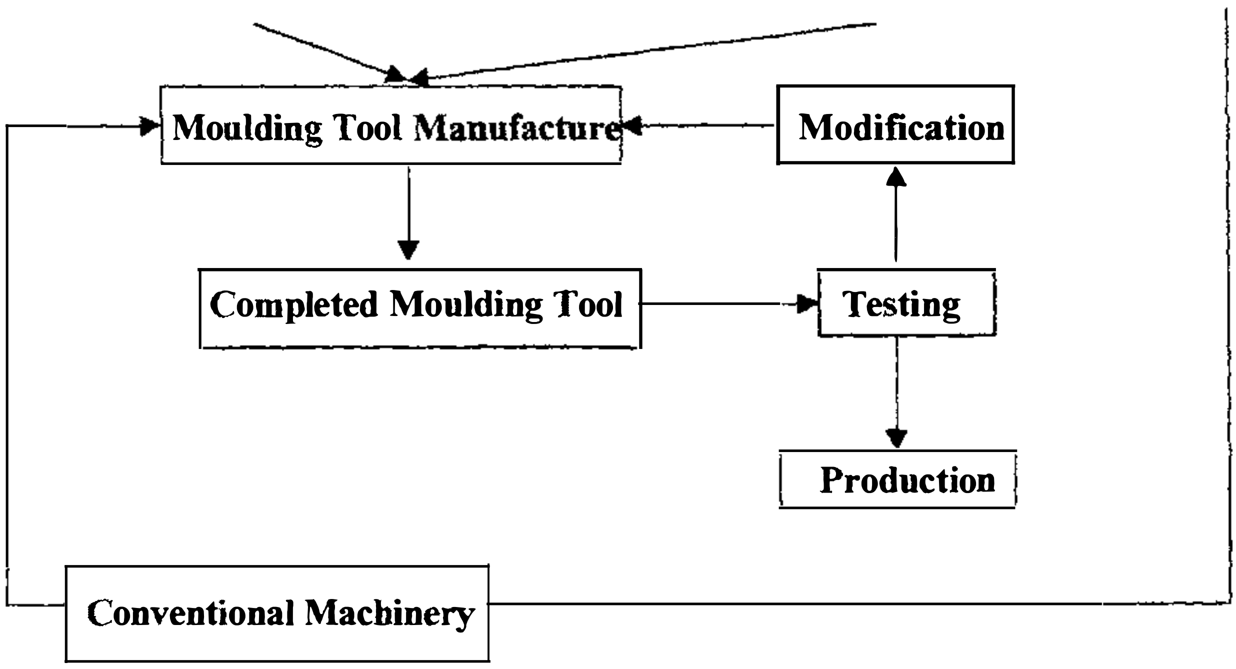

Figure 8.1 Rapid Manufacture of Injection Moulding Tool

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Appendices

Appendix A

Specification or the Injection Moulding Machine in the Department of Industrial Engineering Laboratory

1.1 Make: Welltec Cosmo

Model No: TTI-330/100

1.2 Injection unit

Injection volume (theoretical)	
Ordinary screw	171 cm^3
Enlarged screw	219 cm^3
Diminished screw	129 cm^3
Injection capacity (theoretical)	
Ordinary screw	6.3 oz or 180 g
Enlarged screw	8.0 oz or 230 g
Diminished screw	4.8 oz or 135 g
Screw diameter	
Ordinary screw	38 mm
Enlarged screw	43 mm
Diminished screw	33 mm
Screw L/D ratio	18 : 1
Screw speed range	20- 175 rev/min
Injection pressure (theoretical)	
Ordinary screw	1950 kgf/cm^2
Enlarged screw	1500 kgf/cm^2
Diminished screw	2590 kgf/cm^2
Injection speed	70 mm/sec
Plasticizing capacity	50 kg/hr
Hopper capacity	35 litre
Nozzle stroke	220 mm
Nozzle contact force	3-6 ton

1.3 Clamping unit

Clamping force	100 ton
Clamping stroke	300 mm
Tie bar diameter	60 mm
Distances between tie bar	355 mm * 355 mm
Platen size	535 mm * 535 mm
Mould thickness range	10 mm- 310 mm
Clamping speed	550 mm/sec
Opening speed	460 mm/sec
Ejector force	2.7 ton
Ejector stroke	75 mm
No of ejector pin (Knock out bar)	1 pc

1.4 Power unit

Motor voltage (according to the standard of respective country)

Control system voltage	24 V dc
Electrical motor power	11kW/4p
Pump capacity	76 lit/min
Heater input power	7.5 kW
Current requirement	41 A

1.5 General

Oil tank capacity	170 litre
Floor space	324 cm * 84 cm
Gross weight	2.7 ton

Appendix B

Bridgeport CNC Milling Machine at the Departmental Industrial Engineering Laboratory

Starting and operation procedure

1. Switch on the main switch - All indicators in the controller flash in red VDS screen reads " POWER INTERRUPTED"
2. Press [CE] button on the controller
3. Ensure that there is no work on the machine bed or lower the bed or there is no tool mounted in to the spindle in order to prevent possible accidents due to the direct collision between the tool and the work.
4. Press power enable button (Green button with a bulb) on the controller
5. Look at the screen of the controller

   MANUAL OPERATION

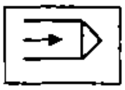
   PRESS OVER Z REFERENCE MARK

   PRESS OVER Y REFERENCE MARK

   PRESS OVER X REFERENCE MARK
6. Press cycle start button 3 times as follows
   - First time- Tool moves rapidly up to Z reference point
   - Second time- Bed moves rapidly along the Y axis to Y reference mark
   - Third time- Bed moves rapidly along the X axis to X reference mark
7. Press electronic hand wheel operation button and take the machine bed and the tool to appropriate position as wish. Movement along X axis- Press X button (key) on the controller and rotate the wheel. Same procedure for Y and Z axis, follows by pressing Y and Z keys respectively on the controller
8. Before machine starts it should be keep in mind to on the air line and to see whether pneumatic brake functions properly or not by using brake control switch
9. Start the machine by using spindle ON/OFF switch
10. Set the speed using speed increase/decrease button
11. Adjust the feed by using feed selector knob and manual operation feed rate selection potentiometer on the controller
12. Fix the required cutter with tool holder to the spindle
13. After mounting the work on the bed by using appropriate jigs and fixtures, set the

tool reference

14.Edit the program directly on the VDU screen of the controller or transfer program to the controller from the PC

After testing the program press either the Automatic program key  (Full sequence) or program run single block key

Tool reference setting

Suppose the tool diameter is ∅ 10 mm. Tool is brought to tool setter datum by using the electronic wheel of the machine after pressing the electronic hand wheel key. X, Y and Z display values of the controller set to 0.000 using the manual key as follows.

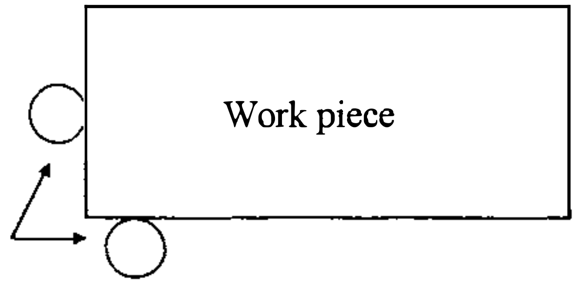
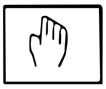


Figure B1

When the tool touches the work, controller should read X= -5.000 and Y= -5.000

- Press  Manual key DATUM SET displays on the screen
- Set X and Y to -5.000, using numerical keys on the controller
- Press the END key
- Repeat the procedure for the Z axis, when tool bottom face just touches the work piece as shown.

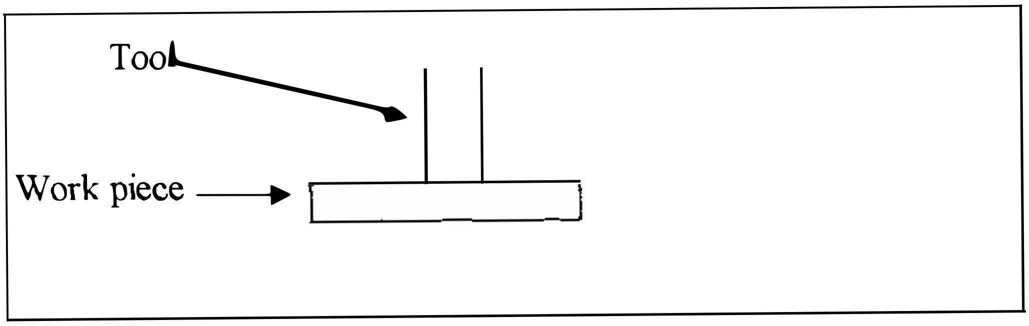


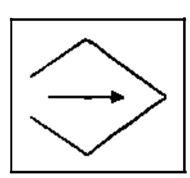
Figure B2

Appendix C

Program transferring procedure between the mill and the PC

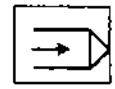
PC to mill

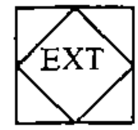
1. Establish correct connection between mill and the PC in use. Mill is on line 8. PC's are on lines A0 to A7, A11. Open the connection box in the CAD lab and connect one end of the cable to 8 and the other end to the appropriate number from 0-11 in the terminal box.
2. Start the PC already selected. (e.g. A7). Ensure the connection between PC and port 7 on the wall.
3. Copy the program to the program in the selected directory as an appropriate file name.
   E.g. Harvey directory as ' Wimalj1.NC'
4. Set the mode on the PC as; C\> Mode Com 1: 2400,E,7,1 and enter.
5. Go into the Harvey directory: C\> CD Harvey and enter
6. Program transferring from PC to mill
   (a) Clear the program already in the mill controller by pressing clear button and pressing enter button respectively.
   (b) Put the mill in 'Program entry mode' by pressing editing/entry button.



   (c) Go to the PC and type:
   "COPY file name COM1:" and press enter
   (d) When PC indicates '1 file copied', go to the mill and see whether the program has already been in the VDU screen or not.

7. Program transferring from mill to PC
   (a) While the PC is in the Harvey directory,
   type "COMMRD2 file name 256"
   (b) Reset the program at line No 0, the beginning
   (c) Press the automatic program mode button in the controller and set

the mill in program operation mode 

(d) Press the 'External' button on the controller. 

(e) When the VDU screen of the controller shows data sent, go to the PC and press enter.

Appendix D

Starting and Operation Procedure of the EDM at the Departmental Industrial Engineering Laboratory

Model: DT 168 (ALTC-1)

Make: HSIU FONG

1. Before start the machine read caution and safety instructions
2. Connect wires according to the polarity selected. (e.g. (+)ve-tool electrode and (+)ve - work piece)
3. Set up the work on the table using appropriate jigs and fixtures, fix the tool electrode to the tool holder.
4. Power on the machine using power on button.
5. Move the quill up to the top position by pressing the top button (Colour- BLUE) on the working head. Speed of travelling can be increased by pressing the ram rapid traverse on button on the operation panel of power supply unit.
6. When the quill or ram reaches its top of the stroke, speed should be lowered.
7. Set ABS to Zero (0.000) on the display by pressing reset button as mechanical travel reference.

ABS distance 0.000

8. Move the quill down until it reaches the work piece by pressing the lower button (Colour- YELLOW) on the working head.
9. Speed of the quill should be lowered when its reaches the work piece and the buzzer sounds when the electrode touches the work piece. Quill should be adjusted till there is no buzzer sound but the electrode seems to be touches the work.
10. Press the mode selector button several times until 'REALLY SET' displays on the panel and after that, by pressing the reset button set the really set of the display to 0.000. This makes the machining surface to Zero.

REALLY SET 0.000 mm

11.Press the reset mode button and return to the display main screen. Main screen should read REL and FNL values as zero mm as follows.

REL	0.000 mm
FNL	0.000 mm

12.Press the reset mode button again and obtain the display of quill
depth setting. Set the depth to the value required by pressing Upward and down buttons. The maximum depth set is -60.000 mm as it is the stroke of the ram. Down ward direction is considered as negative.

DEPTH SET
-025.00 mm

13.Press the reset mode button again and get the main screen. The screen should read as follows.

REL	0.000 mm
FNL	-025.00 mm

14.Press the reset mode button and obtain the jump set in the display. By using upward and downward buttons, set the jump height as required as follows.

JUMP SET
001.60 mm

15.Return to the main screen by pressing the mode button. The screen should read as follows.

REL	000.00 mm
FNL	-025.00 mm

16.By pressing the upward button and reset button together at once, reset the bottom position to zero where the electrode moves its bottom position. This should be displayed in the screen as follows.

REL	000.00 mm
ZER	-000.00 mm

17.Return to the main screen on the display.

18.Select process variables T_{ON}, T_{OFF} and I_P as required by adjusted the knobs on the main panel.

19.Press the dielectric power on switch (Green button switch) and start the pump. Dielectric fluid starts to flow to the working chamber through the nozzle. Adjusted the rate of volume of flow by adjusting two valve provided on the power supply unit situated to the pump.

20.On the sludge flushing button switch (White colour).

21.Start the EDM by pressing the Spark on/off switch (Red colour)

22.Adjust proper gap voltage by adjusting Gap voltage knob and quill sensitivity by adjusting sensitivity control knob.

23.Adjust the working time selector knob as required.

24.The normal display of the main screen while the machine is in operation according to the travel depth of the quill (Say the depth is 5.00 mm) as follows.

REL	-005.00 mm
FNL	-025.00 mm

25.The current machined depth can be read by pressing upward button. Then the screen is displayed as follows.

REL	-005.00 mm
ZER	-005.15 mm

26.Machine can be stopped by pressing Power and dielectric off switch (RED colour button). When the quill reaches to the required depth during the machining machine automatically stops its operation.

Operation Panel of Power Supply Unit

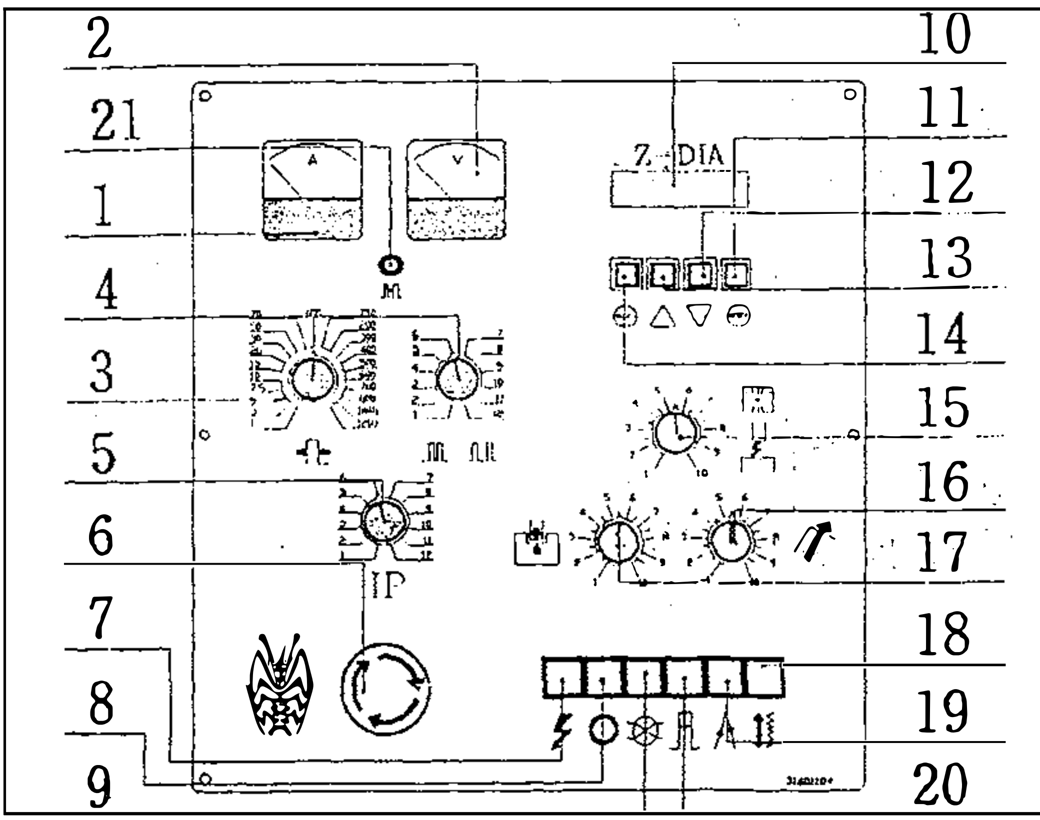


Figure D1

1. Ampere meter
2. Gap voltage indicator knob
3. ON time
4. OFF time
5. IP selection knob
6. Main power/ Emergency stop
7. Spark on/off switch

12. Display downward setting
13. Display upward setting
14. Display mode selector button
15. Working time selector knob
16. Servo speed selector knob
17. Gap voltage selector knob
18. Ram rapid traverse button

8. Power and dielectric off switch

9. Dielectric on switch

10.Digital display

11.Display reset button

19. Jumping mechanism on/off

20. High voltage on/off switch

21 Discharge indicator

Appendix E

Standard G code and M code

PREPARATORY FUNCTION (G FUNCTION)

A number following address G determines the meaning of the command for the concerned block.
G codes are divided into the following two types:

Type	Meaning
One-shot G code	The G code is effective only in the block in which it is specified.
Modal G code	The G code is effective until another G code of the same group is specified.

(Example)
G01 and G00 are modal G codes in group 01.

```
G01X ———;
   Z ———;      G01 is effective in this range.
   X ———;
G00Z ———;
```

The following G codes are offered.

G code	Group	Function
G00	01	Positioning
G01		Linear interpolation
G02		Circular/Helical interpolation CW
G03		Circular/Helical interpolation CCW
G04	00	Dwell
G07		Hypothetical axis interpolation
G09		Exact stop
G10		Data setting
G10.1		PC data setting
G11		Data setting mode cancel
G15	17	Polar coordinates command cancel
G16		Polar coordinates command
G17	02	XpYp plane Xp: X axis or its parallel axis
G18		ZpXp plane Yp: Y axis or its parallel axis
G19		YpZp plane Zp: Z axis or its parallel axis
G20	06	Inch input
G21		Metric input
G22	04	Stored stroke check function on
G23		Stored stroke check function off
G27	00	Reference point return check
G28		Reference point return
G29		Return from reference point
G30		Return to 2nd, 3rd, 4th reference point
G31		Skip function
G31.1		Multi-step skip function 1
G31.2		Multi-step skip function 2
G31.3		Multi-step skip function 3
G33	01	Thread cutting
G37	00	Tool length automatic measurement
G40	07	Cutter radius compensation cancel/3 dimensional tool compensation cancel
G41		Cutter radius compensation leftl/3 dimensional tool compensation
G42		Cutter radius compensation right

G code	Group	Function
G43	08	Tool length compensation +
G44		Tool length compensation -
G45	00	Tool offset increase
G46		Tool offset decrease
G47		Tool offset double increase
G48		Tool offset double decrease
G49	08	Tool length compensation cancel
G50	11	Scaling cancel
G51		Scaling
G50.1	18	Programmable mirror image cancel
G51.1		Programmable mirror image
G52	00	Local coordinate system setting
G53		Machine coordinate system selection
G54	14	Work coordinate system 1 selection
G55		Work coordinate system 2 selection
G56		Work coordinate system 3 selection
G57		Work coordinate system 4 selection
G58		Work coordinate system 5 selection
G59		Work coordinate system 6 selection
G60	00	Single direction positioning
G61	15	Exact stop mode
G62		Automatic corner override mode
G63		Tapping mode
G64		Cutting mode
G65	00	Macro call
G66	12	Macro modal call A
G66.1		Macro modal call B
G67		Macro modal call A/B cancel
G68	16	Coordinate system rotation
G69		Coordinate system rotation cancel
G73	09	Peck drilling cycle
G74		Counter tapping cycle
G76		Fine boring cycle
G80		Canned cycle cancel/external operation function cancel
G81		Drilling cycle, spot boring/external operation
G82		Drilling cycle, counter boring
G83		Peck drilling cycle
G84		Tapping cycle
G85		Boring cycle
G86		Boring cycle
G87		Back boring cycle
G88		Boring cycle
G89		Boring cycle
G90	03	Absolute command
G91		Incremental command
G92	00	Work coordinates change/Maximum spindle speed setting
G93	05	Inverse time feed
G94		Feed per minute
G95		Feed per revolution
G96	13	Constant surface speed control
G97		Constant surface speed control cancel
G98	10	Canned cycle initial level return
G99		Canned cycle R point level return

List of M Codes

M code	Function
M00	Program stop
M01	Optional stop
M02	Program end
M03	Spindle CW ON
M04	Spindle CCW ON
M05	Spindle OFF
M06	Tool change
M07	Coolant mist or oil shut ON
M08	Flood coolant ON
M09	Coolant OFF (Flood, mist, oil shot, air blow, side through, centre through)
M10	B axis rotary table clamp
M11	B axis rotary table unclamp
M12	A/C axis rotary table clamp
M13	A/C axis rotary table unclamp
M19	Spindle orientation
M30	End of tape
M32	Cutter breakage detection by tough switch
M36	Feed rate over ride ON
M37	Feed over ride OFF
M50	Side through coolant ON
M51	Centre through coolant ON
M61	Air blow

M68	Pallet IN
M69	Pallet OUT
M90	External work No. search
M98	Sub program nesting
M99	Sub program end

Appendix F

NC program for a Mould using Heidenhain code

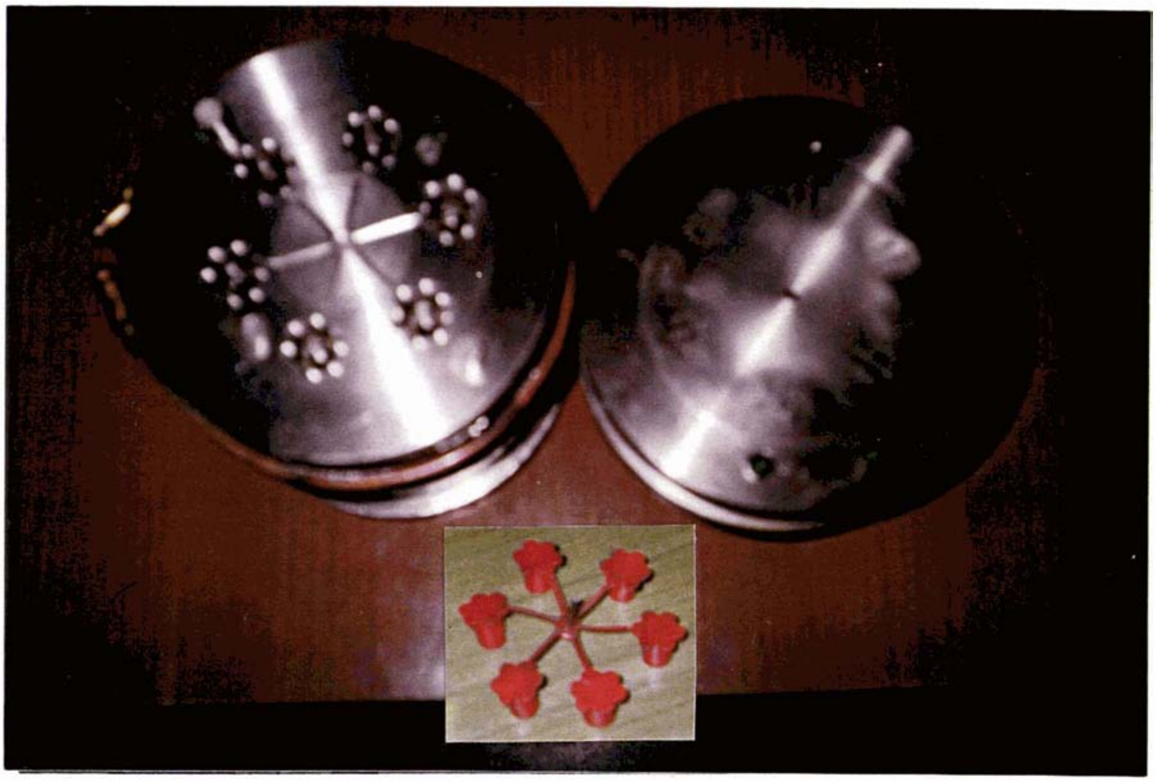
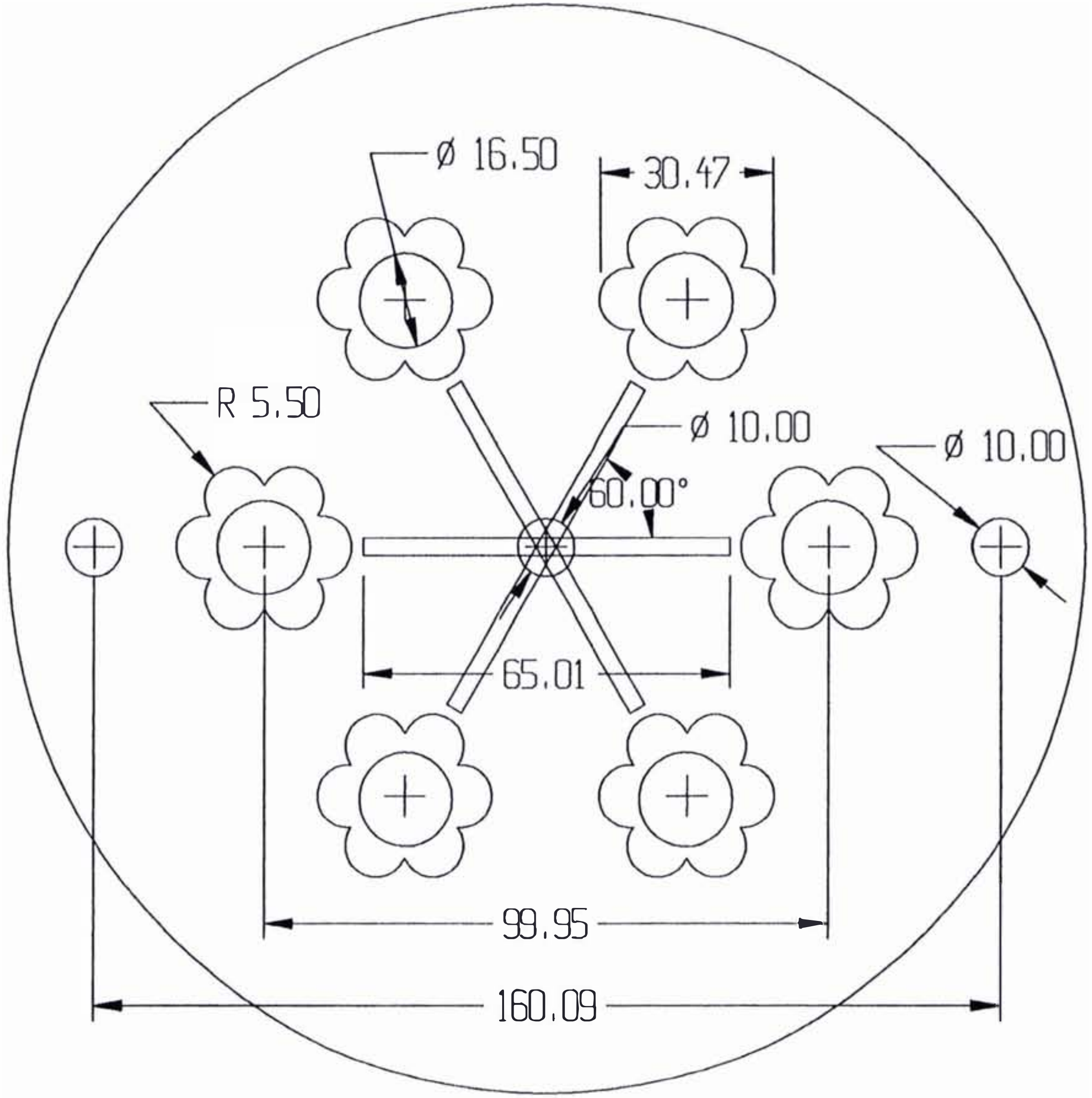


Figure F1- Injection mould made by the author (Flower arrangement)



CORE PLATE

FLOWER ARRANGEMENT

ALL DIMENSIONS ARE IN MILLIMETERS

```
67       Z+0,000                                           R0 F50   M
68       Z-2,000                                           R0 F25   M
69       Z+2,000                                           R0 F200  M
70   L   X+45,000     Y+8,660                              R0 F200  M
71       Z+2,000                                           R0 F200  M
72       Z+0,000                                           R0 F50   M
73       Z-2,000                                           R0 F25   M
74       Z+2,000                                           R0 F200  M
75   L   X+40,000     Y+0,000                              R0 F200  M
76       Z+2,000                                           R0 F200  M
77       Z+0,000                                           R0 F50   M
78       Z-2,000                                           R0 F25   M
79       Z+2,000                                           R0 F200  M
80   L   X+45,000     Y-8,660                              R0 F200  M
81       Z+2,000                                           R0 F200  M
82       Z+0,000                                           R0 F50   M
83       Z-2,000                                           R0 F25   M
84       Z+2,000                                           R0 F200  M
85   L   X+55,000     Y-8,660                              R0 F200  M
86       Z+2,000                                           R0 F200  M
87       Z+0,000                                           R0 F50   M
88       Z-2,000                                           R0 F25   M
89       Z+2,000                                           R0 F200  M
90   LBL  0
91   CALL LBL 2   REP 1    /1
92   CALL LBL 3   REP 1    /1
93   CALL LBL 4   REP 1    /1
94   CALL LBL 5   REP 1    /1
95   CALL LBL 6   REP 1    /1
96   L   X+0,000      Y+0,000                              R0 F400  M
97       Z+50,000                                          R0 F400  M05
98   STOP                                                           M
99   TOOL CALL 2    Z  S 1000,000
100 L    X+0,000      Y+0,000                              R0 F400  M03
101      Z+2,000                                           R0 F400  M
102      Z-1,500                                           R0 F50   M
103 L    X+31,500     Y+0,000                              R0 F50   M
104      Z+2,000                                           R0 F400  M
105 L    X+0,000      Y+0,000                              R0 F400  M
106      Z-1,500                                           R0 F50   M
107 L    X+15,750     Y+27,299                             R0 F50   M
108      Z+2,000                                           R0 F400  M
109 L    X+0,000      Y+0,000                              R0 F400  M
110      Z-1,500                                           R0 F50   M
111 L    X-15,750     Y+27,279                             R0 F50   M
112      Z+2,000                                           R0 F400  M
113 L    X+0,000      Y+0,000                              R0 F400  M
114      Z-1,500                                           R0 F50   M
115 L    X-31,500     Y+0,000                              R0 F50   M
116      Z+2,000                                           R0 F400  M
117 L    X+0,000      Y+0,000                              R0 F400  M
118      Z-1,500                                           R0 F50   M
119 L    X-15,750     Y-27,279                             R0 F50   M
120      Z+2,000                                           R0 F400  M
121 L    X+0,000      Y+0,000                              R0 F400  M
122      Z-1,500                                           R0 F50   M
123 L    X+15,750     Y-27,279                             R0 F50   M
124      Z+50,000                                          R0 F400  M
125 L    X+0,000      Y+0,000                              R0 F400  M05
126 STOP                                                            M02
```

Automatic CNC program generation for the same injection mould using

Mastercam version 5.0

Heidenhain code

```
0 BEGIN  PGM  mm
1 TOOL DEF 1 L+0. R+5.
2 TOOL DEF 5 L+0. R+7.
3 TOOL DEF 2 L+0. R+1.
4 TOOL DEF 3 L+0. R+1.5
5 STOP M25
6 TOOL CALL 01 Z  S1500
7 L X-80.132 Y+0. R0 F400 M03
8 Z+2. R0 F400 M
9 CYCL DEF 1.0 PECKING
10 CYCL DEF 1.1 SET UP -2.
11 CYCL DEF 1.2 DEPTH -30.
12 CYCL DEF 1.3 PECKG -15.
13 CYCL DEF 1.4 DWELL  P0
14 CYCL DEF 1.5  F200
15 CYCL CALL M
16 L X-80.132 Y+0. R0 F400 M99
17 L X+0. R0 F400 M99
18 L X+80.132 R0 F400 M99
19 STOP M25
20 TOOL CALL05 Z  S1500
21 L X-49.737 Y+0. R0 F400 M03
22 Z+2. R0 F400 M
23 CYCL DEF 1.0 PECKING
24 CYCL DEF 1.1 SET UP -2.
25 CYCL DEF 1.2 DEPTH -22.
26 CYCL DEF 1.3 PECKG -11.
27 CYCL DEF 1.4 DWELL  P0
28 CYCL DEF 1.5  F200
29 CYCL CALL M
30 L X-49.737 Y+0. R0 F400 M99
31 L X-24.868 Y-43.658 R0 F400 M99
32 L X+24.868 R0 F400 M99
33 L X+49.737 Y+0. R0 F400 M99
34 L X+24.868 Y+43.105 R0 F400 M99
35 L X-24.868 R0 F400 M99
36 STOP M25
37 TOOL CALL02 Z  S1500
38 L X-31.5 Y+0.5 R0 F400 M03
39 Z+0. R0 F400 M
40 Z-1.5 R0 F200 M
41 L X+31.5 R0 F200 M
42 L Y-0.5 R0 F200 M
43 L X-31.5 R0 F200 M
44 L Y+0.5 R0 F200 M
45 Z+0. R0 F400 M
46 L X+15.317 Y+27.53 R0 F400 M03
47 Z-1.5 R0 F200 M
48 L X-16.183 Y-27.03 R0 F200 M
49 L X-15.317 Y-27.53 R0 F200 M
50 L X+16.183 Y+27.03 R0 F200 M
51 L X+15.317 Y+27.53 R0 F200 M
52 Z+0. R0 F400 M
53 L X-15.317 R0 F400 M03
54 Z-1.5 R0 F200 M
55 L X+16.183 Y-27.03 R0 F200 M
56 L X+15.317 Y-27.53 R0 F200 M
57 L X-16.183 Y+27.03 R0 F200 M
58 L X-15.317 Y+27.53 R0 F200 M
59 Z+0. R0 F400 M
60 STOP M25
61 TOOL CALL03 Z  S1500
62 L X-58.26 Y+6.354 R0 F400 M03
63 Z+0. R0 F400 M
64 Z-1.5 R0 F200 M
65 CC X-55.034 Y+8.72
```

```
66 C X-51.373 Y+10.331 DR- R0 F200 M
67 CC X-50. Y+10.935
68 C X-48.627 Y+10.331 DR+ R0 F200 M
69 CC X-44.966 Y+8.72
70 C X-41.74 Y+6.354 DR- R0 F200 M
71 CC X-40.53 Y+5.467
72 C X-40.367 Y+3.976 DR+ R0 F200 M
73 CC X-39.931 Y+0.
74 C X-40.367 Y-3.976 DR- R0 F200 M
75 CC X-40.53 Y-5.467
76 C X-41.74 Y-6.354 DR+ R0 F200 M
77 CC X-44.966 Y-8.72
78 C X-48.627 Y-10.331 DR- R0 F200 M
79 CC X-50. Y-10.935
80 C X-51.373 Y-10.331 DR+ R0 F200 M
81 CC X-55.034 Y-8.72
82 C X-58.26 Y-6.354 DR- R0 F200 M
83 CC X-59.47 Y-5.467
84 C X-59.633 Y-3.976 DR+ R0 F200 M
85 CC X-60.069 Y+0.
86 C X-59.633 Y+3.976 DR- R0 F200 M
87 CC X-59.47 Y+5.467
88 C X-58.26 Y+6.354 DR+ R0 F200 M
89 Z+0. R0 F400 M
90 L X-34.633 Y-47.277 R0 F400 M03
91 Z-1.5 R0 F200 M
92 CC X-35.069 Y-43.301
93 C X-34.633 Y-39.325 DR- R0 F200 M
94 CC X-34.47 Y-37.834
95 C X-33.26 Y-36.947 DR+ R0 F200 M
96 CC X-30.034 Y-34.582
97 C X-26.373 Y-32.971 DR- R0 F200 M
98 CC X-25. Y-32.367
99 C X-23.627 Y-32.971 DR+ R0 F200 M
100 CC X-19.966 Y-34.582
101 C X-16.74 Y-36.947 DR- R0 F200 M
102 CC X-15.53 Y-37.834
103 C X-15.367 Y-39.325 DR+ R0 F200 M
104 CC X-14.931 Y-43.301
105 C X-15.367 Y-47.277 DR- R0 F200 M
106 CC X-15.53 Y-48.769
107 C X-16.74 Y-49.656 DR+ R0 F200 M
108 CC X-19.966 Y-52.021
109 C X-23.627 Y-53.632 DR- R0 F200 M
110 CC X-25. Y-54.236
111 C X-26.373 Y-53.632 DR+ R0 F200 M
112 CC X-30.034 Y-52.021
113 C X-33.26 Y-49.656 DR- R0 F200 M
114 CC X-34.47 Y-48.769
115 C X-34.633 Y-47.277 DR+ R0 F200 M
116 Z+0. R0 F400 M
117 L X+15.367 Y-39.325 R0 F400 M03
118 Z-1.5 R0 F200 M
119 CC X+14.931 Y-43.301
120 C X+15.367 Y-47.277 DR+ R0 F200 M
121 CC X+15.53 Y-48.769
122 C X+16.74 Y-49.656 DR- R0 F200 M
123 CC X+19.966 Y-52.021
124 C X+23.627 Y-53.632 DR+ R0 F200 M
125 CC X+25. Y-54.236
126 C X+26.373 Y-53.632 DR- R0 F200 M
127 CC X+30.034 Y-52.021
128 C X+33.26 Y-49.656 DR+ R0 F200 M
129 CC X+34.47 Y-48.769
130 C X+34.633 Y-47.277 DR- R0 F200 M
131 CC X+35.069 Y-43.301
```

```
132 C X+34.633 Y-39.325 DR+ R0 F200 M
133 CC X+34.47 Y-37.834
134 C X+33.26 Y-36.947 DR- R0 F200 M
135 CC X+30.034 Y-34.582
136 C X+26.373 Y-32.971 DR+ R0 F200 M
137 CC X+25. Y-32.367
138 C X+23.627 Y-32.971 DR- R0 F200 M
139 CC X+19.966 Y-34.582
140 C X+16.74 Y-36.947 DR+ R0 F200 M
141 CC X+15.53 Y-37.834
142 C X+15.367 Y-39.325 DR- R0 F200 M
143 Z+0. R0 F400 M
144 L X+40.367 Y-3.976 R0 F400 M03
145 Z-1.5 R0 F200 M
146 CC X+39.931 Y+0.
147 C X+40.367 Y+3.976 DR- R0 F200 M
148 CC X+40.53 Y+5.467
149 C X+41.74 Y+6.354 DR+ R0 F200 M
150 CC X+44.966 Y+8.72
151 C X+48.627 Y+10.331 DR- R0 F200 M
152 CC X+50. Y+10.935
153 C X+51.373 Y+10.331 DR+ R0 F200 M
154 CC X+55.034 Y+8.72
155 C X+58.26 Y+6.354 DR- R0 F200 M
156 CC X+59.47 Y+5.467
157 C X+59.633 Y+3.976 DR+ R0 F200 M
158 CC X+60.069 Y+0.
159 C X+59.633 Y-3.976 DR- R0 F200 M
160 CC X+59.47 Y-5.467
161 C X+58.26 Y-6.354 DR+ R0 F200 M
162 CC X+55.034 Y-8.72
163 C X+51.373 Y-10.331 DR- R0 F200 M
164 CC X+50. Y-10.935
165 C X+48.627 Y-10.331 DR+ R0 F200 M
166 CC X+44.966 Y-8.72
167 C X+41.74 Y-6.354 DR- R0 F200 M
168 CC X+40.53 Y-5.467
169 C X+40.367 Y-3.976 DR+ R0 F200 M
170 Z+0. R0 F400 M
171 L X+15.367 Y+47.277 R0 F400 M03
172 Z-1.5 R0 F200 M
173 CC X+14.931 Y+43.301
174 C X+15.367 Y+39.325 DR+ R0 F200 M
175 CC X+15.53 Y+37.834
176 C X+16.74 Y+36.947 DR- R0 F200 M
177 CC X+19.966 Y+34.582
178 C X+23.627 Y+32.971 DR+ R0 F200 M
179 CC X+25. Y+32.367
180 C X+26.373 Y+32.971 DR- R0 F200 M
181 CC X+30.034 Y+34.582
182 C X+33.26 Y+36.947 DR+ R0 F200 M
183 CC X+34.47 Y+37.834
184 C X+34.633 Y+39.325 DR- R0 F200 M
185 CC X+35.069 Y+43.301
186 C X+34.633 Y+47.277 DR+ R0 F200 M
187 CC X+34.47 Y+48.769
188 C X+33.26 Y+49.656 DR- R0 F200 M
189 CC X+30.034 Y+52.021
190 C X+26.373 Y+53.632 DR+ R0 F200 M
191 CC X+25. Y+54.236
192 C X+23.627 Y+53.632 DR- R0 F200 M
193 CC X+19.966 Y+52.021
194 C X+16.74 Y+49.656 DR+ R0 F200 M
195 CC X+15.53 Y+48.769
196 C X+15.367 Y+47.277 DR- R0 F200 M
197 Z+0. R0 F400 M
```

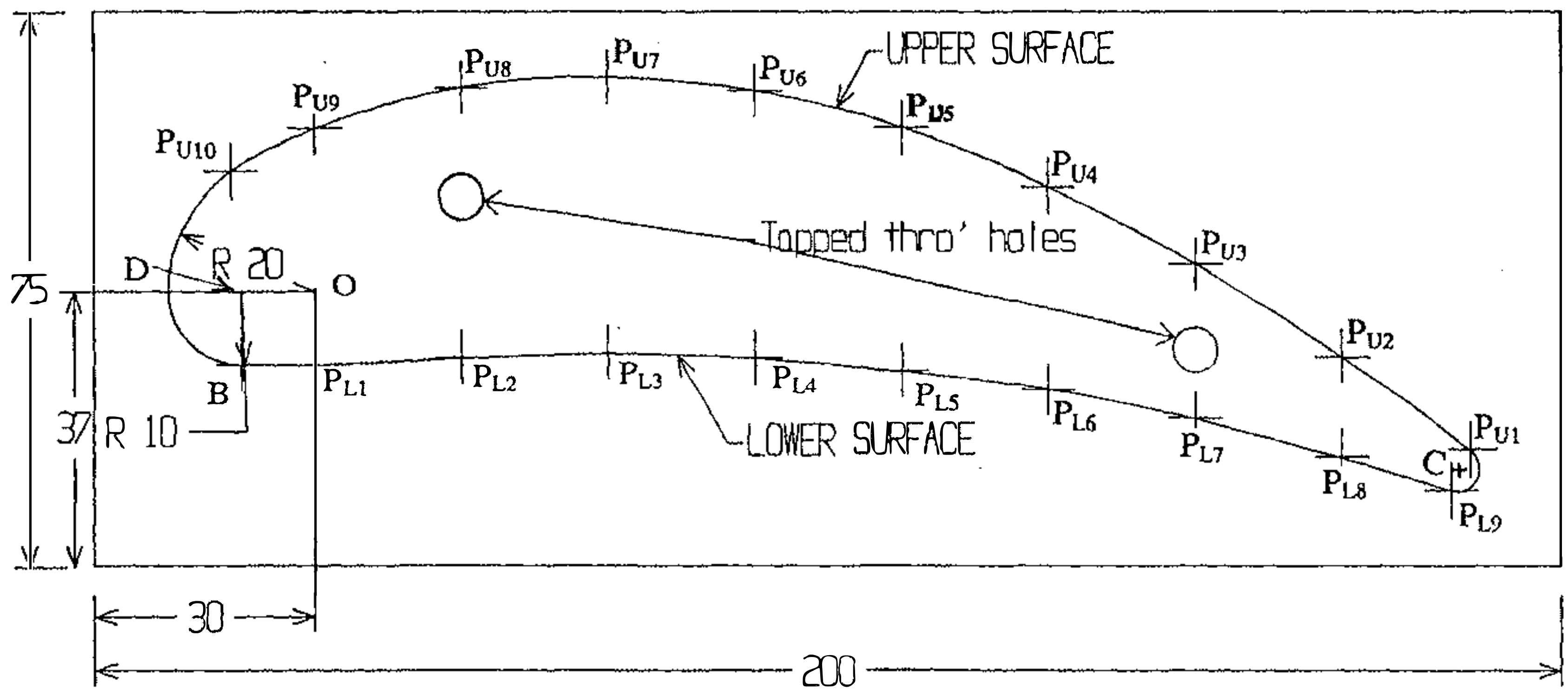
```
198 L X-34.633 R0 F400 M03
199 Z-1.5 R0 F200 M
200 CC X-35.069 Y+43.301
201 C X-34.633 Y+39.325 DR+ R0 F200 M
202 CC X-34.47 Y+37.834
203 C X-33.26 Y+36.947 DR- R0 F200 M
204 CC X-30.034 Y+34.582
205 C X-26.373 Y+32.971 DR+ R0 F200 M
206 CC X-25. Y+32.367
207 C X-23.627 Y+32.971 DR- R0 F200 M
208 CC X-19.966 Y+34.582
209 C X-16.74 Y+36.947 DR+ R0 F200 M
210 CC X-15.53 Y+37.834
211 C X-15.367 Y+39.325 DR- R0 F200 M
212 CC X-14.931 Y+43.301
213 C X-15.367 Y+47.277 DR+ R0 F200 M
214 CC X-15.53 Y+48.769
215 C X-16.74 Y+49.656 DR- R0 F200 M
216 CC X-19.966 Y+52.021
217 C X-23.627 Y+53.632 DR+ R0 F200 M
218 CC X-25. Y+54.236
219 C X-26.373 Y+53.632 DR- R0 F200 M
220 CC X-30.034 Y+52.021
221 C X-33.26 Y+49.656 DR+ R0 F200 M
222 CC X-34.47 Y+48.769
223 C X-34.633 Y+47.277 DR- R0 F200 M
224 Z+0. R0 F400 M
225 STOP M25
226 END PGM  mm
```

♦

APPENDIX G

MACHINING OF FREE FORM CURVE

AEROFOIL



ALL DIMENSIONS IN MILLIMETERS

SCALE FULL SIZE

MATERIAL ALUMINIUM

AEROFOIL

OBJECT: Production of an Aerofoil

GENERAL DESCRIPTION:

According to Figure No. G1 of an Aerofoil, which was drawn as per given co-ordinates;

Radius of an Arc P_{u10} to A is 20mm. This can be proved by Pythogorus Theorem.

Since Triangle $P_{u10}DO$ is a rectangular triangle;

$(OD)^2+(DP_{u10})^2= (11.47)^2+(16.38)^2$

$= 400$

$OP_{u10} = 20$

$B = (-10, -10)$, $P_{l1} = (0,-10)$

Hence B_{Pl1} is a straight line.

$P_{l9} = (155, -26.90)$

$P_{l1} = (157.65, -21,5)$

Distance $P_{L9}P_{Lu1}= [(2.65)^2+(-5.40)^2]^{0.5}$

$= 6mm$

Hence for arc $p_{L9}p_{u1}$, radius is taken as 3mm with the centre point C.

Co-ordinates of point C = [155+157.65]/2, [-26.90-21.50]/2

= (156.325, -24.200)

For accurate machining, given co-ordinates of both Lower and Upper surfaces are not sufficient

Since 2 and half axis Bridgeport milling machine with Heidenhain TNC 145 controller can be used only for either curves with co-ordinates of centre, beginning, end points; angle and radius or straight lines of given co-ordinates.

Therefore let us find co-ordinates of in between points of each segments of both Lower and Upper surfaces as many as we can.

Lower Surface starts from point P_{L1} to P_{L9}. Upper Surface starts from P_{U1} to P_{U10}. In the Lower Surface, there are 8 segments from $P_{L1}P_{L2}$, $P_{L2}P_{L3}$, ...,$P_{L8}P_{L9}$.

In the Upper Surface, there are 9 segments from $P_{U1}P_{U2}$, $P_{U2}P_{U3}$,................,P_{U9},P_{u10}.

THEORY: Fuguson Spline Method.

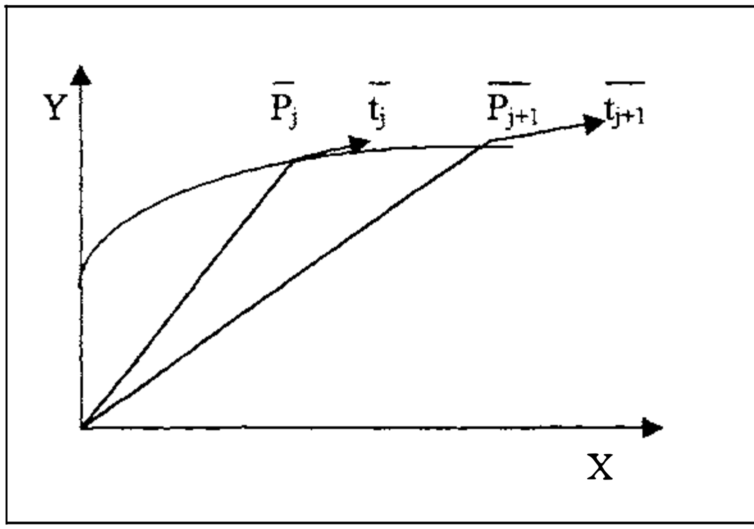


Figure G1

Suppose a Free form curve passes through points j_1, j_2, ..., j_n Co-ordinates of these points are in Cartesian system (P_x, P_y) and they can be represented in vectors P_1,P_2,........,P_n.. Corresponding tangent vectors are represented in t_1, t_2, ..., t_j, t_{j+1}, ..., t_n. The curve passes through j,j+1 points has the form;

$$P_j(u) = \Sigma R_{ij}u^i$$

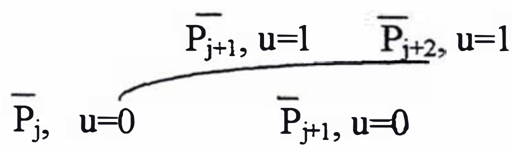
i = 0,1, 2, 3; j = 1,2,......,n.

u is a non dimensional parameter.

where $0 \leq u \leq 1$.

$$P_j(\bar{u}) = R_{3j}u^3+R_{2j}u^2+R_{1j}u+R_0$$

Suppose there are 3 points j, j+1, j+2 on the same curve; Let segments jj+1 and j+1j+2 on the curve.



For a curve which passes through a given set of points smoothly and continuously must satisfy following conditions.

$$\overline{P}_j(1) = \overline{P}_{j+1}(0)$$

$$\overline{P}_j'(1) = \overline{P}_{j+1}'(0)$$

$$\overline{P}_j''(1) = \overline{P}_{j+1}''(0)$$

From this,

$$\overline{P}j(u) = u^3[2(\overline{P}_j-\overline{P}_{j+1})+\overline{t}_j+\overline{t}_{j+1}]+u^2[3(\overline{P}_{j+1}-\overline{P}_j)-2\overline{t}_j-\overline{t}_{j+1}]+u\overline{t}_j+\overline{P}_j \quad \ldots\ldots\ldots\ldots(1)$$

Similarly if points $j_1,j_2,\ldots\ldots\ldots,j_n$ having corresponding vectors $P_1,P_2,\ldots\ldots\ldots,P_n$ are on a same curve, following set of equations can be derived.

$$2\overline{t}_1+\overline{t}_2+0+0+\ldots\ldots\ldots\ldots\ldots\ldots= 3(\overline{P}_2-\overline{P}_1)$$

$$\overline{t}_1+4\overline{t}_2+\overline{t}_3+0+0+\ldots\ldots\ldots\ldots\ldots\ldots=3(\overline{P}_3-\overline{P}_1)$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$0+0+\ldots\ldots\ldots\ldots\ldots\ldots\overline{t}_{n-2}+4\overline{t}_{n-1}+\overline{t}_n=3(\overline{P}_n-\overline{P}_{n-2})$$

$$0+0+\ldots\ldots\ldots\ldots\ldots\ldots\overline{t}_{n-1}+2\overline{t}_n=3(\overline{P}_n-\overline{P}_{n-1})$$

CALCULATIONS

Lower Surface:

Point	P_{L1}	P_{L2}	P_{L3}	P_{L4}	P_{L5}	P_{L6}	P_{L7}	P_{L8}	P_{L9}
X	0	20	40	60	80	100	120	140	155
Y	-10	-9.05	-8.50	-9.05	-10.85	-13.55	-17.50	-22.50	-26.90

Table G1

According to fuguson spline method if points $P_{L1}, P_{L2}, \ldots, P_{L9}$ are on a same smooth, continuous curve (aerofoil lower surface), following set of equation can be written.

$$2t_1+t_2 = 3(P_{L2}-P_{L1})$$

$$t_1+4t_2+t_3 = 3(P_{L3}-P_{L1})$$

$$t_2+4t_3+t_4 = 3(P_{L4}-P_{L2})$$

$$t_3+4t_4+t_5 = 3(P_{L5}-P_{L3})$$

$$t_4+4t_5+t_6 = 3(P_{L6}-P_{L4})$$

$$t_5+4t_6+t_7 = 3(P_{L7}-P_{L5})$$

$$t_6+4t_7+t_8 = 3(P_{L8}-P_{L6})$$

$$t_7+4t_8+t_9 = 3(P_{L9}-P_{L7})$$

$$t_8+2t_9 = 3(P_{L9}-P_{L8})$$

This can be written as;

$$\begin{pmatrix} 2 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 4 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 4 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 4 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 4 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 4 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 4 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 4 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 2 \end{pmatrix} \begin{bmatrix} t_{1x} \\ t_{2x} \\ t_{3x} \\ t_{4x} \\ t_{5x} \\ t_{6x} \\ t_{7x} \\ t_{8x} \\ t_{9x} \end{bmatrix} = 3 \begin{bmatrix} 20 \\ 40 \\ 40 \\ 40 \\ 40 \\ 40 \\ 40 \\ 35 \\ 15 \end{bmatrix}$$

$$[A] \quad . \quad [D] \quad = 3\,[C]$$

$$[D] = 3[B].[C]$$

Where [B] = Inv[A]

Using MATLAB; (Calculations using MATLAB is attached)

$$\begin{bmatrix} t_{1x} \\ t_{2x} \\ t_{3x} \\ t_{4x} \\ t_{5x} \\ t_{6x} \\ t_{7x} \\ t_{8x} \\ t_{9x} \end{bmatrix} = \begin{bmatrix} 20.0005 \\ 19.9991 \\ 20.0032 \\ 19.9880 \\ 20.0446 \\ 19.8334 \\ 20.6218 \\ 17.6795 \\ 13.6603 \end{bmatrix}$$

Similarly for 'Y' co-ordinates;

Following matrix equation can be written

$$\begin{pmatrix} 2 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 4 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 4 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 4 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 4 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 4 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 4 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 4 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 2 \end{pmatrix} \begin{bmatrix} t_{1y} \\ t_{2y} \\ t_{3y} \\ t_{4y} \\ t_{5y} \\ t_{6y} \\ t_{7y} \\ t_{8y} \\ t_{9y} \end{bmatrix} = 3 \begin{pmatrix} -9.05+10.00 \\ -8.50+10.00 \\ -9.05+9.05 \\ -10.85+8.50 \\ -13.55+9.05 \\ -17.50+10.85 \\ -22.50+13.55 \\ -26.90+17.50 \\ -26.90+22.50 \end{pmatrix}$$

$$[A] \quad . \quad [F] = 3[E]$$

$$[F] = 3[B].[E], \quad \text{Where } [B] = \text{Inv}[A]$$

From MATLAB;

$$\begin{bmatrix} t_{1y} \\ t_{2y} \\ t_{3y} \\ t_{4y} \\ t_{5y} \\ t_{6y} \\ t_{7y} \\ t_{8y} \\ t_{9y} \end{bmatrix} = \begin{pmatrix} 0.9989 \\ 0.8522 \\ 0.0923 \\ -1.2213 \\ -2.2571 \\ -3.2501 \\ -4.6923 \\ -4.8308 \\ -4.1846 \end{pmatrix}$$

Using above data and calculations following table can be prepared for segments on the Lower Surface.

Segment	P_{Lxj}	$P_{L(j+1)y}$	t_{Ljx}	$t_{L(j+1)x}$	P_{Lyj}	$P_{L(j+1)y}$	t_{Lyj}	$t_{L(j+1)y}$
$P_{L1}P_{L2}$	0	20	20.0050	19.9991	-10.00	-9.05	0.9989	0.8522
$P_{L2}P_{L3}$	20	40	19.9991	20.0032	-9.05	-8.50	0.8522	0.0923
$P_{L3}P_{L4}$	40	60	20.0032	19.9888	-8.50	-9.05	0.0923	-1.2213
$P_{L4}P_{L5}$	60	80	19.9888	20.0446	-9.05	-10.85	-1.2213	-2.2571
$P_{L5}P_{L6}$	80	100	20.0446	19.8334	-10.85	13.55	-2.2571	-3.2501
$P_{L6}P_{L7}$	100	120	19.8334	20.6218	-13.55	-17.50	-3.2501	-4.6923
$P_{L7}P_{L8}$	120	140	20.6218	17.6795	-17.50	-22.50	-4.6923	-4.8308
$P_{L8}P_{L9}$	140	155	17.6795	13.6603	-22.50	-26.90	-4.8308	-4.1846

Table G2

This data table is stored in 'C:\TP6\DATA.TXT' file and value for each segment from $P_{L1}P_{L2}$, ..., $P_{L8}P_{L9}$ will be substituted to the following equation.

$$\overline{P_j}(u) = u^3[2(\overline{P_j}-\overline{P_{j+1}})+\overline{t_j}+\overline{t_{j+1}}]+u^2[3(\overline{P_{j+1}}-\overline{P_j})-2\overline{t_j}+\overline{t_{j+1}}]+u\overline{t_j}+\overline{P_j}$$

For $P_{L1}P_{L2}$ segment;

$$P_{jx}(u) = u^3[2(0-20)+20.055+19.9991]+u^2[3(20-0)-2(20.005)+19.991]$$

$$+u(20.005)+0$$

When u=0; $P_{jx}(0)$ = X- Co-ordinate of point P_{L1} = 0.000

u=1; $P_{jx}(1)$ = X- Co-ordinate of point P_{L2} = 20.000

Similarly,

$$P_{jy}(u)= u^3[2(-10.00+9.05)+0.9989+0.8522]$$

$$+u^2[3(-9.05+10.00)-2(-10.00)+0.8522]+u(0.9989)-10.00$$

When u=0: $P_{jy}(0)$ = Y co-ordinate of point P_{L1} = -10.00

u=1: $P_{jy}(1)$ = Y co-ordinate of point P_{L2} = -9.05

For values $0 \le u \le 1$ gives X,Y co-ordinates of points on the segment $P_{L1}P_{L2}$ of the Lower Surface.

Similarly, co-ordinates of points on all segments of the Lower Surface can be calculated when $0 \le u \le 1$.

'C:\wimalj1.pas' program is written in Pascal Language for these calculations.

Upper Surface

Point	P_{u1}	P_{u2}	P_{u3}	P_{u4}	P_{u5}	P_{u6}	P_{u7}	P_{u8}	P_{u9}	P_{u10}
X	157.65	140	120	100	80	60	40	20	0	-11.47
Y	-21.5	-8.95	3.85	14.35	22.10	27.15	29	27.55	22	16.38

Table G3

According to Fuguson Spline Method, if points PU1, PU2,PU3,........,PU10 are on a smooth and continuous curve following set of equation can be written.

X co-ordinates;

$2t_{1ux}+t_{2ux} = 3(P_{u2}-P_{u1}) = 3(-157.65+140)$

$t_{1ux}+4t_{2ux}+t_{3ux} = 3(P_{u3}-P_{u1}) = 3(120-157.65)$

$t_{2ux}+4t_{3ux}+t_{4ux} = 3(P_{u4}-P_{u2}) = 3(100-140)$

$t_{3ux}+4t_{4ux}+t_{5ux} = 3(P_{u5}-P_{u3}) = 3(80-120)$

$t_{4ux}+4t_{5ux}+t_{6ux} = 3(P_{u6}-P_{u4}) = 3(60-100)$

$t_{5ux}+4t_{6ux}+t_{7ux} = 3(P_{u7}-P_{u5}) = 3(40-80)$

$t_{6ux}+4t_{7ux}+t_{8ux} = 3(P_{u8}-P_{u6}) = 3(20-60)$

$t_{7ux}+4t_{8ux}+t_{9ux} = 3(P_{u9}-P_{u7}) = 3(0-40)$

$t_{8ux}+4t_{9ux}+t_{10ux} = 3(P_{u10}-P_{u8}) = 3(-11.47-20)$

$t_{9ux}+2t_{10ux} = 3(P_{u10}-P_{u9}) = 3(-11.47-0)$

$$
\begin{pmatrix}
2 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 4 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 4 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 4 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 4 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 4 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 4 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 4 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 4 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 2
\end{pmatrix}
\begin{pmatrix}
t_{1x} \\ t_{2ux} \\ t_{3ux} \\ t_{4ux} \\ t_{5ux} \\ t_{6ux} \\ t_{7ux} \\ t_{8ux} \\ t_{9ux} \\ t_{10ux}
\end{pmatrix}
=3
\begin{pmatrix}
-17.65 \\ -37.65 \\ -40 \\ -40 \\ -40 \\ -40 \\ -40 \\ -40 \\ -31.47 \\ -11.47
\end{pmatrix}
$$

[A1] . [D1] = 3[C1]

[D1] =3[B1].[C1],

Where [B1]= Inv[A1]

Using MATLAB;

(Calculations attached)

$$
\begin{pmatrix}
t_{1ux} \\ t_{2ux} \\ t_{u3x} \\ t_{4ux} \\ t_{5ux} \\ t_{6ux} \\ t_{7ux} \\ t_{8ux} \\ t_{9ux} \\ t_{10ux}
\end{pmatrix}
=
\begin{pmatrix}
-17.0201 \\ -18.9098 \\ -20.2908 \\ -19.9272 \\ -20.0006 \\ -20.0705 \\ -19.7173 \\ -21.0603 \\ -16.0413 \\ -9.1843
\end{pmatrix}
$$

Similarly for 'Y' co-ordinates;

$$\begin{pmatrix} 2 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 4 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 4 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 4 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 4 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 4 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 4 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 4 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 4 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 2 \end{pmatrix} \begin{pmatrix} t_{1uy} \\ t_{u2y} \\ t_{3uy} \\ t_{4uy} \\ t_{5uy} \\ t_{6uy} \\ t_{7uy} \\ t_{8uy} \\ t_{9uy} \\ t_{10uy} \end{pmatrix} = 3 \begin{pmatrix} -8.95+21.5 \\ 3.85+21.5 \\ 14.35+8.95 \\ 22.10-3.85 \\ 27.15-14.35 \\ 29.00-22.10 \\ 27.55-27.15 \\ 22.00-29.00 \\ 16.38-27.55 \\ 16.38-22.00 \end{pmatrix}$$

[A1]. [F1] = 3[E1]

[F1] = 3[B1].[E1}

Where [B1] = Inv[A1}

Using MATLAB; (Calculations attached)

$$[F1]= \begin{pmatrix} t_{1uy} \\ t_{2uy} \\ t_{3uy} \\ t_{4uy} \\ t_{5uy} \\ t_{6uy} \\ t_{7uy} \\ t_{8uy} \\ t_{9uy} \\ t_{10uy} \end{pmatrix} = \begin{pmatrix} 12.3589 \\ 12.9322 \\ 11.9621 \\ 9.1192 \\ 6.3110 \\ 4.0370 \\ -1.7588 \\ 4.1989 \\ 5.9662 \\ 5.4469 \end{pmatrix}$$

From above data and calculations, following table can be made for segments of Upper Surface.

Segments	P_{uxj}	$P_{u(j+1)x}$	t_{ujx}	$t_{u(j+1)x}$	P_{uyj}	$P_{u(j+1)y}$	t_{ujy}	$t_{u(j+1)y}$
$P_{u1}P_{u2}$	157.65	140	-17.0201	-18.9098	-21.5	-8.95	12.3589	12.9322
$P_{u2}P_{u3}$	140	120	-18.9098	-20.2908	-8.95	3.85	12.9322	11.9621
$P_{u3}P_{u4}$	120	100	-20.2908	-19.9272	3.85	14.35	11.9621	9.1192
$P_{u4}P_{u5}$	100	80	-19.9272	-20.0006	14.35	22.10	9.1192	6.3110
$P_{u5}P_{u6}$	80	60	-20.0006	-20.0705	22.10	27.15	6.3110	4.0370
$P_{u6}P_{u7}$	60	40	-20.0705	-19.7173	27.15	29.00	4.0370	-1.7588
Pu7Pu8	40	20	-19.7173	-21.0603	29.00	27.55	-1.7588	4.1981
Pu8Pu9	20	0	-21.0603	-16.0413	27.55	22.00	4.1981	5.9662
Pu9Pu1	0	-11.47	-16.0413	-9.1843	22.00	16.38	5.9662	5.4469

Table G4

These data has been stored in 'C:\TP6\DATA.TXT' file.

For each segment from $P_{u1}P_{u2}$, $P_{u2}P_{u3}$,............, $P_{u9}P_{u10}$ on the Upper Surface values from P_{uxj}...............$t_{u(j+1)y}$ is substituted to the equation as follows.

For Segment $P_{u1}P_{u2}$;

$$\overline{P}_j(u) = u^3[2(\overline{P}_j-\overline{P}_{j+1})+\overline{t}_j+\overline{t}_{j+1}]+u^2[3(\overline{P}_{j+1}-\overline{P}_j)-2\overline{t}_j+\overline{t}_{j+1}]+u\overline{t}_j+\overline{P}_j$$

$$P_{jux}(u)=u^3[2(157.65-140)+(-17.0201-18.9098)]$$

$$+u^2[3(140-157.65)-2(-17.0201)-18.9098]+u(-18.9098)+157.65$$

Where $0 \leq u \leq 1$;

When u=0: $P_{jux}(0) = 157.65$ .... 'X' co-ordinate of point P_{u1}

u=1: $P_{(j+1)ux}(1) = 140$ ....'Y' co-ordinate of point P_{u2}

Similarly,

$P_{juy}(u) = u^3[2(-21.5+8.95)+12.3589+12.9322]$

$+u^2[3(3.85+8.95)-2(12.3589)+12.9322]+u(12.3589)+(-21.5)$

Where $0 \leq u \leq 1$.

When u = 0; $P_{juy} = -21.5$ .... 'Y' co-ordinate of P_{u1}

u = 1; $P_{juy} = -8.95$................... 'Y' co-ordinate of P_{u2}

Values of X,Y co-ordinates of all points on the curve segment $P_{u1}P_{u2}$ can be calculated for each value of u which is $0 \leq u \leq 1$.

For this, 'C:\wimalj1.pas' program has been used. After determining all points, Tool movement between points can be assumed as a straight line. From each small segments a free form curve will be created.

Above data is used to 'wimalj1.pas' program for generating NC program automatically in the right format for TNC 145 - Heidenhain controller mounted on the Brigeport milling machine.

NC program is stored in 'C:\TP6\Results.TXT' file.

Calculations using MATLAB

```
A1= [2 1 0 0 0 0 0 0 0 0; 1 4 1 0 0 0 0 0 0 0; 0 1 4 1 0 0 0 0 0 0; 0
0 1 4 1 0 0 0 0 0; 0 0 0 1 4 1 0 0 0 0; 0 0 0 0 1 4 1 0 0 0; 0 0 0 0
0 1 4 1 0 0; 0 0 0 0 0 0 1 4 1 0; 0 0 0 0 0 0 0 1 4 1; 0 0 0 0 0 0 0
0 1 2]
□

□
A1 =
□

□
     2     1     0     0     0     0     0     0     0     0
     1     4     1     0     0     0     0     0     0     0
     0     1     4     1     0     0     0     0     0     0
     0     0     1     4     1     0     0     0     0     0
     0     0     0     1     4     1     0     0     0     0
     0     0     0     0     1     4     1     0     0     0
     0     0     0     0     0     1     4     1     0     0
     0     0     0     0     0     0     1     4     1     0
     0     0     0     0     0     0     0     1     4     1
     0     0     0     0     0     0     0     0     1     2

» B1=inv(A1)

B1 =

  Columns 1 through 7

    0.5774   -0.1547    0.0415   -0.0111    0.0030   -0.0008
0.0002
   -0.1547    0.3094   -0.0829    0.0222   -0.0060    0.0016   -
0.0004
    0.0415   -0.0829    0.2902   -0.0777    0.0208   -0.0056
0.0015
   -0.0111    0.0222   -0.0777    0.2888   -0.0774    0.0207   -
0.0056
    0.0030   -0.0060    0.0208   -0.0774    0.2887   -0.0774
0.0207
   -0.0008    0.0016   -0.0056    0.0207   -0.0774    0.2887   -
0.0774
    0.0002   -0.0004    0.0015   -0.0056    0.0207   -0.0774
0.2888
   -0.0001    0.0001   -0.0004    0.0015   -0.0056    0.0208   -
0.0777
    0.0000    0.0000    0.0001   -0.0004    0.0016   -0.0060
0.0222
    0.0000    0.0000   -0.0001    0.0002   -0.0008    0.0030   -
0.0111

  Columns 8 through 10

   -0.0001    0.0000    0.0000
    0.0001    0.0000    0.0000
   -0.0004    0.0001   -0.0001
    0.0015   -0.0004    0.0002
   -0.0056    0.0016   -0.0008
    0.0208   -0.0060    0.0030
   -0.0777    0.0222   -0.0111
```

```
    0.2902   -0.0829    0.0415
   -0.0829    0.3094   -0.1547
    0.0415   -0.1547    0.5774

» C1= [-17.65; -37.65; -40; -40; -40; -40; -40; -40; -31.47; -11.47]

C1 =

  -17.6500
  -37.6500
  -40.0000
  -40.0000
  -40.0000
  -40.0000
  -40.0000
  -40.0000
  -31.4700
  -11.4700

» D1=3 *(B1)*(C1)

D1 =

  -17.0201
  -18.9098
  -20.2908
  -19.9272
  -20.0006
  -20.0705
  -19.7173
  -21.0603
  -16.0413
   -9.1843

» E1= [12.55; 25.35; 23.30; 18.25; 12.8; 6.9; 0.4; 7.0; 11.17; 5.620]

E1 =

   12.5500
   25.3500
   23.3000
   18.2500
   12.8000
    6.9000
    0.4000
    7.0000
   11.1700
    5.6200

» F1=3*(B1)*(E1)

F1 =

   12.3589
   12.9322
   11.9621
    9.1192
    6.3110
    4.0370
   -1.7588
    4.1981
    5.9662
    5.4469
```

```
» A=[2 1 0 0 0 0 0 0 0; 1 4 1 0 0 0 0 0 0; 0 1 4 1 0 0 0 0 0; 0 0 1 4
1 0 0 0 0; 0 0 0 1 4 1 0 0 0; 0 0 0 0 1 4 1 0 0; 0 0 0 0 0 1 4 1 0; 0
0 0 0 0 0 1 4 1; 0 0 0 0 0 0 0 1 2]

A =

     2     1     0     0     0     0     0     0     0
     1     4     1     0     0     0     0     0     0
     0     1     4     1     0     0     0     0     0
     0     0     1     4     1     0     0     0     0
     0     0     0     1     4     1     0     0     0
     0     0     0     0     1     4     1     0     0
     0     0     0     0     0     1     4     1     0
     0     0     0     0     0     0     1     4     1
     0     0     0     0     0     0     0     1     2

» B=inv(A)

B =

  Columns 1 through 7

    0.5774   -0.1547    0.0415   -0.0111    0.0030   -0.0008
0.0002
   -0.1547    0.3094   -0.0829    0.0222   -0.0060    0.0016   -
0.0004
    0.0415   -0.0829    0.2902   -0.0777    0.0208   -0.0056
0.0015
   -0.0111    0.0222   -0.0777    0.2888   -0.0774    0.0207   -
0.0056
    0.0030   -0.0060    0.0208   -0.0774    0.2887   -0.0774
0.0208
   -0.0008    0.0016   -0.0056    0.0207   -0.0774    0.2888   -
0.0777
    0.0002   -0.0004    0.0015   -0.0056    0.0208   -0.0777
0.2902
   -0.0001    0.0001   -0.0004    0.0016   -0.0060    0.0222   -
0.0829
    0.0000   -0.0001    0.0002   -0.0008    0.0030   -0.0111
0.0415

  Columns 8 through 9

   -0.0001    0.0000
    0.0001   -0.0001
   -0.0004    0.0002
    0.0016   -0.0008
   -0.0060    0.0030
    0.0222   -0.0111
   -0.0829    0.0415
    0.3094   -0.1547
   -0.1547    0.5774

» C= [20; 40; 40; 40; 40; 40; 40; 35; 15]
```

```
C =

    20
    40
    40
    40
    40
    40
    40
    35
    15

» D=3*(B)*(C)

D =

   20.0005
   19.9991
   20.0032
   19.9880
   20.0446
   19.8334
   20.6218
   17.6795
   13.6603

» E= [0.950; 1.50; 0; -2.35; -4.50; -6.650; -8.950; -9.40; -4.4]

E =

    0.9500
    1.5000
         0
   -2.3500
   -4.5000
   -6.6500
   -8.9500
   -9.4000
   -4.4000

» F=3*(B)*(E)

F =

    0.9989
    0.8522
    0.0923
   -1.2213
   -2.2571
   -3.2501
   -4.6923
   -4.8308
   -4.1846

»
```

Data.txt file

```
0 20 20.005 19.991 -10 -9.05 0.9989 0.8522
□
20 40 19.9991 20.0032 -9.05 -8.50 .8522 0.0923
□
40 60 20.0032 19.9888 -8.50 -9.05 0.0923 -1.2213
□
60 80 19.9888 20.0446 -9.05 -10.85 -1.2213 -2.2571
80 100 20.0446 19.8334 -10.85 -13.55 -2.2571 -3.2501
100 120 19.8334 20.6218 -13.55 -17.50 -3.2501 -4.6923
120 140 20.6218 17.6795 -17.50 -22.50 -4.6923 -4.8308
140 155 17.6795 13.6603 -22.50 -26.90 -4.8308  -4.1846

157.65 140 -17.0201 -18.9098 -21.5 -8.95 12.3589 12.9322
140.00 120.00 -18.9098 -20.2908 -8.95 3.85 12.9322 11.9621
120.00 100.00 -20.2908 -19.9272 3.85 14.35 11.9621 9.1192
100.00 80.00 -19.9272 -20.0006 14.35 22.10 9.1192 6.3110
80.00 60.00 -20.0006 -20.0705 22.10 27.15 6.3110 4.0370
60.00 40.00 -20.0705 -19.7173 27.15 29.00 4.0370 -1.7588
40.00 20.00 -19.7173 -21.0603 29.00 27.55 -1.7588 4.1981
20.00 0.00 -21.0603 -16.0413 27.55 22.00 4.1981 5.9662
0.00 -11.47 -16.0413 -9.1843 22.00 16.38 5.9662 5.4469
```

Pascal program to generate NC code to machining aerofoil

File name: Wimalj.pas

```
program  aerofoil;

const NLvalues=8;

      NLsegments=8;

      NUsegments=8;

      NUvalues=9;

Var Infile, Outfile :text;
    Values: array[1..NLsegments,1..NLvalues] of real;
    value:array[1..NUsegments,1..NUvalues] of real;
    a,b,u: real;
    i,j:integer;

Begin


    {open input and output files}
    assign(Infile,'C:\TP6\DATA.TXT');
    reset(Infile);
    assign(Outfile,'c:\tp6\results.txt');
    rewrite(Outfile);

    {obtain tool definitions from the user and write into machine
code file}

    writeln(Outfile,'1 ',  '   TOOL DEF 1   L 0.000    R 5.000' );
    writeln(Outfile,'2 ',  '   TOOL CALL 1   Z    S  1500 ' );
    writeln(Outfile,'3 ',  '   CYCL DEF 7.0  DATUM SHIFT ' );
    writeln(Outfile,'4 ',  '   CYCL DEF 7.1  X -30.000 ' );
    writeln(Outfile,'5 ',  '   CYCL DEF 7.2  Y -37.000 ' );
    writeln(Outfile,'6 ',  '   CYCL DEF 7.3  Z  ');
    writeln(Outfile,'7 ',  '   LBL 1  ');
    writeln(Outfile,'8 ',  '   L ',' X-11.470  Y  16.380 ','    RR
F400 M03 ');
    writeln(Outfile,'9 ', '     Z  2.000 ','              RR F400 M
');
    writeln(Outfile,'10 ', '    Z  0.000 ','              RR F200 M
');
    writeln(Outfile,'11 ', '   IZ -2.000 ','              RR F50  M
');
    writeln(Outfile,'12 ', '  CC ','X  0.000  Y   0.000 ' );
    writeln(Outfile,'13 ', '  C ',' X-20.000  Y   0.000 ','DR+ RR F50
M ' );
    writeln(Outfile,'14 ', '  CC ','X-10.000  Y   0.000 ');
    writeln(Outfile,'15 ', '  C ',' X-10.000  Y -10.000 ','DR+ RR F50
M ' );

    {read lower surface data into values array, calculate machine
code
            and place results into machine code file}
    for i:=1 to 8 do
    Begin
        for j:=1 to NLsegments do
        read(Infile ,values[j,i]);
        readln(Infile);
```

```
        u:=0;
        While u<1 do
        Begin
           a:=u*sqr(u)*(2*(values[1,i]-
values[2,i])+values[3,i]+values[4,i])
                                   +sqr(u)*(3*(values[2,i]-values[1,i])-
2*values[3,i]-values[4,i])
                                   +u*values[3,i]+values[1,i];
           b:=u*sqr(u)*(2*(values[5,i]-
values[6,i])+values[7,i]+values[8,i])
                                   +sqr(u)*(3*(values[6,i]-values[5,i])-
2*values[7,i]-values[8,i])
                                   +u*values[7,i]+values[5,i];
           Writeln(Outfile, round((i-1)*10+(u+0.1)*10+15 ),'   L ' ,'
X', a:7:3  , '  Y ', b:7:3,'     RR F50  M');
           u:=u+0.1;
         end;  {while u}
      end;  {for i}

    {write corner code into machine code file}
    writeln(Outfile,'96 ',' L ',' X155.000  Y -26.900 ','    RR F50
M ');
    writeln(Outfile,'97 ',' CC ','X156.325  Y -24.200 ');
    writeln(Outfile,'98 ',' C ',' X157.650  Y -21.500 ','DR+ RR F50
M ');

    {read upper surface data into value array, calculate machine code
     and write into machine code file}
    readln(Infile);
    for i:=1 to NUvalues do
     Begin
                for j:=1 to NUsegments do
           read(Infile, value[j,i]);
           readln(Infile);
           u:=0.1;
           while u<1.1 do
           Begin
           a:= u*sqr(u)*(2*(value[1,i]-
value[2,i])+value[3,i]+value[4,i])
               +sqr(u)*(3*(value[2,i]-value[1,i])-2*value[3,i]-
value[4,i])
               +u*value[3,i]+value[1,i];
           b:= u*sqr(u)*(2*(value[5,i]-
value[6,i])+value[7,i]+value[8,i])
               +sqr(u)*(3*(value[6,i]-value[5,i])-2*value[7,i]-
value[8,i])
               +u*value[7,i]+value[5,i];
           writeln(Outfile, round((i-1)*10+(u+0.1)*10+98 ),'  L ','
X', a:7:3 ,'  Y ', b:7:3 ,'     RR F50  M ');
           u:=u+0.1;
           end;  {while u}
      end; {for i}

    writeln(Outfile,'190 ', ' LBL 0  '   );
    writeln(Outfile,'191 ', ' CALL LBL 1 ', '  REP  2       /2  ');
    writeln(Outfile,'192 ', ' CYCL DEF 7.0  DATUM SHIFT    ');
    writeln(Outfile,'193 ', ' CYCL DEF 7.1      X +0.000  ');
    writeln(Outfile,'194 ', ' CYCL DEF 7.2      Y +0.000  ');
    writeln(Outfile,'195 ', ' CYCL DEF 7.3      Z         ');
    writeln(Outfile,'196 ', ' Z   50.000    ','                RR F400
M  ');
    writeln(Outfile,'197 ', ' L ',' X 0.000 ', ' Y 0.000 ','
RR F400  M05 ');
    writeln(Outfile,'198 ', ' STOP  ',            '  M02 ');
```

```
    {close input and output files}
    close(Infile);
    close(Outfile);
end
```

NC program using Heidenhein code

File name: Results.txt

```
1     TOOL DEF 1    L 0.000    R 5.000
2     TOOL CALL 1    Z     S  1500
3     CYCL DEF 7.0  DATUM SHIFT
4     CYCL DEF 7.1  X -30.000
5     CYCL DEF 7.2  Y -37.000
6     CYCL DEF 7.3  Z
7     LBL 1
8     L  X-11.470  Y  16.380      RR F400 M03
9        Z  2.000                 RR F400 M
10       Z  0.000                 RR F200 M
11      IZ -2.000                 RR F50  M
12    CC X   0.000  Y   0.000
13    C  X-20.000  Y   0.000 DR+ RR F50  M
14    CC X-10.000  Y   0.000
15    C  X-10.000  Y -10.000 DR+ RR F50  M
16    L  X   0.000  Y -10.000     RR F50  M
17    L  X   2.000  Y  -9.900     RR F50  M
18    L  X   4.001  Y  -9.801     RR F50  M
19    L  X   6.001  Y  -9.702     RR F50  M
20    L  X   8.002  Y  -9.604     RR F50  M
21    L  X 10.002  Y  -9.507      RR F50  M
22    L  X 12.002  Y  -9.411      RR F50  M
23    L  X 14.002  Y  -9.318      RR F50  M
24    L  X 16.001  Y  -9.226      RR F50  M
25    L  X 18.001  Y  -9.137      RR F50  M
26    L  X 20.000  Y  -9.050      RR F50  M
27    L  X 22.000  Y  -8.966      RR F50  M
28    L  X 24.000  Y  -8.887      RR F50  M
29    L  X 26.000  Y  -8.812      RR F50  M
30    L  X 28.000  Y  -8.743      RR F50  M
31    L  X 29.999  Y  -8.680      RR F50  M
32    L  X 31.999  Y  -8.625      RR F50  M
33    L  X 33.999  Y  -8.579      RR F50  M
34    L  X 36.000  Y  -8.542      RR F50  M
35    L  X 38.000  Y  -8.515      RR F50  M
36    L  X 40.000  Y  -8.500      RR F50  M
37    L  X 42.000  Y  -8.497      RR F50  M
38    L  X 44.001  Y  -8.506      RR F50  M
39    L  X 46.001  Y  -8.528      RR F50  M
40    L  X 48.002  Y  -8.563      RR F50  M
41    L  X 50.002  Y  -8.611      RR F50  M
42    L  X 52.002  Y  -8.672      RR F50  M
43    L  X 54.002  Y  -8.746      RR F50  M
44    L  X 56.002  Y  -8.834      RR F50  M
45    L  X 58.001  Y  -8.935      RR F50  M
46    L  X 60.000  Y  -9.050      RR F50  M
47    L  X 61.999  Y  -9.179      RR F50  M
48    L  X 63.997  Y  -9.321      RR F50  M
49    L  X 65.996  Y  -9.476      RR F50  M
50    L  X 67.994  Y  -9.643      RR F50  M
51    L  X 69.993  Y  -9.821      RR F50  M
```

```
52   L  X 71.993  Y -10.009      RR F50  M
53   L  X 73.993  Y -10.206      RR F50  M
54   L  X 75.994  Y -10.413      RR F50  M
55   L  X 77.996  Y -10.628      RR F50  M
56   L  X 80.000  Y -10.850      RR F50  M
57   L  X 82.005  Y -11.079      RR F50  M
58   L  X 84.011  Y -11.316      RR F50  M
59   L  X 86.017  Y -11.560      RR F50  M
60   L  X 88.022  Y -11.813      RR F50  M
61   L  X 90.026  Y -12.076      RR F50  M
62   L  X 92.028  Y -12.348      RR F50  M
63   L  X 94.027  Y -12.631      RR F50  M
64   L  X 96.023  Y -12.925      RR F50  M
65   L  X 98.014  Y -13.231      RR F50  M
66   L  X100.000  Y -13.550      RR F50  M
67   L  X101.981  Y -13.882      RR F50  M
68   L  X103.959  Y -14.227      RR F50  M
69   L  X105.936  Y -14.585      RR F50  M
70   L  X107.916  Y -14.958      RR F50  M
71   L  X109.901  Y -15.345      RR F50  M
72   L  X111.894  Y -15.746      RR F50  M
73   L  X113.898  Y -16.162      RR F50  M
74   L  X115.915  Y -16.593      RR F50  M
75   L  X117.948  Y -17.039      RR F50  M
76   L  X120.000  Y -17.500      RR F50  M
77   L  X122.071  Y -17.977      RR F50  M
78   L  X124.154  Y -18.466      RR F50  M
79   L  X126.238  Y -18.965      RR F50  M
80   L  X128.312  Y -19.472      RR F50  M
81   L  X130.368  Y -19.983      RR F50  M
82   L  X132.394  Y -20.495      RR F50  M
83   L  X134.380  Y -21.005      RR F50  M
84   L  X136.317  Y -21.512      RR F50  M
85   L  X138.194  Y -22.011      RR F50  M
86   L  X140.000  Y -22.500      RR F50  M
87   L  X141.729  Y -22.977      RR F50  M
88   L  X143.386  Y -23.442      RR F50  M
89   L  X144.978  Y -23.897      RR F50  M
90   L  X146.514  Y -24.343      RR F50  M
91   L  X148.002  Y -24.781      RR F50  M
92   L  X149.450  Y -25.212      RR F50  M
93   L  X150.866  Y -25.639      RR F50  M
94   L  X152.257  Y -26.061      RR F50  M
95   L  X153.633  Y -26.481      RR F50  M
96   L  X155.000  Y -26.900      RR F50  M
97   CC X156.325  Y -24.200
98   C  X157.650  Y -21.500 DR+ RR F50  M
99  L  X157.650  Y -21.500     RR F50  M
100  L  X155.947  Y -20.264      RR F50  M
101  L  X154.241  Y -19.027      RR F50  M
102  L  X152.527  Y -17.787      RR F50  M
103  L  X150.802  Y -16.544      RR F50  M
104  L  X149.061  Y -15.297      RR F50  M
105  L  X147.302  Y -14.043      RR F50  M
106  L  X145.520  Y -12.783      RR F50  M
107  L  X143.711  Y -11.515      RR F50  M
108  L  X141.873  Y -10.238      RR F50  M
109  L  X140.000  Y  -8.950      RR F50  M
110  L  X138.091  Y  -7.652      RR F50  M
111  L  X136.149  Y  -6.346      RR F50  M
112  L  X134.179  Y  -5.038      RR F50  M
113  L  X132.185  Y  -3.731      RR F50  M
114  L  X130.173  Y  -2.429      RR F50  M
115  L  X128.147  Y  -1.137      RR F50  M
```

116	L	X126.111	Y	0.141	RR	F50	M
117	L	X124.072	Y	1.401	RR	F50	M
118	L	X122.033	Y	2.639	RR	F50	M
119	L	X120.000	Y	3.850	RR	F50	M
120	L	X117.976	Y	5.031	RR	F50	M
121	L	X115.960	Y	6.181	RR	F50	M
122	L	X113.953	Y	7.302	RR	F50	M
123	L	X111.951	Y	8.393	RR	F50	M
124	L	X109.955	Y	9.455	RR	F50	M
125	L	X107.962	Y	10.489	RR	F50	M
126	L	X105.971	Y	11.495	RR	F50	M
127	L	X103.981	Y	12.474	RR	F50	M
128	L	X101.991	Y	13.425	RR	F50	M
129	L	X100.000	Y	14.350	RR	F50	M
130	L	X 98.006	Y	15.249	RR	F50	M
131	L	X 96.009	Y	16.121	RR	F50	M
132	L	X 94.011	Y	16.967	RR	F50	M
133	L	X 92.011	Y	17.785	RR	F50	M
134	L	X 90.009	Y	18.576	RR	F50	M
135	L	X 88.007	Y	19.339	RR	F50	M
136	L	X 86.005	Y	20.073	RR	F50	M
137	L	X 84.002	Y	20.778	RR	F50	M
138	L	X 82.001	Y	21.454	RR	F50	M
139	L	X 80.000	Y	22.100	RR	F50	M
140	L	X 78.001	Y	22.716	RR	F50	M
141	L	X 76.002	Y	23.304	RR	F50	M
142	L	X 74.004	Y	23.864	RR	F50	M
143	L	X 72.007	Y	24.399	RR	F50	M
144	L	X 70.009	Y	24.909	RR	F50	M
145	L	X 68.010	Y	25.397	RR	F50	M
146	L	X 66.010	Y	25.863	RR	F50	M
147	L	X 64.009	Y	26.310	RR	F50	M
148	L	X 62.006	Y	26.738	RR	F50	M
149	L	X 60.000	Y	27.150	RR	F50	M
150	L	X 57.992	Y	27.545	RR	F50	M
151	L	X 55.982	Y	27.915	RR	F50	M
152	L	X 53.972	Y	28.254	RR	F50	M
153	L	X 51.963	Y	28.551	RR	F50	M
154	L	X 49.956	Y	28.799	RR	F50	M
155	L	X 47.953	Y	28.990	RR	F50	M
156	L	X 45.954	Y	29.113	RR	F50	M
157	L	X 43.962	Y	29.162	RR	F50	M
158	L	X 41.976	Y	29.127	RR	F50	M
159	L	X 40.000	Y	29.000	RR	F50	M
160	L	X 38.032	Y	28.779	RR	F50	M
161	L	X 36.070	Y	28.490	RR	F50	M
162	L	X 34.108	Y	28.164	RR	F50	M
163	L	X 32.142	Y	27.833	RR	F50	M
164	L	X 30.168	Y	27.530	RR	F50	M
165	L	X 28.180	Y	27.287	RR	F50	M
166	L	X 26.174	Y	27.135	RR	F50	M
167	L	X 24.145	Y	27.107	RR	F50	M
168	L	X 22.088	Y	27.235	RR	F50	M
169	L	X 20.000	Y	27.550	RR	F50	M
170	L	X 17.878	Y	27.681	RR	F50	M
171	L	X 15.738	Y	27.319	RR	F50	M
172	L	X 13.595	Y	26.592	RR	F50	M
173	L	X 11.467	Y	25.628	RR	F50	M
174	L	X 9.373	Y	24.554	RR	F50	M
175	L	X 7.328	Y	23.497	RR	F50	M
176	L	X 5.351	Y	22.586	RR	F50	M
177	L	X 3.459	Y	21.948	RR	F50	M
178	L	X 1.670	Y	21.710	RR	F50	M
179	L	X 0.000	Y	22.000	RR	F50	M

```
180  L  X -1.538  Y  22.277     RR F50  M
181  L  X -2.952  Y  22.005     RR F50  M
182  L  X -4.257  Y  21.320     RR F50  M
183  L  X -5.466  Y  20.358     RR F50  M
184  L  X -6.592  Y  19.255     RR F50  M
185  L  X -7.650  Y  18.147     RR F50  M
186  L  X -8.653  Y  17.169     RR F50  M
187  L  X -9.615  Y  16.458     RR F50  M
188  L  X-10.549  Y  16.150     RR F50  M
189  L  X-11.470  Y  16.380     RR F50  M
190  LBL 0
191  CALL LBL 1   REP  2       /2
192  CYCL DEF 7.0  DATUM SHIFT
193  CYCL DEF 7.1       X +0.000
194  CYCL DEF 7.2       Y +0.000
195  CYCL DEF 7.3       Z
196  Z   50.000                  RR F400  M
197  L  X 0.000  Y 0.000         RR F400  M05
198  STOP    M02
```

Appendix H

Relationship between I, I_P, T_{ON} and T_{OFF}

Effect Analysis using MINITAB.

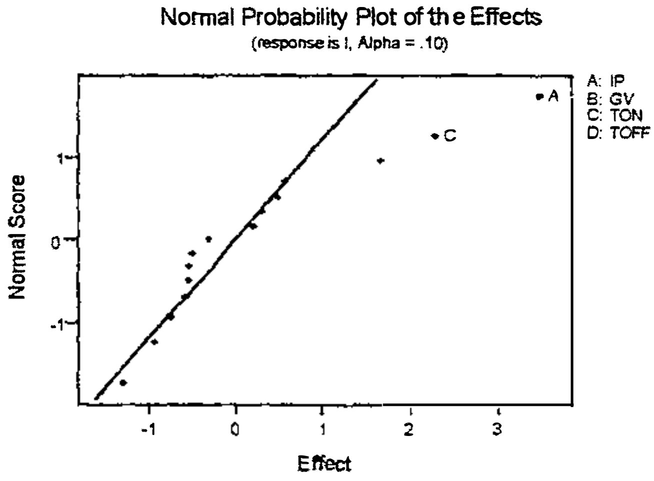
Fractional Factorial Fit

Estimated Effects and Coefficients for I

Term	Effect	Coef
Constant		2.7125
IP	3.4875	1.7437
GV	-0.7375	-0.3687
TON	2.3000	1.1500
TOFF	-1.2750	-0.6375
IP*GV	-0.5500	-0.2750
IP*TON	1.6625	0.8312
IP*TOFF	-0.9375	-0.4688
GV*TON	-0.5125	-0.2563
GV*TOFF	0.5875	0.2937
TON*TOFF	-0.6000	-0.3000
IP*GV*TON	-0.3250	-0.1625
IP*GV*TOFF	0.5000	0.2500
IP*TON*TOFF	-0.5625	-0.2812
GV*TON*TOFF	0.3125	0.1562
IP*GV*TON*TOFF	0.2250	0.1125

Analysis of Variance for I

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	4	78.489	78.4887	19.6222	**	
2-Way Interactions	6	19.652	19.6525	3.2754	**	
3-Way Interactions	4	3.079	3.0788	0.7697	**	
4-Way Interactions	1	0.203	0.2025	0.2025	**	
Residual Error	0	0.000	0.0000	0.0000		
Total	15	101.422				



Fractional Factorial Fit

Estimated Effects and Coefficients for I

Term	Effect	Coef	StDev Coef	T	P
Constant		2.7125	0.2025	13.39	0.000
IP	3.4875	1.7437	0.2025	8.61	0.000
GV	-0.7375	-0.3687	0.2025	-1.82	0.128
TON	2.3000	1.1500	0.2025	5.68	0.002
TOFF	-1.2750	-0.6375	0.2025	-3.15	0.025
IP*GV	-0.5500	-0.2750	0.2025	-1.36	0.233
IP*TON	1.6625	0.8312	0.2025	4.10	0.009
IP*TOFF	-0.9375	-0.4688	0.2025	-2.31	0.069
GV*TON	-0.5125	-0.2563	0.2025	-1.27	0.262
GV*TOFF	0.5875	0.2937	0.2025	1.45	0.207
TON*TOFF	-0.6000	-0.3000	0.2025	-1.48	0.199

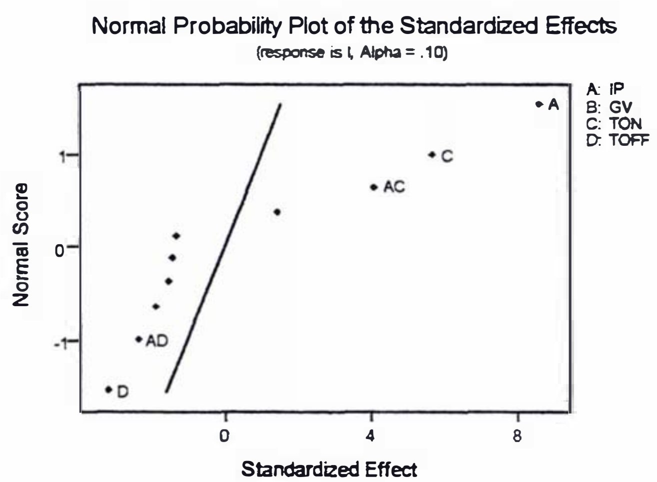
Analysis of Variance for I

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	4	78.489	78.489	19.6222	29.90	0.001
2-Way Interactions	6	19.652	19.652	3.2754	4.99	0.049
Residual Error	5	3.281	3.281	0.6563		
Total	15	101.422				

Unusual Observations for I

Obs	I	Fit	StDev Fit	Residual	St Resid
6	10.0000	9.0375	0.6717	0.9625	2.13R

R denotes an observation with a large standardized residual



Regression Analysis

Model 1.0

The regression equation is
LogeI = - 1.88 + 1.20 LogeIP + 0.210 LogeTON - 0.302 LogeTOFF

Predictor	Coef	StDev	T	P
Constant	-1.8773	0.1322	-14.20	0.000
LogeIP	1.20176	0.04637	25.92	0.000
LogeTON	0.20955	0.01579	13.27	0.000
LogeTOFF	-0.30209	0.02948	-10.25	0.000

S = 0.1548   R-Sq = 95.1%   R-Sq(adj) = 94.8%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	23.3784	7.7928	325.39	0.000
Error	50	1.1974	0.0239		
Total	53	24.5758			

Source	DF	Seq SS
LogeIP	1	15.4947
LogeTON	1	5.3683
LogeTOFF	1	2.5153

Unusual Observations

Obs	LogeIP	LogeI	Fit	StDev Fit	Residual	St Resid
8	1.79	0.9163	1.2410	0.0458	-0.3247	-2.20R
39	2.30	0.1823	0.6768	0.0592	-0.4945	-3.46R

R denotes an observation with a large standardized residual

Model 1.1

Regression Analysis

The regression equation is
LogeI = - 2.10 + 1.21 LogeIP + 0.233 LogeTON/TOFF

Predictor	Coef	StDev	T	P
Constant	-2.0983	0.1071	-19.59	0.000
LogeIP	1.20690	0.04889	24.68	0.000
LogeTON/	0.23303	0.01370	17.01	0.000

S = 0.1633   R-Sq = 94.5%   R-Sq(adj) = 94.2%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	2	23.215	11.608	435.13	0.000
Error	51	1.361	0.027		
Total	53	24.576			

Source	DF	Seq SS
LogeIP	1	15.495
LogeTON/	1	7.721

Unusual Observations

Obs	LogeIP	LogeI	Fit	StDev Fit	Residual	St Resid
39	2.30	0.1823	0.6807	0.0625	-0.4984	-3.30R
40	1.10	-0.6931	-0.7724	0.0685	0.0792	0.53 X

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.

Appendix I

Effect analysis using MINITAB release 10 for P_R and S_R

I_P	G_V	T_{ON} (usec)	T_{OFF} (usec)	P_R (mm/min)	S_R (umRs)
3	2	10	3	0.078	2.75
10	2	10	3	0.196	5.00
3	9	10	3	0.095	2.75
10	9	10	3	0.212	4.65
3	2	600	3	0.272	11.25
10	2	600	3	1.369	19.00
3	9	600	3	0.198	13.00
10	9	600	3	0.911	12.50
3	2	10	10	0.034	2.85
10	2	10	10	0.171	5.25
3	9	10	10	0.056	3.55
10	9	10	10	0.189	4.40
3	2	600	10	0.182	10.00
10	2	600	10	0.748	18.00
3	9	600	10	0.152	10.50
10	9	600	10	0.608	19.00

Analysis for P_R

```
MTB > Name C21 'FITS8' C22 'EFFE8'
MTB > FFactorial 'PR' = C1 C2 C3 C4 C1*C2 C1*C3 C1*C4 C2*C3 C2*C4 C3*C4
C1*C2*C3 &
CONT> C1*C2*C4 C1*C3*C4 C2*C3*C4 C1*C2*C3*C4;
SUBC>   GEffects 0.9;
SUBC>   RType 1;
SUBC>   Alias;
SUBC>   Fits 'FITS8';
SUBC>   Effects 'EFFE8'.
```

Fractional Factorial Fit

Estimated Effects and Coefficients for PR

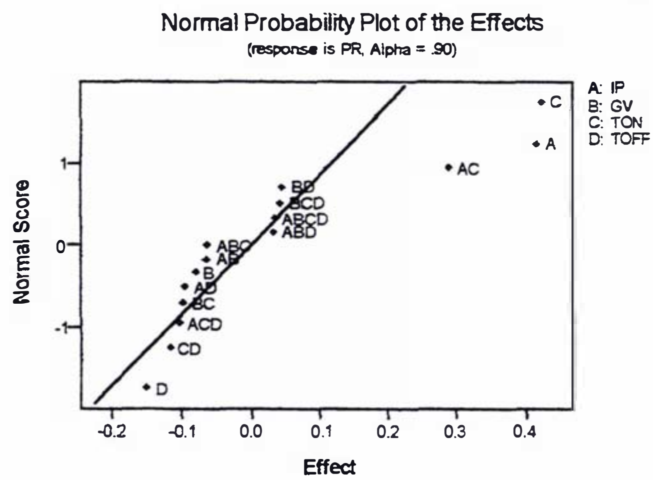
Term	Effect	Coef
Constant		0.34194
IP	0.41713	0.20856
GV	-0.07863	-0.03931
TON	0.42613	0.21306
TOFF	-0.14887	-0.07444
IP*GV	-0.06238	-0.03119
IP*TON	0.29088	0.14544
IP*TOFF	-0.09412	-0.04706
GV*TON	-0.09687	-0.04844
GV*TOFF	0.04613	0.02306
TON*TOFF	-0.11613	-0.05806
IP*GV*TON	-0.06113	-0.03056
IP*GV*TOFF	0.03388	0.01694
IP*TON*TOFF	-0.10288	-0.05144
GV*TON*TOFF	0.04438	0.02219
IP*GV*TON*TOFF	0.03462	0.01731

Analysis of Variance for PR

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	4	1.53569	1.53569	0.383921	**	
2-Way Interactions	6	0.48942	0.48942	0.081570	**	
3-Way Interactions	4	0.06974	0.06974	0.017436	**	
4-Way Interactions	1	0.00480	0.00480	0.004796	**	
Residual Error	0	0.00000	0.00000	0.000000		
Total	15	2.09965				

Alias Structure

I
IP
GV
TON
TOFF
IP*GV
IP*TON
IP*TOFF
GV*TON
GV*TOFF
TON*TOFF
IP*GV*TON
IP*GV*TOFF
IP*TON*TOFF
GV*TON*TOFF
IP*GV*TON*TOFF



Effects of two way interactions

```
MTB > Name C25 'FITS10' C26 'EFFE10'
MTB > FFactorial 'PR' = C1 C2 C3 C4 C1*C2 C1*C3 C1*C4 C2*C3 C2*C4 C3*C4;
SUBC>   GEffects 0.9;
SUBC>   RType 1;
SUBC>   Alias;
SUBC>   Fits 'FITS10';
SUBC>   Effects 'EFFE10'.
```

Fractional Factorial Fit

Estimated Effects and Coefficients for PR

Term	Effect	Coef	StDev Coef	T	P
Constant		0.34194	0.03052	11.20	0.000
IP	0.41713	0.20856	0.03052	6.83	0.001
GV	-0.07863	-0.03931	0.03052	-1.29	0.254
TON	0.42613	0.21306	0.03052	6.98	0.001
TOFF	-0.14887	-0.07444	0.03052	-2.44	0.059
IP*GV	-0.06238	-0.03119	0.03052	-1.02	0.354
IP*TON	0.29088	0.14544	0.03052	4.76	0.005
IP*TOFF	-0.09412	-0.04706	0.03052	-1.54	0.184
GV*TON	-0.09687	-0.04844	0.03052	-1.59	0.173
GV*TOFF	0.04612	0.02306	0.03052	0.76	0.484
TON*TOFF	-0.11613	-0.05806	0.03052	-1.90	0.116

Analysis of Variance for PR

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	4	1.53569	1.53569	0.38392	25.75	0.002
2-Way Interactions	6	0.48942	0.48942	0.08157	5.47	0.041
Residual Error	5	0.07454	0.07454	0.01491		
Total	15	2.09965				

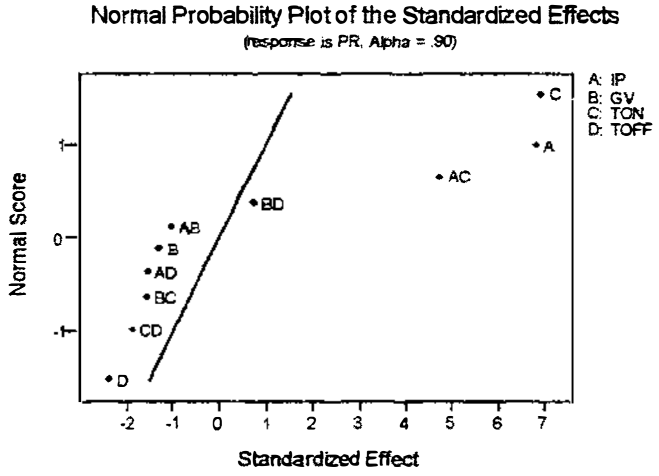
Unusual Observations for PR

Obs	PR	Fit	StDev Fit	Residual	St Resid
6	1.36900	1.23056	0.10124	0.13844	2.03R

R denotes an observation with a large standardized residual

Alias Structure

I
IP
GV
TON
TOFF
IP*GV
IP*TON
IP*TOFF
GV*TON
GV*TOFF
TON*TOFF



Analysis For S_R

```
MTB > FFactorial 'SR' = C1 C2 C3 C4 C1*C2 C1*C3 C1*C4 C2*C3 C2*C4 C3*C4
C1*C2*C3 &
CONT> C1*C2*C4 C1*C3*C4 C2*C3*C4 C1*C2*C3*C4;
SUBC>   GEffects 0.9;
SUBC>   RType 1;
SUBC>   Alias.
```

Fractional Factorial Fit

Estimated Effects and Coefficients for SR

Term	Effect	Coef
Constant		9.0281
IP	3.8938	1.9469
GV	-0.4687	-0.2344
TON	10.2562	5.1281
TOFF	0.3313	0.1656
IP*GV	-1.2063	-0.6031
IP*TON	2.0437	1.0219
IP*TOFF	1.0438	0.5219
GV*TON	-0.3437	-0.1719
GV*TOFF	0.8062	0.4031
TON*TOFF	0.1063	0.0531
IP*GV*TON	-0.7312	-0.3656
IP*GV*TOFF	0.9438	0.4719
IP*TON*TOFF	1.2688	0.6344
GV*TON*TOFF	0.7563	0.3781
IP*GV*TON*TOFF	1.2438	0.6219

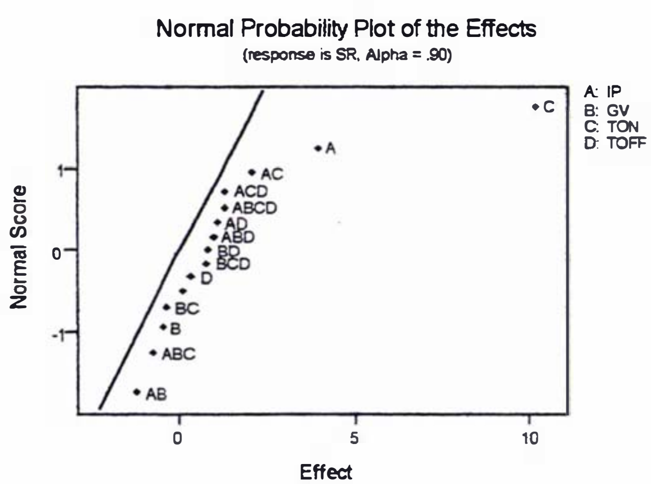
Analysis of Variance for SR

Source	DF	Seq SS	Adj SS	Adj MS	F	P

Main Effects	4	482.726	482.726	120.681	**
2-Way Interactions	6	30.003	30.003	5.001	**
3-Way Interactions	4	14.428	14.428	3.607	**
4-Way Interactions	1	6.188	6.188	6.188	**
Residual Error	0	0.000	0.000	0.000	
Total	15	533.345			

Alias Structure

I
IP
GV
TON
TOFF
IP*GV
IP*TON
IP*TOFF
GV*TON
GV*TOFF
TON*TOFF
IP*GV*TON
IP*GV*TOFF
IP*TON*TOFF
GV*TON*TOFF
IP*GV*TON*TOFF



Effects of two way interactions

```
MTB > FFactorial 'SR' = C1 C2 C3 C4 C1*C2 C1*C3 C1*C4 C2*C3 C2*C4 C3*C4;
SUBC>   GEffects 0.9;
SUBC>   RType 1;
SUBC>   Alias.
```

Fractional Factorial Fit

Estimated Effects and Coefficients for SR

Term	Effect	Coef	StDev Coef	T	P
Constant		9.0281	0.5076	17.78	0.000
IP	3.8938	1.9469	0.5076	3.84	0.012
GV	-0.4687	-0.2344	0.5076	-0.46	0.664
TON	10.2562	5.1281	0.5076	10.10	0.000
TOFF	0.3313	0.1656	0.5076	0.33	0.757
IP*GV	-1.2062	-0.6031	0.5076	-1.19	0.288
IP*TON	2.0437	1.0219	0.5076	2.01	0.100
IP*TOFF	1.0438	0.5219	0.5076	1.03	0.351
GV*TON	-0.3437	-0.1719	0.5076	-0.34	0.749
GV*TOFF	0.8063	0.4031	0.5076	0.79	0.463
TON*TOFF	0.1063	0.0531	0.5076	0.10	0.921

Analysis of Variance for SR

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	4	482.73	482.73	120.681	29.27	0.001
2-Way Interactions	6	30.00	30.00	5.001	1.21	0.425
Residual Error	5	20.62	20.62	4.123		
Total	15	533.34				

Unusual Observations for SR

Obs	SR	Fit	StDev Fit	Residual	St Resid
8	12.5000	14.9719	1.6836	-2.4719	-2.18R

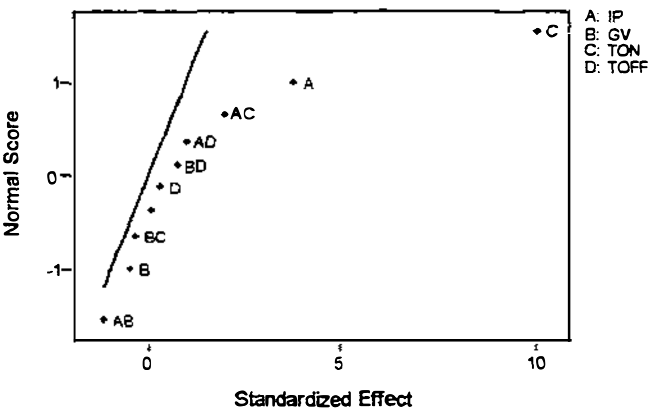
R denotes an observation with a large standardized residual

Alias Structure

I
IP
GV
TON
TOFF
IP*GV
IP*TON
IP*TOFF
GV*TON
GV*TOFF
TON*TOFF

Normal Probability Plot of the Standardized Effects

(response is SR, Alpha = .90)



Appendix J

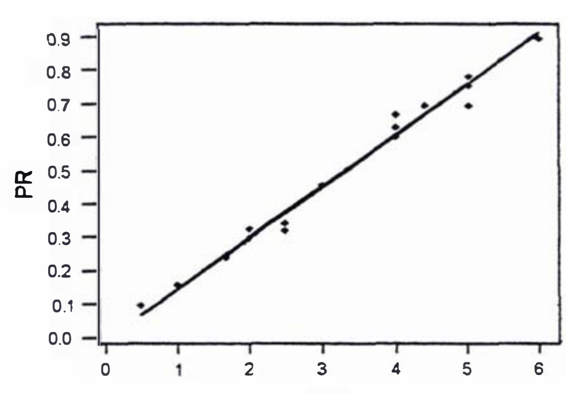
Regression Analysis using MINITAB for P_R

PR Vs (I/A)

```
MTB > Name c3 = 'FITS1'
MTB > Regress c1 1 c2;
SUBC>   Fits 'FITS1';
SUBC>   Constant.
```

Regression Analysis

```
The regression equation is
PR = - 0.0055 + 0.152 (I/A)

Predictor        Coef        StDev          T        P
Constant     -0.00554      0.01827      -0.30    0.766
(I/A)        0.152416     0.005141      29.65    0.000

S = 0.03318     R-Sq = 98.3%     R-Sq(adj) = 98.2%

Analysis of Variance

Source        DF          SS          MS         F        P
Regression     1     0.96753     0.96753    879.06    0.000
Error         15     0.01651     0.00110
Total         16     0.98404

Unusual Observations
Obs      (I/A)        PR         Fit   StDev Fit    Residual     St Resid
  7       5.00   0.69400     0.75654     0.01230    -0.06254       -2.03R
 11       4.00   0.66900     0.60413     0.00906     0.06487        2.03R

R denotes an observation with a large standardized residual
```



Plot j1 P_R Vs (I/A)

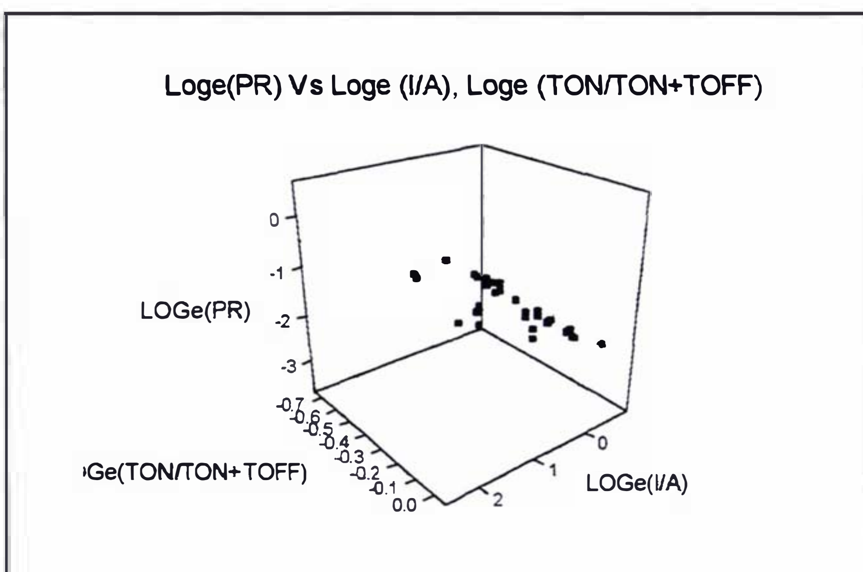
P_R (mm/min)	(I/A) (Amp/cm^2)	B	A	Loge(P_R)	Loge(I/A)	Loge(B)	Loge(A)
0.608	4.500	0.984	60.000	-0.49758	1.50408	-0.016129	4.09434
0.911	6.250	0.995	200.000	-0.09321	1.83258	-0.005013	5.29832
0.189	2.000	0.500	1.000	-1.66601	0.69315	-0.693147	0.00000
0.212	2.500	0.769	3.333	-1.55117	0.91629	-0.262664	1.20387
0.748	5.000	0.984	60.000	-0.29035	1.60944	-0.016129	4.09434
1.369	10.000	0.995	200.000	0.31408	2.30259	-0.005013	5.29832
0.171	1.900	0.500	1.000	-1.76609	0.64185	-0.693147	0.00000
0.196	3.500	0.769	3.333	-1.62964	1.25276	-0.262664	1.20387
0.152	1.000	0.984	60.000	-1.88387	0.00000	-0.016129	4.09434
0.198	1.200	0.995	200.000	-1.61949	0.18232	-0.005013	5.29832
0.056	0.500	0.500	1.000	-2.88240	-0.69315	-0.693147	0.00000
0.095	0.800	0.769	3.333	-2.35388	-0.22314	-0.262664	1.20387
0.182	1.200	0.984	60.000	-1.70375	0.18232	-0.016129	4.09434
0.272	1.750	0.995	200.000	-1.30195	0.55962	-0.005013	5.29832
0.034	0.500	0.500	1.000	-3.38139	-0.69315	-0.693147	0.00000
0.078	0.800	0.769	3.333	-2.55105	-0.22314	-0.262664	1.20387
0.600	4.000	0.971	33.333	-0.51083	1.38629	-0.029429	3.50655
0.693	4.400	0.971	33.333	-0.36673	1.48160	-0.029429	3.50655
0.238	1.667	0.971	33.333	-1.43548	0.51103	-0.029429	3.50655
0.243	1.667	0.971	33.333	-1.41469	0.51103	-0.029429	3.50655
0.315	2.500	0.971	33.333	-1.15518	0.91629	-0.029429	3.50655
0.340	2.500	0.971	33.333	-1.07881	0.91629	-0.029429	3.50655
0.694	5.000	0.971	33.333	-0.36528	1.60944	-0.029429	3.50655
0.758	5.000	0.971	33.333	-0.27707	1.60944	-0.029429	3.50655
0.782	5.000	0.971	33.333	-0.24590	1.60944	-0.029429	3.50655
0.296	2.000	0.971	33.333	-1.21740	0.69315	-0.029429	3.50655
0.669	4.000	0.971	33.333	-0.40197	1.38629	-0.029429	3.50655
0.630	4.000	0.971	33.333	-0.46204	1.38629	-0.029429	3.50655
0.896	6.000	0.971	33.333	-0.10981	1.79176	-0.029429	3.50655
0.151	1.000	0.971	33.333	-1.89048	0.00000	-0.029429	3.50655
0.321	2.000	0.971	33.333	-1.13631	0.69315	-0.029429	3.50655
0.452	3.000	0.971	33.333	-0.79407	1.09861	-0.029429	3.50655
0.094	0.500	0.971	33.333	-2.36446	-0.69315	-0.029429	3.50655

Where $A = (T_{ON}/T_{OFF})$ and $B= (T_{ON})/(T_{ON}+T_{OFF})$

```
MTB > Let c5 =  LOGE(c1)
MTB > Let c6 =  LOGE(c2)
MTB > Let c7 =  LOGE(c3)
MTB > Let c8 =  LOGE(c4)
MTB > Regress 'LOGe(PR)' 2 'LOGe(I/A)' 'LOGe(TON/TON+TOFF)';
SUBC>   Constant.
```

Regression Analysis

```
The regression equation is
LOGe(PR) = - 1.85 + 0.944 LOGe(I/A) + 0.976 LOGe(TON/TON+TOFF)

Predictor        Coef       StDev          T        P
Constant     -1.84948     0.05948     -31.10    0.000
LOGe(I/A      0.94391     0.04538      20.80    0.000
LOGe(TON       0.9760      0.1607       6.08    0.000

S = 0.1830      R-Sq = 96.1%     R-Sq(adj) = 95.8%

Analysis of Variance

Source        DF          SS          MS         F        P
Regression     2      24.444      12.222    364.96    0.000
Error         30       1.005       0.033
Total         32      25.448

Source        DF      Seq SS
LOGe(I/A       1      23.208
LOGe(TON       1       1.236

Unusual Observations
Obs  LOGe(I/A  LOGe(PR)        Fit  StDev Fit   Residual    St Resid
  8      1.25   -1.6296    -0.9233     0.0471    -0.7063      -3.99R

R denotes an observation with a large standardized residual
```

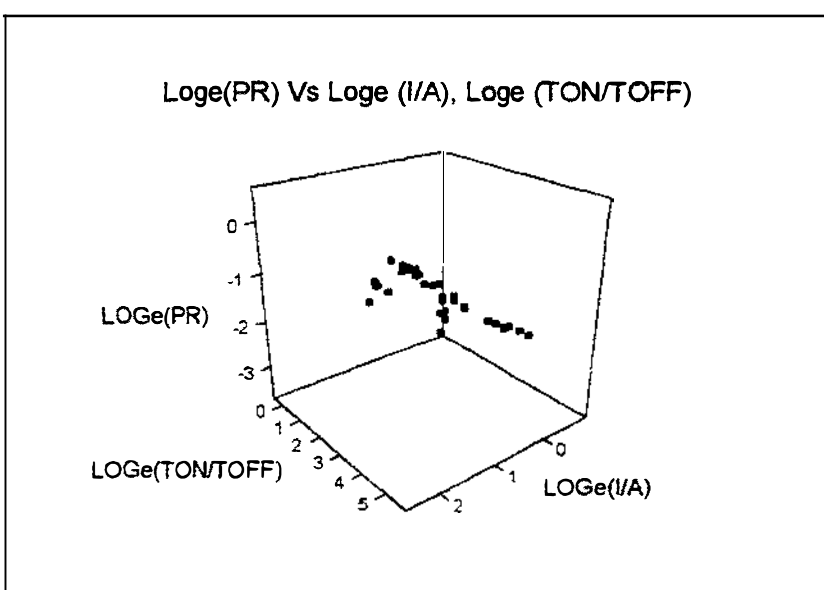


Plot j2 $\text{Log}_e\, P_R$ Vs Log_e (I/A), $\text{Log}_e\, (T_{ON}/T_{ON}+T_{OFF})$

```
MTB > Regress 'LOGe(PR)' 2 'LOGe(I/A)' 'LOGe(TON/TOFF)';
SUBC>   Constant.
```

Regression Analysis

```
The regression equation is
LOGe(PR) = - 2.43 + 0.937 LOGe(I/A) + 0.148 LOGe(TON/TOFF)

Predictor        Coef         StDev          T        P
Constant     -2.43125       0.06613     -36.77    0.000
LOGe(I/A      0.93681       0.04207      22.27    0.000
LOGe(TON      0.14791       0.02137       6.92    0.000

S = 0.1696      R-Sq = 96.6%     R-Sq(adj) = 96.4%

Analysis of Variance

Source         DF          SS          MS         F        P
Regression      2      24.586      12.293    427.41    0.000
Error          30       0.863       0.029
Total          32      25.448

Source         DF      Seq SS
LOGe(I/A        1      23.208
LOGe(TON        1       1.378

Unusual Observations
Obs  LOGe(I/A   LOGe(PR)        Fit  StDev Fit    Residual     St Resid
  8      1.25    -1.6296    -1.0796     0.0593     -0.5501       -3.46R

R denotes an observation with a large standardized residual
```



Plot j3- $\log_e P_R$ Vs $\log_e (I/A)$, $\log_e (T_{ON}/T_{OFF})$

Appendix K

Regression Analysis using MINITAB release 10 for S_R

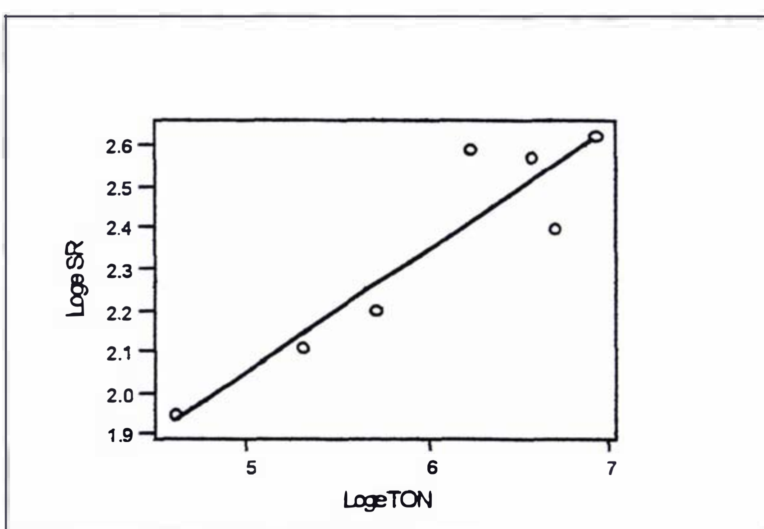
Experimental observations measured by METCAL

S_R Vs T_{ON}

I_P=6, T_{OFF}=1

S_R	T_{ON}	$Log_e S_R$	$Log_e T_{ON}$
7.00	100	1.94591	4.60517
8.25	200	2.11021	5.29832
9.00	300	2.19722	5.70378
13.25	500	2.58400	6.21461
13.00	700	2.56495	6.55108
11.00	800	2.39790	6.68461
13.75	1000	2.62104	6.90776

Table k1 S_R Vs T_{ON}




```
MTB > Let C3 =  LOGE(SR)
MTB > Let C4 =  LOGE(TON)
MTB > Regress 'LOG e SR' 1 'LOGETON';
SUBC>   Constant.
```

Regression Analysis

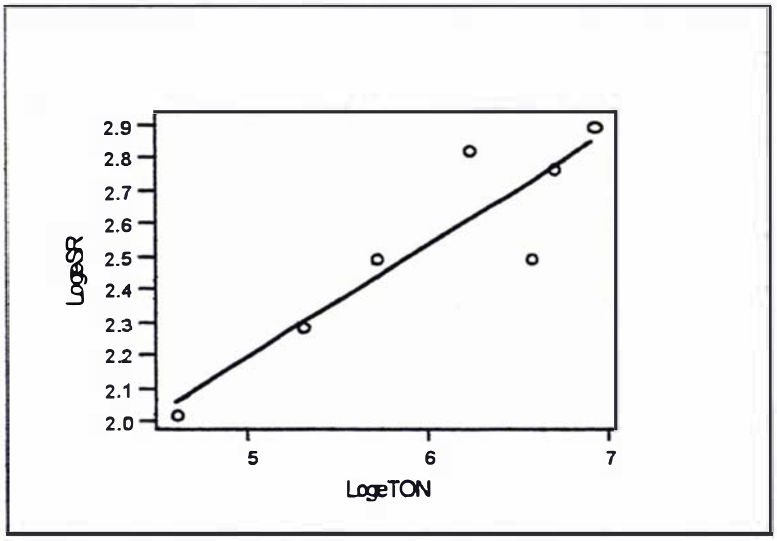
```
The regression equation is
LOG e SR = 0.585 + 0.294 LOGETON

Predictor        Coef       StDev          T        P
Constant       0.5846      0.3270       1.79    0.134
LOGETON       0.29379     0.05409       5.43    0.003

S = 0.1104      R-Sq = 85.5%     R-Sq(adj) = 82.6%

Analysis of Variance

Source       DF          SS          MS         F        P
Regression    1     0.35975     0.35975     29.50    0.003
Error         5     0.06098     0.01220
Total         6     0.42072


MTB >
```

S_R Vs T_{ON}

T_{OFF}=10, I_P= 6

S_R	T_{ON}	$Log_e S_R$	$Log_e T_{ON}$
7.50	100	2.01490	4.60517
9.75	200	2.27727	5.29832
12.00	300	2.48491	5.70378
16.75	500	2.81840	6.21461
12.00	700	2.48491	6.55108
15.75	800	2.75684	6.68461
18.00	1000	2.89037	6.90776

Table k2 S_R Vs T_{ON}



Plot K2 $LogeS_R$ Vs $LogeT_{ON}$

```
MTB > Let C3 =  LOGE(SR)
MTB > Let 'LOGETON' =  LOGE(ton)
MTB > Regress 'LOG e SR' 1 'LOGETON';
SUBC>   Constant.
```

Regression Analysis

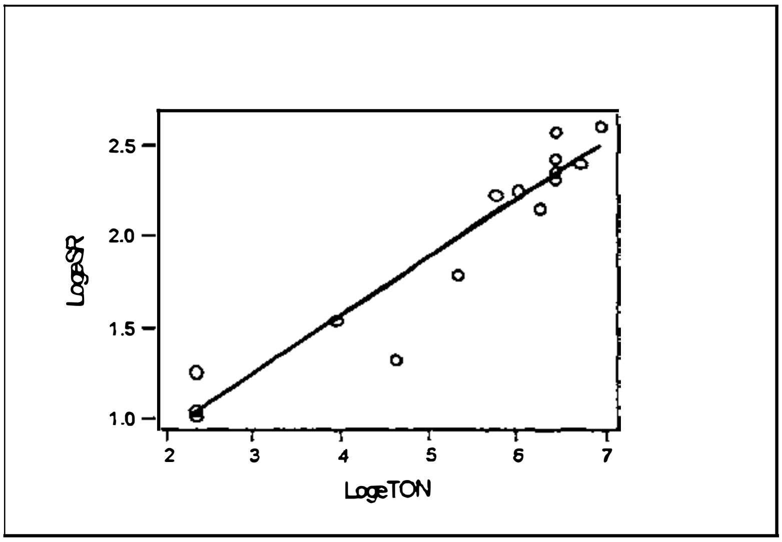
```
The regression equation is
LOG e SR = 0.477 + 0.343 LOGETON

Predictor       Coef        StDev          T        P
Constant      0.4775       0.4351       1.10    0.322
LOGETON      0.34279      0.07198       4.76    0.005

S = 0.1469      R-Sq = 81.9%     R-Sq(adj) = 78.3%

Analysis of Variance

Source       DF         SS          MS        F        P
Regression    1    0.48975     0.48975    22.68    0.005
Error         5    0.10797     0.02159
Total         6    0.59772
```

S_R Vs T_{ON}

I_P=3, T_{OFF}=10

S_R	T_{ON}	$Log_e S_R$	$Log_e T_{ON}$
4.625	50	1.53148	3.91202
3.750	100	1.32176	4.60517
6.000	200	1.79176	5.29832
9.250	300	2.22462	5.70378
9.500	400	2.25129	5.99146
8.625	500	2.15466	6.21461
11.000	800	2.39790	6.68461
13.500	1000	2.60269	6.90776
10.500	600	2.35138	6.39693
13.000	600	2.56495	6.39693
10.000	600	2.30259	6.39693
11.250	600	2.42037	6.39693
3.550	10	1.26695	2.30259
2.750	10	1.01160	2.30259
2.850	10	1.04732	2.30259
2.750	10	1.01160	2.30259

Table k3 S_R Vs T_{ON}



Plot k3 S_R Vs T_{ON}

```
MTB > Let c3 =  LOGE(c1)
MTB > Let c4 =  LOGE(c2)
MTB > Regress 'LOG e SR' 1  'LOGETON';
SUBC>   Constant.
```

Regression Analysis

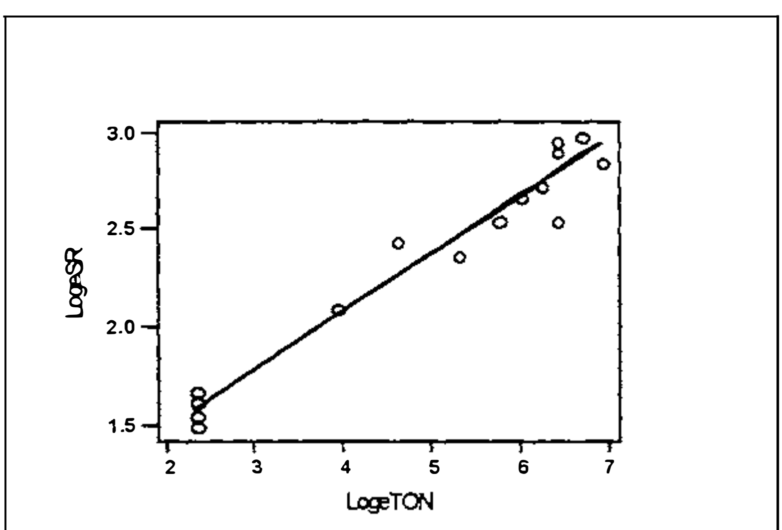
```
The regression equation is
LOG e SR = 0.286 + 0.321 LOGETON

Predictor        Coef       StDev          T        P
Constant       0.2857      0.1283       2.23    0.043
LOGETON       0.32056     0.02422      13.23    0.000

S = 0.1674      R-Sq = 92.6%     R-Sq(adj) = 92.1%


Analysis of Variance

Source        DF          SS          MS         F        P
Regression     1      4.9085      4.9085    175.13    0.000
Error         14      0.3924      0.0280
Total         15      5.3009

Unusual Observations
Obs  LOGETON   LOG e SR        Fit  StDev Fit   Residual    St Resid
  2     4.61     1.3218     1.7619     0.0430    -0.4402      -2.72R

R denotes an observation with a large standardized residual
```

S_R Vs T_{ON}

I_P= 10, T_{OFF}= 10

S_R	T_{ON}	$Log_e S_R$	$Log_e T_{ON}$
8.00	50	2.07944	3.91202
11.25	100	2.42037	4.60517
10.50	200	2.35138	5.29832
12.50	300	2.52573	5.70378
14.25	400	2.65676	5.99146
15.00	500	2.70805	6.21461
19.50	800	2.97041	6.68461
17.00	1000	2.83321	6.90776
19.00	600	2.94444	6.39693
12.50	600	2.52573	6.39693
18.00	600	2.89037	6.39693
19.00	600	2.94444	6.39693
4.40	10	1.48160	2.30259
4.65	10	1.53687	2.30259
5.25	10	1.65823	2.30259
5.00	10	1.60944	2.30259

Table k4 S_R Vs T_{ON}



Plot k4 $Log_e S_R$ Vs $Log_e T_{ON}$

```
MTB > Let c3 =  LOGE(c1)
MTB > Let c4 =  LOGE(c2)
MTB > Regress 'LOG e SR' 1  'LOGETON';
SUBC>   Constant.
```

Regression Analysis

```
The regression equation is
LOG e SR = 0.900 + 0.296 LOGETON

Predictor        Coef        StDev           T        P
Constant      0.89994      0.09390        9.58    0.000
LOGETON       0.29629      0.01773       16.71    0.000

S = 0.1225      R-Sq = 95.2%     R-Sq(adj) = 94.9%

Analysis of Variance

Source         DF          SS          MS          F        P
Regression      1      4.1935      4.1935     279.36    0.000
Error          14      0.2102      0.0150
Total          15      4.4036

Unusual Observations
Obs    LOGETON   LOG e SR         Fit   StDev Fit    Residual    St Resid
 10       6.40     2.5257      2.7953      0.0393     -0.2696      -2.32R

R denotes an observation with a large standardized residual
```

SR (umRs)	TON (usec)	(I/A) (Amp/cm^2)	(TON)/(TON+TOFF)	LOGe SR	LOGe TON	LOGe(I/A)	LOGe(TON)/(TON+TOFF)
19.000	600	2.250	0.984	2.94444	6.39693	0.81093	-0.016129
12.500	600	3.125	0.995	2.52573	6.39693	1.13943	-0.005013
4.400	10	1.000	0.500	1.48160	2.30259	0.00000	-0.693147
4.650	10	1.250	0.769	1.53687	2.30259	0.22314	-0.262664
18.000	600	2.500	0.984	2.89037	6.39693	0.91629	-0.016129
19.000	600	5.000	0.995	2.94444	6.39693	1.60944	-0.005013
5.250	10	0.950	0.500	1.65823	2.30259	-0.05129	-0.693147
5.000	10	1.750	0.769	1.60944	2.30259	0.55962	-0.262664
10.500	600	0.500	0.984	2.35138	6.39693	-0.69315	-0.016129
13.000	600	0.600	0.995	2.56495	6.39693	-0.51083	-0.005013
3.550	10	0.250	0.500	1.26695	2.30259	-1.38629	-0.693147
2.750	10	0.400	0.769	1.01160	2.30259	-0.91629	-0.262664
10.000	600	0.600	0.984	2.30259	6.39693	-0.51083	-0.016129
11.250	600	0.875	0.995	2.42037	6.39693	-0.13353	-0.005013
2.850	10	0.250	0.500	1.04732	2.30259	-1.38629	-0.693147

2.750	10	0.400	0.769	1.01160	2.30259	-0.91629	-0.262664
7.500	100	1.000	0.909	2.01490	4.60517	0.00000	-0.095410
9.750	200	1.000	0.952	2.27727	5.29832	0.00000	-0.049190
12.000	300	1.400	0.968	2.48491	5.70378	0.33647	-0.032523
16.750	500	1.400	0.980	2.81840	6.21461	0.33647	-0.020203
12.000	700	1.250	0.986	2.48491	6.55108	0.22314	-0.014099
15.750	800	1.250	0.988	2.75684	6.68461	0.22314	-0.012073
18.000	1000	1.250	0.990	2.89037	6.90776	0.22314	-0.010050
7.000	100	2.050	0.990	1.94591	4.60517	0.71784	-0.010050
8.250	200	2.100	0.995	2.11021	5.29832	0.74194	-0.005013
9.000	300	2.250	0.997	2.19722	5.70378	0.81093	-0.003005
13.250	500	2.400	0.998	2.58400	6.21461	0.87547	-0.002002
13.000	700	2.450	0.999	2.56495	6.55108	0.89609	-0.001001
11.000	800	2.500	0.999	2.39790	6.68461	0.91629	-0.001001
13.750	1000	3.000	0.999	2.62104	6.90776	1.09861	-0.001001
8.000	50	1.875	0.943	2.07944	3.91202	0.62861	-0.058689
11.250	100	2.500	0.971	2.42037	4.60517	0.91629	-0.029429
10.500	200	2.500	0.985	2.35138	5.29832	0.91629	-0.015114
12.500	300	2.750	0.990	2.52573	5.70378	1.01160	-0.010050
14.250	400	2.750	0.993	2.65676	5.99146	1.01160	-0.007025
15.000	500	2.750	0.994	2.70805	6.21461	1.01160	-0.006018
19.500	800	3.250	0.996	2.97041	6.68461	1.17865	-0.004008
17.000	1000	3.500	0.997	2.83321	6.90776	1.25276	-0.003005
4.625	50	0.500	0.943	1.53148	3.91202	-0.69315	-0.058689
3.750	100	0.600	0.971	1.32176	4.60517	-0.51083	-0.029429
6.000	200	0.650	0.985	1.79176	5.29832	-0.43078	-0.015114
9.250	300	0.750	0.990	2.22462	5.70378	-0.28768	-0.010050
9.500	400	0.750	0.993	2.25129	5.99146	-0.28768	-0.007025
8.625	500	0.750	0.994	2.15466	6.21461	-0.28768	-0.006018
11.000	800	0.750	0.996	2.39790	6.68461	-0.28768	-0.004008
13.500	1000	0.825	0.997	2.60269	6.90776	-0.19237	-0.003005
2.875	10	0.350	0.500	1.05605	2.30259	-1.04982	-0.693147

13.000	600	1.000	0.984	2.56495	6.39693	0.00000	-0.016129
4.750	10	0.600	0.500	1.55814	2.30259	-0.51083	-0.693147
15.500	600	2.100	0.984	2.74084	6.39693	0.74194	-0.016129
16.000	600	1.250	0.984	2.77259	6.39693	0.22314	-0.016129
13.750	600	1.250	0.984	2.62104	6.39693	0.22314	-0.016129

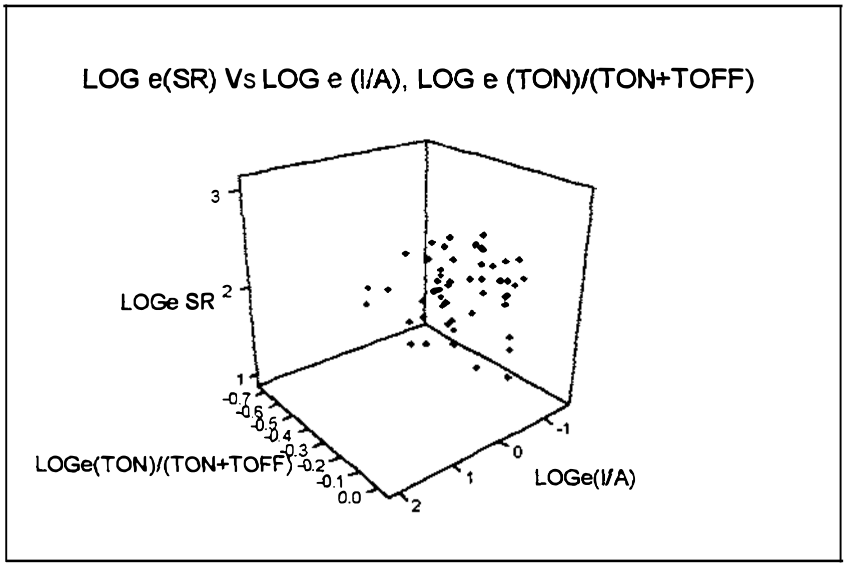
Table k5 S_R Vs (I/A), (T_{ON}), (T_{ON})/(T_{ON}+T_{OFF})

S_R Vs (I/A) and (T_{ON})/[(T_{ON}+T_{OFF})]

```
MTB > Let c5 =  LOGE(c1)
MTB > Let c6 =  LOGE(c2)
MTB > Let c7 =  LOGE(c3)
MTB > Let c8 =  LOGE(c4)
MTB > Regress C5 2 'LOGe(I/A)' 'LOGe(TON)/(TON+TOFF)';
SUBC>   Constant.
```

Regression Analysis

```
The regression equation is
LOGe SR = 2.30 + 0.344 LOGe(I/A) + 1.24 LOGe(TON)/(TON+TOFF)

Predictor        Coef       StDev          T        P
Constant      2.29707     0.06048      37.98    0.000
LOGe(I/A      0.34404     0.07575       4.54    0.000
LOGe(TON       1.2390      0.2490       4.98    0.000

S = 0.3344      R-Sq = 66.4%     R-Sq(adj) = 65.1%

Analysis of Variance

Source        DF          SS          MS         F        P
Regression     2     10.8444      5.4222     48.47    0.000
Error         49      5.4809      0.1119
Total         51     16.3254

Source        DF      Seq SS
LOGe(I/A       1      8.0742
LOGe(TON       1      2.7703

Unusual Observations
Obs  LOGe(I/A    LOGe SR        Fit  StDev Fit   Residual    St Resid
  3      0.00     1.4816     1.4382     0.1444     0.0434      0.14 X
  7     -0.05     1.6582     1.4206     0.1428     0.2376      0.79 X
 40     -0.51     1.3218     2.0849     0.0821    -0.7631     -2.35R

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.
```



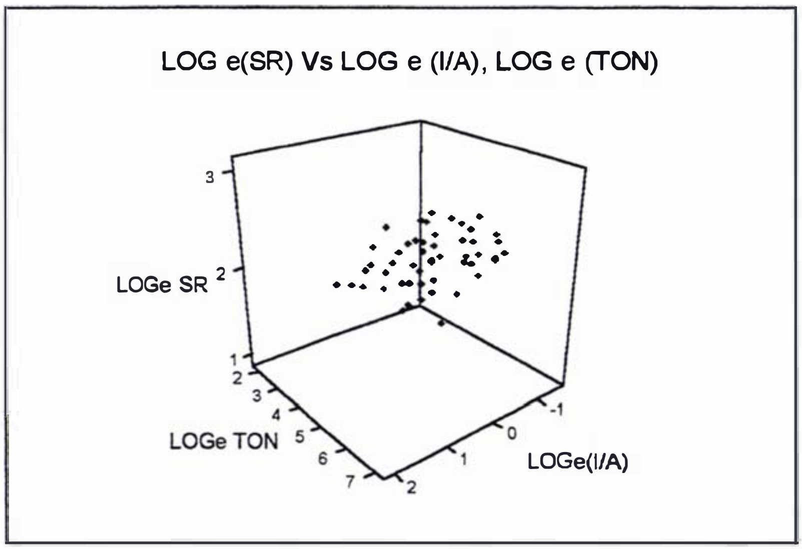
Plot K5

S_R Vs (I/A) and (T_{ON})

```
MTB > Regress C5 2 'LOGe(I/A)' 'LOGe TON'   ;
SUBC>   Constant.
```

Regression Analysis

```
The regression equation is
LOGe SR = 0.834 + 0.254 LOGe(I/A) + 0.254 LOGe TON

Predictor        Coef        StDev          T        P
Constant      0.83447      0.09894       8.43    0.000
LOGe(I/A      0.25416      0.04221       6.02    0.000
LOGe TON      0.25417      0.01887      13.47    0.000

S = 0.1892      R-Sq = 89.3%     R-Sq(adj) = 88.8%

Analysis of Variance

Source        DF          SS          MS         F        P
Regression     2     14.5707      7.2854    203.45    0.000
Error         49      1.7546      0.0358
Total         51     16.3254

Source        DF      Seq SS
LOGe(I/A       1      8.0742
LOGe TON       1      6.4966

Unusual Observations
Obs  LOGe(I/A    LOGe SR        Fit  StDev Fit   Residual    St Resid
 40     -0.51     1.3218     1.8751     0.0371    -0.5534      -2.98R

R denotes an observation with a large standardized residual
```


LOG e(SR) Vs LOG e (I/A), LOG e (TON)
3
LOGe SR 2
1
2
3
4
LOGe TON 5
6
7
2
1
0
-1
LOGe(I/A)

Plot k6

Appendix L

Different types of gates and guide lines for gate design

Submarine Gate

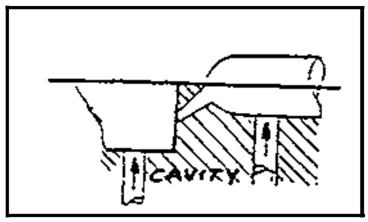


Figure L1

Characteristics

- Used for automatically seperating parts and runners duing eject
- High local orientation
- Small visual defect
- Moderately large pressure loss
- Parts and runner automatically separate
- Plastic freezes quickly
- High molecular orientation at the gate

Manifold gate

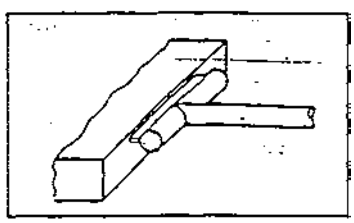


Figure L2

Characteristics

- Used to minimize orientation in the gate area
- Usually noticeable visual defect
- Small pressure loss
- Plastic frezzes moderately fast

Fan Gate

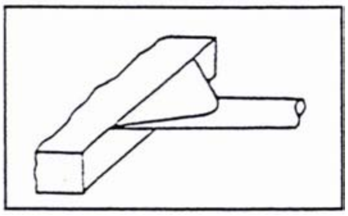


Figure L3

Characteristics

- Reduces orientation by spreading out the flow
- Characteristics similar to manifold gate

Tab Gate

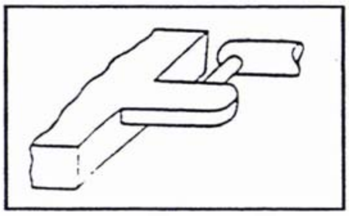


Figure L4

Characteristics

- Eliminates orientation in the gate area of the part
- Requires a secondary trim step
- Items such as optical lenses are moulded using tab gate

Diaphragm gate

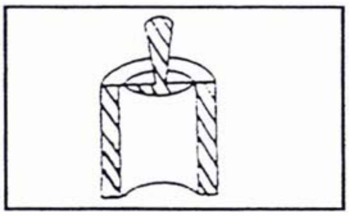


Figure L5

Characteristics

- Used when plastic must flow symmetrically down all sides of a hollow part
- Minimizes warp due to uneven molecular orientation

Multiple gating

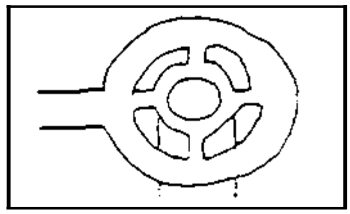


Figure L6

Characteristics

- A simple method for distributing the flowing plastic more evenly
- There will be a weldline between each gate
- Used to fill large cavities

Centric gate

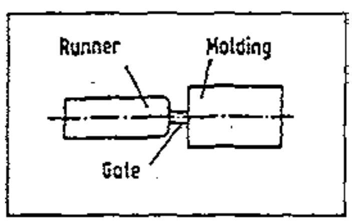


Figure L7

Characteristics

- Small surface to volume ratio of circular cross section reduces heat loss and friction
- Difficult machining operation in both mould halves needed. Costs for rectangular cross section likewise prohibitive
- Centric position renders separartion more difficult and may require postoperation
- Gate promotes jetting

Eccentric gate

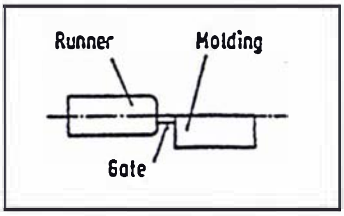


Figure L8

Characteristics

- The eccentric position of the gate facilitates machining
- Ease of demoulding and separation from moulding is another advantage
- Gate orifice aligned to a wall impedes jetting

Pin point gate

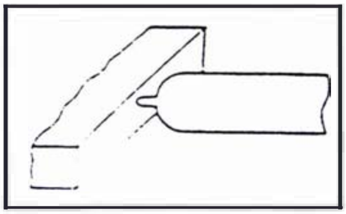


Figure L9

Characteristics

- Typically 0.5 to 1.0 mm diameter
- Highest local molecular orientation
- High local stress
- Low apperance defect
- Large pressure loss
- Plastic freezes quickly

Conventional gate

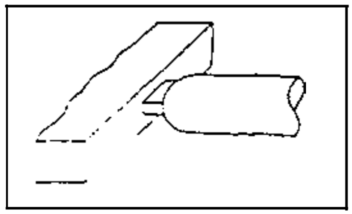


Figure L10

Characteristics

- 1/4 to ½ the cross sectional area of the runner
- Visual defect is large
- Small pressure loss
- Plastic freezes slowly

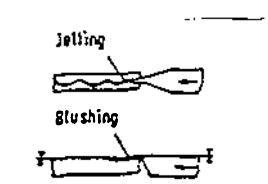
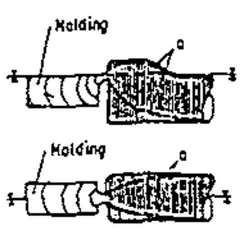
Gate design	Characteristics
 Poor gate design	Gate should be positioned in such a way that no jetting can occur causing troublesome marks; melt must impinge on wall or other obstacle. If gate is machined only into one mould half cold "skin" may be carried into cavity. This also results in blush marks. Remedy: A special cold slug well accepts cold material.
 Good design practice	Centric location of gate with abrupt transition and rough walls prevents transport of cold surface layer. (a indicates the boundaries of the hot, fluid core) Radius at transition causes laminar flow of melt into cavity and prevents jetting. Radii at transition make gate removed more difficult. They should, nevertheless, be preferred because of better flow conditions which result in higher quality with respect to dimensions and mechanical strength.

Table L1 Guide lines for gate design

Position of the gate at the part

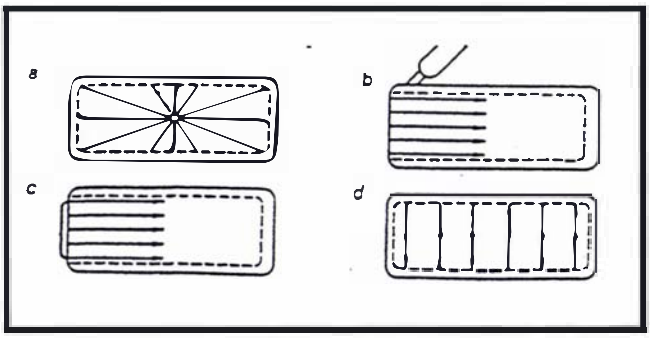


Figure L11 Flow path of melt with gates in various positions

a. Central sprue or pintpoint gating

b. lateral standard gating causing desired turbulent flow

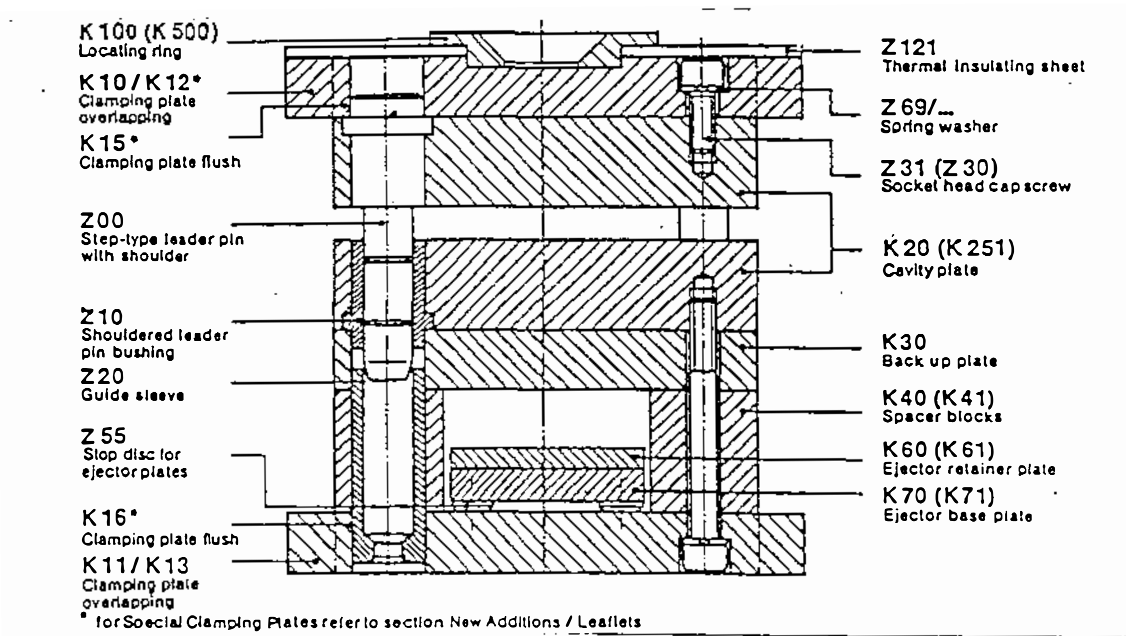
c. Edge gating

d. Multiple pintpoint gating

The position of the gate determines the direction of the material flow within the cavity. Physical properties and shrinkage in the direction of flow, however, differ in most cases from those in a perpendicular direction. This results from an orientation of the molecules. The degree of orientation is particularely high in thin-walled articles. The best values for tensile and impact strength are achieved in the direction of flow while perpendicular to it, reduced toughness and increased tendency to stress cracking can be expected.

Appendix M

Specifications of moulding tool materials

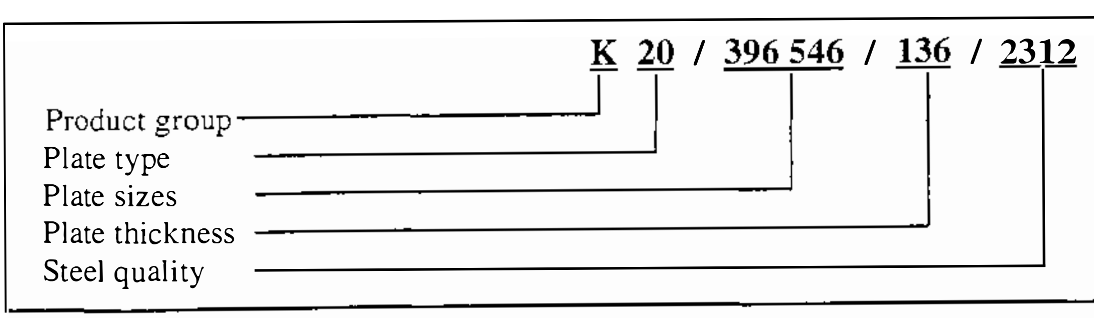


Plates thicknes

S (mm)	S (Inc
6	0.23
9	0.35
12	0.47
17	0.66
22	0.86
27	1.06
36	1.417
46	1.811
56	2.205
66	2.598
76	2.992
86	3.386
96	3.780
116	4.567
136	5.354
156	6.142
196	7.717
246	9.685

Figure M1 Standards parts of injection moulding tool

K- Order Number

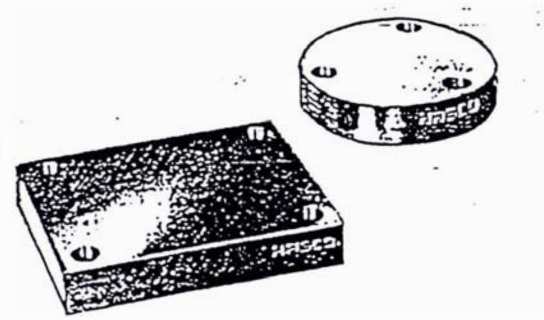


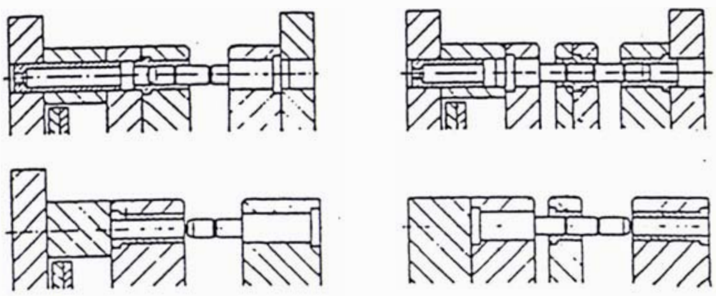
K - Standards

Interchangeable finished plates for mold base assemblies according to the tried and tested

MODULAR SYSTEM

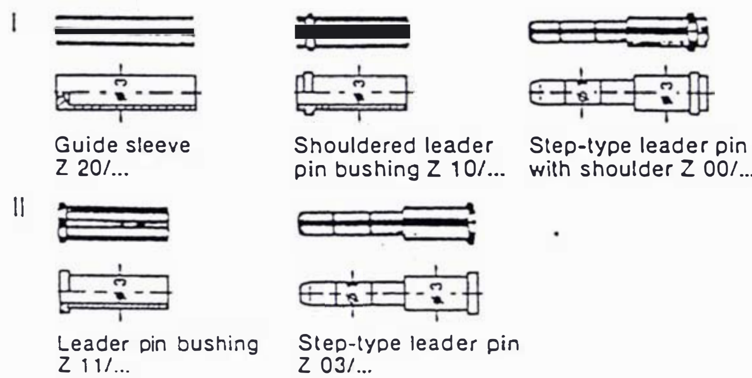
They are used for the design of die casting dies, compression – and injection molds.

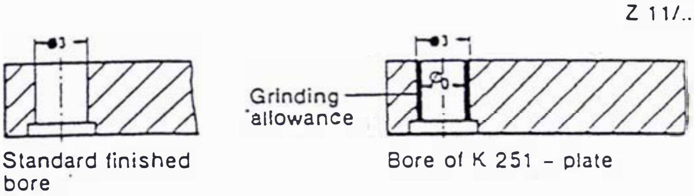




The tooling engineer has every choice to combine K-Standards for individual mold designs, because total interchangeability is ensured.
Normally the combined guiding-and centering system (I) is used. Pins and bushings without shoulder (II) are designed for simple molds.

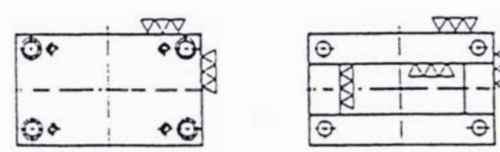
All guiding and centering components belong to a particular mold base size have uniform fitting diameters (∅ 3).
No offset! To ensure proper assembly of mold base, prefer. to use one leader pin with a smaller guiding diameter (∅ 1).

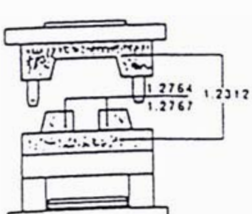


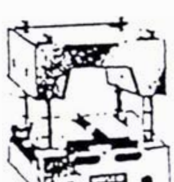


Hardening or stock removal may cause distortion of K 251/... – plates.
By regrinding of guide holes (∅ 0) any misalignment can by eliminated.

All side faces of K 20/... cavity plates are ground or precision machined (▽▽▽) to close tolerances and can be used for alignment or as datum face.







KB

Split Mold Kits "KB" offer an additional parting area to produce moldings with undercuts. Split Mold Kits are designed to match K-Standards.

KR

The Insert – Modular System "KR" contains of bolster plates and precision inserts, which can be systematically sectioned. The KR-Plates are designed to match dimensions of K-Standards.

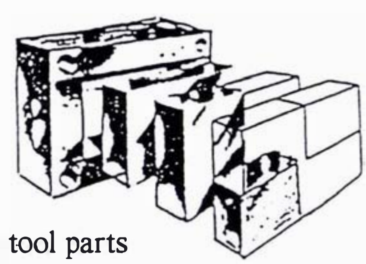


Figure M2 Pre-manufactured moulding tool parts

COLD WORK TOOL STEELS

GRADE		CHEMICAL COMPOSITION %						Hardness supplied approx. HB	Ref. STANDARD			CHARACTERISTICS	Soft annealing °C	Hardening temp °C	Quenching	Hardness HRC after tempering °C			
	C	Mn	Cr	Mo	V	W	Others		AISI	W.nr	JIS					200	300	500	600
ARNE (DF-2)	0.90	1.20	0.60		0.10	0.50		190	01	1.2510	SKS3	General purpose tool steel, good surface hardness, wear resistance, easy to harden.	780	790-850	Oil or martempering	62	58		40
RIGOR (XW-10)	1.00	0.60	5.30	1.10	0.20			215	A2	1.2363	SKD12	Good hardenability and wear resistance. Excellent size stability. For medium runs	850	925-980	Air or oil	61	59		48
VIKING	0.50	0.50	8.00	1.50	0.50		Si 1.00	225				Tool steel for heavy blanking. Very good combination of wear resistance and toughness.	850	980-1050	Air or oil	59	58	52	48
REGIN 3 (M-4)	0.50		1.30		0.20	2.50	Si 0.75	175	S1	1.2542		Tool steel for heavy blanking.	780	860-920	Oil or martempering	57	58		45
SVERKER 3 (XW-6)	2.05	0.80	12.5			1.30		240	D3/D6	1.2436	SKD2	High performance tool steel. Supreme wear resistance.	850	920-1000	Air or oil	64	61	52	48
SVERKER 21 (XW-41)	1.55		12.0	0.80	0.80			210	D2	1.2379	SKD11	High performance tool steel. High wear resistance and toughness.	850	990-1050	Air or oil	63	60	53	48
PLASTIC MOULD STEELS																			
IMPAX SUPREME (718)	0.33	1.40	1.80	0.20			Ni 0.9	290-330				Prehardened plastic mould steel. Very good polishability and good machinability.	700	850	Oil or martempering	51	47		28
HOLDAX	0.33	1.50	1.90	0.20			S 0.07	290-330				Prehardened steel for holder blocks with very good machinability.							
STAVAX ESR	0.38	0.50	13.6		0.30			215	420	1.2083		Stainless plastic mould steel with excellent polishability and corrosion resistance.	780	980-1050	Air or oil	54	53		
RAMAX S	0.28	1.10	16.7				S 0.12	300-340				Stainless steel for holder blocks with excellent machinability and corrosion resistance.							
PRODAX	Tooling Aluminium							145				Aluminium for plastic moulds, blow moulding and vacuum moulding							
HOT WORK TOOL STEELS																			
ORVAR M SUPREME (8407 Supreme)	0.37	0.40	5.30	1.40	1.00		Si 1.00	185	H13	1.7343 1.2344	SKD61	Good high temperature strength and extreme thermal fatigue resistance steel for diecasting.	850	980-1000	Air or martempering	52	52	52	48
ORVAR 2M (8407)	0.37	0.40	5.30	1.40	1.00		Si 1.00	185	H13	1.2344	SKD61	Good high temperature strength and thermal fatigue resistance steel for extrusion and diecasting	850	980-1080	Air or martempering	54	54	52	48
QRO 90 SUPREME	0.40	0.75	2.60	2.25	0.90			180				Very good high temperature strength and very good thermal fatigue resistance.	850	1010-1080	Air or martempering	54	52	52	50
SOMDIE	0.48	1.00	1.20	0.56	0.10		Ni 1.00			1.2714		Dieblock steel with isotropic properties	700	830-900	Oil	54	52	42	38
HIGH SPEED STEELS																			
KM 2 (HSP-41)	0.87		4.20	5.00	1.90	6.40		240	M2	1.3343		HSS for cold work and cutting tools with good wear resistance	850-900	1050-1220	Martempering			65	
ASP 23	1.27		4.20	5.00	3.10	6.40		260				Powder HSS Excellent wear resistance and toughness	850-900	1050-1180	Martempering			65	
ASP 30	1.27		4.20	5.00	3.10	6.40	Co 8.5	260				Powder HSS for cutting tools. Excellent wear resistance and toughness. Good hot hardness	850-900	1050-1180	Martempering			66	
ASP 60	2.30		4.20	7.00	6.50	6.50	Co 10.5	300				Powder HSS for cutting and cold work tools Extreme wear resistance. High hot hardness	850-900	1100-1190	Martempering			69	

Table M1 Properties of steel grades

Comparison of prices between Aluminium and Mould steel

Aluminium		Mould steel	
Size (mm)	Price (NZ$)	Size (mm)	Price (NZ$)
150*150*80	100.10	150*150*80	132.62
200*205*90	185.45	200*200*90	240.22
200*205*120	246.54	200*200*130	394.11
260*205*20	48.10	260*205*20	64.46
260*205*25	57.63	260*205*25	78.07
260*205*40	86.21	260*205*40	118.90
260*205*50	105.27	260*205*50	146.15
315*305*35	168.00	305*300*30	700.51
300*300*50	232.20	305*300*50	312.89
300*300*60	277.80	305*300*60	368.26

Table M2 Relative prices of aluminium and mould steel