COMPUTER AIDED DESIGN AND MANUFACTURE OF PLASTICATING EXTRUDER SCREWS FOR POLYMER PROCESSING

FARHAD FASSIHI-TASH

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The Nottingham Trent University

از رنج کشیدن آدمی حر گردد
قطره چو کشد حبس صدف در گردد

گر مال نماند سر بماناد بجای
پیمانه چو شد تهی دگر پر گردد

Hardness makes men gallant;
Worthless dust turns into pearl, if trapped in a shell;

Forget the possessions, for only knowledge will remain;
Such as the goblet, which is refilled when it's vain.

Ommar Khayyam Shirazi.

To Fereshteh
&
Farzan

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ABSTRACT

The work carried out throughout this study is concerned with single screw extruder screws and the application of computers in the integration of their design and manufacture (Computer Integrated Manufacture). During the course of this work; the screw manufacturing process has been examined, different mechanisms for its design and manufacture have been reviewed and the thinking behind screw add-ons were discussed. This was followed by a general review of the latest in manufacturing technology. Subsequently, and based on theses evaluations, a provisional system was proposed to suit. Within the proposed framework, a melting simulation program was chosen and the melting model reviewed. This has formed the basis of the optimisation procedure and has been integrated within a range of programs which will together form a new advanced tool for optimised design and manufacture of plasticating extruder screws. During the development phase, a program was developed to interpret the results of the rheometry test which provides the necessary information in the right format for the optimisation program. A mathematical model of the screw geometry was then analyzed to form the foundation of parametric programs which were developed on a CAD system to generate the 3D wire frame, 2D orthographic drawing and a 3D shaded model of the designed screw. This program utilises the results obtained from the optimisation program. Next, a program (Fortran) developed to calculate the set up values for the target Computer Numerically Controlled (CNC) machine. Finally, the information generated by the previous programs was used to calculate the cutter paths for the target CNC machine with considerations for its communication with the CNC machine.

This project was carried out in the belief that the right screw design in the first place will eliminate the need for expensive complex screw designs with various add-ons. It is hoped that completion of this work will provide an effective tool for polymer processors and polymer processing equipment manufacturers alike. Future work in this area would involve introduction of Artificial Intelligence and expert systems concepts as well as object orientated solutions to increase the accuracy of the model and a subsequent reduction in computing time.

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CHAPTER 1

BACKGROUND TO THE RESEARCH

1-1 AIMS AND OBJECTIVES

The aims and objectives of this research are to examine current practices in the plastics processing industry and to consider methods of improving quality, productivity and, above all, the cost effectiveness of the industry. To this end it is proposed to develop new tools which combine the design and manufacture of extruder screws and to combine these with new concepts in the plastics manufacturing environment.

Until very recently extruder screws were designed by purely arbitrary means based on a very inefficient 'suck it and see' principle which involved the manufacture of a screw designed using preconceived ideas of the designer. The screw would then be used on a proving run to measure its effectiveness. If the initial design proved satisfactory after this first use - a scenario which one would imagine is highly unlikely - machine tools were set up to manufacture a large number of this particular design of screw. If however the more likely situation occurred in which the screw did not perform as expected, modifications were made to the design and another screw would be cut. This procedure would then be repeated until a satisfactory performance was achieved, in which case this would become the preferred design. In many cases the modifications adopted involved the use of devices introduced to increase the amount of shear and hence the amount of work heat transmitted to the polymer during processing. These devices will be discussed later in this chapter. However, for some years now a number of computer based design tools have been available for optimising the performance of plasticating extruder screws taking into account the needs of solids conveying, melting and melt pumping [21-59] and these will be discussed in the relevant section. Although these programs have demonstrated a degree of success in highlighting potential improvements in the design and performance of extruder screws without the expensive need for cutting metal there has always remained the problem of manufacturing one-off examples of the proposed screw.

Even with the simplest of screw designs, those with just the three elements of feed, compression and metering, the architecture of the screw is very complex and cutting using conventional machine tools is very difficult. So until recently, prior to the advent of Computer Numerically Controlled (CNC) machine tools, once a satisfactory design was arrived at, conventional lathes were set up using motorised cams and taper cutting devices to manufacture a relatively large number of that particular design. At this stage it must be borne in mind that, because of the physics of the extrusion process, ie the rate of melting governed by the thermal properties of the polymer, that this design applies only to one material under one set of processing conditions. Rapid development in the modification of plastic materials for particular applications means that a screw intended for one use might not be suitable for another seemingly similar one. There is, therefore, a need for a system which might lead to the production of custom made screws and take us away from the so called 'General purpose screw' which, by its very nature, is designed to process a range of polymers but none with a high efficiency.

Having established that a suitable design program is available it is proposed to create a manufacturing tool which is able to use the screw design data generated by one of these programs based on the Edmonson & Fenner model [39] which is being developed concurrently in the Manufacturing Engineering Department of this University. This data will be used as input to a second set of programs which will set a CNC machine to cut the optimised screw from the relevant feedstock material and will generate the necessary G-Codes for the control computer of the machine to operate and to produce the screw. The use of such a design and manufacturing package is hoped to greatly reduce the time necessary for production of extruder screws, to make possible the economical production of one-off screws for use with non standard polymers and to reduce incidents of operator error. With the development of this new tool it is hoped that a satisfactory performance of a properly designed screw can be achieved without the need to include the shear enhancing devices mentioned above. It has been shown [60] that excessive shear detrimentally influences the properties of the polymer by reducing its molecular weight and its fracture properties. Elimination of the need for such devices and limiting the design of screws to those with simple three elements will improve the quality of the melt and will also simplify the manufacture of these screws. It is proposed that this system be developed to run on readily available, relatively cheap, desktop computers to minimise its initial installation cost. This combination of factors, ie the simplification of design, the reduction in machine set-up time and machining time using operators with reduced skill levels, the potential eradication of operator based errors and the improvement of melt quality, should lead to a more efficient and more cost effective method of producing a vital component to the plastics processing industry.

The proposed task list can be envisaged as follows:

1) Review of existing processes,equipment and methods.
2) Identification of the main areas for improvement.
3) Creation and development of the necessary programs.
4) Test and evaluation of individual elements of programs.
5) Test the overall effectiveness of the system.
6) Conclusions and report.

This thesis constitutes the final report - item 6) above. Chapter 1 describes the background of the research and discusses the relevant aspects of polymer processing. Chapter 2 is a technology audit which reviews current practice and identifies potential problem areas. The next two chapters are dedicated to system definition and to the corresponding development of the system. Chapter 5 describes the completed system and the test of the system whilst chapter 6 reports the conclusions drawn from this work Chapter 6 also includes suggestions for any future development of this work. Relevant information, not of major importance to this work but which may be of interest is included in two appendices.

1-2 INTRODUCTION

The use of plastics and plastic components continues to increase in our daily life, and new products are continually being developed with great awareness of cost and energy efficiency. At the same time political, as well as financial, pressures are on the increase for development of more environmentally friendly products. Most manufacturing industries are either already using plastics or beginning to introduce plastics as one important form of raw material. The most familiar applications of plastics are in automobile bodies and interiors, and in packaging. The use of plastics, however, is extending rapidly to such applications as huge marine structures, fibre optics and constructional cladding, to name but a few [1].

Plastics are part of a larger family called polymers. Polymers were initially natural substances such as rubber and cellulose with a very long chained molecular structure,but most are now synthetic. Polymer materials may be classified into two sub-groups of thermosetting and thermoplastic materials.

In a thermoplastic material, the molecules are held together by relatively weak forces. When the material is heated, the intermolecular forces are weakened so that it becomes soft and flexible and eventually, at high temperatures, it turns into a viscous fluid. Cooling down will cause the material to solidify again and so there is an obvious potential for moulding.

A thermosetting plastic is produced in two stages through a chemical reaction. The first stage will result in the formation of long molecular chains. The second stage is carried out during moulding in the presence of heat and pressure to cross-link the molecular chains. Unlike thermoplastic materials, the thermosetting reaction is irreversible and the material cannot be reformed after moulding [2].

Despite the present difficult economic situation, the overall picture is that the plastics industry has grown in Western Europe by about 75%, since 1982, as shown in Table 1 which is taken from ref[3]. The consumption of plastics will undoubtedly further increase in the next few years [4-10]. Even existing production facilities will provide additional consumption rates for most product classes. On the whole, it is expected that the consumption of plastics in Western Europe will grow by an average of 3 to 5 percent per year through to the end of this decade [3].

This situation is mirrored in the USA and Japan, two of the three major manufacturers (besides Western Europe) of plastics materials and components. The trend in the USA is particularly important because plastics production there is greater than in the whole of Western Europe [6]. When new plastics production facilities in the Far East are taken into account, it is clear to see that the importance of plastics production will continue to grow and hence it is timely to review the processes involved, with a view to identifying areas for improvement.

Table 1

Resin	Consumption(in 1000t)				Change(%)
	1982	1985	1988	1991	1982/91
Polyvinyl Chloride(PVC)	3600	4000	4920	5120	42
Low Density Polyethylene(PE-LD/PE-LLD	3560	4300	5100	5500	54
High Density Polyethylene(PE-HD)	1420	1880	2700	3140	121
Polypropylene(PP)	1470	2140	3110	4045	175
Polystyrene(PS,SB)	1160	1300	1660	1760	52
Polystyrene, expandable(EPS)	440	450	500	545	24
Acrylonitrile-butadienestyrene copolymers(ABS)	320	425	490	495	55
Polyamides(PA)	180	245	340	385	114
Polyesters, saturated(PET,PBT)	150	255	410	680	353
Polymethyl methacrylate(PMMA)	140	170	220	270	93
Polycarbonate(PC)	75	100	140	175	133
Polyoxymethylene(POM)	55	80	95	107	95
PUR raw materials	1000	1150	1400	1600	60
UP resins	300	340	450	440	47
PF-,MF- and UF- moulding compounds(1)	155	140	130	125	-19
Epoxide resins	115	135	170	290	152
Others(2)	90	130	185	220	144
Total	14240	17240	22035	24897	75

1- Thermosetting moulding compounds based on Phenolic, melamine, Urea and UP resins.

2- SAN/ASA, PPE, ABS/PC blends, PC/PBT/PET blends, fluoroplastics.

1-3 PROCESS REVIEW

Looking at the current state of the plastics processing industry, the most common processes are found to be:

Extrusion.
Film/sheet blowing.
Injection moulding.
Blow moulding.
Thermoforming (Vacuum/pressure forming).
Calendering.
Rotation Casting.

There are of course other processes which are such a slight modification that they may be treated more or less the same as the above, or the usage of those operations is so limited that it does not justify their detailed study. These operations are all used to process thermoplastic materials.

So far as the thermosetting materials are concerned, production is getting less frequent due to higher material cost, higher production cost and most of all their inability to be re-processed. This is shown as a negative growth rate of -19% in Table 1 for thermosetting materials. Therefore, it seems logical to focus on the above processes for thermoplastics and a summary description of each is presented as follows.

1-3-1 EXTRUSION

Extrusion, in principle, is a process used to form a wide range of materials by forcing them through a die. The material to be shaped may be any material from hard solids such as metals, to soft substances such as pasta. The level of difficulty, of course, depends on the material and the die. The extrusion process is not only used in polymer processing, but also in food processing and the packaging industry. In this process, the substance is fed into the extruder through an inlet chute into a trough, and is discharged through a die. A screw is mounted at the centre of the trough and this is the most important element of the extrusion line. It is this screw which pushes the material forward and creates the necessary pressure to extrude it through the die. The screw makes the process into a continuous operation. The screw and its shape are critical factors in determining the outcome of the extrusion process . Figure 1.1 illustrates a typical extrusion process.

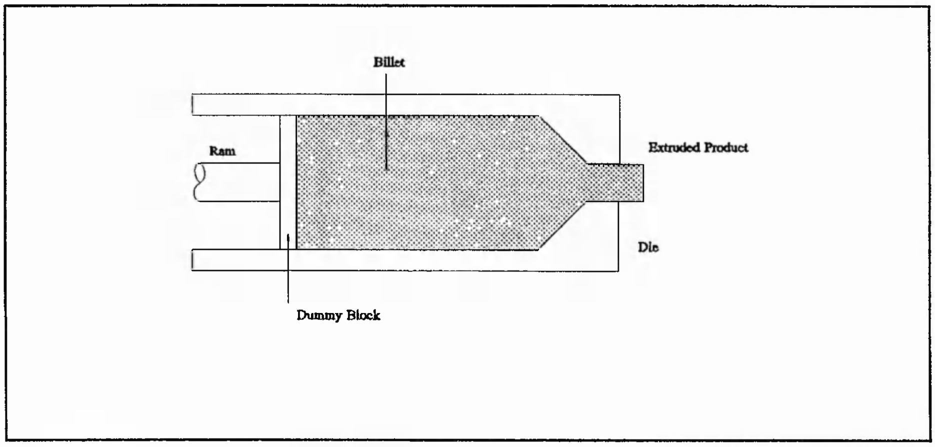


Figure 1.1
Basic direct extrusion process.

The extrusion process is used in many different ways in polymer processing; single screw extrusion, double screw extrusion and even multiple screw extrusion. The most basic process of all is single screw extrusion. It is a process in which plastics materials, usually in the form of pellets, are continuously formed into tubing, rods, sheet, pipe, wire and paper coating, film and scores of profile shapes. "Continuously" is the key-word, since each of the above items could be made by other techniques but only in relatively short lengths. The screw extrusion process is particularly useful when extended lengths of a product are required. The extrusion line usually has other complementary functions such as mixing, blending, and chopping the extruded material into the right lengths. A single screw extruder essentially consists of the following elements:

-A feed hopper into which the polymer pellets are placed.

-The barrel which contains the screw and is equipped, on its exterior, with elements for heating and sometimes cooling.

-The screw which plasticates the pellets and conveys them.

-A motor and a gear reduction unit to turn the screw.

-Screen packs and breaker plates to filter the melt and create back-pressure.

-The die, which determines the shape of the extrudate.

-Instrumentation and control devices to indicate and control different operational variables such as temperature, pressure, screw speed, ...etc. Figure 1.2 represents a basic screw extruder for polymers.

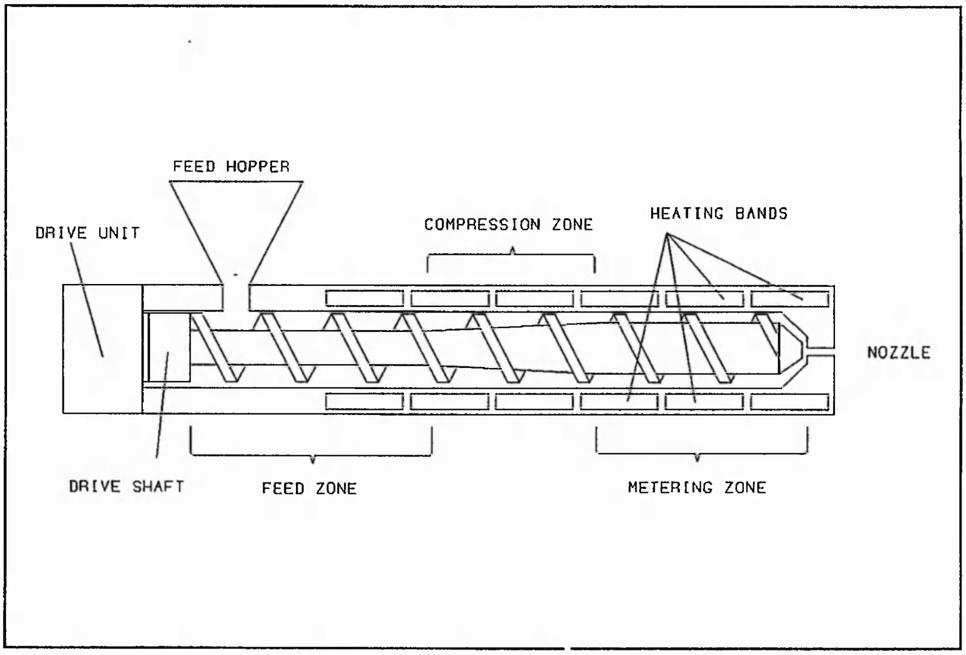


FIGURE 1.2
A typical plastics screw extruder.

The double screw extruder or twin screw extruder process is in many ways similar to its single screw counterpart with some rudimentary differences. First of all, as the name suggests, it contains two screws instead of one. The barrel has the shape of a figure of eight, instead of being round. Screws can be closely intermeshing or non-intermeshing. The non-intermeshing extruder consists of two single extruder screws mounted parallel to each other with a mutual interaction with an axial distance of no less than the screw outer diameter. The inter-meshing twin extruder could still be subdivided into two groups of Counter-rotating and Co-rotating. Due to the close intermesh of the screws, separate spaces (the so called C-shaped chambers) exist on each screw. These chambers interact with each other through the leakage gaps. There is also another type of twin extruder in which the screws clean each other during the operation. They can be considered either as having one continuous channel with flow restrictions or as a series of C-shaped chambers with large leakage gaps [11].

Apart from the obvious physical differences, the main difference between single and twin screw extruders is the transport mechanism. The transport in a single extruder is dependent upon the friction between the material and the channel walls; if the polymer slips at the barrel wall, the material will rotate with the screw and no displacement action will take place. In twin extruders, the channels of the screws are interrupted by the flights of the other screw and transport takes place by the positive conveying action of the chambers (positive displacement). Figure 1.3a shows the C shaped chamber while 1.3b represents different twin screw set ups.

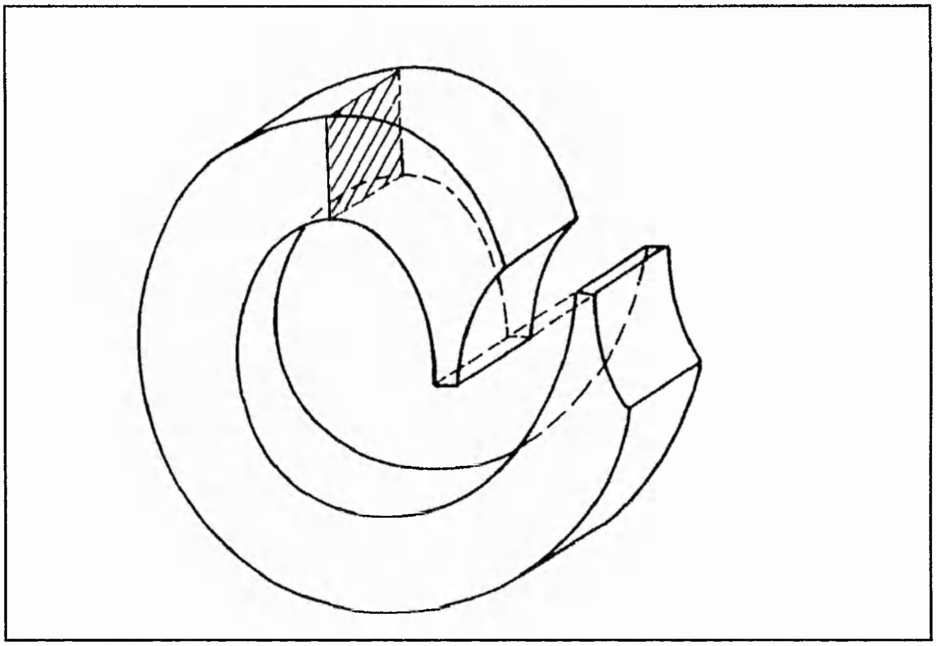


Figure 1.3a
C shape chamber.

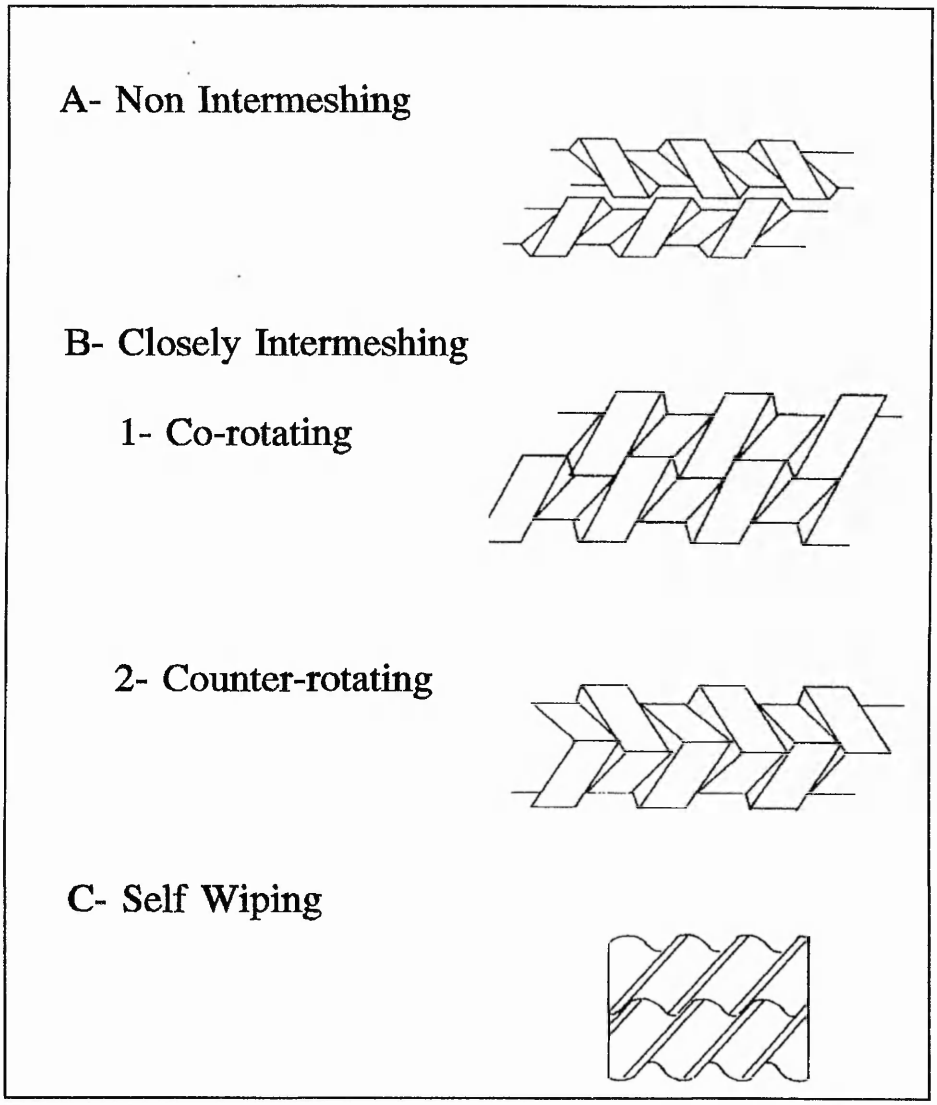


Figure 1.3b
Different twin screw arrangements.

1-3-2 FILM PRODUCTION

By general agreement in the plastics industry, plastic films are any plastics materials made in flat form with a thickness of 250 micro metres or less. Flat stock with thickness greater than 250 micro metres is referred to as sheet. Films are made from any of the commonly used plastics materials, however, the majority of films are thermoplastics. The most common method for producing film and sheet is by extrusion from a melt. Virtually any thermoplastic material can be extruded into film and sheet using the set up illustrated in figure 1.4.

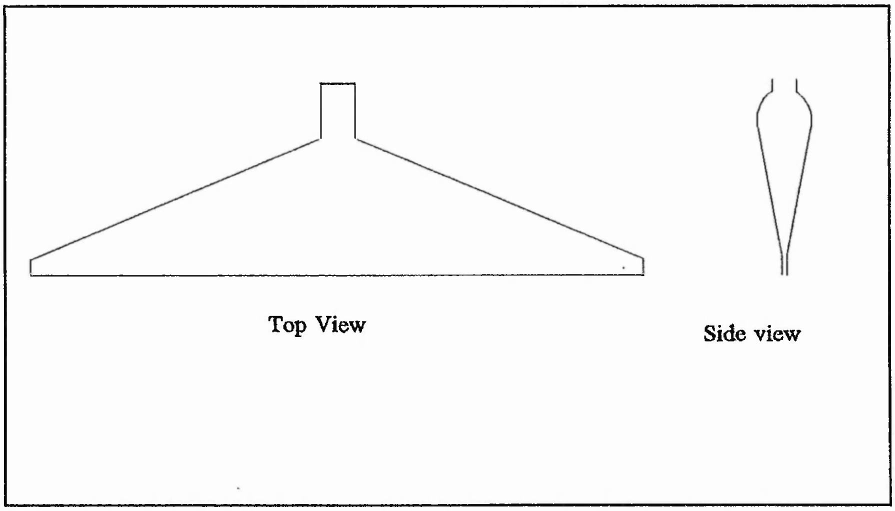


Figure 1.4
A basic coathanger die.

One of the major problems in the production of films by extrusion is the maintenance of uniform thickness throughout the width of the film. The best way of manufacturing the thinner films is by the Bubble process. In this process the melt is extruded as a relatively thick tubular extrusion and then is inflated by internal air pressure to form a thin-walled tube. The tube is then slit to form a sheet of thin film or is left as flattened tube known as "lay-flat tubing". To improve gauge uniformity in this process, the circular extrusion die, the air cooling ring, or both are frequently rotated. Figure 1.5 presents a bubble process. Obviously, the thinner the film becomes the more crucial becomes the quality of the melt. As can be seen the input to the system is provided through an extruder with an ordinary three stage screw. In some cases to ensure constant pressure and quality, a filtering system and melt pump are installed between the extruder and the die.

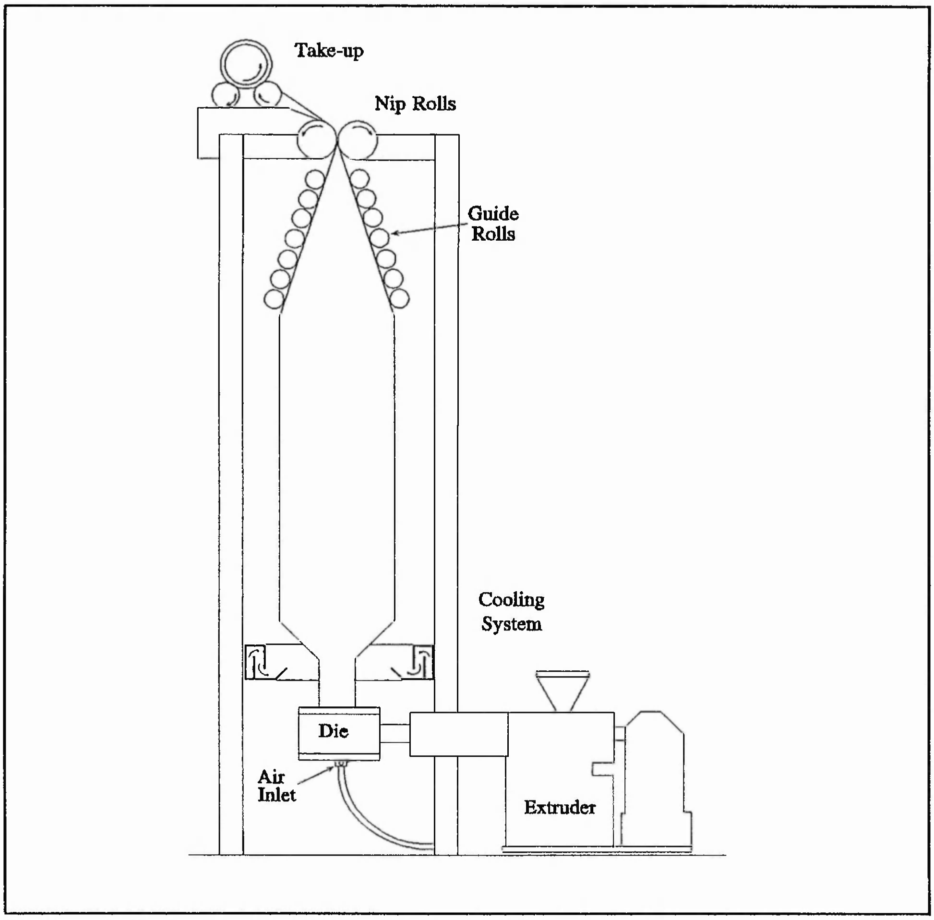


Figure 1.5
Bubble blowing process.

1-3-3 INJECTION MOULDING

Injection moulding is the process of heating thermoplastic granules in a cylinder until they are liquid, and then injecting the molten material into a relatively cold mould where it freezes and takes the shape of the mould cavity. No chemical change takes place in the material, and consequently, the process may be repeated over again. This process is thus distinguished from the injection moulding of thermoset materials, since with thermosets the mould is hot and the liquid undergoes a chemical reaction causing it to solidify.

The major advantages of injection moulding are the speed with which parts can be made, the possibility of obtaining finished, flash-free parts, and the fact that many parts can be made simultaneously. A further advantage when moulding thermoplastics is that any scrap from flash sprues, and runners, may be used by re-grinding and mixing with the virgin material. Injection moulding machines have changed greatly since their first introduction. The most commonly used form of injection moulding is now the reciprocating screw machine.

Figure 1.6 illustrates a typical reciprocating injection moulding machine. In this design, as the screw rotates, it is forced backwards by the build up of material in the front portion of the cylinder. At a predetermined point, rotation stops and the screw moves forward, acting as a ram to force the melt into the mould. The screw remains forward until the melt gates (die cavity entrance) freeze, then pumps back to repeat the cycle while the mould opens. The injection screw is very much like the extrusion screw. The only difference is the shut-off valve that stops back-flow during the injection cycle.

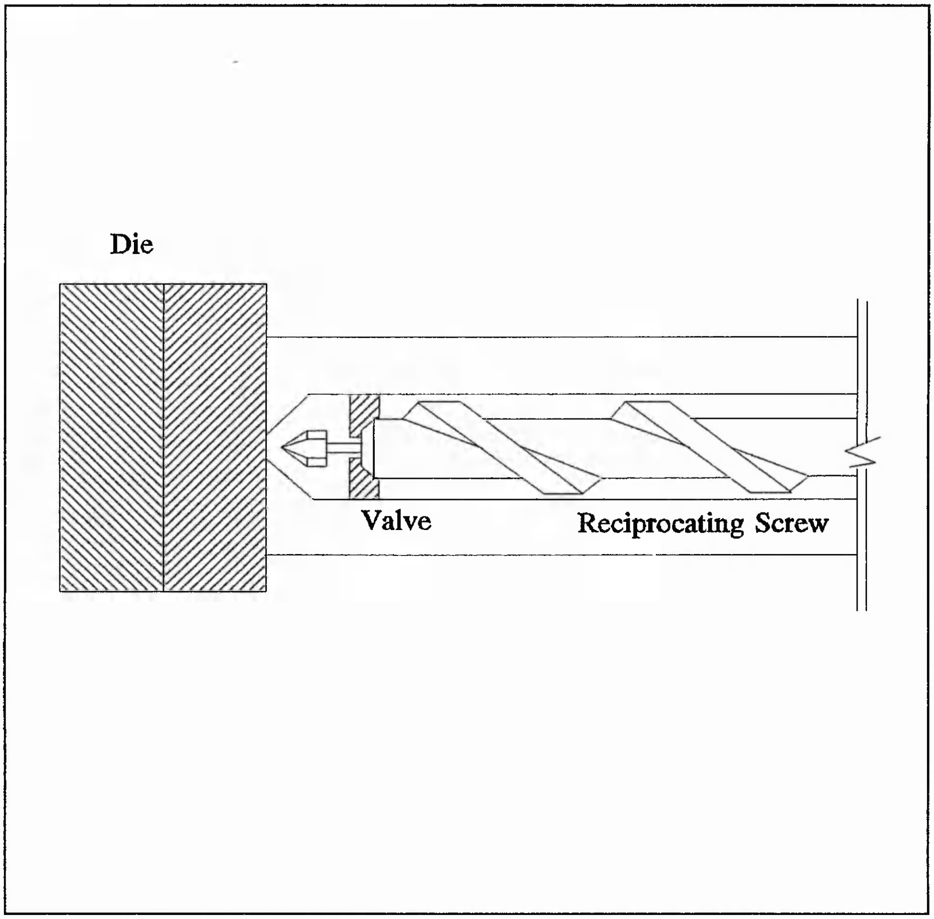


Figure 1.6
A basic injection moulding machine.

1-3-4 BLOW MOULDING

Blow moulding is a centuries old technique of forming hollow articles from a molten material. The process was used in ancient times by the Egyptians and Babylonians to blow glass and molten amber to form small containers and decorative figurines. Basically, the process consists of forming a tube of the melt and introducing air into the tube to expand it, either to a free blown object or against a mould to form it to a definite size and shape.

Blow-moulding of plastic is essentially the same process as outlined above, except that the materials and the equipment have been changed and made considerably more complex. The original technique developed for blow-moulding of plastics may be considered an extension of the extrusion process, since an extruder was the most vital piece of equipment in the procedure. In the first techniques developed, the extruder was used to produce a tube which was, and still is, called a parison. The hot parison, immediately on emerging from the die, is clamped in a mould. Air is then introduced and after a cooling period, a hollow container is ejected from the mould. This basic process is illustrated in figure 1.7

There are some slight variations of this process, namely " Injection Blow Moulding " and " Cold Preform Blow Moulding ", which are similar to the ordinary Blow Moulding or Extrusion Blow Moulding. Injection blow moulding, as the name implies, uses an injection moulding press to produce

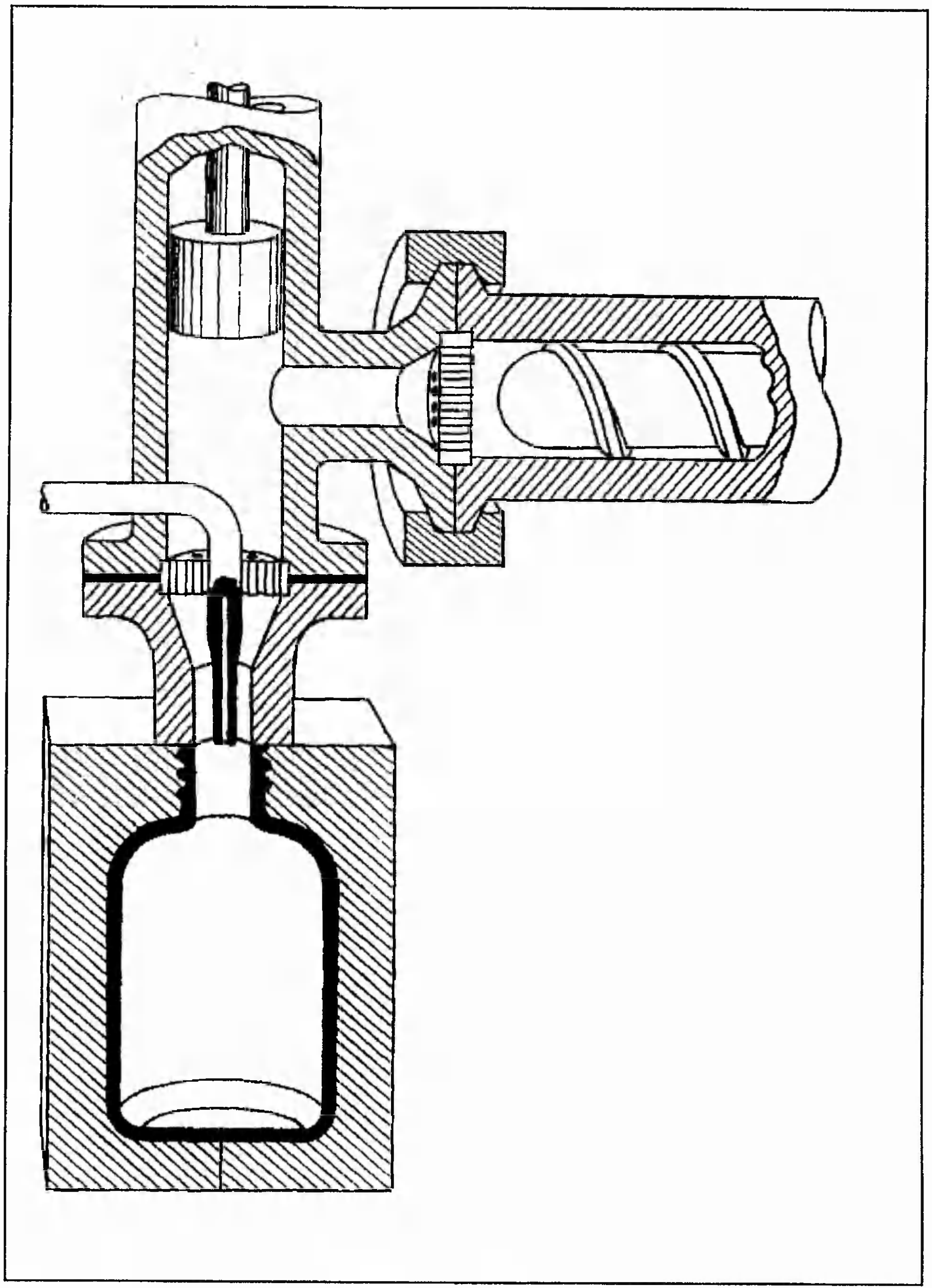


Figure 1.7
Blow moulding process.

the parison. However this is not accomplished in the same manner as previously described for intermittent extrusion. In injection blow moulding, the parison is injected into a preform cavity and around a core pin, in the exact quantity required to form the container. The preform mould is kept at a precisely controlled temperature, which is just a little cooler than the melt temperature. After injection, the mould opens and the core pins and the still warm preform are rotated 120 degrees. A blow mould then closes over the preform and air is injected through the core pin. After the bottle is blown, it is rapidly cooled by contact with the walls of the blow mould, which are kept at a constant temperature by cold air or fluid circulation through the mould passageways. The mould is then opened, a second 120 degrees rotation occurs, and the part is stripped from the core pin. Then a third 120 degrees rotation of transfer head returns the core pin to the preform injection mould, and the cycle is repeated. This operation could also take place in two rotations of 180 degree.

The other variation as suggested was Cold Preform Blow Moulding. This production process is not as widely used as the others. It consists of extruding a number of parisons, or tubing which is then cut to length to serve as parisons, which are allowed to cool. They can then be conveyed to the blow moulding machine, which may be at another facility. The parisons are then heated either selectively, so particular shapes may be obtained or to just the thermoelastic state, so that on stretching, a small amount of cold working occurs, resulting in a material which is oriented and strengthened. Because the material is stronger, the container can be made lighter, and thus effect a saving in the total amount of material used.

1-3-5 THERMOFORMING

Thermoforming of plastics refers to forming plastic sheets on some kind of mould after it is heated and softened. This method was first introduced during the 1950s but its lack of accuracy and the crudity of the equipment was a major drawback to its large scale deployment. In recent years advances in technology in areas such as machine design, mould design and material design have contributed to its more frequent use. A wide range of products could be now identified that are made using this method. Amongst them are aircraft window reveals, refrigerator liners, car bumpers,...etc. Thermoforming could be subdivided into two sub-divisions of "Pressure" and "Vacuum" forming.

In the vacuum forming process a sheet of thermoplastic is shaped by creation of a vacuum (pressure gap) between the mould and the sheet which is heated and softened. The most simple type of such a machine is something similar to the machine shown in figure 1.8 and is known as "Negative forming". Basically, in this method a plastic plate is clamped on the mould and a heater panel is placed above the sheet. After a nominal time which depends on the size and nature of the material, and having reached the adequate softening, the heater will be removed and the vacuum will be applied. This method is capable of producing parts with depths of 30% to 50% of the material width. In some instances this technique might not be able to produce a satisfactory result eg. when dealing with thick materials or using moulds with tight corners. In these cases a slight variation of this method called "Positive forming" is used. In this method after initially heating the material, a male (positive) mould is pushed into the material before the application of the vacuum. This results in a more uniform wall thickness and higher width to depth ratios (upto 100%).

The other type of thermoforming is "Pressure forming". This method is essentially the same as Vacuum forming with the difference that instead of creating a vacuum in the mould to achieve the pressure gap, a positive pressure is produced outside the plastic material to force it into the mould. This technique has the advantage of being able to use higher pressure gaps between the outside of the material and the mould. Figure 1.9 explains the principles of pressure forming.

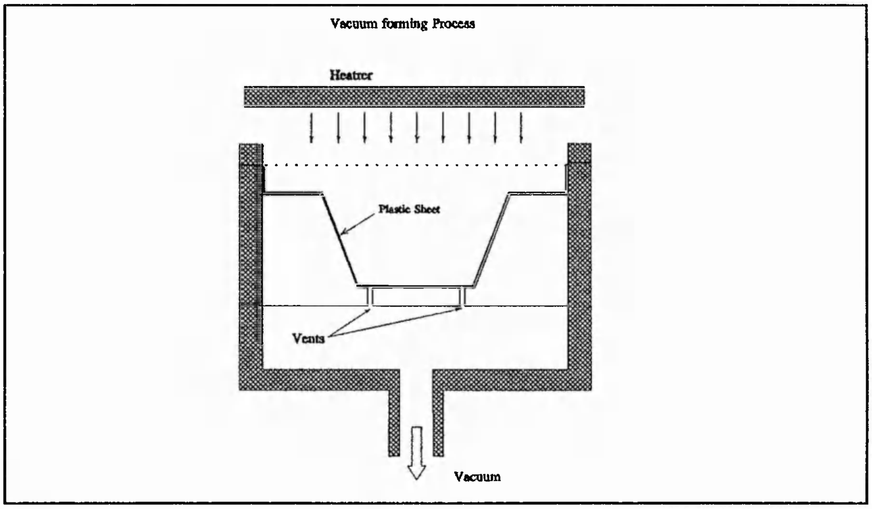


Figure 1.8
Basic Vacuum Forming Process

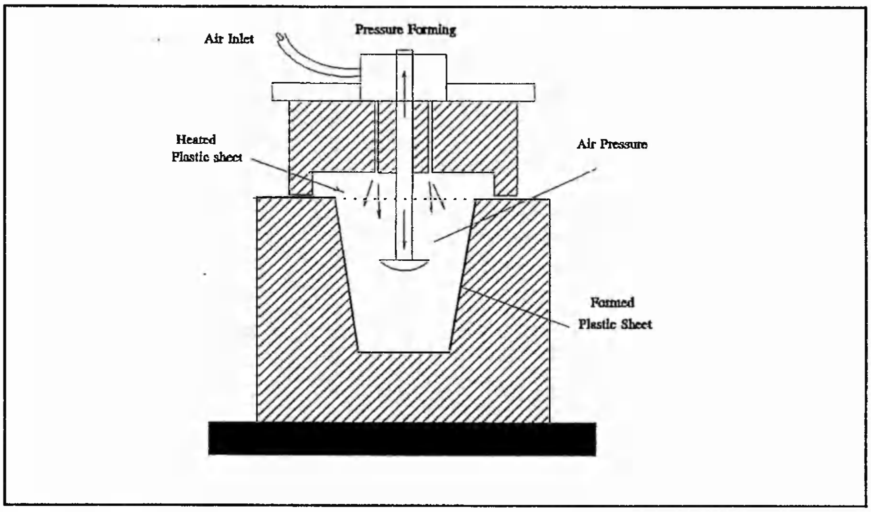


Figure 1.9
Basic Pressure Forming Process

1-3-6 CALENDERING

Calendering is a method of producing plastic film and sheet by squeezing the plastic through the gap between two counter rotating cylinders. This method has its roots in the paper industry but the scene has changed drastically since the early days of this method's use in the polymer industry in the middle 19th century where this method was used for mixing additives into rubber [2&12]. The application of modern control techniques and instrumentation has improved the quality and efficiency of these machines enormously. A typical sheet production unit starts mixing the polymer in a Banbury Mixer and/or a screw extruder. The resulting material is then fed to the calender rolls for shaping into sheets. Figure 1.10 represents a typical arrangement of the calender rolls. As may be seen in Figure 1.10, a small drum is positioned at the end of the process. This is a small high speed drum, intended to peel off the sticky sheet onto the drum, before sending it to the cooling and wind-up drums [13].

Clearly, the common component in all the above processes is the screw. It may also be regarded as the most important component since its performance could effect all the above processes and indeed the majority of plasticating processes. Even when these processes do not use a screw directly, they use materials processed by a screw, eg. in thermoforming, before a sheet is formed in a mould it has already passed through a screw extruder of some kind to be turned into sheet in the first place. Although there are possibilities

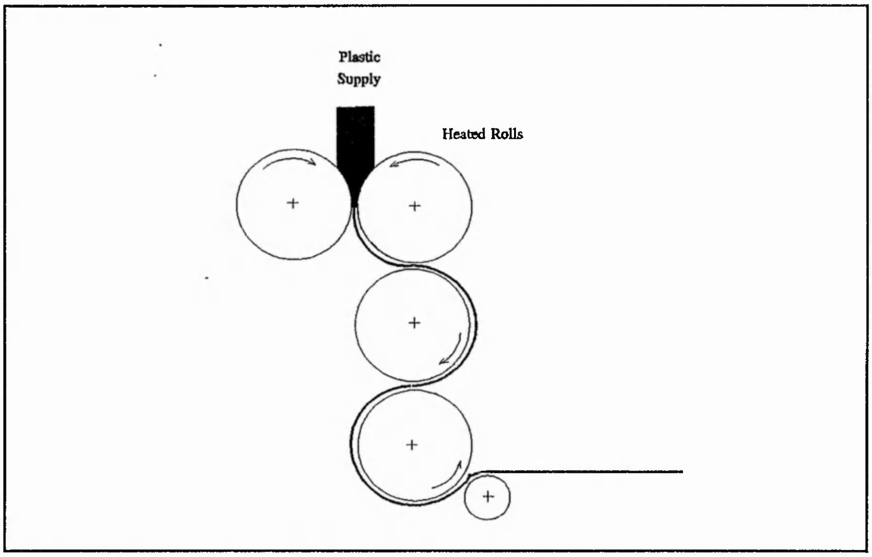


Figure 1.10
Typical arrangement of calender rolls.

for improving all of the above processes in many different ways, the fact is that any improvement in the screw design and manufacture would have a major impact on the industry as a whole and more processes would benefit from that. Therefore it seems logical to choose this area as the prime target of this research programme. In order to identify the shortcomings of this piece of equipment and suggest ways of improvement in its design and manufacture, it is necessary first to review it in further detail and analyze its form, function and operation.

1-4 THE EXTRUDER SCREW

An Extruder Screw in general is a mechanism in use in material handling and processing. Reputedly, it was first invented by Archimedes for pumping water and was later used by the Egyptians to irrigate their land from the Nile river [14]. Screws have changed a great deal since that time and are mostly used for pumping more viscous fluids or processing materials while in transfer. The right screw geometry and operational conditions will guarantee achieving that. The most important applications of screws are the food processing and polymer processing industries. However, from now on the only screws to be discussed are the ones used for polymer processing.

There are several parameters by which a screw can be identified and these are listed as follows:

Pitch
Screw Diameter
Screw Length
Flight Thickness
Channel Depth

Often, where the screw is used to change the nature of the material, the channel depth changes along the length of the screw. For instance in processing plastics, this usually takes place in three stages, in the Feed, Compression and Metering regions. The first stage is the feed zone where the channel is relatively deep so as to entrain enough material in the barrel to maintain the necessary throughput in the metering section. The second stage or Compression zone has a gradually reducing channel depth to create the pressure required to push the polymer through the die. Another function of the compression region is to eliminate any air inclusions by squeezing them back into the feed section. The rate of depth change is normally dictated by the required change in material state and necessary compression. Finally, there is a metering section with a constant channel depth which is, of course, lower than the feed depth to maintain a steady pressurised output at the end of the screw and into the die assembly. This now introduces five new parameters. These parameters define the screw profile and are feed, compression and metering lengths plus feed and metering depths. The ratio of change in diameter in compression region is governed by the feed and metering diameters and the compression length. Figure 1.11 describes a typical plasticating extruder screw.

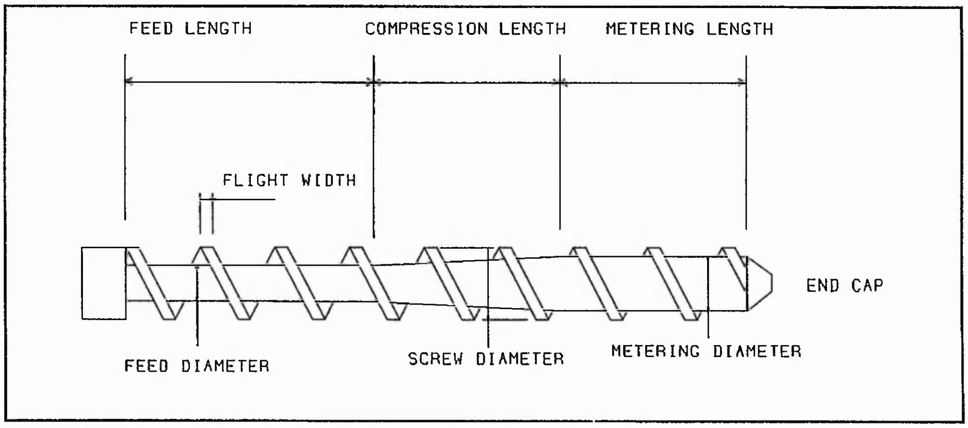


FIGURE 1.11
A typical plasticating extruder screw.

Apart from the simple screws and screw sections there are a range of complementary devices in the market, each designed to improve the overall performance of the screw and hence the operation of the extruder. These devices are usually built onto the screw shaft and are very expensive to make and the extent of their effectiveness is not quantified.

Looking at the extruder screws and different complementary devices available for them and the number of possible screw specifications by just using different combinations of screws and devices, it is not difficult to realise the complexity of design and manufacture of such screws. This level of difficulty and the prospect of improvements in quality and productivity, qualifies the "screw design and manufacturing process" as an important area of research and development in the plastics industry. Therefore, it will form the basis of this project.

In order to improve screw design and manufacture, current methods should be reviewed and the shortcomings outlined. Having looked briefly at different screws and the supplementary devices for them, it is now necessary to understand the detailed design methodology and the thinking behind it. This, combined with an in-depth review of screw production methods and practices, should create a realistic image of the polymer processing support industry which is responsible for polymer processing equipment manufacture. It then becomes possible to propose detailed changes to extruder screw manufacture. This is the subject of the discussion in the next section.

1-5 SCREW DESIGN AND MANUFACTURE

1-5-1 INTRODUCTION

The history of thermoplastics goes back a mere 50-60 years. During this period, a great deal of innovation and improvement has been introduced to this new branch of engineering. In fact at first it was not even regarded as engineering and still today some do not recognize its rightful value. Until recently, only five major polymers formed the majority of consumer components. This becomes evident by looking at the plastics journals and the rare global statistics concerning the use of polymers prior to 1980s [15]. These five materials are:

Polyethylene (PE)
Polypropylene (PP)
Polyester (PS)
Poly Vinyl Chloride (PVC)
Polyamide (PA)(Nylon)

The main reason for there being such a limited range was the fact that the manufacture and processing of those materials had become effective only after a great deal of time and money had been spent in the refinement of the processes to achieve relative satisfaction. Using any material other than those five led to problems. Although relative satisfaction in the design of screws was believed to have been achieved, in the sense that products could be made, the extent of their effectiveness was not known and could not be measured. As technology progressed and the necessity to cut production costs arose, designers looked to the advantages of polymers in their new products. When new applications were developed, the need for more sophisticated materials became more apparent. Eventually, as new and more complex materials became available, the need for more efficient processing techniques was felt more acutely. The complexity of the melting process meant that the prediction of the outcome of the process was virtually impossible. This was extremely important because the quality of the melt bore a direct relationship to the quality of the product. As a result of this, the only means of producing a good quality melt, and therefore product, was highly dependent on screw design and the operating conditions.

This is due to the fact that plastic melt is a very good thermal insulator. As soon as plastic pellets start to melt, the melt forms an isolating layer around the solid bulk of the pellet which prevents the heat flux from getting to the solid plastic. The solution is therefore, to apply shearing forces to the now viscus solid/melt. This will deliver the thermal energy where it is needed by transforming the mechanical power. This in itself is a difficult task to perform, for each material has a certain degradation temperature (maximum melting temperature) and can only remain in its melting temperature (within the barrel) for a limited time before loosing its physical and chemical properties. All these are considered with another constraint which is the process rate which is the main criteria for making profit. This made the performance of the screw and the behaviour of the process hard to predict.

Even assuming that the screw behaviour and the process outcome could be predicted with sufficient accuracy, the complexity of screw manufacture and the capital intensive nature of the process prevented the viability of customised screws.

The result was that the emphasis was placed on manipulating the operating conditions and the industry found itself defining so called "General purpose screws" which were supposedly effective for most of the materials. This in itself was not trouble free and in fact different people had different perceptions of "the ideal screw" and came up with their own version of the "standard screw" which again corresponded to a new set of operating conditions. The truth of the matter was that because it was not commercially viable to alter the manufacturing set-ups to produce different screws for different polymer materials, there had to be a compromise. This becomes more tangible when the screw manufacture practices are reviewed and difficulties associated with them are analyzed. In order to further enhance the picture and explain the production difficulties, the current manufacturing practices are studied in further depth.

Screws are generally produced in three different ways. These are called the "Helicoid", "Sectional" and "Integrated" methods [16]. Helicoid screws are made from helicoid flights welded onto a piece of pipe. The helicoid flight itself is made by rolling a flat bar or strip through two cones into a continuous helix. Figure 1.12 represent a section of a screw constructed in that manner.

Fights manufactured in this way have a thinner outer-edge compared to their inner edge.

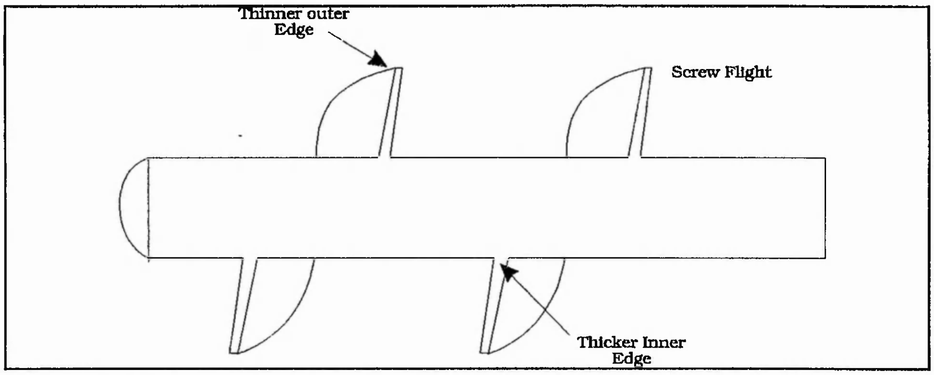


Figure 1.12
A section of a screw with "Helicoid" flight.

In the Sectional method the screw is also manufactured by welding flights to a piece of pipe or bar. The difference lies in the way the flights are manufactured. Sectional flights are formed from flat discs. Several pieces of the flight are welded together and to the pipe. In this method there is no problem of varying flight thickness, but it takes longer to construct pieces of the flight.

Integrated screws however, are manufactured in one piece by cutting a metal rod with a machine tool. Screws manufactured in this manner are capable of withstanding higher pressures and shearing forces, but are more expensive. The screw production method amongst other things, is a function of its application. Integrated screws are usually used in processing industries for their mechanical capabilities while the Helicoid and Sectional techniques are mostly used for manufacturing screws used in material handling devices.

Because of the mechanical requirements, the screws used in polymer processing are manufactured using the integrated method. Since all the screws relevant to this study are produced in integrated fashion any further discussion will, from now on, relate to this type of screw.

Integrated screws are cut by rotating a solid bar with a constant velocity and engaging a tool while moving along the bar, removing some material on the way, in a cylindrical machine tool (Lathe). This creates a helical channel on the surface of the rotating cylinder. This action is repeated several times till enough material is removed and the screw channel is formed. Figure 1.13 illustrates the cutter paths for a typical screw.

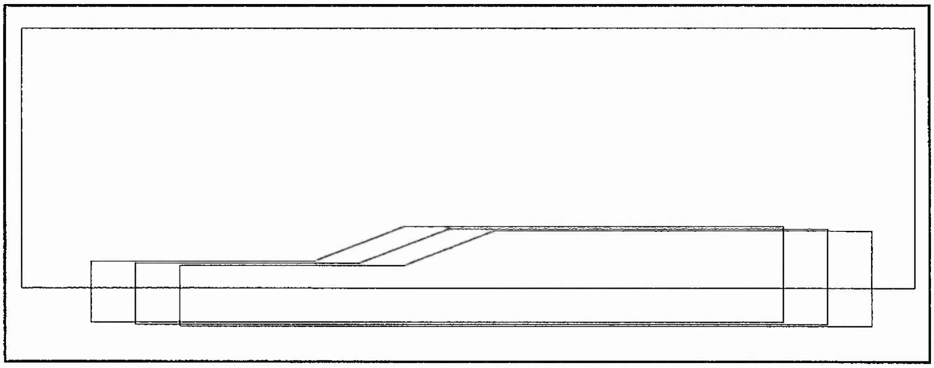


Figure 1.13
Screw cutter paths.

The most basic parameter of any screw is its pitch. In order to get a satisfactory result and generate the right screw pitch, the traverse (tool post) speed must be linked to the rotational velocity of the bar. This operation is executed in the lathe's thread cutting mode where a set of combined gears will correlate the traverse and spindle speeds to give the right pitch. At the same time, the rotational velocity of the spindle will determine the cutting speed of the material. In practice there are times when the gear combination cannot provide the required pitch. This is because the rotational movement of the spindle is translated into linear movement along the machine bed. Every spindle turn therefore corresponds to a certain value for the linear movement of the traverse along the machine bed. This value is the screw pitch and since for any machine tool there are only a limited number of gears available with limited combinations, therefore it is impossible to get the exact pitch in all cases. Even if the right pitch can be cut there are still problems with manufacturing screws with variable root diameters. This is because the traverse movement can be automated along the machine bed but not across it.

This makes the cutting process of the tapered sections very difficult. To overcome this problem machines were designed that were able to "read" a special disc (cam) which mechanically moved the tool across the machine accordingly. The problem now became the design and manufacture of these discs for individual screws. Attempts were made to automate the design and manufacture of these cams [17 & 18] but this was still not the ideal solution for this application. The problem was aggravated by the structure of the industry and the one-off nature of its products. Apart from the relatively high set up time, the task in manual processes is highly skill dependent. Until the development of the high performance CNC machine tools there was not much room for improvement.

After these new developments, it was possible to improve productivity, but following discussions with machinery manufacturers [19], it became obvious that the new skill requirements for operating these CNC machines and the actual replacement cost of the existing manual or semi-automated machinery proved to be strong enough to prevent the change, at least for the time being while existing equipment and machinery is maintainable. The polymer processors therefore, continued to use screws designed by the "trial and error method", with the intention of melting any material by putting more energy and shear into the material.

One major deficiency of this design method was the move towards introducing different add-ons, as a supplement to the lack of good design and a compensation for the inability to manufacture any better designs which might have improved the situation. This approach succeeded to the extent that it led to eventual melting of the polymer and satisfaction of the user, but this was achieved without knowing much about what was happening inside the barrel and to the material.

Although, the need to manufacture screws with more complex features was reducing the efficiency of the process, Screw manufacturers introduced different add-ons and incorporated them into the design of their original screw in order to create the "General Purpose Screw".

Some even introduced more than one device per design to ensure that there was no material capable of going through the process and leaving the barrel unmelted. As a result, this created increasingly complex screws.

There are so many different types of these devices, each with different theory and purpose, that it is impossible to describe them all within the confines of this review. However, it is important to recognize and understand the more popular designs of these devices.

1-5-2 MADDOX MIXING DEVICE (HEAD OR SECTION)

This device is featured in figure 1.14 and could be machined into the middle of a screw or alternatively cut or screwed into the end of a screw. As it can be seen, it is formed by parallel channels with the two openings at opposite ends. These channels could be along the length of screw or at an oblique angle. The device works on the principle of the solid or solid/melt mixture entering into the channel, where the only way out is across a weir and into the next channel with the opening at the opposite end. During this process material passes through the narrow gap between the screw and the barrel through channels. This leads to mechanically generated heat which in turn melts the material [13].

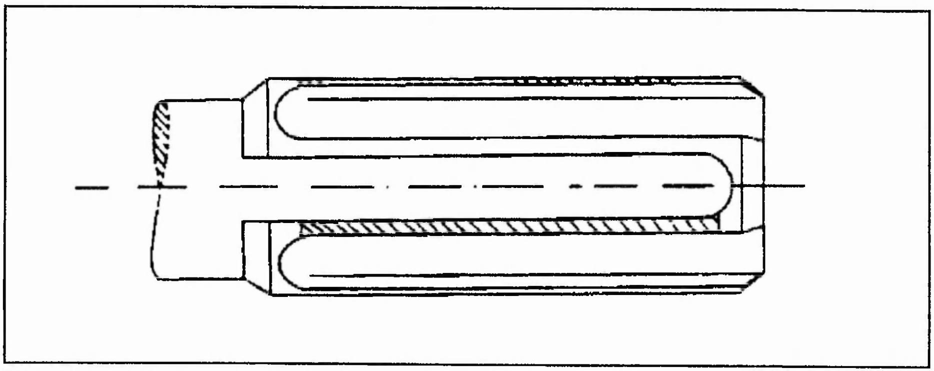


Figure 1.14
Maddox mixing head.

1-5-3 PARALLEL INTERRUPTED MIXING FLIGHTS

This device is formed by cutting narrow channels in the path of the material on the screw shaft. Sometimes more than one set of these devices is cut on each screw. Usually this section is placed around the end of the screw but there is no hard and fast rule for that. This device also utilises the shearing energy created by the unmelted material trying to negotiate its way round the narrow passages. Figure 1.15 illustrates this section.

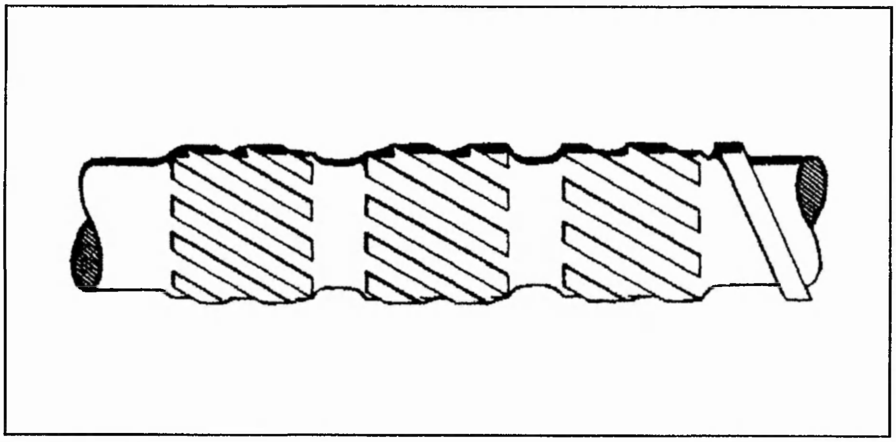


Figure 1.15
Parallel interrupted mixing flights.

1-5-4 Mixing pins

This device is formed by mounting cylindrical pins in the path of the material as illustrated in figure 1.16. The main reason for using this type of device is mixing but because of its nature and the fact that it is blocking a proportion of the screw channel, it will naturally create extra shearing for extra melting.

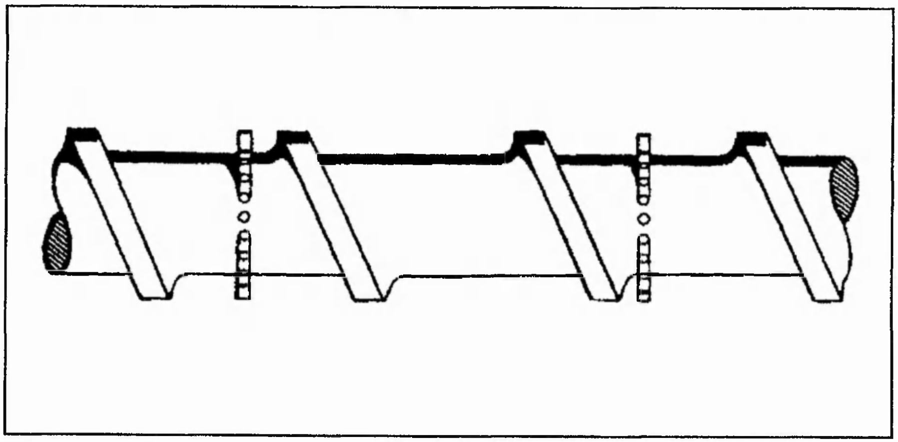


Figure 1.16
Mixing pins.

1-5-5 RING TYPE BARRIER

This device is formed by cutting a ring at the appropriate position on the screw. This will result in the material having to pass through the gap between this ring and the barrel before leaving the screw,leading to very high shearing forces which will eventually produce melting of the materials. Figure 1.17 illustrates the device.

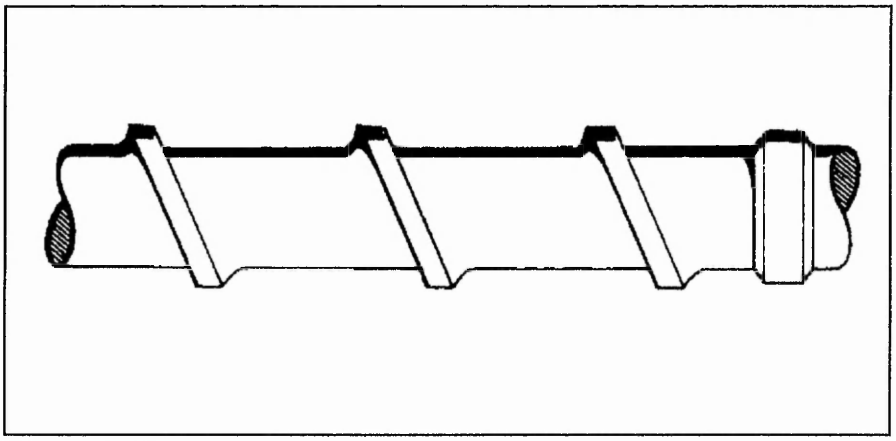


Figure 1.17
Ring type barrier.

1-5-6 UNDERCUT SPIRAL BARRIER TYPE

This device is effectively produced by creating two different channels for solid and melt. It could form a section of the screw or the whole screw could be cut on that principle. It works on the assumption of a known melting rate so that as the solid material proceeds along its path in the channel, it becomes melted and moves over the flight to the melt channel at a known flow rate. As the solid channel narrows and gets shallower along the screw, so the melt channel widens and gets deeper to accept the increased volume of melt. This system can produce higher quality melt and guaranteed melting under certain circumstances. The problem is however, that the two channels are formed by the introduction of an extra flight which increases the dead space in the extruder barrel. Hence, for the same size screw with the same screw speed there will be less throughput. Furthermore, since the melting rate of the material is generally neither linear nor known before hand, the melt channel is either not full or contains solids. In either of these two cases the result is far from satisfactory. Figure 1.18 represents a typical barrier type section.

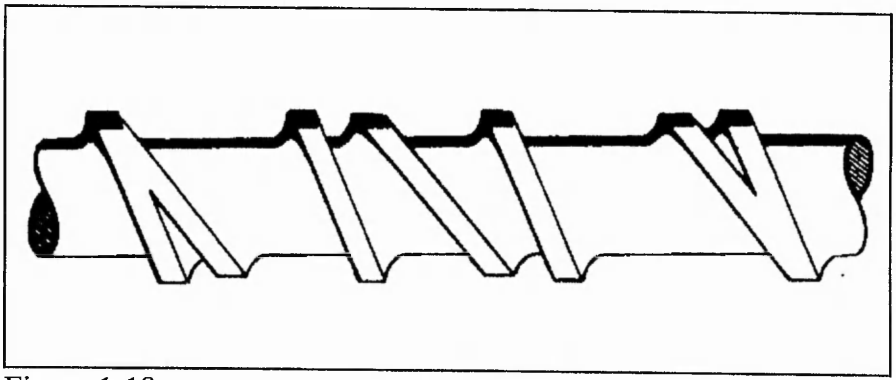


Figure 1.18
Undercut Spiral barrier.

1-5-7 CAVITY TRANSFER MIXER (RAPRA)

This device is mounted towards the end of screw and is also based on shearing materials in its cavities. These cavities are cut on both barrel (stator) or screw (rotor). During the operation, melt is systematically cut and rotated before being subjected to further shear. It is assumed that the greater the number of operations (cuts and rotations) the greater is the mixing efficiency [20]. Its major disadvantage is most probably its manufacture, which is extremely complex. This device is illustrated in figure 1.19.

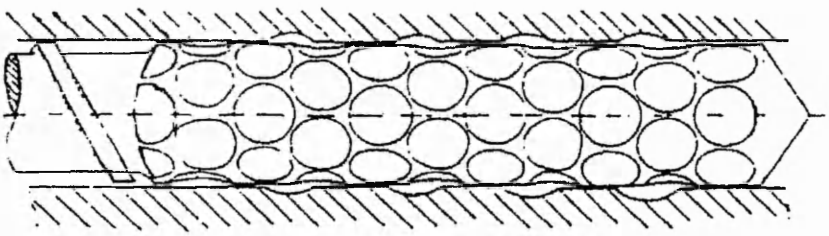


Figure 1.19
Cavity transfer mixer.

1-5-8 PINEAPPLE MIXING SECTION

This is very similar to the "parallel interrupted mixing flights". The difference is in smaller (usually square) straight instead of angled flights. They also have top edges which taper to a point. It works on the same principle which introduces shear into the material when it passes through the channels. Figure 1.20 describes this device.

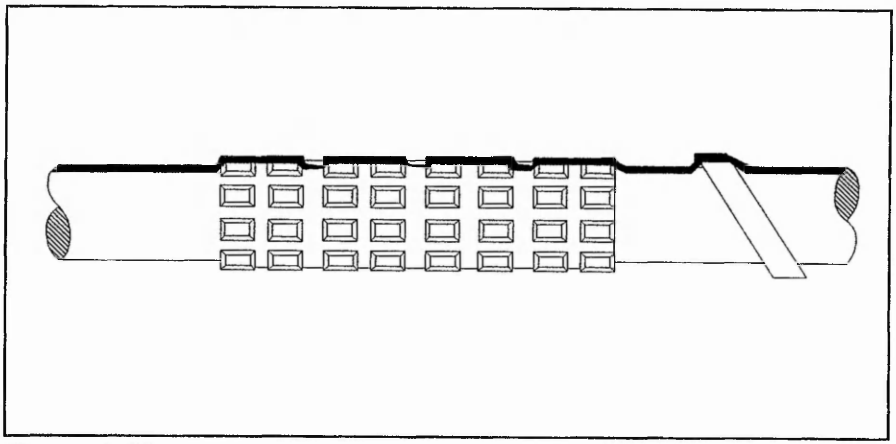


Figure 1.20
Pineapple mixing section.

1-6 SCREW OPTIMISATION

As described above, screw design methodology has been fairly primitive and unreliable especially in the case of the newer materials and processes. The basis of this method as mentioned before was the system of trial and error. This problem inspired engineers to try and rationalize their approach to screw design and try to optimise the screw for a particular process. Developments in computer hardware and software and maturation of techniques such as "Finite Element" and "Finite Difference" helped to lay the foundation for their efforts. Despite all these developments, the perfect model which allows the screw design using only the properties of the polymer does not exist. However, this has paved the way to a better understanding of the processes and will eventually lead to optimisation of the screw for the process.

Before mathematically modelling the material flow in the screw extrusion process, it is important to realise that the material passes through three distinct states before leaving the process. These three can be classified as follows:

Solid conveying
Melting
Melt pumping

In the first region, the solid material is conveyed before forming the melt film at the barrel before entering the next phase. A few turns further along the screw, the screw melt film is formed, and whilst travelling in the down-stream the screw and barrel films develop. This process continues until there is no solid left in the channel. From this point on only melt is left in the channel and the screw acts as a melt pump. This action continues until the melt is discharged through a die, at the end of the barrel. Each of these phases are modeled separately while interdependency of them is maintained. Available models for these three states are reviewed as follows.

1-6-1 SOLID CONVEYING

There are relatively fewer studies and publications regarding this stage of process (solid conveying). The first model of this phase was presented in 1956 [21]. According to this model, the solid is conveyed as a result of the difference between the friction forces at the screw and barrel surfaces. This acts on the solid as a non-deformable bed, creating a situation known as the "plug flow". In 1969, a major modification was introduced to this model by Schneider [22]. This was the introduction of a correction factor to take into account the effects of the flights on the flow of solids.

A new model was introduced in 1970[23] where presence of polymer melt films generated by friction on metal surfaces was introduced as the main reason for the solid flow. This was still assuming that the solid bed was non deformable. Broyer extended the first model presented by Darnell and Mol to include the effects of flights in Schnider's model, as well as a thermal analysis of the solid bed [24-26]. An experimental study reported in 1973 which showed the fast compaction of solids to form a non-deformable solid bed. It also showed that the shear rate in polymer melt films was negligible and hence concluded that the solid bed motion was due to friction forces[27,28]. This study was followed by a model which assumed that solids were surrounded by melt and expressed that this mixture was incompressible. This theory however, was not supported by any experimental data [29].

Zhu, Fang and Wang [30] presented their model in 1980. They divided the width and depth of the solid bed into several parts in order to identify plug flow. They also introduced a new factor, namely rigidity factor of polymers and its relationship with the flow. The experimental results were in agreement with the predictions of the model.

1-6-2 SOLID MELTING

This is the most complex of the three stages stated above. The main reason is the existence of both solids and melts in the channel at the same time. Until recently, the majority of models presented were based on solving a number of interdependent equations, simultaneously, based on a series of assumptions.

The first model was developed at the end of 1966 [31]. In this model, a constant solid bed velocity, a constant film thickness across the channel and a negligible leakage flow through the flight clearance were the main assumptions. It was also considered that the fluid was Newtonian (constant coefficient of viscosity). A year later, the same model was modified to consider and incorporate the flow of a Power law fluid (non-Newtonian fluid) [32]. A few further works presented with slight modification of the same model [33-37]. Donovan introduced a major modification to the Tadmor model in 1971, by introduction of a new factor called "solid bed acceleration parameter" [37,38)]. He allowed for the solid bed break up and its subsequent acceleration due to the surrounding viscus fluid in his model.

He also considered the viscous dissipation of the solid bed and described the temperature profile during a drag flow of a power law fluid, between two parallel plates. Edmondson and Fenner model[39], calculated the solid bed velocity. They modelled the presence of melt film on the barrel and screw. In 1976, they presented a new model with the consideration of a variation of the melt film thickness in the cross channel direction[40,41]. These were based on the assumption that the fluid was Newtonian. Later, they introduced a model based on the power law fluids. Cox, Williams and Isherwood [42] have describe some experimental work using this melting mechanism.

Fukase, Kunio, Shinya and Nomura [43], developed their model within which the solid bed travelled at a constant rate between the screw and barrel melt films. The melt film is assumed to be disappearing and solid bed accelerating as the channel depth reduces. The flow was considered to be of a non-Newtonian fluid and experimental values supports its predictions. A few more models were presented with slight modification to the existing models[44-46], before Rauwendaal [47] presented a model similar to Donovan's with the exception of constant solid bed velocity.

1-6-3 MELT PUMPING

This state of the process has been covered extensively over the years. The main reason for this is probably its simplicity. Also the ease with which the fluid's temperature, pressure and other properties can be measured compared to solids and melt/solid mixtures. The main assumptions for the development of these models could be listed as follows:

Fluid Nature (Newtonian and Non-Newtonian fluids).
Thermal consideration of the model (Isothermal and Non-Isothermal).
Consideration of the number of flow Dimensions (1,2 and 3).
Consideration of the convection.
Consideration of leakage flow.
Consideration of slip factor at the walls.

Most of the people who worked on the melting model devised a pumping model too [48-59]. There is no merit in reviewing all of those in detail for there are enough general purpose fluid flow models covering this area, hence, its discussions is avoided.

Having considered that the pumping model's detail description was inappropriate to our discussion, the same argument could also be applied to solid conveying. In this case too, the material is of a known state with stable properties during the conveying process. Therefore there is not much benefit in analysing that in further detail. The problem however, is in the melting state where there is a mixture of solid and melt with variable properties with a changing mixture ratio. Therefore, to get a better picture of the melting process and therefore polymer extrusion, one of the most recent models is to be described.

Before formulating the melting model it is important to note the significance of the material properties. These are established by referring to material data books or more importantly, "rheology tests", which will be discussed in a later section when appropriate.

The melting model presented here is a simplified version of the Fenner model which was developed further at the Nottingham Trent University, by our research partners. Fundamental to this model is the solution of the following four equations.

1- The conservation of mass (continuity)

$$\frac{\partial \rho}{\partial t} = -\left[\frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) + \frac{\partial}{\partial z}(\rho w)\right]$$

Where ρ is the density and u,v and w are velocities in x,y and z directions respectively.

2- The conservation of momentum (equilibrium)

$$\frac{\partial}{\partial t}\rho v_z + [\frac{\partial}{\partial x}(\rho uv) + \frac{\partial}{\partial y}(\rho vw) + \frac{\partial}{\partial z}(\rho ww)]$$

$$= -[\frac{\partial}{\partial x}\tau_{xz} + \frac{\partial}{\partial y}\tau_{yx} + \frac{\partial}{\partial z}\tau_{zz}] - \frac{\partial P}{\partial z} + \rho g_z$$

Where τ is the stress tensor, P is the pressure and g_z is the component of the gravitational force in the z direction and hence ρg_z gives the body force. The equation presented here is for the down stream component or z direction because in this instance there is no movement in the x and y directions (laminar flow because of low Reynolds numbers R_e). Therefore the other components are not illustrated.

3- The conservation of energy

$$\rho C_p[\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z}] = k\,[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}]$$

$$+ \tau_{xx}\frac{\partial u}{\partial x} + \tau_{yy}\frac{\partial v}{\partial y} + \tau_{zz}\frac{\partial w}{\partial z} + \tau_{xy}(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x})$$

$$+ \tau_{yx}(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}) + \tau_{xz}(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z})$$

In this equation, k is the thermal conductivity, C_P is the specific heat capacity at constant pressure and τ is the stress tensor.

4- Rheological equation of state (power law)

$$\eta = \eta_0 \, \dot{\gamma}^{n-1} \, e^{-b(T-T_0)}$$

In the above equation,

η, η_0 are the viscosity to be determined and viscosity at unit shear rate respectively.

b is the temperature coefficient of viscosity

n is the power law index

T is the temperature

T_0 is the reference temperature at which η_0 was measured

$\dot{\gamma}$ represents the shear rate.

Above equations governing the process when: the first equation is concerned with the mass and utilises the fact that the same mass exits the system as enters. The second equation deals with momentum and employs the principle that the overall momentum within the system is zero in order to calculate velocities at different times. The third equation expresses the fact that all the energy used within the system, regardless of its nature (mechanical, thermal...), will be used to convert the material state and no energy remains within the system. The last equation defines the material and the relationship between temperature and shear rate which in turn influences the results of the previous equations.

Having established that these models require to receive some input in the form of the material's characteristics and its behaviour at different conditions, it is useful to study rheology and its principles in further detail.

1-7 RHEOLOGY

The main concern in rheology is the establishment of the behaviour of the material at different conditions, namely shear rates and shear stresses, and their corresponding relationship with the viscosity and temperature. Material characteristics are established experimentally, the main reason being that these characteristics may change from manufacturer to manufacturer even for the same grade of the same material. There are different tests performed on different pieces of apparatus; the best method for polymer melts is a rheometry test using a capillary rheometer. This enables relatively high strain rates to be applied to highly viscous materials and the resulting shear stress to be identified over a range of temperatures and shears.

A capillary rheometer mainly consists of a vertically positioned cylinder with controllable heater bands around it. This cylinder is capable of holding different dies with different lengths and internal diameters, inserted from the bottom end. A steel piston with a controllable drive system is to be driven in from the top end. The piston is connected to a load cell which measures the force at the piston head (figure 1.21). Solid polymers are heated within the cylinder, at certain temperatures to measure their behaviour under different shear stresses, applied by the piston during its extrusion.

The test process starts by pre-heating the cylinder to a temperature nominally above the material melting temperature. The material is then poured into the

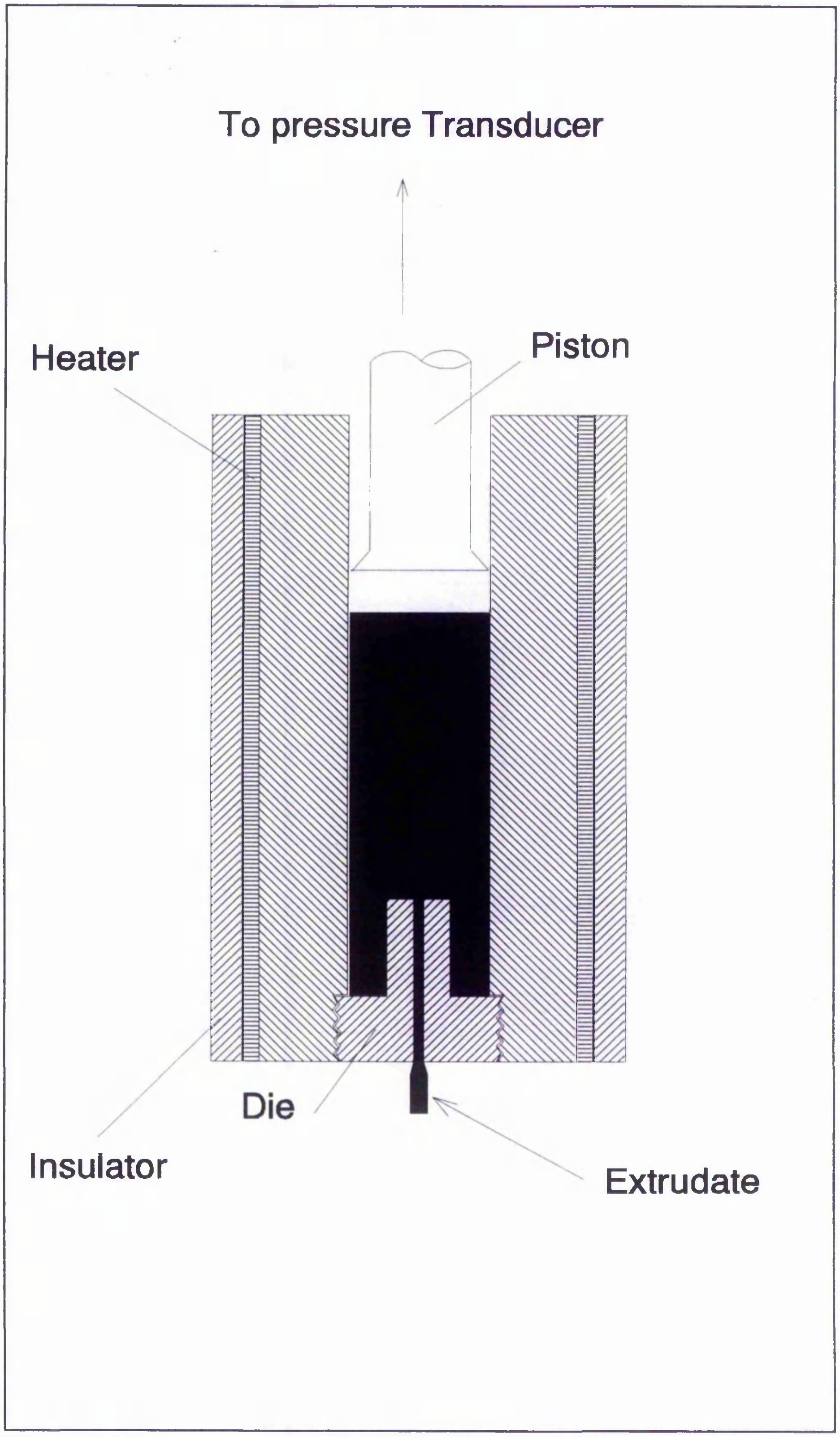


Figure 1.21
A basic capillary rheometer.

cylinder with the die in place at the bottom end, and packed thoroughly. After the system reaches thermal equilibrium, the piston is driven into the cylinder and the force read by a load cell is recorded at different extrusion rates. The process is repeated at three different temperatures with "long" and "zero length" dies at each temperature. Use of zero length die is for the Bagley correction (entrance and exit effects) [60].

The experiment outcome is in the form of a piston force at seven different piston velocities for each die at each temperature. These figures are then manipulated to give the three following relationships:

a)- shear rate vs shear stress
b)- viscosity vs shear stress
c)- viscosity vs shear rate

Depending on the computer model all or any combination of these relationships will be used to predict the material flow properties. There are standard relationships which could be used to arrive at those values. The details of these techniques are available in the relevant books and reference literature [60,61].

1-8 SUMMARY DISCUSSION

So far, it has been explained that the early advances in modelling of the melting process made it possible to predict the outcome of the extrusion process with a certain degree of accuracy. Obviously, these models could be deployed in an optimisation process. This however, did not in itself trigger the wide-spread use of these new tools. This was partly due to the deficiencies of these models in predicting the process outcome with sufficient accuracy. The other factor was the lack of sufficient computing power on the systems available to industry at the time. Hence there was a lack of industrial interest for its deployment and therefore little support of its further development. The main problem was however, the manufacture of the complex screw forms. Although with the existing system it was possible to optimise the screw to a certain degree, there was still no guarantee for its manufacturability, due to the problems associated with the intricate machining. Therefore, the screw optimisation methods were to a certain extend neglected.

After the recent developments in computers and computer controlled systems, especially in the machine tool industry, and the introduction of high power "Computer Numerically Controlled" machine tools, it has once again become feasible to use the design optimisation systems. This time, however, it is important to create the necessary environment for the success of this methodology. The associated problems to overcome are the capital investment and training of the labour force capable of operating this new machinery.

The investment problem is something that is outside the scope of this project. Besides, there are several government agencies and financial experts who could tackle this problem better than we could. Moreover, at this stage providing that a sufficiently efficient manufacturing system is available on the market, sooner or later, some of the processing equipment manufacturers will have to invest in new machinery.

However, the problem of the shortage of a highly skilled work force is something that could be addressed. This is where "Computer Aided Engineering" and automation enters the formulations. Design of an integrated design and manufacture system for extruder screws would encourage the plastic industry to accept the design program more readily, for it is now possible to manufacture any designed screw. This could trigger further development and research which could in turn enhance the optimisation. Furthermore, because it is possible to design and optimise the screw for each material, there is no need for the add-ons to be incorporated in the screw design and so future screw designs will avoid complexity. This avoidance in turn will contribute to the better manufacturability of the screw and will reduce the cost. The other advantage of such a system is its reduced response time to the customer orders and a shorter manufacturing lead time. Also increased capacity for future expansion due to shortening of the work in progress time.

CHAPTER 2

TECHNOLOGY AUDIT

2-1 INTRODUCTION

It was explained that the technologies relevant to this project should be reviewed and appropriate technologies should be chosen for adoption. Looking at the Manufacturing engineering area, there are various technologies available which are technically possible, but not necessarily commercially feasible in all applications. Each technology is applicable to a particular type of manufacturing environment and should be chosen accordingly.

For many people, specially in the industrialised nations, manufacturing has become the most important route to prosperity. However, it is becoming increasingly difficult to compete on an international level and meet the customer's demand in a rapidly changing market and conditions. Automation became the answer to demands for higher production rates and was sufficient for a while. But, conventional means of automation (hard automation) is no longer able to meet these challenges [62]. The reason for this is that although those methods are good in controlling operations, they lack the ability to process information. Recent developments in computer technology has made it possible to develop new tools with both of the above capabilities and more. These tools could improve the productivity and speed the reaction to the market by providing design and manufacturing tools as well as process planning, resource monitoring, even quality supervision. This matches some of our intention within this project.

When computer becomes a major component of a manufacturing system and helps to plan and operate it, it could be called Computer Integrated Manufacture [62]. It includes:

Computer Aided Engineering (CAE).
Computer Aided Production Planning(CAPP).
Computer Aided Quality Control(CAQ).

Integration of Computer Aided Design and Computer Aided Manufacture CAD/CAM, form CAE or Computer Aided Engineering. Data Communication is also important within the CIM frame-work. Another philosophy relevant to the manufacturing is "Concurrent Engineering" which needs to be reviewed in this discussion. In the following sections, CIM, CE and their elements will be discussed in further depth.

2-2 COMPUTER INTEGRATED MANUFACTURE (CIM)

Computer Integrated Manufacture is a concept much talked about in the recent years but its first introduction dates back to 1960s [63]. It has been defined in many different ways and it means different things to different people, perhaps, far too many to summarize. It is considered as the western world's answer to the manufacturing might of the far east. Digital Equipment Corporation (DEC) has defined CIM as follows [64]:

" CIM is the application of computer science technology to the enterprise of manufacturing in order to provide the right information to the right place at the right time, which enables the achievement of its product, process and business goals".

This is a general definition and the approach to CIM is different for different companies even different countries and it needs to be expanded further to address specific requirements. The main reason for this is specific requirements such as: different market strategies, labour availability, wages, market sizes, ...etc.

In order to fulfil the promises expressed in the CIM definition, certain principles have to be applied and particular tools have to be used. Before further discussing the tools listed above, it is important to review some of the basic principles in utilisation of CIM.

Two basic rules have been defined for CIM [65]. The first rule is that "however profitable the CIM system, someone who understands in depth both the problem and the system, will make it more profitable". The second rule expresses the fact that the implementation of CIM for each company would be unique.

The scale of improvement in a manufacturing environment as a result of CIM implementation is different for different companies as is its implementation. However, experience has shown the following typical benefits [62]:

a- Reduction of design costs by 15-30%.

b- Improved product design; ability to examine design variants 3-30 times more than the conventional methods.

c- Reduction of the in-shop time of a part by 30 - 60%.

d- Improved Productivity by 40 - 70%.

f- Better Product quality; Reduction of scrap by 20 - 50%.

Design of a CIM system is tedious and time consuming and requires extensive manufacturing and computing experience to tie the computers into a production process. The scope of the CIM model should comprise all functions which are necessary for running a business. A typical CIM model contains the following features:

a- Presentation of the business functions.

b- Integration of the management information data base.

c- Presentation of the material and product flow.

d- Presentation of the information flow.

e- Description of the interfaces and communication protocols.

f- The presentation of the hierarchical planning and control functions.

g- The inclusion of time.

The heart of a CIM system is its unifying data base which serves all the functions of the manufacturing system's operations at any stage. The main functions of a manufacturing system could be listed as:

1- Market research.
2- Long range forecasting.
3- capital equipment and facility planning.
4- customer order servicing.
5- Engineering and design.
6- Manufacturing process planning.
7- Marketing.
8- Production scheduling and manufacturing monitoring and control.
9- Purchasing and receiving.
10-Inventory management.
11-Quality control.
12-Maintenance.
13-Accounting.

Looking at the list of functions covered in the manufacturing system, it becomes evident that there is a need to create a range of tools, each covering a specific area, all supporting the main goal of the manufacturing system and share information between them. The following sections will discuss some of the tools discussed earlier.

2-2-1 COMPUTER AIDED DESIGN

CAD or Computer Aided Design, is a fast developing area of computer application in engineering. CAD usage has not been limited to Mechanical engineering but it has been utilised in so many different areas from Civil engineering, Electrical and Electronics, even Arts and Architecture. Whilst the precise definition of CAD is in a state of flux, one of the most general definitions is the one of Groover and Zimmers [65]:

> *Computer Aided Design (CAD) can be defined as the use of computer systems to assist in the creation, modification, analysis or optimisation of a design. The computer system consist of the hardware and software to perform the specialised design functions required by the particular user firm.*

The CAD revolution began following the rise of interactive computer graphics. During 1962, Ivan Sutherland at the Massachuset Institute of Technology (MIT) stated in his Ph.D. thesis that interactive computer graphics was commercially viable. Sutherland's work and its publicity created a great deal of interest in the subject. Sutherland himself introduced many of the fundamental ideas and techniques that are still in use today. During the same period, General Motors Corporation and Lincoln Laboratories independently demonstrated the feasibility of developing a Cathode Ray Tube (CRT) into a graphics display. By 1965 large scale computer graphics research was being carried out at GM, MIT, Bell Labs, Lockheed and McDonnell Douglas [66].

Although the word CAD could be used to classify many applications, the common perception of a CAD system is a computer work-station with a graphics display, capable of generating lines, arcs and models which are widely used in Engineering. Nowadays, there are a range of Engineering CAD systems available in the market with different capabilities. Despite of this variety, the range of tasks performed by these systems are limited in their nature. These tasks could be classified into four major areas [65] as follows:

Geometric modelling.
Engineering analysis.
Design evaluation and review.
Automated Drafting.

The most common feature of CAD systems which is the ability to generate geometric entities on the screen, is in fact geometric modelling. It works on the principal of interfacing a graphics program to perform some standard and well defined tasks. These tasks are usually carried out interactively and should be quite fast before they are of some benefit to the end users. Several modules are now in existence within the CAD systems to extend its use as a powerful tool in engineering. The important modules existing within CAD systems could be listed as following:

Wire frame modeller
Solid modeller

Shading module

Artificial Intelligence (AI) applications

Each module has its advantages and limitations and different systems offer different combination of the above modules to serve different applications. The wire frame model of an object is a model where all the edges are defined and drawn on the screen. This is very fast and versatile and can be handled easily. Its drawback however is the obscure nature of the 3D models it creates. Figures 2.1 describe the model of a simple object and 3 different possible interpretations of the same object.

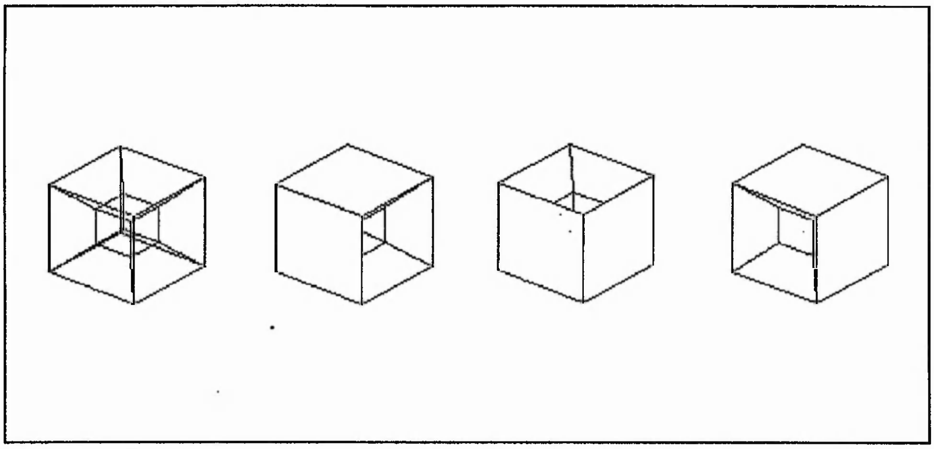


Figure 2.1
Different interpretations of the same object.

Another deficiency of wire frame models is their inability to distinguish the solid side of any surface from the model. An improvement from this model shapes in the form of a "Solid model".

A solid modeller uses a different approach to illustrate objects. In this method, models are represented as solid objects to the viewer. This eliminates the problem of misinterpretation all together. There are two main methods of creating solid models. The first method is based on the creation of an object by assembling it from primitive entities like boxes, cylinders, spheres and so on. This method is called Constructive Solid Geometry (CSG) or C-Rep. Boolean operations between these primitives create the model. The other method is Boundary Representation or B-Rep. In this method, the object is constructed by definition of the boundaries forming each view of the object. Each approach has its advantages, for instance, the C-Rep presentation system is easier to use to create objects, while the B-Rep method is more appropriate when designing complex shapes such as car panels or aircraft fuselage shapes.

The only draw-back of solid modelling is however, its extensive computing requirements. There are a few more methods that are not as widely used as the first two, but some systems combine all these methods to create more flexibility and ease of use. These methods could be listed as follows:

Analytical Solid Modelling (ASM)
Sweep representation
Primitive instancing
Cell decomposition
Spatial occupancy enumeration
Octree encoding

ASM modelling was developed primarily for use with Finite Element (FE) systems. It can be presented more as a representation scheme for design than for manufacturing purposes, due to its formulation which does not involve orientable surfaces. Sweep representation modellers are on the other hand useful in creating solids of uniform thickness in a given direction (extruded objects) and axisymetric solids [67]. The rest of the above list is used less frequently and their details are not of concern to this discussion.

Another feature of CAD systems is their ability to shade models. A consideration of the colour and orientation of the visible face is necessary to add realism to the designed object. Colour and surface texture of the surface is simulated by one of the two forms of Diffuse and Point-Source Illumination.

Diffuse illumination is when the light of equal intensity strikes the objects from all directions. On the contrast, Point-source illumination is a situation when a single source of light at a certain position with a certain intensity is illuminating the object. This realism was further improved by sophisticated techniques to calculate the reflection of light from the object surface. Gouraud and Phong techniques are two of such techniques [68].

The next attribute of CAD was described as the application of AI in CAD. The fact is that CAD is now used extensively in industry and companies find it less capable as they use it more, and their expectation from CAD is getting higher by the day.

CAD is considered to be concentrating rather too much on providing means of representing the final form of the design, instead of becoming a tool for the design process. There was even concerns that the existing systems could not even cope with design representation because the final design has properties that include form, dimension, tolerance, material, surface condition, structure and function whilst the average CAD systems could only accommodate for the first two properties.

One of the research areas in AI is concerned with the creation of machines capable of simulating some intelligent behaviour. The main themes in the application of AI are currently to explore the formal representation of knowledge and also to develop techniques for reasoning with or applying this knowledge [68]. Application of AI in CAD however is our main concern and could be classified under three different headings which are described below.

1-Design automation systems, which is usually applied to automate the design of parts that are similar in nature (family of parts). Often, in such systems variables are different part dimensions.

2-Analytical aids, which captures the expertise of a specialist in the application of a design technique. This is usually in the form of an expert system for defining the model or interpreting the result of a design analysis (ie. FE analysis).

3-"Design-for" aids, which aim to capture the expertise of an expert in some aspect of manufacture or use of a design, and to make this expertise available to assist in optimizing the design in the area of expertise. Systems for giving advice on assembly and material selection and design strategies for corrosive environments could be given as examples of such systems.

Early developments in this field took place mainly in the first and second class of the above classification. As example, systems with "parametric design" and "Finite Element analysis" capabilities. Parametric design is a higher level programming environment that offers facilities such as graphic entity generation and logical decision making. Intelligent CAD systems with Finite Element module, enabled the user to utilise the developed model for analytical investigation of different properties of the part.

To develop the AI in a design environment, it is important to identify the tasks requiring intelligent input. One of the skills implicit in a design expert's task is the ability to interpret the geometrical forms and concepts and their implication in the design process (eg. implications of designing an airplane from steel) and the final product. Problem of emulating this behaviour within an expert CAD system is something that is not easily soluble. Part of the difficulty in geometric interpretation is that methods used for geometry modelling in CAD are not semantically very rich. The answer therefore lies in explaining forms as higher level entities with certain properties. Such entities are called "features". It would be of no surprise to learn that so many different definition has been offered as the definition of feature. Brown [69] defined feature as:

> *Any perceived geometric or functional element or property of an object useful in understanding the function, behaviour or performance of that object.*

The definition of a feature is dependant on the context. Features required for manufacturing may be quite different from the features required for design. Even within the manufacturing domain different sectors might require different features. For instance, features required for planning a machining operation may differ considerably from those required for metal forming. The current generation of CAD systems as described earlier, place emphasis on geometric shapes. In these systems features should be extracted from existing geometric shapes [70]. The alternative to this method is of course, design using the features.

"Design by feature" is the subject of close scrutiny and research and a great deal of literature is published covering different aspects of features and their role in design [71-86]. A number of methods for designing with features have been explored from which the following two are given as example.

The first method is called "**destructive solid geometry**". In this method, features typically representing machining operations. These features are then applied to (subtracted from) a blank workpiece. Operations are continued till the appropriate shape is acquired and the model is constructed. In the second approach however, no billet is required and the model is constructed by adding and subtracting features. Because of this, it is sometimes called "**constructive solid geometry**". Advantage of the first method is that the system could automatically generate the process plan, while the second method is closer to the actual design process and the way that the designer actually thinks.

Each of the main categories of AI application in design has its advantages and it is best useful in a different environment. However, the main idea in developing these methods has been to ease the journey from CAD to CAM or design to manufacture. The next section will explore Computer Aided Manufacture in further depth.

2-2-2 COMPUTER AIDED MANUFACTURE

Computer Aided Manufacturing can be defined as the manufacturing side of CAE and can be defined as the use of computer systems in efficient running and maintenance of a manufacturing process or plant. This takes place in three distinctive forms [65] of:

Monitoring
Control
Manufacturing support

In the case of the first category, the computer system is used to collect, analyze and display data to aid the human operator to perform his tasks more efficiently. Next category is Computer control, within which the computer system will not only monitors the situation, but also controls the machinery as well. The third group or Manufacturing support is concerned with pre-planning the manufacturing process in order to achieve better production rates and efficiency. Amongst the many different topics the followings are a representative.

Computer aided quality control.
Computer aided material requirement planning.
Computer aided scheduling.
Computer aided simulation of manufacturing systems.
Computer aided part programming.

These systems are either stand alone software packages dealing with a specific issue or offered as a part of a more extensive multi purpose CAE system. With a few exception, most of these computer packages cover a specific area and are not integrated with or linked to other complementary packages [87].

Looking at the three CAM subgroups listed above, it goes without saying that tools which provide automation at monitoring level and decision aids are not sufficiently complex or suitable for this project. On the other hand, Manufacturing support area is diverse and enough research has been and is being carried out in this area. The time factor associated with this project, along with the field diversity of this area will mean that involvement in this aspect of CAM might prove fruitless if pursued and therefore its further investigation is avoided. Consequently, the most relevant area remains to be the control of manufacturing environment.

Again referring to this project and the nature of the final product, it is obvious that the most relevant area becomes the control of machine tools, namely turning machines or Lathes, and their computerised control. The state of the art machine tools in this area are all controlled by NC (Numerical Control) codes. NC and CNC (Computer Numerical Control) are the two major areas of manufacturing that should be discussed in further depth before continuing with the control aspects of these machines. Therefore at this stage and before going any further to discuss automatic control of machine tools, different aspects of NC and CNC machine control is discussed.

2-2-3 COMPUTER NUMERICALLY CONTROLLED MACHINES

As described in previous section, one of the important agents in today's manufacturing industry is NC and CNC machining control. NC is abbreviation for Numerical Control. Many years after its first use, it was defined as:

> *A method of automatically controlling machine tools by means of numbers, letters and symbols that control movements through some form of input medium.*

There are different mediums and ways of applying the numerical control. Consequently, different types of devices are available for control adaptation. From these devices the most important media and the one which is used for this project is CNC (Computer Numerical Control) or CNC controller. In this method, computers are used to communicate the control codes to operate the machine tools whether it is by defining tool paths or simply switching different elements. This approach was taken to maintain the compatibility with the projet objectives and with the design stage.

Looking back at the history of the machine tools, one would realise that they have been in use from before 18th century. As the technology progressed and designs became more complex, the need for more versatile systems became apparent. First machines to be improved and automated were the weaving machines. In 1728 Joseph Jacquard of France, in search of improvements in the productivity in his competitive business, found a way to automate the process of creating and weaving patterns. The process was finally patented in 1801 which changed the whole industry. Next step was the invention of the Pianola which took place in 1863, which was the first use of the paper tapes. The real break-through however, came about late 1940s. At that time the US air force was facing a difficult situation. They needed to machine special contours and pockets for their new designs which were difficult to machine with the existing systems. John Parson who was later on known as the father of NC, received an assignment from the US air force to work on this problem. His experimental machine was a planer mill, with NC procedures. At this point, the Massachusetts Institute of Technology (MIT) agreed to help him refine his machine. Together they developed the first usable one axis machine in 1950 and later on the first three axis machine in 1952.

CNC control in its current state is applied in the International Standard Organisation(ISO) command form or the G-CODES with "Word address" format. In this format the term "word" refers to a set of characters that supplies a unit of information. Information is grouped into blocks of data where each data is preceded by a special key-word known to the controller, with each block containing a number of words. There is a range of commands from simple linear movements to more complex thread cutting, canned cycles and repeat patterns, available on these machines. These commands all start with "G" followed by two digits. There are also auxiliary commands defining other operational concerns rather than the tool movement. These other functions or subroutines might have been developed by either the user or the system developers. The command structure is basically simple and starts with a line number followed by the main commands succeeded by one set of coordinates. Often, some auxiliary command proceed or succeed the main command. The control computer recognises the command and executes it to drive the tool to the destination point, accordingly. List L1 shows a simple sequence of these G-CODES as example.

LIST L1

```
..
N110  G90 G00 G42 X150 Z115
N120  G01 X160 Z135
N130  G02 X50 Z80
N140  G36 R5 X50 Z85
N150      X50 Z70
N160      X40 Z60
N170  G36 R2 X40 Z50
..
```

In the above program for instance, in the first line, G90 will set the programming to absolute programming mode, G00 positions the tool by a rapid movement to x150 and z115 and G42 will set the system for a right hand compensation mode. G01 moves the tool in a linear interpolation mode to the coordinates followed it in the second line. The third line drives the tool to the position following the G02, in a circular interpolation mode, and so on. A more comprehensive list of the command accessible by the machine used in project is provided in appendix A.

2-2-4 METHODS OF CNC AUTOMATION

One of the important areas of manufacturing automation is part programming and with the same token computer aided part programming. This is the topic at the centre of the attention in this section. It was described that CNC and its application revolutionised the whole manufacturing industry, it was also mentioned that as part of the general automation policy, systems were introduced that could automate the generation of the NC codes. It is now necessary to look at such systems in order to choose the appropriate methods.

The main idea in computer aided part programming is the ability to create computer files for controlling the machine actions. Part programming is carried out in three independent methods which could be identified as:

Manual Part Programming.
Computer Assisted Part Programming.
CAD Assisted Part Programming.

In the case of the "manual part programming", the programmer deals with the problem at a very low level. The programs are constructed by coding the key-words and their relevant information in a data file in the appropriate fashion which enables the computer to guide the tool to cut the part.

In the "computer assisted part programming" however, the problem is faced at a higher level. In this method, the task involves the use of a high level computer language to define the cutter path instead of fitting different pieces of data together to construct control blocks. The programmer also does not need to be as aware of the command details and their format structure, compared to the programmer using the first case. He only needs to define the elementary cutter paths such as lines and arcs and so on. Automatically Programming Tools (APT) can be named as one of the earliest examples of such programs. Whilst at the end of a long list of development phase, programs such as COMPACT, PROMPT, MINITURN and PEPS could be named as the latest developments in this category [88-91].

The third option came about after the introduction of CAD and employs a CAD system as its core and utilises an existing CAD model in order to guide the tool. This takes place either during an interactive session where the programmer identifies the cutter paths on the screen or semi-automatically using an intelligent process. The relevant information is then retrieved from the data base and translated into the pertinent programs, using a post-processor.

Despite all this the full automation and integration of design and manufacture has not come about. The main reason is that so far all of the above systems to a certain extend require human interaction. This should be further studied and appropriate actions should take place later on in the relevant chapters.

2-2-5 CAD - CAM INTEGRATION

The key to a successful CAE system was recognized as an integrated CAD/CAM system. It was also claimed in the previous section, despite the popular belief the integration between CAD and CAM is not something that is readily available. The common problem is the lack of a standard format for data structure at the beginning of the CAD revolution. Major difficulty in this area was the exchange of data between different databases with different data structure such as data exchange between two different CAD or CAM systems. This problem surfaced after rapid expansion of CAD/CAM and introduction of different systems. The necessity of communication between different CAD systems and from CAD to CAM, brought about the necessity of standardisation of data format for communication in general and for CAE in particular.

One obstacle in the way was the exchange of data between existing systems. These systems often configured for dedicated applications, presented a major difficulty in the way of full scale automation. This problem was addressed by many national organisations and even it was raised at international level [92]. The solution was to interface different existing systems and development of viable interface. Different interfaces were introduced in which Data eXchange Format DXF was amongst the first standards to be set by the industry. Later on other interfaces at national and international level were set.

Amongst these, French standard of SET (Standard d'Echange et de Transfert) and German VDAFS (Verband der Automobilindustrie Flächenschnittstelle), American standards of IGES (Initial Graphics Exchange Specification) , PDDI (Product Definition Data Interface) which later on combined into PDES (Product Data Exchange Specification) were national standards. Also at the international level CAD*1 and CIM-OSA (Computer Integrated Manufacturing Open System Architecture) and finally STEP (Standard for External Representation of Product Data) sponsored by ISO organisation were amongst the latest systems.

Once again the detailed description of these interface systems are beyond the scope of our study and is therefore avoided. Further information about the above systems could be found in the appropriate references [62,68,93-95].

2-2-6 DATA COMMUNICATION

One of the important aspects of manufacturing technology as it was explained before is the data communication. It is important to establish an efficient and effective method for data communication. This data could be anything from information exchanged between two people, or data transfer between two machines. The vital part of this communication is the actual link or communication methods. In the context of our discussion, all the communications take place between two computers. The actual physical link between two computers could be divided into five categories of:

1- Loose Communication link
2- Direct Communication.
3- Interactive Communication.
4- Communication via Mailbox.
5- Communication via centralized Databases.

In the first instance, which is the simplest form of communication, data is stored on a storage device (computer disc) and physically transferred to the receiver unit. In this method, the important feature of the data is its format and its transparency to the receiver unit.

A simple solution to tedious task of manual data transfer with a loose communication link is the direct connection of the receiver and sender units.

This will require system interfacing as well as definition of communication protocols for both machines, in addition to agreement on data formats.

Interactive communication method is a better way of communicating between the two units at the same time. In this method, communication between the two system is done via another device (usually a terminal). The user should be able to log into the sender database through the intermediate device and vice versa. A query language should be provided to facilitate this transaction.

In the Communication via a mailbox case, data is deposited by the sender on an intermediary device, often called a mailbox, which is accessible to the receiver. This method overcomes the synchronization problems associated with direct communication. Use of the same data format and structure is also necessary to this method. The draw back of such system is its high data redundancy.

The final form of communication link was mentioned to be through centralised databases. In this method both receiver and sender units have access to the same database and using the same data format and structure. This method is more suited for multi-user operation. A database manager is required to maintain system and data integrity.

Having studied these possible methods, with the exception of the loose communication, there are more problems to be addressed. The physical limitations in the actual connecting of these machines and development of a communication protocol to enable the communication process to take place are only starters. Problems such as communication topology or the way a communication network is put together and consideration of its effects on operational security, capability and its economics has to be solved. This is further hampered by the fact that the requirements for an office network is different from the ones imposed by a factory shop-floor environment. The office network is primarily concerned with inter-computer file access or transfer whilst in the latter case, communication with machinery and operation control is added to the task list.

Different protocols and standards have been set by different organisations. Following is a number of commonly used protocols [62]:

a - MAP/TOP which is the acronym for Manufacturing Automation Protocol/ Technical and Office Protocol. This came about as a result of an initiative of General Motors and Boeing of USA, using International Standards Organisation (ISO) standards.

b - Mini MAP which is the smaller version of MAP with improvements in memory requirements suitable for some applications.

c - CNMA which is the acronym for Communication Network for Manufacturing Applications, was sponsored by the European Community's

European Strategic Programme for Research and development in Information Technology (ESPRIT) project.

There are more protocols and possibility of replacement of some of the existing ones by the advancement of technology. The detailed study of these protocols are beyond the scope of our study and is avoided. However, there is sufficient information available through the appropriate resources which explains these protocols in further depths. Figure 2.2 describes three different connection topology in a communication network.

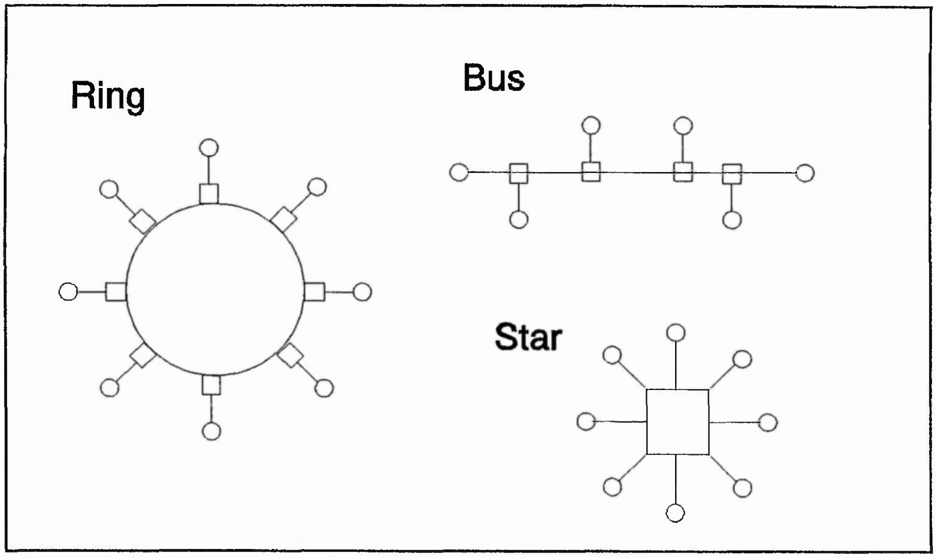


Figure 2.2
Various Computer Communication Topologies.

2-3 CONCURRENT ENGINEERING

Another major manufacturing concept that appeared in the late 1980s was "Concurrent Engineering (CE). Although this was only the time when the phrase established as a jargon, the concept is believed to have been practised by industry long before that. Having established as one of major methodologies in manufacturing it was later defined as:

A systematic approach to the integrated, concurrent design of product and their related processes, including manufacturing support.

This concept is known by many other names such as:

Team design
Simultaneous Engineering
Producibility Engineering
Concurrent Design
Transition to manufacturing
Integrated product development

Carter [96] symbolises five reasons as the major contributors to the pressure to change the product development environment. These five are:

Technology, Tools, Tasks, Talent, Time

The main reason being the ever improving technology and its impact on the manufacturing sector. As a result of this improvement in technology, the tools would change and become more complex. This in turn would have an impact on the nature of the tasks and make them more sophisticated. The sophistication in task would in turn demands for more capable and talented work force. Finally time , which has always been an important factor and all the fore-mentioned factors contribute to demands for an enhanced efficiency and time saving.

Each of the above five would raise a series of questions which their answer could lead the way to a better manufacturing environment. These are:

Technology:

How successfully does a manufacturing system take advantage of the available technologies? Are they developing technologies that create market leadership?

Tools:

What are the best tools to use in the particular environment? How well organised is the impact of introduction of new tools? How compatible are the new tools with the old ones?

Tasks:

How the tasks are defined, divided and managed? Is the process continually improved to increase productivity? Would tasks automation improves the efficiency?

Talent:

How does the system get talented people to work more effectively? How does it ensure a long term supply of talent?

Time:

How does the company shortens the product time-to-market ? How quickly the product improvements are introduced? Are there any supervisions for improving product development cycle time?

Carter [96] expresses the solution in balancing four key dimensions of:

Organization
Communication infrastructure
Requirements
Product development

The heart of the first dimension is balancing of the two major contributors of managers and development teams. Managers have to be supportive of the development teams and its members with inter-disciplinary nature of their tasks. Team members on the other hand should take responsibility for their actions and be team players.

The second dimension is about communication infrastructure which has always been important. Sound infrastructure would make possible, linking people, ideas, product data, specification,...etc.

The third dimension is requirements which is a variable dimension and could vary according to the time, customers, market and so on. The most important of the above variables is the customer. The company should be able to determine what the customer wants and ensure that he gets what he wants. Good design and planning are important to achieve that goal.

Finally, the product development dimension which includes consideration of manufacturing and support processes at the design stage. It mainly concerns with having multidisciplinary design teams to oversee potential problems further down the process [96-98].

Although a great deal of articles have been published to cover the whole subject which is relevant to any cases, However because of the nature of this project, it seems that the latter case has Particular importance in our study and should be considered in further details.

2-3-1 THE PRODUCT DEVELOPMENT ENVIRONMENT

After introduction of new tools, some companies still finding it hard to compete. The problem is despite the changes in the tools that are being used, the attitude is at large still unchanged. New tools require new culture and a change in vision and attitude to product development. The old practice of compartmentalisation of tasks has to be changed. The design process has evolved from the seventy's which was Prototyping and testing before finding out wether it was the best design, to eighty's approach of finding out wether the design work before building it only to measure its performance at a later stage. For the ninety's the approach has to a certain extend changed and still is changing in a sense that the design's performance should be analyzed to be the best before making sure that it works, prior to building it.

This should be taken one step further and manufacturing and support considerations has to be taken into account at the early stages of design process. The most widely used approach as mentioned before is the idea of having design teams consisting of people of different backgrounds, working on projects at the design stage.

2-4 SUMMARY DISCUSSION

In this chapter it was tried to cover most of the relevant technological topics as best as it was possible. This effort to a certain extend was hampered by the fuzzy nature of the relevant technologies and ever increasing overlapping of these areas. Another important factor was the consideration of the project goals which to a certain extend limited the relevancy of some of the topics.

As a result of this survey a general approach could be outlined for the project as a whole. This includes the development of a series of loosely integrated design and manufacturing tools with a total commitment to principles of CAE, CIM and CE.

This however does not mean that a complete CIM system would emerge or a full scale CE system would appear. Instead, a system which is capable of being used in any such set up. The reason for proposing the system the way it is contemplated is due to considerations given at appropriate sections. According to the points raised, it is unwise to design tightly integrated systems without having specific goals, targets, requirements and objectives.

In the next chapter the system design will be considered and specific targets for development phase of the project will be set with reflection to the aims and objectives described in the first chapter.

CHAPTER 3

SYSTEM DESIGN

3-1 INTRODUCTION

The secret of success in any design process is pre-planning especially in a multifaceted project such as this. Three major factors need to be looked at to establish the system outlook, before attending to the details when a new system is being designed. These components can be listed as:

1- Constraint assessment
2- Process analysis
3- Priority assessment

Constraints assessment entails identification of any financial or policy constraint which might conflict with the company's corporate objectives. Process analysis takes place to quantify the current system's efficiency (or lack of it). This will result in mapping the strong and weak points in the system and highlights the areas requiring attention. Priority assessment on the other hand, establishes the major problem areas and their importance in delivering any improvement. These three, combined with the aims and objective and technology audit should make it possible to identify the basic form of the system.

In this study, it is difficult to quantify any policy restriction for this is not a case study. However, one important factor that is common in most industries is improvement of quality and increase of competitiveness. The same argument is also valid in a financial sense and no figure can be presented as the budget ceiling. Again it is legitimate to argue that the cheaper the system, the wider becomes the user base. With this in mind, the constraint assessment could be eliminated to attend to the process analysis and priority assessment, before attempting to design the system.

3-2 THE PROCESS ANALYSIS

As mentioned above, it is crucial to establish the system properties and its nature. In this instance, the target is a manufacturing system for production of an extruder screw.

This is a one-off production regime, run by heavy engineering specialists with a limited knowledge of the physics of plastics processing. This results in weak communication with the customer, usually a polymer processor, not particularly appreciative of heavy engineering practices. The manufacturing process, mainly manual, at best is unable to cope with high output regimes currently expected from it unless further production lines are introduced. This of course means a high capital investment with the risk of it being idle at times when manufacturing throughput is not high enough. Another problem with the latter approach is finding the skilled work-force to operate the new machinery and dealing with the socio-technical problems associated with it. The amount of time spent on the manufacturing of these screws means that the value added to the raw material is relatively low and therefore unacceptable. As mentioned before, the customer or the end user of these screws are plastic processors, plastics processing machinery manufacturers or chemical companies manufacturing virgin plastics. Figure 3.1 represents a data flow diagram of a screw manufacturing set-up. Table T 3.1 describes the links between units (data dictionary).

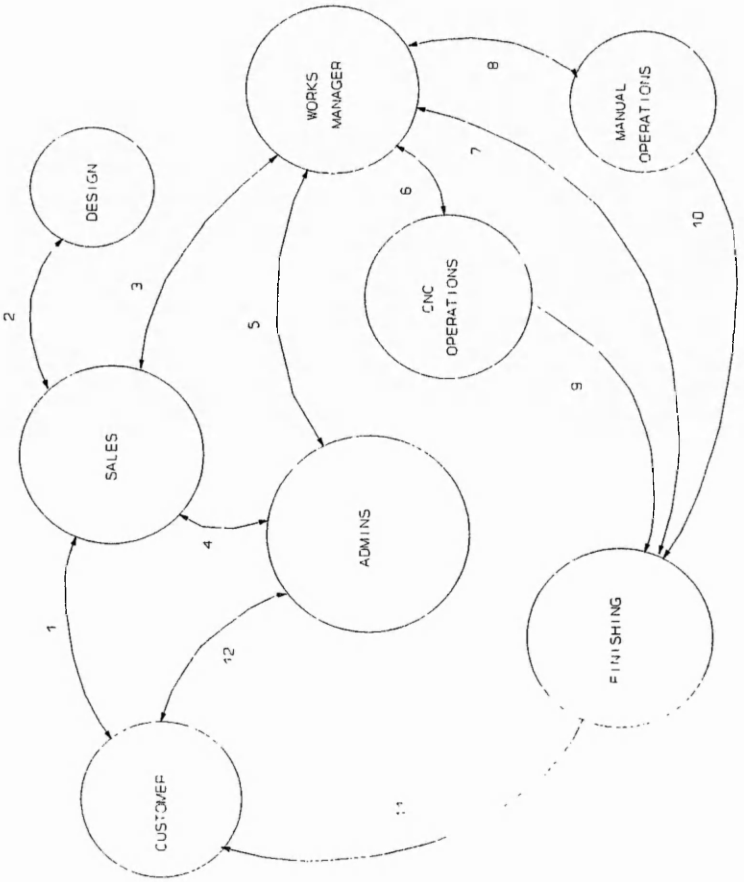


Figure 2.1
A screw manufacturing structure.

data dictionary

1- Telephone/fax/letter/visit enquiry or request.

Formal order documented on paper requesting a screw for a specific application or a screw defined on a blue print.

2- Usually an oral request.

3- Manufacturing order usually defined on a standard drawing with the dimensions and specifications listed, sometimes with the customer drawing.

4 & 5- Oral and documented communications for record keeping and financial planning.

6, 7 & 8- Documented manufacturing orders and relevant information for the respective sections.

9 & 10- Transportation of unfinished product to the finishing section.

11- Transport of the finished item to the customer

12- Documented invoice and/or financial transactions.

Table T 3.1

As one can see from the above organisational structure, the order could come in two different forms of the actual screw order in the shape of a drawing or a request for a screw for a specific application. The first order type goes directly through the sales to the manufacturing department. The second route, which is a design for a particular process, is referred to the design unit. Normally, the design unit is relatively small and is often a part of the sales or manufacturing units. There is hardly a case in which plastics processing specialists are employed for solving the customer problems at the expense of the company. Therefore, the design is often based on the recommendations of either the sales or manufacturing departments, itself established heuristically over the years and based on previous experience. This approach is successful in some cases but not so in others. There is no information about the rate of success for there has rarely been a system of recording the design problems. Based on some guess work, it is not far out to forecast that success usually has been associated with the conventional materials in conventional operations and would not logically extend to newer, more sophisticated materials in newer processes. Manufacturing operations also follow two routes, manual and Computer Numerically Controlled (CNC) machining. The standard of technical drawings is sometimes mediocre, and has much to be desired. Organisational transactions are old fashioned and based on paperwork. It could be deduced that the efficiency is low.

This is partly because of the industry's reluctance to contemplate any changes, due to the nature of the market place and uncertainty about the result of investment and its return level. Having surveyed the operation of a series of manufacturers [19], the major problem areas were detected as follows:

-Long manufacturing lead times.

-High manufacturing cost.

-Product deficiency.

As a result of this review, a company profile was formed. According to this profile, the average manufacturer envisaged to be:

An established engineering firm which has been in business for a long time and has a customer base. The firm would most probably have diversified into other aspects of plastics processing equipment manufacture and services. Their workshop is most probably equipped with manual machine tools, some of them modified for special applications. Some CNC machine tools are also available.

From this introduction, it becomes evident that the deficiencies mentioned above, are all major problem areas. The first two problems could be as a result of out of date manufacturing practices, whilst the last problem could be resulting from design deficiencies. Having established these objectives, bearing in mind the original project aims and the necessity of introduction of computers in design and manufacture in a concurrent manner, the priorities have to be assessed. The next section deals with this in further detail.

3-3 PRIORITY ASSESSMENT

From what was discussed in the previous section, the major problem seems to be the manufacturing strategy and techniques. Deficiency in manufacturing strategy can cause long lead times and customer dissatisfaction [99]. At the same time, problems with manufacturing techniques result in high production costs which are again transferred to the customer and will cause disappointment. Product deficiency is also blamed as one of the problem areas of this kind of manufacturing environment. This could be as a result of a bad design or manufacturing method which itself could be as a consequence of an inappropriate design/manufacturing strategy and/or tools. Communication in general and customer relations and communication in particular could also have a role in the general deficiency of the system.

According to this discussion, the priority list could be drawn with the highest priority given to redefinition of design and manufacturing strategy as well as techniques. These two (design and manufacture) have been given the same priority for it is difficult to put one before the other. The new thinking and the current trend towards automation and production efficiency has revolutionised old ideas.

The new approach to product manufacture now dictates the production rate and method at the design stage. The computerised manufacturing scheme demands a great deal of thought at the design stage about manufacturing methods and their outcome. The list is immediately continued by the restructuring of communication aids and the introduction of planning, scheduling and office automation tools. Having established this, it is now more clear as to what needs to be done and will be discussed in greater detail in the next section.

3-4 THE PROPOSED SYSTEM

With this background, it is now time to assess the nature of the tools developed for the design and manufacture of this particular product within this industry. Surveys of the available tools revealed that the following aids were available.

- A number of flow simulation programs.
- Computerised rheometer.
- Program to calculate the flow properties from rheology data.

Adding to the above, one could always include the following general purpose automation tools.

- Computer Aided Design (CAD) packages.
- Computer Aided Manufacture (CAM) packages.
- Data communication software packages.
- Planning and Scheduling packages.

Looking at the above list, it can be seen that first of all there is no total solution available to the end user, in particular, the screw designer/ manufacturer, to assist him in his task, without having to master using different new tools.

Having acknowledged this fact, it was felt necessary to design an integrated system in such a way that the screw manufacturer could use a new tool to cover all aspects of his job.

On the other hand the challenge became the introduction of change in a controlled manner and in a way that was implementable by the majority of the companies in the industry, including the supporting body, by implementation of the technologies previously discussed. First of all the corporate objectives of the average company in general and the collaborating company in particular had to be established. The simplest and most common one as discussed before was; "to make a profit both now and in the future". The inevitability of the introduction of high-tech into the establishment posed the question of the introduction of the new system under control at the same time catering for the needs of the companies, both for now and for the future, whilst remaining within the practical organisational constraints. It is a fact that it is always possible to get the best technical solutions individually for each problem but they are not necessarily compatible and within the financial limitations of the company. In order to define the system properly, the level of integration of different elements within it had to be evaluated and their degree of cohesion had to be defined.

In the beginning, it was believed that the system should consist of two modules of CAD and CAM. The CAM module had to be developed in such a way that using an intelligent mechanism could interpret the objects developed within the CAD module and identify the process and the necessary control routines for the target machine, using the expertise built into the system. This was something similar to the work that was being carried out in Japan by Fumihiko Kimura, [100-104], using solid models.

This was making the task more complex and had a few disadvantages. First of all, the focus of the project, i.e. the plastic processing industry, would have been undermined. Secondly, the system would have become bigger and therefore more expensive. Next, such a system would have been more abstract leading to a greater complexity at the operation level. The only advantage of that kind of system could however stem from the fact that the system is general purpose, hence, it could have been applied to more problems and could have had a greater impact in the market place.

Based on the above discussion, it was decided to define the system as simply as possible, in a modular fashion; dedicated to this special application. The system should have the capability to be assembled in a modular manner so that at each stage the appropriate module could be added according to the needs of the company.

This is particularly important when the needs of the average company considered at the design stage. The main reason for this is that each organisation has a certain degree of freedom to respond to its particular constraints and should be able to customise its operations. At the same time, the best possible solution should also be considered for those whose corporate objectives and constraints allow its implementation. Interaction between the different modules should be simple and standard and should allow system customisation. Data extraction should become much easier under the new regime and should provide a useful tool for management and administration purposes.

So far as manufacturing is concerned, it was decided to design a module or modules to utilise the latest in automation technology in order to increase productivity and quality. The system as a whole should be easily maintainable and low cost. The more detailed system considerations and implementations will be reviewed later on within the relevant chapters.

Based on the above discussion, and in order to maintain parity with the presentation of the system presented previously, the system was defined at an abstract level. Figure 3.2 outlines the data flow diagram of the proposed new system.

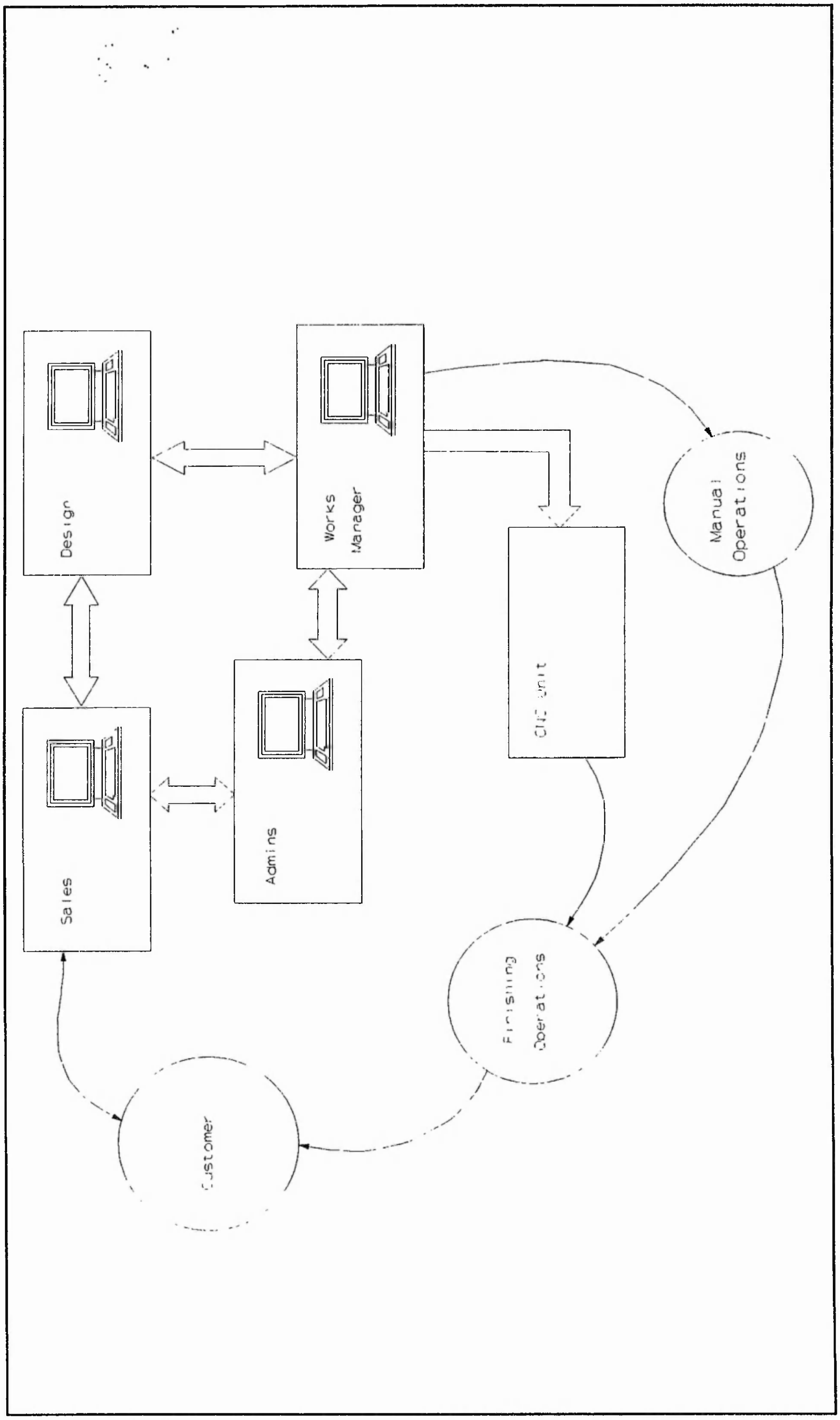


Figure 3.2
The proposed system outline.

Within the new proposal, objectives are that the design needs of the user will be catered for more appropriately by addressing the problems facing the manufacturers explained previously.

So far as interfacing and data communication is concerned, there are different methods of communicating data between two systems, already discussed in the previous chapter. The chosen method has been the loosely integrated data exchange to transfer the data to an intermediate device under a known format. The main reason for it is its simplicity and cost. This way, if any of the units was omitted for customisation or indeed for any other reason, the operation of the other parts of the system would not be hampered. At the same time it is technically possible to replace that with a more sophisticated and integrated communication network; the decision for which has to be left to the end user. There are various integrated communication networks systems available in the market which can be utilised.

To develop the modules shown in the proposed system, every module should be analysed independently at a lower level. The major modules described in the proposal are the design and manufacturing modules which are dealt with and analysed next.

3-4-1 THE DESIGN MODULE

The term "screw design" can be applied to both optimising the process and creating drawings and manufacturing information. Currently, the two stages are mostly carried out independently and in fact that is the main problem with conventional methodology. Design in terms of the actual drawing and communicating the findings of the optimisation process to the manufacturer, carries less importance compared with the optimisation design process. This was also confirmed in the literature survey which revealed that no attempt had been made to explore this area. The complex nature of the melting process and lack of understanding of the subject has led to an emphasis on optimising at the cost of design for manufacture. This belief was somewhat credible under the old production regimes but not any more. As described previously, screw design was carried out in two stages. Each screw was first defined in terms of crude ideas and perhaps some rough sketches which were later transformed into the drawings and manufacturing information.

With the proposed structure in the previous chapter, creation of the drawings should become a system utility. This takes the form of optimising the screw for a particular process and devise a program that will manipulate the optimisation data to generate the technical drawings. In other words, the combination of screw design optimisation and screw manufacture forms the fundamental argument outlined in this section in particular and in this thesis in general.

The production method and its feasibility has to be taken care of. This is done by designing for the manufacture of a family of screws. This also removes the need for designing complex screws resulting from the lack of an appropriate design tool.

Looking at the design optimisation process, it takes the following form. Any optimisation procedure starts with the definition of resources and requirements. Resources in this frame-work is the description of the available extruder equipment. This would automatically impose some restrictions which are usually screw length and diameter, adaptor type and so on. A further variable in the equation is the polymer material which needs to be processed. Another set of variables are also imposed due to the type and capabilities of the machine and the production output requirements; e.g. thermal range of the heater bands or the revolution rates (RPM) that provide a certain output rate. Hence, the optimisation procedure requires three sets of inputs:

Screw Geometrical Constraints
Machine Operating Condition
Material Characteristics Data

The parameters in the first two categories are fairly straight-forward and well known to its operators. The information mentioned in the latter case is however provided by obtaining the results of the actual physical test on the material and analysing them.

Alternatively, in cases where the material is well established, the material data might be found in some data handbooks.

The optimisation module should then generate the screw geometry and recommendations about the operating conditions for the optimum result. The geometrical data should then be passed on to the drawing module to identify the screw material and generate detailed drawings, ready to be passed on to the manufacturing module. This is illustrated in figure 3.3.

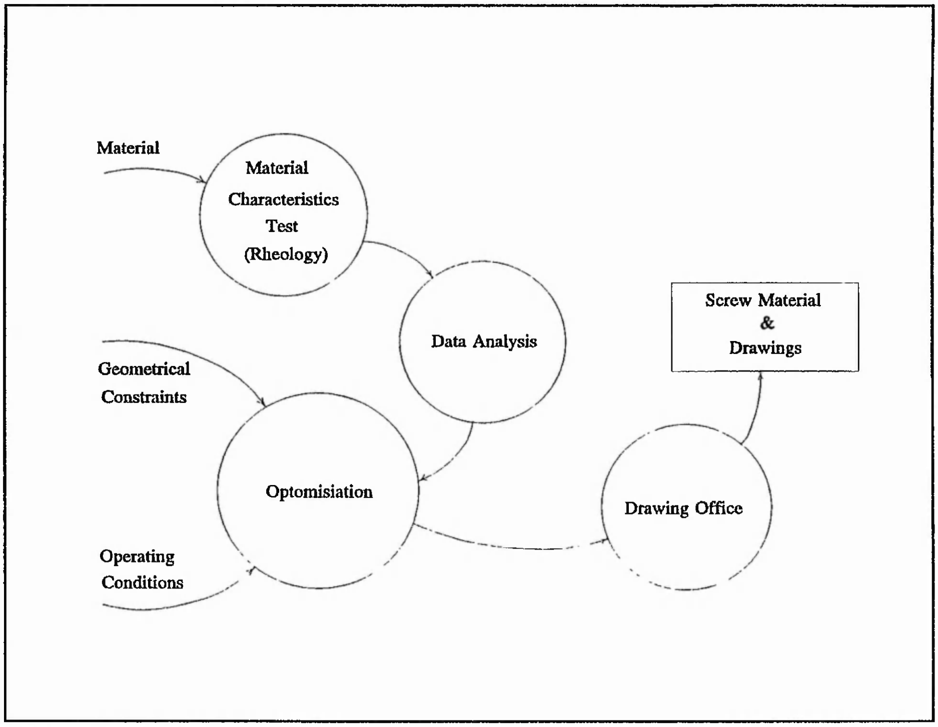


Figure 3.3
Design module's Operational diagram.

According to this diagram, four independent processes are implicated in the design unit along with the communication method or interfacing between these operations. The following sections will deal with each individual operation in detail.

3-4-1-1 MATERIAL TEST

It was mentioned that the rheological properties of the material had to be considered in order to get an accurate picture of the operation. The fact is, all the material properties could change from batch to batch let alone from manufacturer to manufacturer and sharing the same name does not match the material property. The appearance of different data bases of materials developed by various raw material manufacturers bears witness to the very same fact. Of course there is a long way to go before a substantial data base which covers all the materials that can be expected and provides all the necessary details in it. Besides, the rate at which new materials are coming into the market or are being developed is not helping the situation. Therefore till such a time, the safest route is to generate the required data from a sample of the material.

Material testing methods and their related apparatus were described previously (chapter 1). There are different ways in which this test procedure could be improved and automated. Fortunately, the manufacturers of test equipment have already dealt with some of those problems and have developed advanced pieces of machinery with computerised operation control, data collection, data analysis and so forth. This improves the test procedure extensively and meets the overall project requirements. It even removes the need to develop the next unit (data analysis) for it offers that service as a standard feature. The only problem is the capital cost of these machines which could be tens of thousands of pounds. As mentioned before, this is acceptable for the companies whose financial situation would allow this but, could prove to be a problem for those who cannot afford it. Therefore, it was decided to consider the worst case (a manually controlled rheometer) and rebuild the system around it allowing the replacement of it by a better machine where appropriate. Consequently, a basic capillary rheometer became the standard apparatus for the test.

As for the test procedure, there is no British Standard procedure for this type of test therefore, the manufacturer's recommended procedure is considered as the operational routine which is described previously.

Assuming that all the data collected during the test is correct the next stage is interpretation of that data. A consequence of inaccurate data interpretation could lead to problems in the whole design process.

3-4-1-2 DATA ANALYSIS

Having completed the experiment, the outcome is in the form of corresponding forces at seven different piston velocities for each die (long and zero length) at each temperature. These figures should then be manipulated to give three relationships of:

a)-	shear rate	vs	shear stress
b)-	viscosity	vs	shear stress
c)-	viscosity	vs	shear rate

There are a series of formulae to extract the required information from the available data. As argued before, because of the system requirement it was felt necessary to develop a programme and customise it for the new system requirement. The detailed discussion of this component of the system is presented in the next chapter.

3-4-1-3 OPTIMISATION

It was claimed that one of the first problems of processors was the shortage of a rational and accurate design for specific materials and it was argued that it was mainly due to the lack of a good design tool. In this section the objective is to choose or develop a system to solve this problem. As was described, major steps were taken after attempts were made to model the melting process, and in due course different solutions became available. These solutions mainly included computer programs ranging from general purpose finite element (FE) packages to a few more specialised software packages, developed for this application.

Usage of general purpose FE systems that deals with fluid flow was inappropriate in this instance. This is because they require specialist skills to operate, and training to that level could cost a great deal of time and money. This is still without considering that there is yet no general purpose package in the market that could accurately model Non-Newtonian Fluid Flow. The alternative is therefore to use one of the specialist packages for simulating the melting process.

Two programs were studied at the time the project was running which could be used for this purpose. These two were Extrucad [105] and Melting [106]. The first of these is based on the Tadmor's melting model. The second program based on Fenner's model [56] was chosen for the optimisation process because of two reasons. First of all, the first program did not allow for the flow acceleration in the channel (constant velocity) and hence, could not predict break up of the solid bed in the channel, hence the surge of the molten material created because of it. Secondly, the latter program was freely available for trials and there was parallel research going on to improve its performance. However, it is anticipated that newer, more up to date programmes should appear in the market from time to time, and the system should be able to utilise the available technology. In either case, it should be simple to introduce the newer programs, as and when better, more advanced packages become available. A more detailed discussion about the system is left for later stages when dealing with details in relevant chapters.

3-4-1-4 TECHNICAL DRAWINGS

It was mentioned that in the conventional design process, drawing was left to be carried out at a later stage for it seemed less important in the whole design process. It was also expressed that as part of the automation strategy it would be necessary to develop a unit for generating the necessary hard copies.

Looking at the relationship between the different units in the design module, it could be seen that it is at the end of the design process. At this stage, the screw shape and size are already known and what remains to be done is to turn this information into actual drawings. It is clear that like any other engineering problem, for maximum benefit, the tools should be consistent with the task. At the same time the right tool for this task proved to be expensive. This was because the screw had to be geometrically modelled first. Then the model had to be manipulated within a design system to carry out some intelligent operations such as hiding lines and surfaces, before it could finalise the model and present the drawings. This meant that the base system would be amongst one of the more expensive systems in the market. A literature survey of the CAD vendors and their systems also revealed the same concern. This was in conflict with the corporate objectives defined for the system. Apart from that and despite the common perception of the automatic link between CAD and CAM, only a few expensive systems in the market offered that sort of built-in integration.

Even with the systems that offered the sort of integration suitable for this application, there was still the problem of machine dependency to be solved. This means that for every machine tool, there must be a suitable post-processor which will translate the information generated by the system into a format acceptable for the target machine tool.

There was therefore two alternative solutions when two different types of system could be considered. First of all a well established but expensive CAD/CAM system which minimizes the development effort and maximizes the capital cost. Second, a less powerful PC based system to minimize the capital cost but probably increase the development phase and cost. In the second alternative care had to be exercised in choosing the system specially because of the introduction surge of new systems into the market, each with a different capability and often untried by end users. At the end of much speculation and studying different sales literature and reviewing different systems, a compromise solution was finally adopted.

This was to use a powerful system in the first phase to develop the basics of the system and then transfer the know-how to a cheaper system. The idea was that the learning curve and research time would shorten as a result of the friendly nature of the system. Also the more powerful system would reveal the discrepancies of the proposed solution at an earlier stage. At the same time because the final system or the production system would be introduced on a desk-top machine, it still retains its price advantage.

Following the above decisions, the McDonnel Douglas Unigraphics-II system was chosen as the primary target system because of its powerful GRIP programming environment and overall capability and above all because of its availability at that time for research purposes. This system can be run on VAX-VMS, Data General AOS/VS and Hewlett Packard UNIX operating systems. The current version of this system is 8 and it may be run on any VAX mainframe or VAX station, as well as Hewlett Packard machines and DEC's SPARC workstations. It supports a wide range of activities from 2D/3D design to manufacturing operations. It supports the IGES communication protocol and offers a wide range of interfaces to the other computerised solutions. Perhaps the best feature of this system apart from its versatility is its internal interface between its different modules [107-109].

The information resulting from the mathematical modelling of the screw within this system, forms the basis of the drawings creation module within the whole system. The chosen target user system was Mountford and Laxon's MULTICAD system. Apart from the normal 2D/3D drafting routines it provided a programming environment for parametric design [110]. It also offered a Data Base Management System as well as Shading facilities. The main reason for choosing that system amongst the leading CAD software systems available, was the advanced parametric programming facility it provided at the time. It requires an INTEL 80386 (or above) based PC (Dell system 325, 25 MHz.) with a Maths. co-processor(INTEL 80387), plus a minimum of 1 Mega byte RAM and two screen drivers. The excess RAM memory is utilised via an Expanded Memory Manager (QEMM). A more detailed discussion about the system and its development phase is described in the next chapter in the appropriate section.

3-4-2 MANUFACTURING MODULE

Having defined the design module, it is time to outline the manufacturing module. As described before, the manufacturing module was initially considered to be a general system that has the capability and intelligence to detect the manufacturing operations required for making the designed object and hence producing the control codes for the appropriate controller. During the feasibility study, this proved to be ambitious and beyond the project time scale. Also, the fact that this project was research into production techniques rather than the tools and was sponsored by industry was limiting the freedom of choice to a certain extent. After rejecting this option on resources grounds, a new approach had to be adopted, based on a compromise to secure the final result and minimise the general research costs.

This approach is formed around a system which is defined to perform one particular task very well with the minimum of supervision. The system should be intelligent in the predefined areas and should be accessed by the clearly defined user or system commands. The major advantage is the system flexibility. At the same time by spending time at the system definition stage, the need for a specialist operator would be reduced by defining a suitable interface. Also because the system is designed and developed in house, it will be incomparably cheaper than implementing a general purpose ready made software system. A disadvantage of the in-house development is however, increased time and cost at the system development stage.

At this stage and after careful consideration of the requirements described in the first chapter and potential resources outlined in the second chapter, a computerised system had to be planned and defined in further detail.

According to the discussion so far, this module has to perform two necessary tasks;

First, to look at the material requirements of the screw and the screw geometry to set the cutting parameters.

Second, using the cutting features and screw geometry to generate the control codes for the cutting process for the appropriate machine.

Again looking at the problem from a higher level, it was explained that there was a choice of three approaches of:

a - Use an integrated system with a proper post-processor.
b - Search to find an already existing system appropriate for the job.
c - Develop a new system based on the requirement.

The first choice was already discussed at the design stage and was rejected because of its capital cost. The second option was a valid one but for the fact that market review revealed that there was no such system in existence supported by the very fact that this research was sponsored by industry.

Therefore the third option had to be adopted and a system had to be developed for this application. To develop the program, the system characteristics had to be drawn and its details identified. Two tasks were mentioned as the primary requirement of the CAM module. These two were definition of the set up parameters, and generation of the control codes for a suitable CNC machine. The same principles about interfacing and communication discussed at the design stage would still apply here. Figure 3.4 describes the detailed manufacturing module.

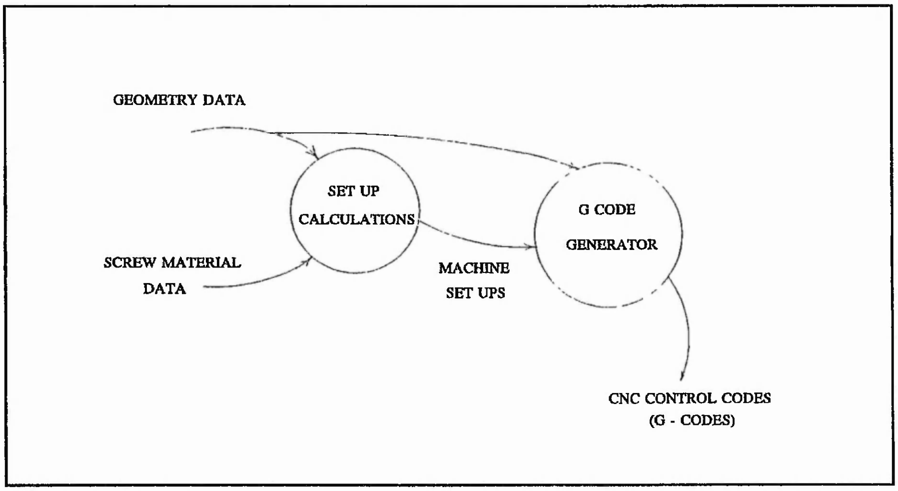


Figure 3.4
Proposed manufacturing module.

Having identified what needs to be done, it is also necessary to define the best method of doing it. In the previous chapter the possible methods of CNC part programming were identified as:

1) Manual Part Programming.
2) Computer Assisted Part Programming.
3) CAD Assisted Part Programming.

With this background and considering the three options discussed before, there was no room for option No. 1, the manual part programming, in an automated environment. Therefore, the first choice became to install a computer assisted part programming software system as an extension to the existing CAD software. This involved long feasibility studies, learning curve and program customisation phases. Parametrisation of the design process could also bring about a compatibility problem and could prove to be expensive to interface.

Next option then became to invest in a combined CAD/CAM system and follow the CAD assisted part programming. This option had already been rejected previously at the design stage. Besides, there were major difficulties with this approach including the time it takes to define a part in the system and of course its cost. This comes from the fact that the cutting paths should be defined interactively or within special programming environments.

Neither of the above solutions satisfies the project objectives in its entirety. This led to an investigation into the development of a new approach to part programming. The objectives of this effort was to develop a tailor made problem-specific CAM solution.

This choice has its own advantages as well as disadvantages. It is a cross between options two and three and from now on is called "Computer Integrated Part Programming". The advantages of this approach are its minimal cost, ability to produce a complete solution to the problem, freedom of choice in selecting other parts of the system (CAD) without considering the interface problems. The only disadvantage is however the development cost and time, which looking back at the two previous choices, the same sort of problems were faced to different degrees. One important consideration while designing specialist high-tech tools within a manufacturing organisation is the possibility of upgrading manufacturing systems and techniques and catering for those potential changes when introducing new systems. Tailor made system development provides a good opportunity to cater for those possible changes if carefully thought through. From this point on, this approach is called "Computer Integrated Part Programming" any where it has been referred to in this thesis.

Considering the above, it was concluded that the computer integrated part programming was the most appropriate approach and it is in the best interest of the manufacturers to use this method to develop the manufacturing part of the system in accordance with the special system requirements.

At this stage and after finalising the decision on the system approach, the physical details had to be determined. This included details such as the target CNC controller and the other necessary information required to develop the final system.

The detailed discussion of the manufacturing system and its development phase is described in the next chapter.

CHAPTER 4

DEVELOPMENT PHASE

4-1 INTRODUCTION

Having reviewed the problem in the first chapter and after the technology audit brought in the next, the system basics were defined in the third chapter. Having decided on the initial system design, it is now time to develop the system and finalise the design. This is the subject of this chapter and it is dealt with in four different sections.

Section one is dedicated to the rheology data analysis and the related problem solving process. The next section considers the optimisation program and the basics of this particular system and outlines the general methodology guiding its development phase. The third section is concerned with the geometric modelling of the screw and all the CAD related development work. Finally, the manufacturing module is the subject of scrutiny in the fourth chapter.

It is important to state that although the work described in the second section has not been carried out as part of this study, however, in order to provide the necessary understanding of the whole process it has been included to reduce the chances of misunderstanding.

4-2 RHEOLOGY DATA ANALYSIS

In previous chapters the rheology test and its importance was discussed and the test procedure briefly described. Since it was decided to leave the choice of test equipment (rheometer) to the end user, it is not necessary to address the procedure any further as long as the equipment manufacturer provides sufficient information about the unit and recommended test procedures in its documents. It was explained that the next step was the interpretation of the data and the extraction of the relevant data. The mathematical formulae used to develop this programme is described in the Neil Cogswell's book, "Polymer melt rheology" [60]. The main objective of this exercise in brief is calculating different viscosity values corresponding to different shear rates.

One of the variables calculated in this program is called "the power law index (n)" and is obtained by plotting the flow curves of apparent viscosity against apparent shear rate (on a logarithmic scale) at three different experimental temperatures. By using the most appropriate temperature as the datum temperature of viscosity, the viscosity is recorded at unit shear rate and the power law index is defined by the line gradient. The temperature coefficient of viscosity also needs to be calculated which results from choosing a common shear rate (usually 500 s^{-1}) at each temperature and finding its gradient. The real material behaviour should then emerge from these experimental values. The last two values are usually found by manual plotting and regressing, but, as a part of the overall automation strategy, one objective became a rewrite of the program to include a routine to regress the best possible fit through the points generated by the experiments and handle the data and prepare the information for the simulation program. These results are then placed on a file which can be printed where necessary.

This is a relatively simple program but its outcome saves a lot of time. Care has to be exercised in choosing the regression model because the number of the points are limited. Having considered the above fact, The "Least square method" considered as the appropriate model. According to this model, if the true line is represented as:

$$Y = \alpha + \beta X$$

The values should follow the following relationship:

$$Y_i = \alpha + \beta X_i + \xi_i \quad , \qquad i = 1, \ldots, n$$

This is the "simple regression model" and the term ξ_i is an independent random variable with the mean zero(0) and variance σ^2 , representing the error. It is also assumed that the values of X_i are not subject to error and only Y_i variables are subject to error. After estimating and placing confidence intervals on the values of $\overset{\wedge}{\alpha}$ and $\overset{\wedge}{\beta}$, the estimated regression model becomes [28]:

$$\hat{Y} = \hat{\alpha} + \hat{\beta} X$$

where:

$$\hat{\beta} = \frac{\sum_{i=1}^{n} X_i Y_i - \overline{X} \sum_{i=1}^{n} Y_i}{\sum_{i=1}^{n} X_i^2 - \overline{X} \sum_{i=1}^{n} X_i}$$

and

$$\hat{\alpha} = \overline{Y} - \hat{\beta} X_i$$

In the above equations the values with hat(^) are the estimated values, where the over-lined values (-) are the average values. The program flow diagram and a copy of the printed results are shown at figure 4.1 and figure 4.2 respectively.

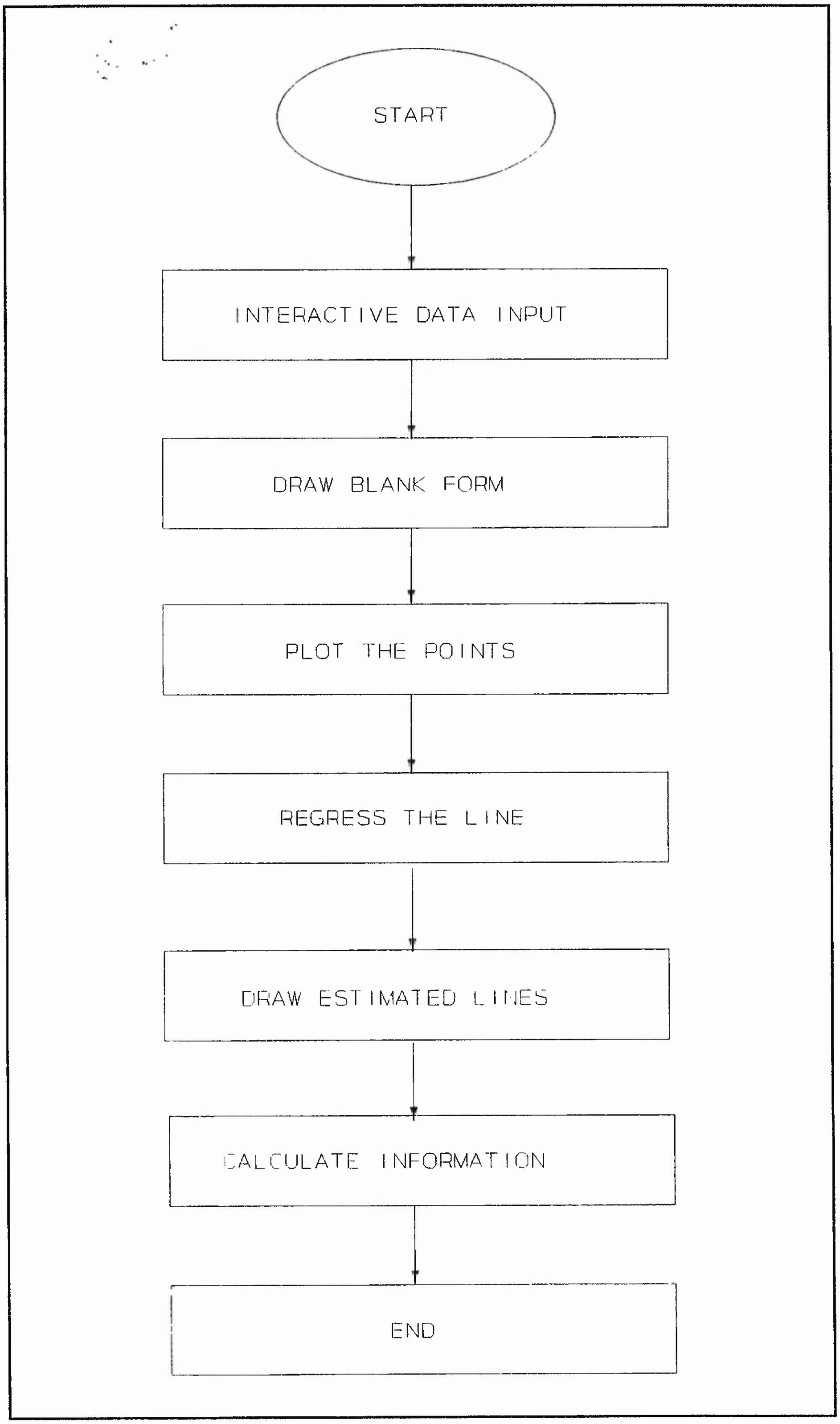
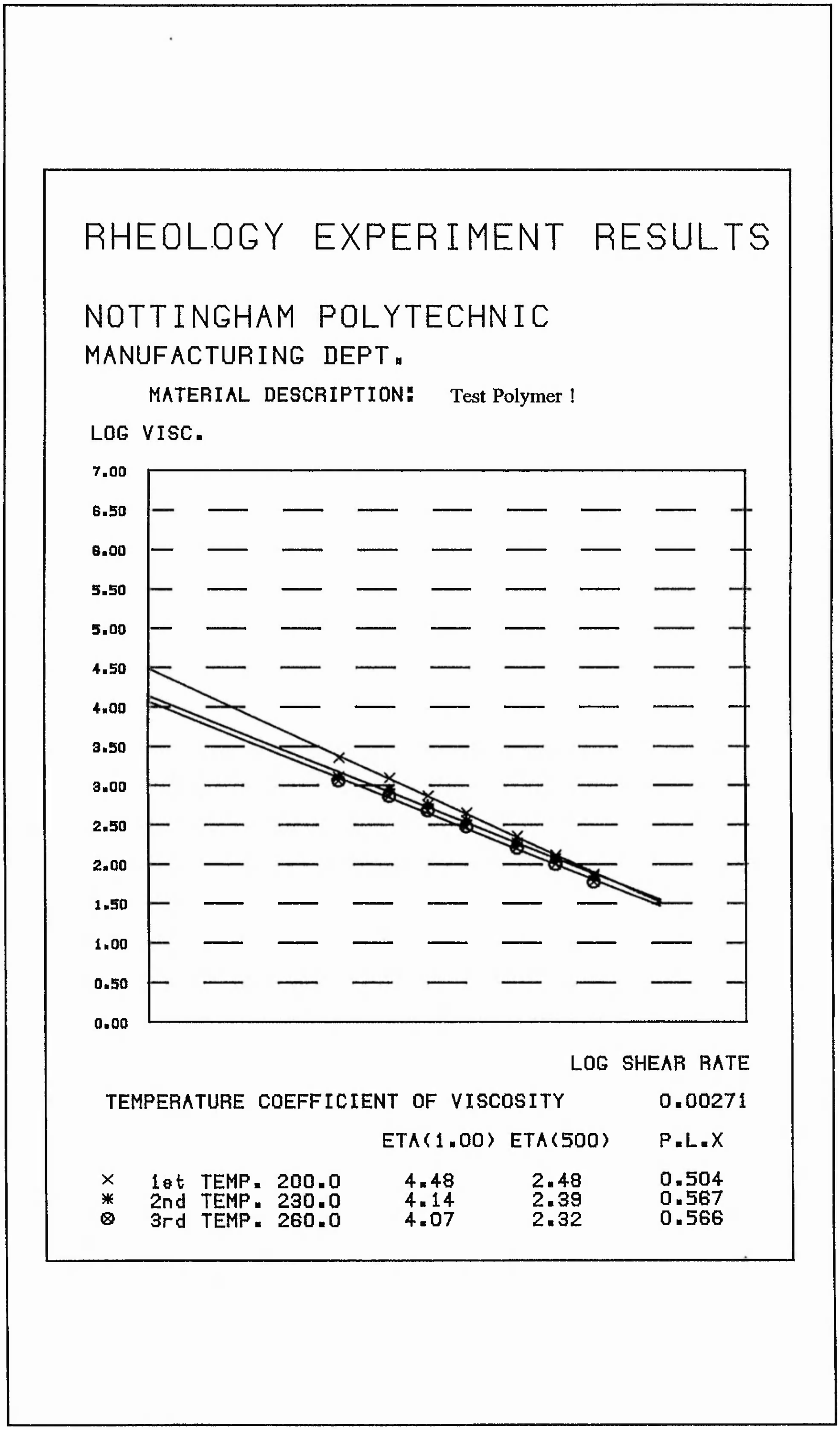


FIGURE 4.1
Regression flow chart.



RHEOLOGY EXPERIMENT RESULTS

NOTTINGHAM POLYTECHNIC
MANUFACTURING DEPT.

MATERIAL DESCRIPTION: Test Polymer !

```
TEMPERATURE COEFFICIENT OF VISCOSITY          0.00271

                             ETA(1.00) ETA(500)    P.L.X

×   1st TEMP. 200.0          4.48      2.48        0.504
*   2nd TEMP. 230.0          4.14      2.39        0.567
⊗   3rd TEMP. 260.0          4.07      2.32        0.566
```

Figure 4.2
A sample results print out.

4-3 OPTIMISATION PROGRAM

It was explained that a program (Melting) was considered to simulate the passage of the material in the barrel. The melting program was the result of the research which had originally started by McElvey [50] in the fifties and developed at Imperial College, London [56] during the seventies and is continuing at the Nottingham Trent University. It takes into account the rheological state of the material and is structured on balancing three conservation equations as follows:

1- The conservation of Mass (continuity).
2- The conservation of Momentum(equilibrium).
3- The conservation of Energy.

This particular research examines the melting theory and evaluates the predictions using a test rig specially developed for this purpose. The rig consists of an ordinary 2.5 inch Francis Shaw single screw extruder which is fully instrumented to give the pressure and temperature at the barrel at any stage along the length of the extruder. Several types of screw are available for comparison of their performance, where the screws themselves are drilled and tapped and thermocouples are fitted to provide the temperature profile of the screw. There are also devices mounted at the back of the extruder which measure torque, rotational velocity and power consumption. The generated data is electronically transferred and recorded. The extruder is surrounded by a network of water pipes which can be flooded to crash cool the extruder and its contents, after stopping the operation. This enables freezing of the material for detailed analysis of its state. There is also a hydraulic jack designed and mounted in a horizontal position on a separate attachment to pull the screw and the frozen material stuck to it, out of the barrel. Figures 4.3 , 4.4 and 4.5 represent the test rig and its accessories. The objectives of the research is to simulate the melting process, using a computer and compare the predicted results with the experimental data in order to refine the computer model for newer, more sophisticated materials and develop the ultimate design tool. Figure 4.6 shows the frozen material stripped off the screw after stopping the process for analysis.

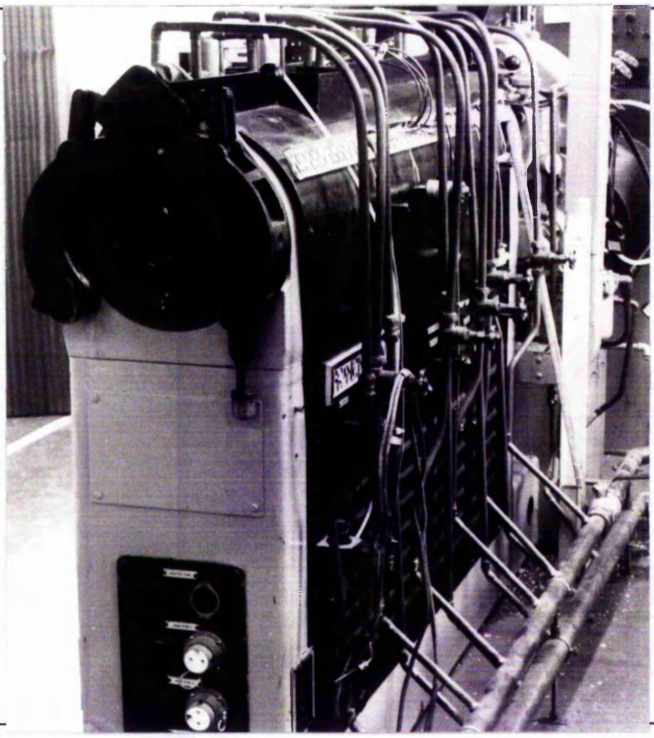


Figure 4.3
The Instrumented extruder unit.

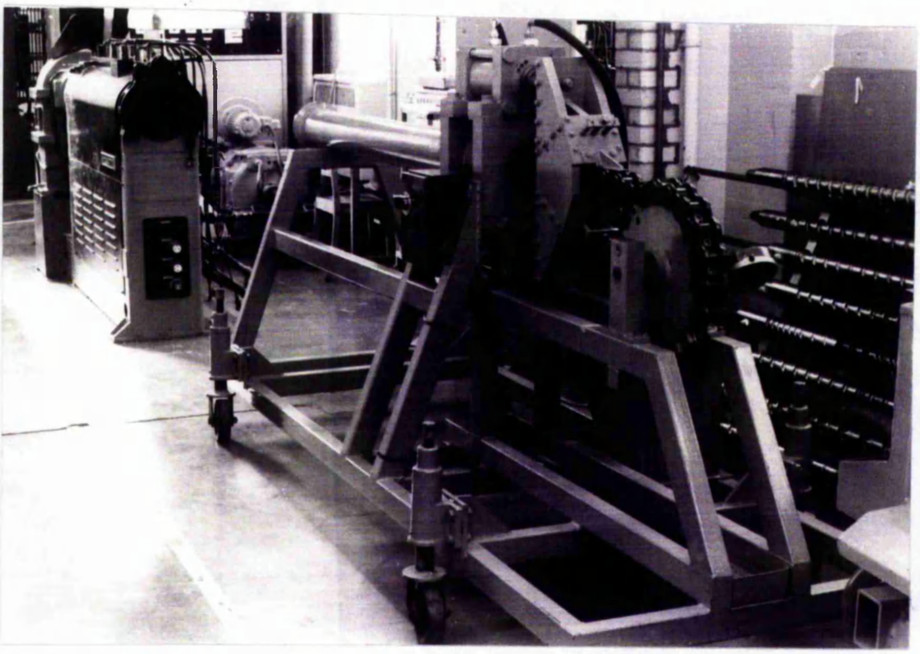


Figure 4.4
The extractor unit.

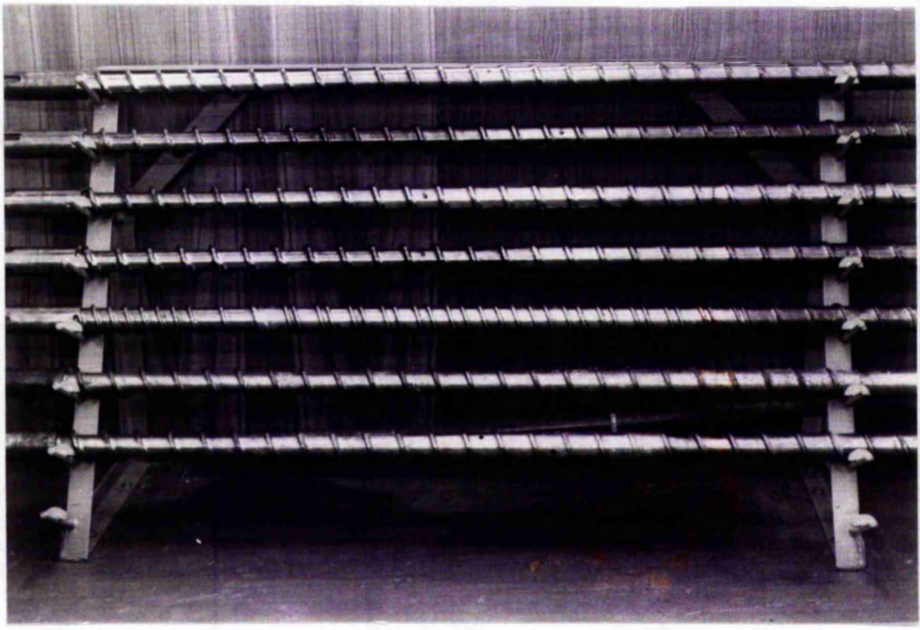


Figure 4.5
Instrumented test screws.

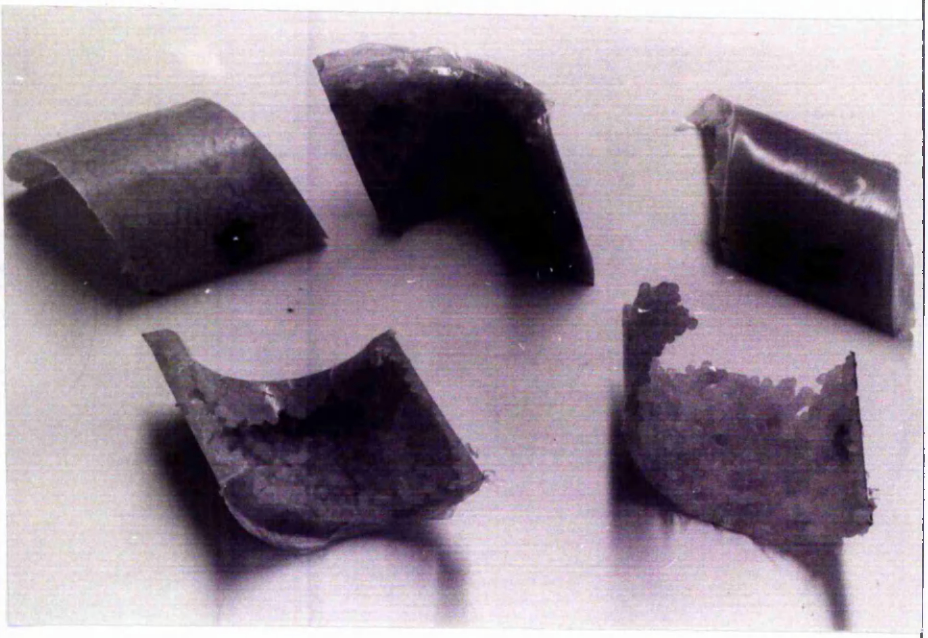


Figure 4.6
Material cuttings, stripped off the screw.

Five regions are considered in the melting model which are:

- The melt film at the barrel.
- The melt film at the screw.
- The solid bed.
- The melt pool at the leading flight edge.
- The thin film between the flight tip and the barrel.

Assumptions have been made to simplify the model and hence reduce the complexity and computing time to a reasonable level.

4-3-1 GEOMETRIC ASSUMPTIONS

The geometry of the screw channel is simplified in the following manner;

(a): The sides of the flights are radial to the screw axis.

(b): The depth of the channel is constant across its width.

(c): The corners of the channel are sharp and not filleted.

Figure 4.7 represents the dimensions conventions and figure 4.8 is the representation of the cross section of screw channel.

Because the width of the screw channel is large compared to the depth, it can be treated as flat rectilinear channel rather than a helical channel therefore, cartesian coordinates are used (figure 4.8). The helix angle and channel width are taken at the flight tip.

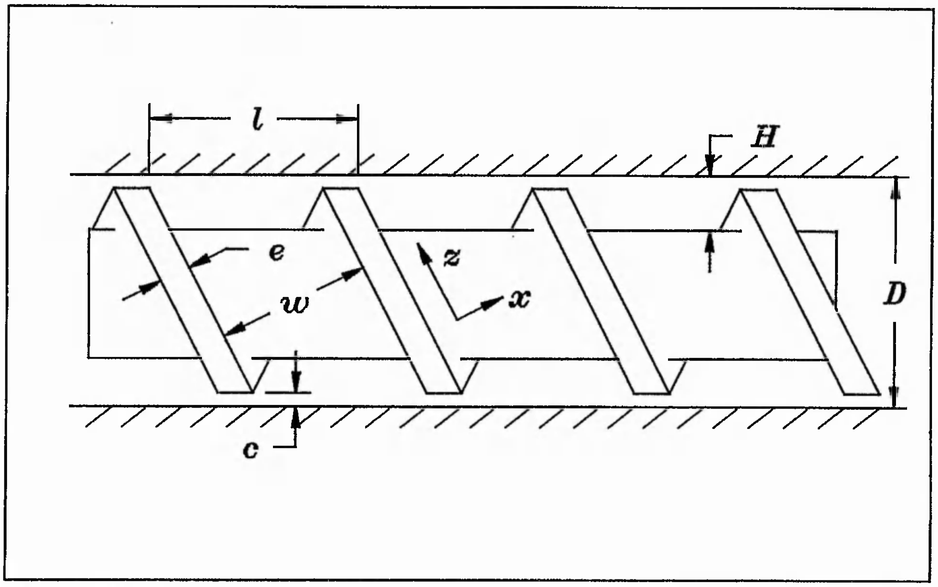


Figure 4.7
Screw dimensions

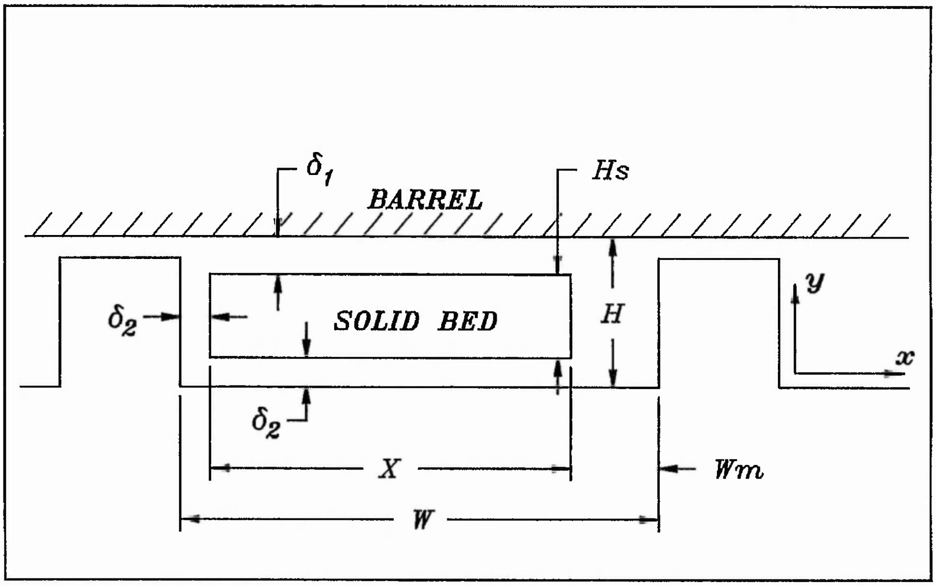


Figure 4.8
Cross section of screw channel.

4-3-2 MATERIAL CHARACTERISTICS

The material characteristics considered are as follows:

Polymer granules or unmolten polymer is treated as a "solid bed" but is allowed to deform as its velocity slowly increases in the downstream direction.

Molten polymer is a highly viscous fluid and hence has a very low Reynolds number, because of this any body forces such as those due to Gravity and Inertia forces can be neglected.

In the extrusion process, viscosity may be treated as being independent of pressure.

4-3-3 MODELLING ASSUMPTIONS

The screw film consists of two parts, the film between the solid bed and the screw root and the film between the side of the solid and trailing flight edge. These two films are treated as one with the cross sectional area of $\delta_2(X+H_s)$ the reasons for which will be discussed later in the solid bed analysis section.

The flow is considered as Isothermal, Newtonian, Drag flow and the leakage flow over the flights is accounted for.

The solid bed velocity slowly increases in the downstream direction. However, no analysis of deformation is performed. Any sharp increase in acceleration is assumed to be an indication of solid bed break up, while the bed is still considered continuous.

Both the melting rate and thicknesses of the barrel and screw melt films are constant for any cross channel position. This assumption is not necessarily valid but the modelling process is simplified if an average value is taken.

Both melting at the interface between the solid bed and the melt pool and the shear stress in the melt pool between the leading flight edge and the solid bed are neglected from the total mass and force balance equations. This is because of simplifications which have been made in the analysis of the two regions in order to reduce the computing time.

Calculation commences at the point where the barrel melt film starts to form. It has been found experimentally that this usually occurs at about turn four, and the screw melt film starts at turn five. Initial estimates for film thickness at the barrel, downstream velocity relative to screw, width of solid bed, and pressure gradient in downstream direction (δ_1,V_{SZ},X,P_Z) are made to provide the first values for the mass flow rate, melting rate and shear stress in the barrel melt film. From this point the model goes into a loop, incrementing along the screw in steps of one tenth of a turn until either the end of the screw is reached or there is negligible solid remaining in the channel.

The program works in steps and the stepping procedure is as follows:

1- Calculate values for V_{SZ},δ_1 and thickness of film at the screw (δ_2), using the Newton- Raphson method to solve for the three unknowns from the three downstream mass flow rate equations. The calculations also yield the P_Z,X and the shear stresses in the melt films(τ_2).

2- Calculate the melting rates into the two melt films.

3- Test the energy balance to give an idea of the error in the calculation. The error factor is given by the difference between input energy due to the barrel heaters and drive motor, and output energy given by thermal and pressure energy stored in the system.

4- Calculate the barrel and screw melt film mass flow rates for the next step along the screw.

5- Repeat steps 1 to 4 until melting is complete or the end of the screw is reached [111].

A full operating guide is given later on, in appendix B.

4-4 GEOMETRIC MODELLING

4-4-1 MATHEMATICAL ANALYSIS

It was described that there is a need to communicate the findings of the optimisation program to the manufacturing unit prior to the manufacturing of the screw. According to the project objectives, a model of the screw had to be produced in a pilot scheme, from the information supplied by the optimisation stage, before moving on to the system design on the target machine. It was mentioned that the McDonnel Douglas Unigraphics II was to be used as the base system at the pilot stage. Because the parametric facility of this system had to be utilised it became necessary to develop the mathematical model of the geometry prior to developing of the programs in computers.

Examination of an extruder screw and previous modelling of screw conveyors [16] identifies two main components, the "screw body" and the "screw flights". The screw body itself is made up of four different elements forming the three main regions of the screw and the drive helix. From these four distinct sections, the drive helix is something which changes from one manufacturer to the next and there is no benefit in modelling it except for each manufacturer as their standard range. Besides, because of its simplicity, its modelling would not be considered much of an achievement. The remaining parts are feed, metering and compression regions. The first two sections are simple cylinders while the last one is a truncated cone. There are different ways of generating these surfaces and different individuals choose the method according to their preferences. In this model the way this structure is modelled is by rotating a poly-line around an axis parallel to the poly-line in the feed and metering sections and perpendicular at the two bottom ends (figure 4.5). The main reason for it is that all three sections will be generated simultaneously.

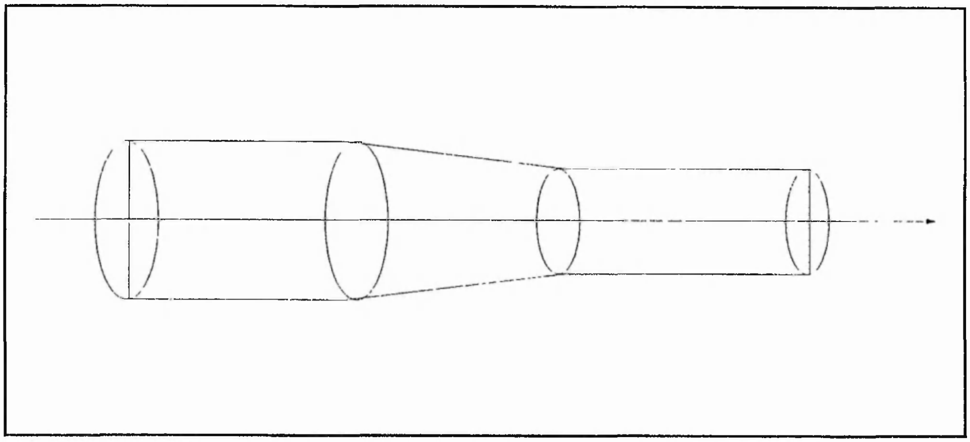


Figure 4.5
The poly-line forming the screw body.

The most difficult part is, however, modelling the flights. Looking at the flights more carefully will reveal that each flight has four edges, two of which follow the body profile (inner helices), while the other two (outer helices) follow the barrel [16].

The latter two edges could be defined as the locus of all points that have the same distance from an axis and their height changes with a certain rate. They are Mathematically defined as:

$$X(\phi)=R.\cos(\phi+\Theta)$$

$$Y(\phi)=R.\sin(\phi+\Theta)$$

$$Z(\phi)=K.\phi$$

In the above equations R is the radius, ϕ is the polar angle in respect to the origin, Θ is the offset value of ϕ ($0 > \Theta > 360$) and K is a constant depending on the helix angle α and is defined as:

$$K=(2\pi.R.\tan(\alpha))/360$$

The helix angle itself is calculated using the following formula:

$$\alpha = Arctan\left(\frac{P}{2\pi R}\right)$$

where P represents the pitch. For the variable pitch screws K itself is a function of height (Z) and could change but as long as the change is linear it could be catered for.

Generally, in the variable pitch screws used in polymer processing this change is expressed in terms of pitch change rate (C) and could be defined as:

$$P_{new} = C \cdot P_{old}$$

$$\alpha_{new} = \alpha_{old} + C\left(\frac{\phi}{360}\right)$$

The two inner helices that follow the body profile could be defined more or less in the same way at the feed and metering sections except that the radius would change at each section.

$$X(\phi)=RF.\cos(\phi+\Theta) \qquad X(\phi)=RM.\cos(\phi+\Theta)$$

$$Y(\phi)=RF.\sin(\phi+\Theta) \quad \& \quad Y(\phi)=RM.\sin(\phi+\Theta)$$

$$Z(\phi)=K.\phi \qquad Z(\phi)=K.\phi$$

In the above equations RF stands for feed radius and RM for metering radius. The compression section is slightly more complex where the RC or compression radius varies and is a function of the height. Assuming that the section of the flight that follows the truncated cone section of the body starts at ZC and finishes at ZM ($ZM>ZC$), RC would be defined as:

$$RC=RF+((RM-RF)/(ZM-ZC)).(Z(\phi)-ZC)$$

The rest of the equations would be similar to the ones expressed for the other two. At this stage it has to be mentioned that the helix angle (α) will vary from section to section at the inner helices and is different from the angle at the outer helices. Figure 4.6 represents the four helices forming the flights.

Having arrived at this stage one of the unknown parameters is the amount of the angular offset or (Θ) which is different for every helix. Assume that the flight thickness is e and that it is perpendicular to the body at each point and its centre-line will superimpose on the normal at the centre of the flight (figure 4.7). If the reference point is considered at angular coordinate 0, the offset value for each of those helices would be as follows:

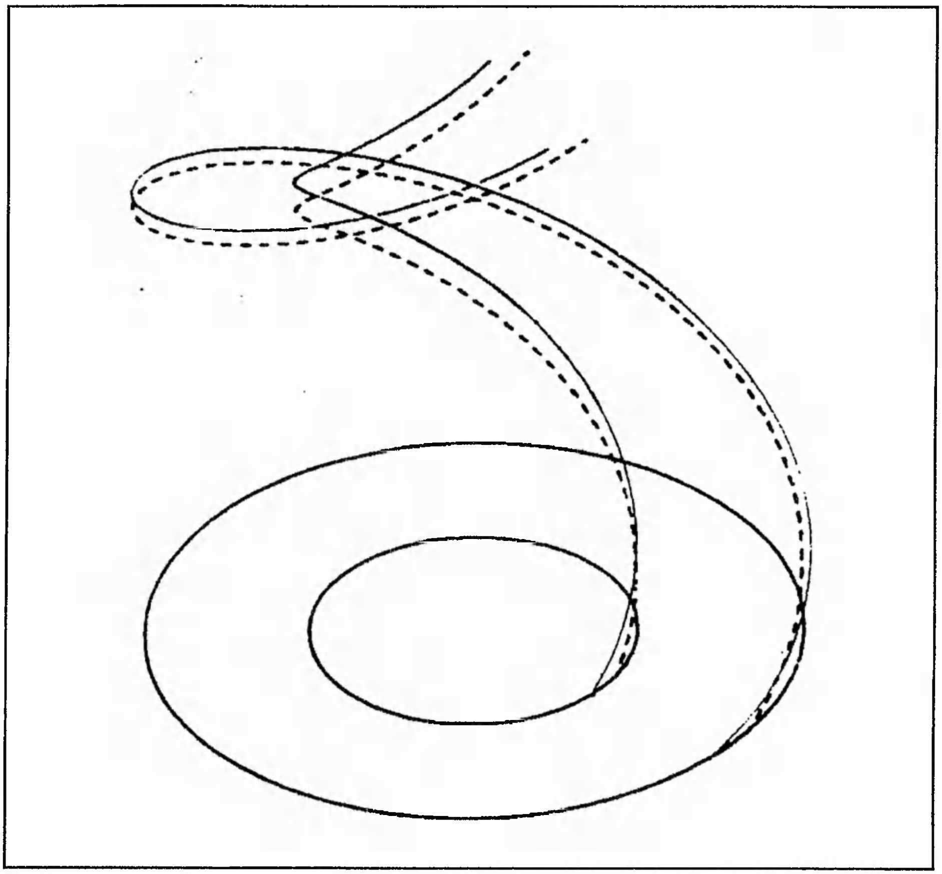


Figure 4.6
The four major helices in the formation of the flights.

$\Theta 1 = \text{Arcsin}(e/ 2.RF)$ $\Theta 3 = \text{Arcsin}(e/ 2.R)$

$\Theta 2 = - \Theta 1$ $\Theta 4 = - \Theta 3$

As can be expected, the offset values would be a function of radius and therefore for the metering section RF will be replaced by RM and in the compression section with RC. Having got to this stage, what remains is defining the three surfaces forming the flights. The two side panels will be defined by creating a sculptured surface passing through the helices 1 and 3 and 2 and 4. The outer edge of the flight is defined by sweeping the arc between the starting point of the helices 3 and 4 along one of them. Completing this section will leave two simple surfaces to be drawn to complete the screw and there are the bounded planes at the bottom and top end of the screw. The limiting boundaries of these two planes are well defined and completing them will end the design process.

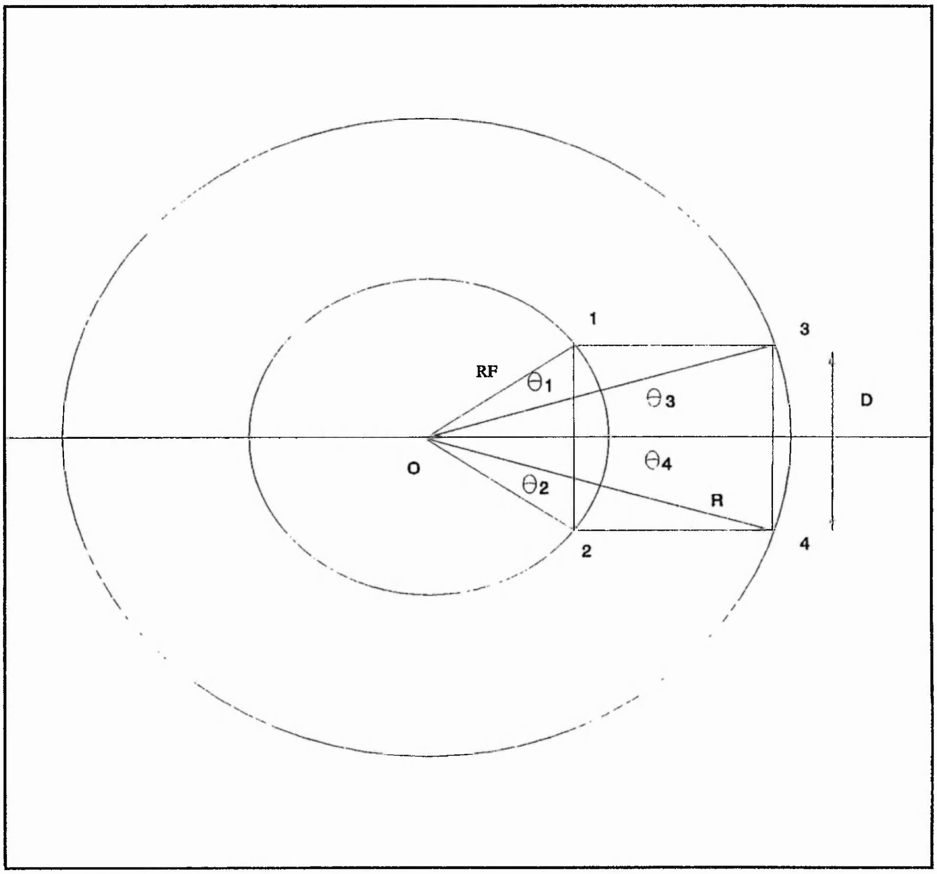


Figure 4.7
Geometrical presentation of flight at starting plane.

4-4-1-1 DESIGN ALGORITHM

The mathematical relationships governing the whole screw structure was analyzed in the previous section, at this stage therefore, an algorithm should be defined to turn those formulae to executable programs. First of all initialisation should take place, then the interactive session with the user to define the required screw. After the data input process, the flight construction starts first and begins in the first region (feed). In order to avoid huge memory requirements at any time, the screw is divided into sub-screws of one pitch length. Every sub-screw is then constructed before attending to the next. In general there are two possibilities facing the construction of one turn of flight at any time, it could either finish within the boundaries of the starting region or in the next. When it finishes in the same region, after drawing the helix and performing a few housekeeping operations the loop is resumed. However should the flight finish beyond the boundaries of the starting region, a subroutine is called which calculates the final point which is at the boundary and the penultimate point before that. A spline will then be computed to pass through the created points and a new offset value will be calculated for each helix. To save time at each passage of the program control through the loop, all four points on the four helices are calculated and therefore at the end four separate helices would be drawn. At this stage the surfaces that form the flights are computed and constructed. This routine continues to the end of the third region (metering) before moving to the next stage of the operation or screw body construction. This stage is fairly simple and requires the definition of a poly-line and rotating it around its axis of rotation, as described at the mathematical model. Chart 4.1 represents the flow chart and its subroutines.

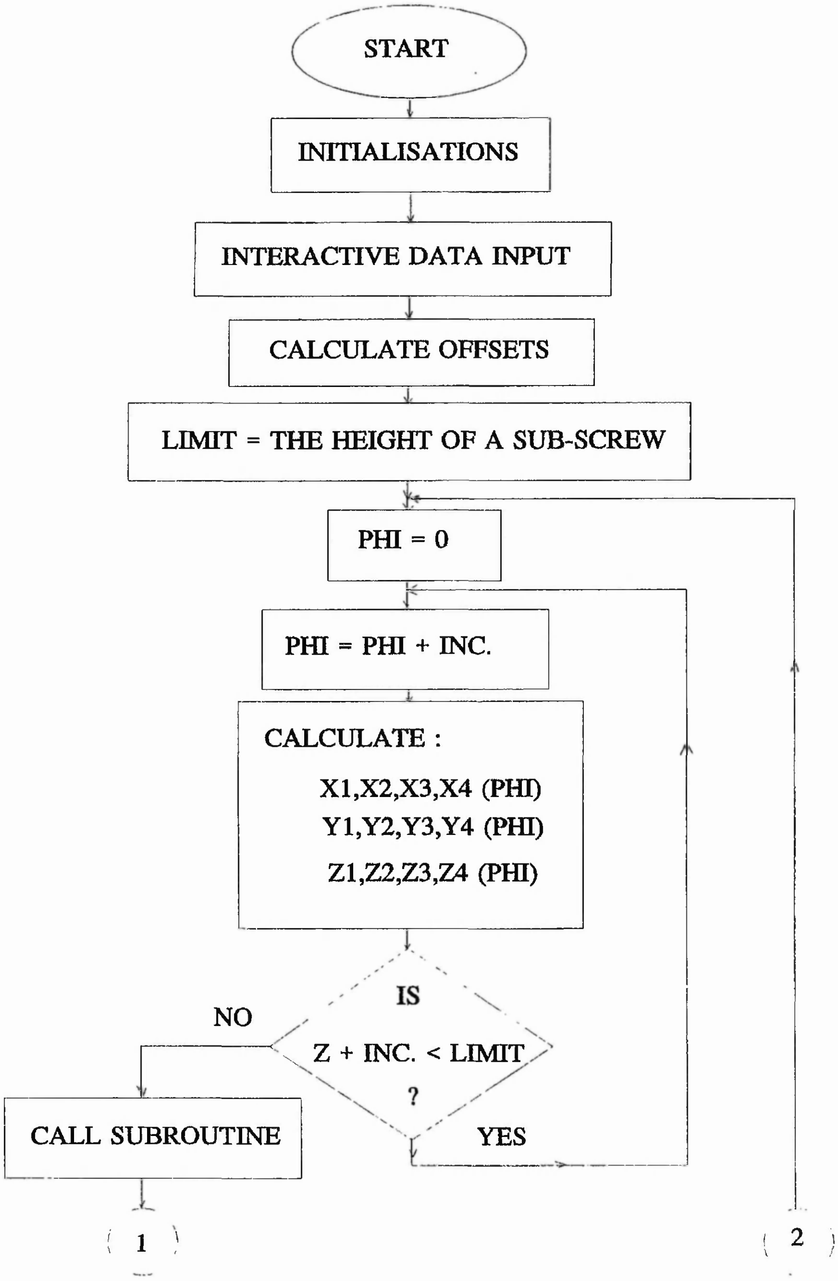


Chart 4.1 (part one)
3D screw program flow chart

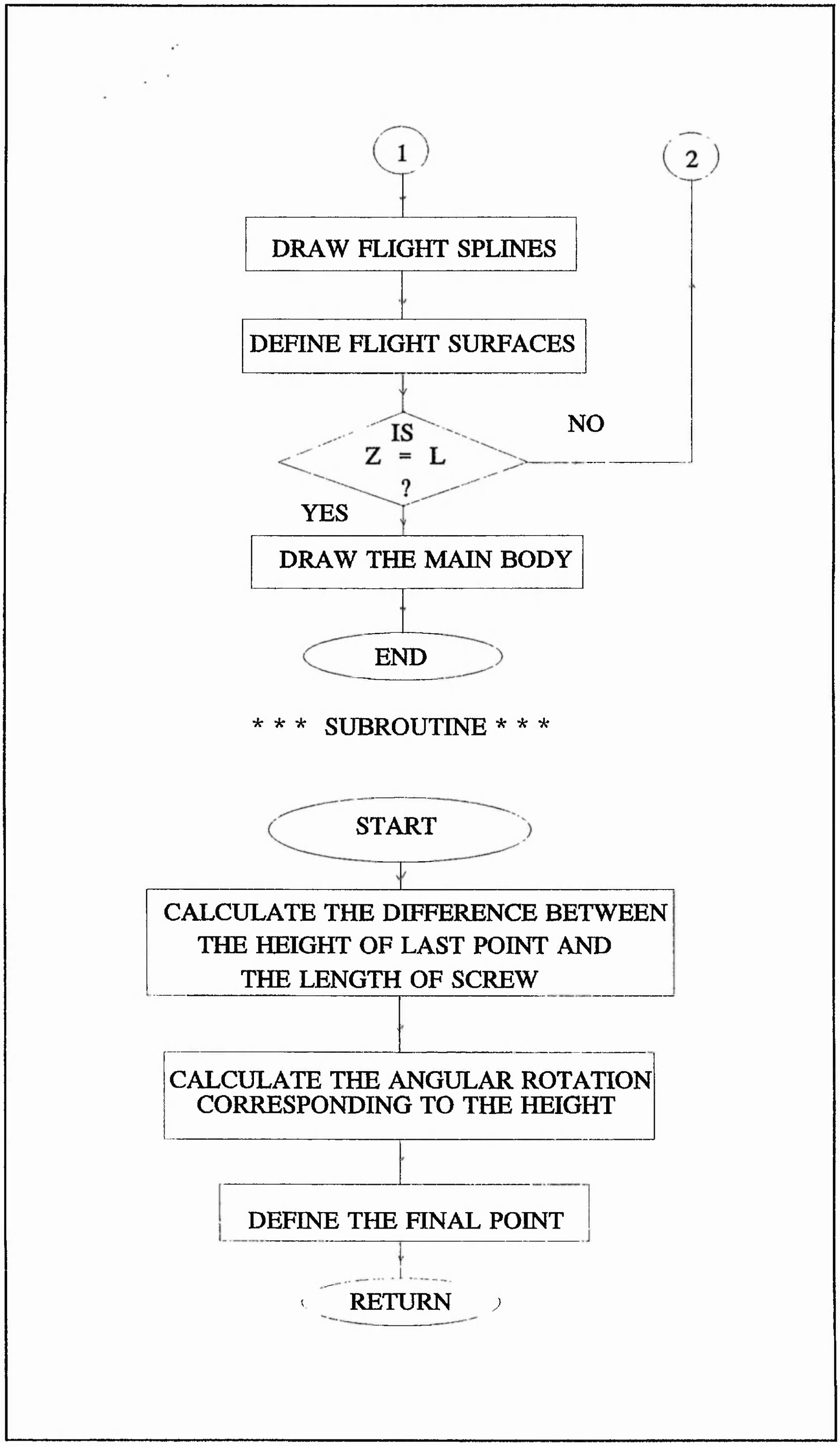


Chart 4.1 (part 2)
3D screw program flow chart.

4-4-2 PRODUCTION SYSTEM DESIGN

Having arrived at this stage it was time to reshape the model and make it usable by the PC based CAD system. Having completed the development on the mainframe based system and after initial trials with the new system, it was realised that a slight change of direction was necessary. This was because first of all, the chosen system (Multicad) could not generate bounded surfaces between two splines. Secondly, it could not hide entities of a 3D model on a 2D presentation. Thirdly, the surfaces that could be generated within the system was not accurate enough to give a reasonable drawing in a 2D presentation. Therefore it was decided to use the system to generate the 2D drawings of the screw directly, and to use the 3D option for the solid model generation. According to the new approach, a mathematical model of the drawing had to be parametrically constructed.

4-4-2-1 DRAWING MODEL

Basically this model is a complex calculation of the intersection point of two lines and its assessment. The intersection of two lines is calculated by solving a simple system of two linear equations described below.

Assuming that a line defined by:

$$A1\ X + B1\ Y = C1 \qquad k1 > X > k2\ ,\ k3 > Y > k4$$

is intersecting another line defined by:

$$A2\ X + B2\ Y = C2 \qquad j1 > X > j2\ ,\ j3 > Y > j4$$

The intersection point PI(x,y) is defined by:

$$X = \frac{C1 - \frac{C2\,.\,B1}{B2}}{A1 - \frac{A2\,.\,B1}{B2}} \qquad y = C1 + \frac{X\,.\,A1}{B1}$$

Point PI(x,y) is the intersection point of the two lines only if x and y satisfy the following boundary conditions.

$$(k1 > x > k2)\ \&\ (j1 > x > j2)$$

$$(k3 > y > k4)\ \&\ (j3 > y > j4)$$

Having defined the above concept it is then utilised in defining a parametric screw. To achieve that, a suitable algorithm should be adopted which is described in the next section.

4-4-2-2 DRAWING ALGORITHM

Looking at an orthographic drawing of a screw (figure 4.8) will reveal that one element repeats itself (figure 4.9) and all the other details follow that element. There are also six main lines that form the core of the structure (figure 4.10).

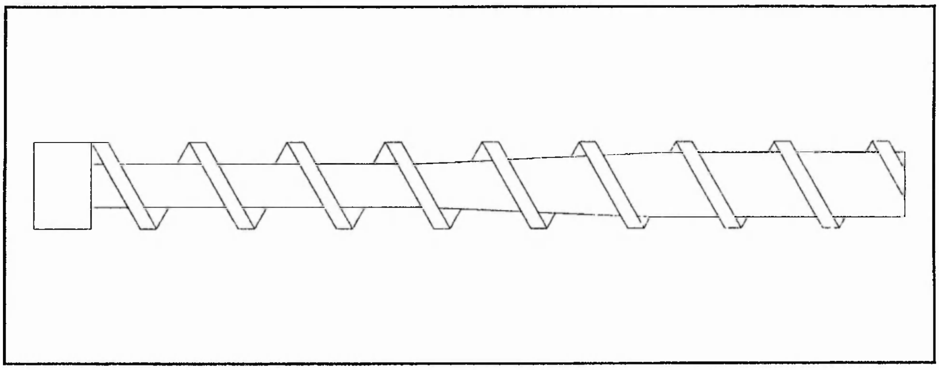


Figure 4.8
A screw drawing.

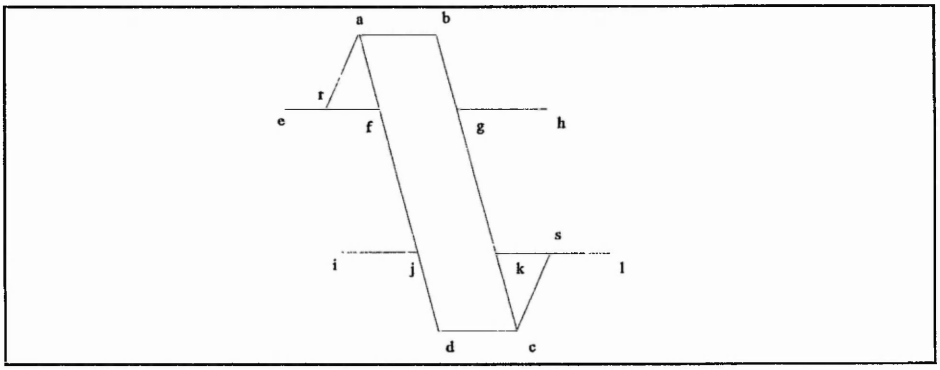


Figure 4.9
Repeating element in a screw drawing.

The key to the solution therefore lies in defining this element parametrically and constructing the rest of the screw around it. This is done by defining these

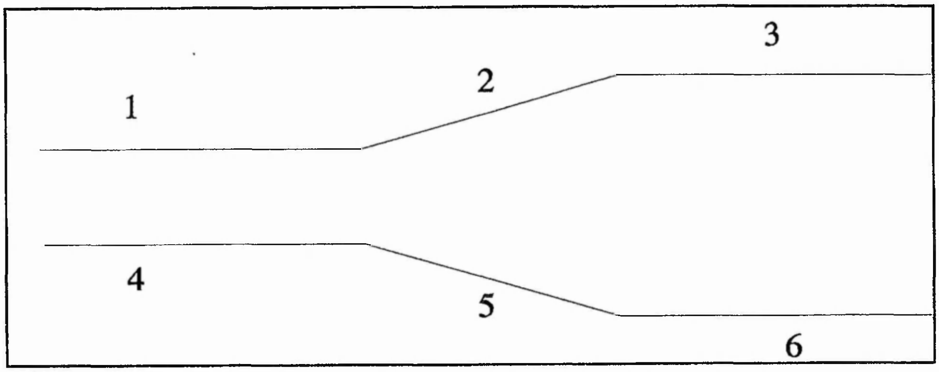


Figure 4.10
Screw core.

points in a loop and defining the points and drawing them at each passage.

Concentrating on figure 4.9 will expose the fact that the whole structure is constructed using fourteen points named as:

a,b,c,d,e,f,g,h,i,j,k,l,r,s

Considering point "a" as the reference point for the whole structure, it is parametrically defined and repeated at known intervals. According to figure 4.8, repetition occurs at every pitch, starting from the reference point. The relationship between the structural points of the flight are defined as following where x(i) and y(i) are x and y coordinates of point i.

$$x(a) = X0+n.P \qquad y(a) = D$$

$$x(b) = xa+e' \qquad y(b) = D$$

$$x(c) = D.\tan(\ \alpha'\ )+e' \qquad y(c) = 0$$

$$x(d) = D.\tan(\ \alpha'\ ) \qquad y(d)=0$$

In the above relationships, P is the pitch, D is the screw diameter, e' is the apparent flight width and α' is the apparent helix angle. "e'" is calculated from:

$$e' = e\cos(\alpha')$$

The α' is defined as:

$$\alpha' = Arc\tan(\frac{P-e}{D})$$

Where the helix angle itself is calculated from

$$\alpha = Arc\cos(\frac{P}{\pi.D})$$

To define the other eight points, the intersection principle will be utilised. At the same time, it was necessary that two sets of points were defined at every stage. This was because the point "h" of the first group was the same as point "e" of the next and similarly "l" was the same as "i". (ints. = intersection of)

$$x(e1) = x(h2) \qquad y(e1) = y(h2)$$

$$x(f1)\ ,\ y(f1) = \text{ints.}(LT\ \&\ ad)$$

$$x(g1)\ ,\ y(g1) = \text{ints.}(LT\ \&\ bc)$$

$$x(h1) = x(e1)+P \qquad y(h1) = D-((D-D')/2)$$

$$x(i1) = x(l2) \qquad y(i1) = y(i2)$$

$$x(j1)\ ,\ y(j1) = \text{ints.}(LB\ \&\ ad)$$

$$x(k1)\ ,\ y(k1) = \text{ints.}(LB\ \&\ bc)$$

$$x(l1) = x(j1)+P \qquad y(l1) = (D-D')/2$$

In the above relationships, D' represents the current value of the variable representing feed and metering diameter LT and LB are representing lines(1,2 or 3) and (4,5 or 6) respectively (figure 4.10) depending on the x coordinate of the point which is being calculated. As can be seen in two points in particular the relationship in the first group is dependant on the values at the second group. All the initial coordinate values of the second group are therefore set to zero to begin the drawing from the beginning. Having calculated the values of the first group and drawing the lines, the first group will then become the second group and form the basis of the calculation for a new "first group".

The remaining points "r" and "s" are also defined using the intersection model and are formulated as:

$$x(r1)\ ,\ y(r1) = \text{ints}\ (LT\ \&\ ac')$$

$$x(s1)\ ,\ y(s1) = \text{ints}(LB\ \&\ ca')$$

Where a' and c' are

$$x(a') = x(a)+P \quad \& \quad y(a') = y(a)$$

$$x(c') = x(c)-P \quad \& \quad y(c') = y(c)$$

Since the target screws have three stages, the intersecting lines LT and LB have to be defined parametrically. Similarly, the feed and metering diameters should be defined parametrically. D' represents the value of feed or metering diameter. There is also a control mechanism which is based on comparison of the intersections and the regional coordinates. This takes place in order to switch the values of LT, LB and D' at different stages.

When at the compression section, the situation is slightly different and the "y" values of points will change and should be taken into account. These changes (increase or decrease) are linear and for every pitch are governed by:

$$y = \pm \ DF \ P\{[(D-DM)/2]-[(D-DF)/2]\}/CL$$

In the above equation, D, DM and DF are screw, metering and feed diameters respectively and CL is the compression length.

This process repeats n times where n is the number of possible full flights. The next stage is drawing the final pitch, which will not be completed using this routine. For this purpose, the same intersection routine is used and all the possibilities are explored. Figure 4.11 will explain the possible finishes to the screw end. Looking at the figure 4.11 and it can be seen that the screw will end on any of the lines numbered from 2 to 6 or in the regions identified by two consecutive regions from 1 to 6 or before line 6.

It is obvious that screw can not finish at the region beyond 1 since this is the extent of a complete turn. With this in mind, the possible end to the drawing could have 10 possible outcomes each using the same intersection routine to find the intersection between different sets of lines, arranged in a logical sequence.

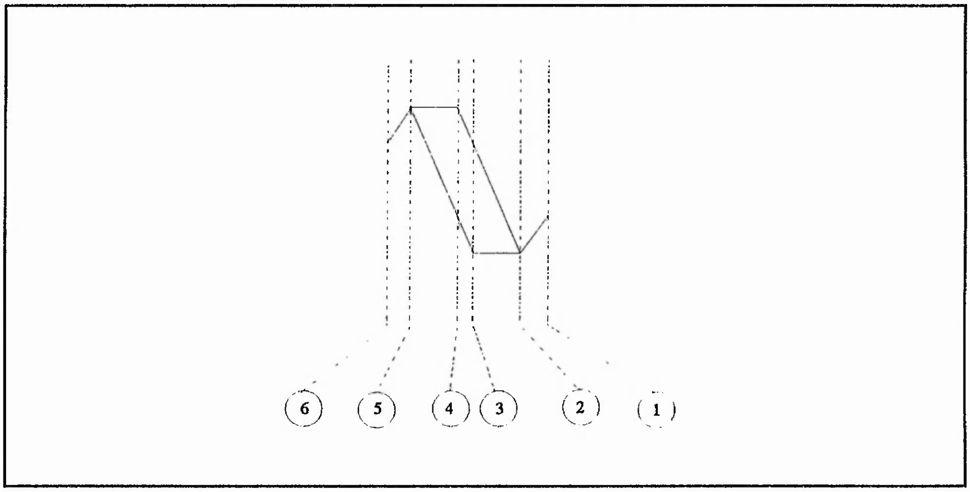


Figure 4.11
Different possible finishes at the end of screw.

Chart 4.2 will describe the brief flow chart of the program.

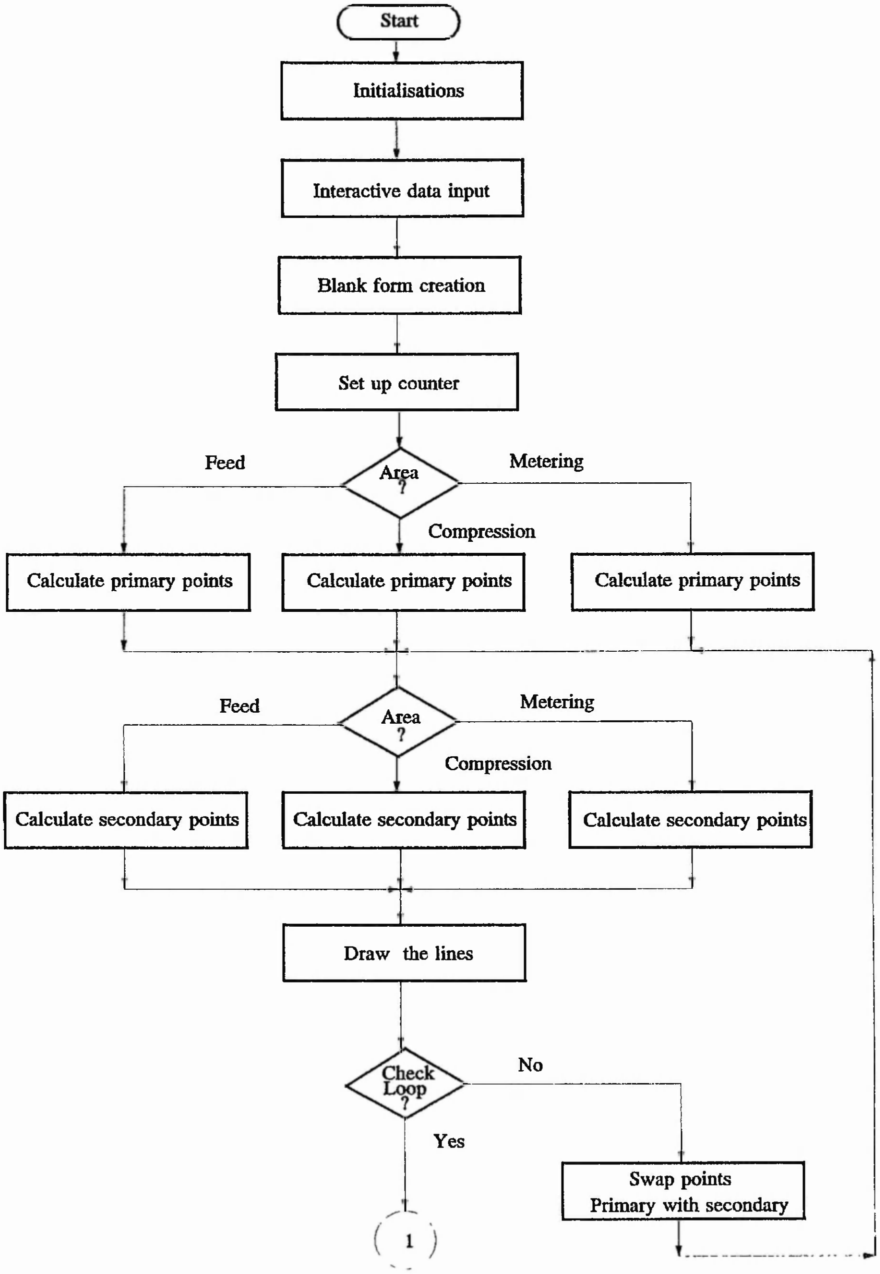


Chart 4.2 (part one)
2D drawing program flow chart.

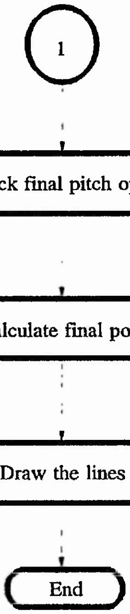


Chart 4.2 (part two)
2D drawing program flow chart.

4-4-3 SHADED MODEL

So far both the wire frame model and the 2D Drawing have been described and constructed. These models are adequate for production purposes. However it was felt necessary to build the solid model as well. This is to overcome the mis-interpretation problem and gives the engineer a better idea of what he is about to make. Considering the capabilities and limitations of the CAD system and due to the fact that the target system was not capable of constructing solid models, it was decided to get round this problem by creating a surface model and shade that model. At the same time, it was realized that as stated before, the system was not capable of constructing complex surfaces by the definition of their boundaries either. Therefore, it became necessary to construct a 3D model based on simple surfaces before shading it. This meant that some compromises had to be made to define those complex surfaces in simple terms. Because at this stage the accuracy of the model was not very crucial, this was acceptable and therefore was implemented.

Knowing that the system could cope with defining simple surfaces like a rectangle or a triangle, it is only a matter of deciding on a solution where these surfaces could be defined parametrically and that is what is attempted at this section. Figures 4.12-a and 4.12-b represent the real surface and its approximation (used within this model).

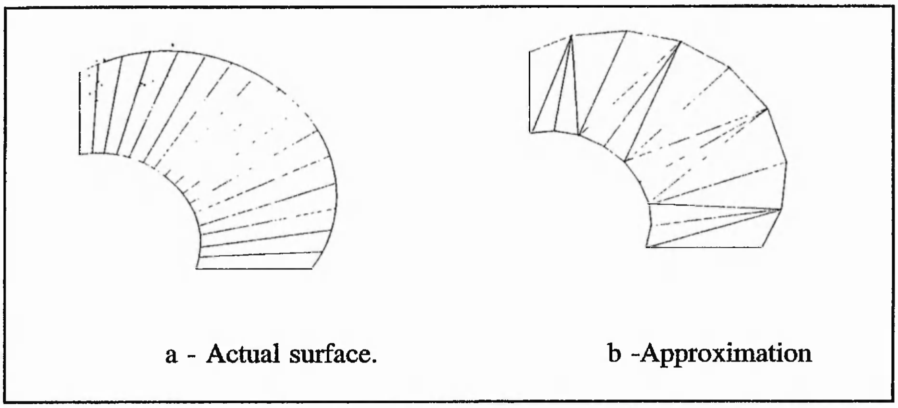

a - Actual surface.
b -Approximation

Figure 4.12
Flight surface and its approximation.

Upon defining these surfaces, the system function will be used to define and shade the solid screw.

At this stage of the project, because of utilising the system functions, most of the task was to design the algorithm rather than a mathematical model. However, it has to be remembered that the underlying process is a mathematical one. In this module the only major mathematical concept in use is the bounded plane definition. What remains at this stage is calculating the points defining the boundaries of the planes. This task is similar to the one performed in constructing the 3D wire frame model. Examining the screw again reveals that the major obstacle, as for the previous stages, is the screw flights construction. If an imaginary screw is cut along its main axis at two points and then sectioned again through its centre at two different angles, what remains would be similar to the object shown in figure 4.13-A. Subtracting the middle part (main body) will leave the screw flight element, figure 4.13-B. In reality, if this element is rotated and shifted along its z axis so that its lower end finishes where its top end is, the screw flight can be constructed.

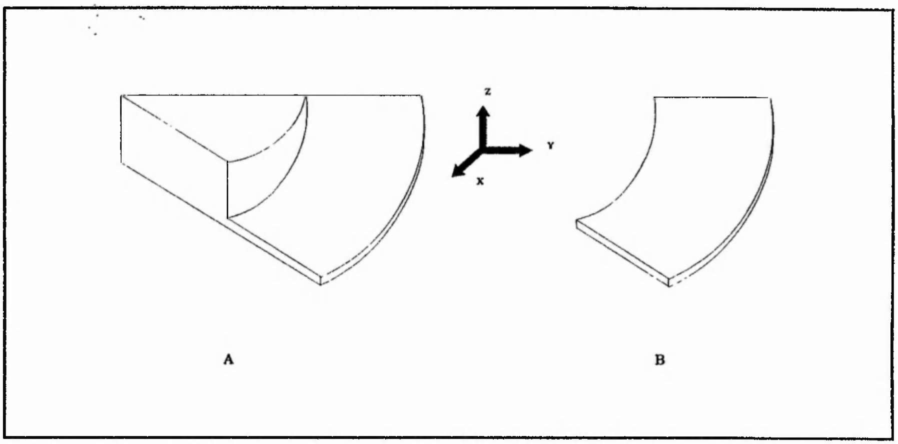


Figure 4.13
Screw sections.

In fact this sounds more like assembling the screw from elementary pieces. In practice the new position could be obtained by two different transformations. These are a rotation and a translation which, combined together, can give the new coordinates. In simple rotation around an axis the new coordinates could be calculated by matrix multiplication of the coordinate vector and the transformation matrix (X'= R.X). This is where

$$X=[x \quad y \quad z] \qquad \& \qquad X'=[x' \quad y' \quad z']$$

and

$$R=\begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

In this relationship ψ is the rotation angle.

To translate the coordinate system to a new height the new

$$X' = R.X \Rightarrow [x' \quad y' \quad z' \quad 1] = [x \quad y \quad z \quad 1].\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & a & 1 \end{bmatrix}$$

As illustrated above for translation in any direction there is a further dimension needed to express the translation. This is called the homogeneous dimension or homogeneous element. Combining the two transformation matrices will give the new coordinate system:

$$[x' \quad y' \quad z' \quad 1] = [x \quad y \quad z \quad 1].\begin{bmatrix} \cos\psi & \sin\psi & 0 & 0 \\ \sin\psi & \cos\psi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & a & 1 \end{bmatrix}$$

Having calculated the new system of coordinates, the same object could be constructed in the new coordinate system. At this stage and after defining the first set of points what remains to be done is transformation of each set of points to find the next. Following the same pattern of flight construction at the compression section in this module would not create any problem. That is because the excess part of the flight will be hidden inside the screw body and underneath the surface of the truncated cone. For the less powerful systems however the points could be calculated using the following formulae:

$$x1 = x0 + R\cos(\theta)\ ,\ y1 = y0 + R\sin(\theta)\ ,\ z1 = z0$$

$$x2 = x0 + R\cos(\theta)\ ,\ y2 = y0 + R\sin(\theta)\ ,\ z3 = z0 + dh$$

$$x3 = x0 + RFcos(\theta)\ ,\ y3 = y0 + RFsin(\theta)\ ,\ z3 = z0 + dh$$

$$x4 = x0 + RFcos(\theta)\ ,\ y4 = y0 + RFsin(\theta)\ ,\ z4 = z0$$

$$x5 = x0 + Rcos(\theta + \phi)\ ,\ y5 = y0 + Rsin(\theta + \phi)\ ,\ z5 = z0 + \delta h$$

$$x6 = x0 + Rcos(\theta + \phi)\ ,\ y6 = y0 + Rsin(\theta + \phi)\ ,\ z6 = z0 + dh + \delta h$$

$$x7 = x0 + RF\cos(\theta + \phi)\ ,\ y7 = y0 + RFsin(\theta + \phi)\ ,\ z7 = z0 + dh + \delta h$$

$$x8 = x0 + RFcos(\theta + \phi)\ ,\ y8 = y0 + RFcos(\theta + \phi)\ ,\ z8 = z0 + \delta h$$

In the above relationships:

$$\delta h = \frac{2\Pi . R.m}{360}$$

and

$$dh = d.\sin(\alpha)$$

where α is the helix angle, R is the screw radius and RF is the feed radius.

Also m is defined as: $$m = \frac{\phi}{360}$$

where ϕ is the increment angle from the start to the end of the element. x0, y0, z0 are offset values of the starting points while θ is the offset angle.

Looking at the two main structures of the screw it can be seen that the main body can be approximated by a series of rectangular surfaces similar to the one described in figure 4.14.

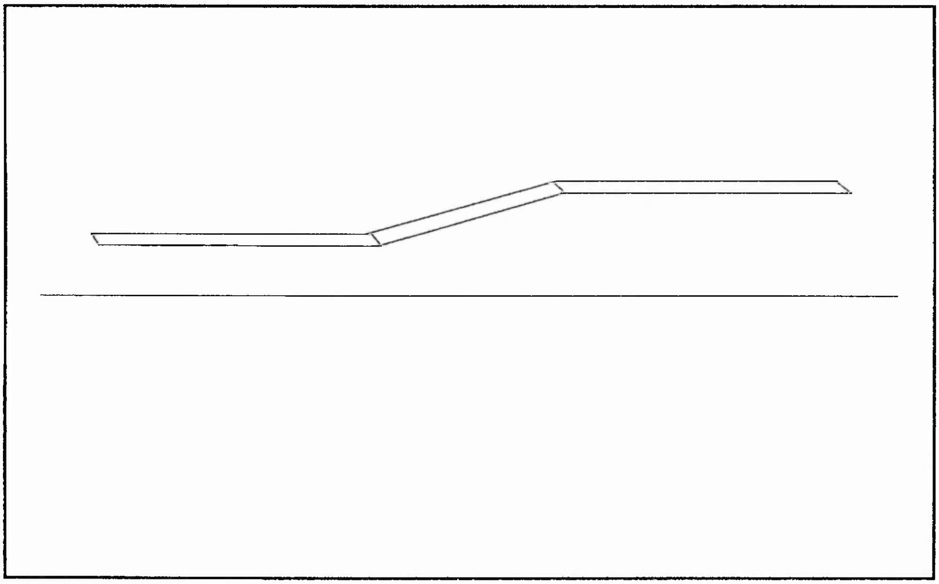


Figure 4.14
Basic element in modelling the main body.

The more of these elementary surfaces that are constructed, the closer the model gets to the real object. Of course the more surfaces defined, the more computer time is required. For the flight construction what is required is to construct the new flight elements in a loop using either of the above methods and unite them together as an object or a surface. Adding to this object the body constructed by defining the rectangular surfaces will provide the screw itself. Chart 4.3 represents the flow diagram for this module. Having got the screw model, what remains is to use system commands to shade and paint the screw the details of which are described in chapter five.

The importance of this module as described before is that it facilitates a powerful communication tool with a nontechnical audience and the fact that it removes the chances of accepting unrealistic proportions in screw design. This is particularly important because there is not a cheap FE tool available on a PC platform to analyze the stresses on the screw.

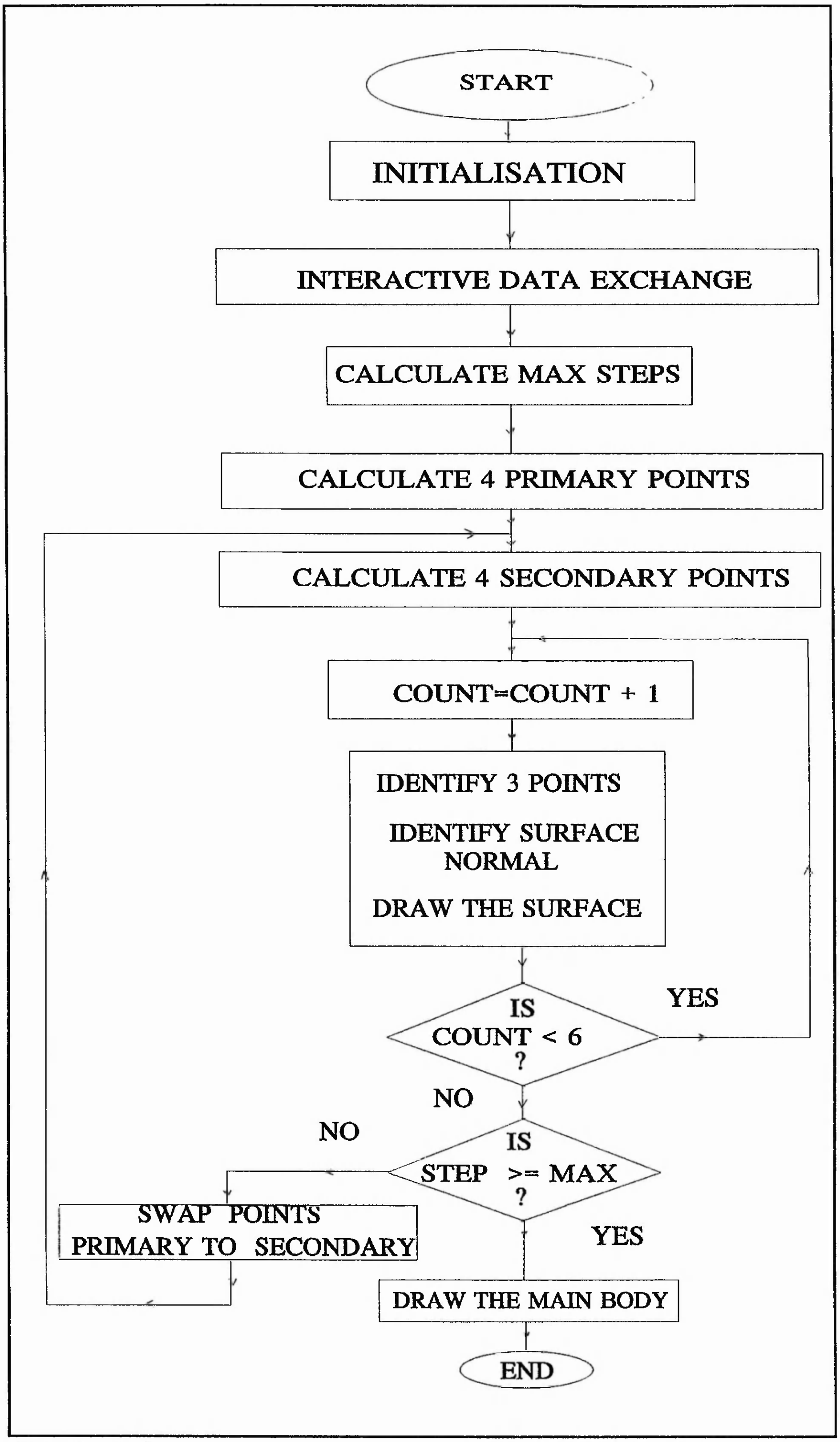


Chart 4.3
Surface model program flow chart

4-5 MANUFACTURING MODULE

It was decided to develop a system based on the computer integrated part programming (CIP) approach, to manufacture these screws. A number of points has to be taken into account before development of this program. These are the size of the components and the nature of the operation which includes a series of long continuous cuts along the bar. These can cause three major problems whilst operation is in progress. These are:

1 - Thermal stresses created on the bar.
2 - Rapid tool-ware.
3 - Increased possibility of the tool breakage during operation.

The first problem could reduce quality and increase operational time, in the later stages of the finishing operation. This is due to inaccurate cuts resulting from the change in the material dimensions. The second problem would also cause a reduction in quality caused by the cuts occurring at a shallower depth due to the tool-ware and hence the need to introduce further re-work. The worn out tool would also contribute to further increase in the thermal stresses generated within the bar, during the cutting process. The third problem will increase the chances of breaking the tool or the bar which apart from the increased risk of accident in the work shop, it raises the possibility of creating scrap or at the least it will force the line to stop for repair or tool change. The natural solution to avoid this problem is to reduce the feed rate and increase the coolant flow. It can be seen that this could cause a reduction in productivity and is undesirable.

A major development in machine design created the opportunity to get away from these dilemmas. This was the introduction of the whirling process. This is a very high speed cutting process for cutting cylindrical pieces. It is also known as "bar peeling" what it was initially used for. This is a metal chip cutting operation and designed specifically for use in cutting worms, gears or helical surfaces. In this process carbide tipped tools are mounted in a ring rotating at high speed in such a way as to produce a series of interrupted cuts. This results in a very high production rate and good accuracy.

The tool ring rotates at high speed in an eccentric path to the axis of a slowly rotating workpiece (figure 4.15), producing a series of interrupted cuts. Each tool is in contact with the bar for a very short time in its path. This is about 1/4 to 1/6 of the workpiece circumference and produces only small chips. As a result the cooling rate is favourable, especially because the tool is travelling at high speed in air for most of its action. Apart from that, most of the heat generated during the cutting period is inside the chips which are removed from the bar completely.

Having decided on basing the operation on a CNC machine tool (whirler), the target machine has to be identified. Because of the nature of the operation and the size of the parts to be cut, there was not much choice. Two vendors were

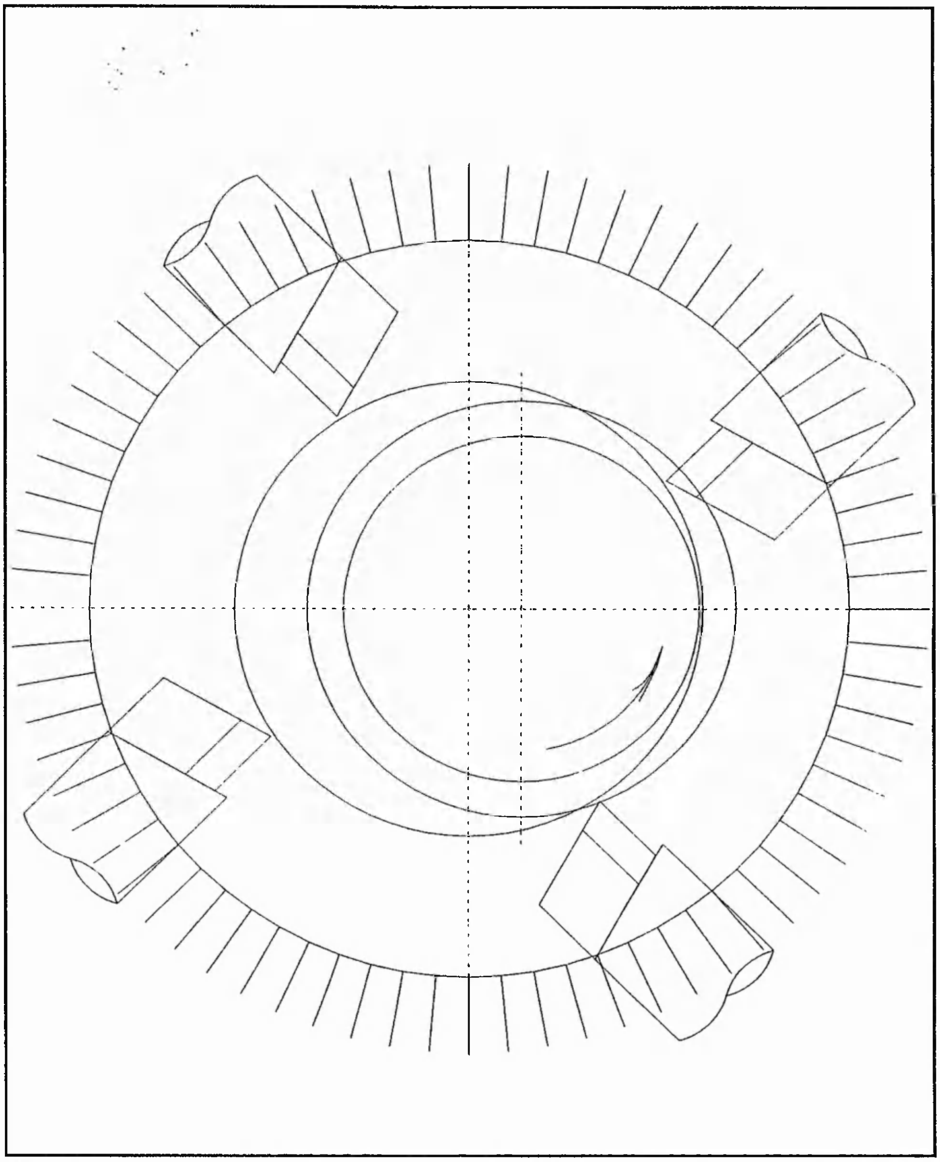


Figure 4.15
Whirler head.

supplying this kind of machine suitable for this purpose; Linsinger (an Austrian company) and Binns & Berry (a British company). Between these two vendors, the one considered was Binns and Berry with their eight meter bed lathe fitted with a Burgsmuller L4 whirling head (a German machine). This decision was taken because of availability of this machine for research in the collaborating company more than anything else. This machine has a

Fagor CNC 8020 T controller and can be programmed both from its front panel and from external peripherals via a serial (RS232) port. This includes tape readers, cassette reader/ recorder and computer. The memory capacity available for part programming is 32K. The machine is controlled using the ISO standard commands. A positive property of this system is its operations compatibility with its old counterpart (lathe), despite all their differences.

As described earlier, the manufacturing module has to be developed according to the special requirements of this problem. In choosing the "Computer Integrated Part Programming" method, it was explained that the system comprises of two major elements of; the "set-up processor" and the "G-CODE generator". Having considered the CNC machine and its controller details, it is time to deal with the components of the manufacturing module.

4-5-1 THE SET-UP PROCESSOR

The first part to deal with is the "set-up values" program which considers the geometry of the screw and the hardness of the material to be machined and calculates the different parameters of the whirling operation. As mentioned earlier, the operating variables could be generally calculated, using the reference books but in this case there were a few new parameters. Although most of the variables used, could be successfully computed according to the operations hand-book, there were some variables where it was not possible to trace their origin in order to calculate them. Hence, in order to maintain the operational integrity of the machine, it was decided to formulate and calculate the values where possible and simulate the operations manual where no apparent explanation was found, especially when no direct interpretation was provided by the suppliers.

According to the operations manual, the set-up values are determined using a graphical method. In this method, a ruler is fixed between two known variable points on two scaled ladders and the unknown variable is read from the corresponding point on the third ladder. Also there are certain tables dictating some values conditional on other values.

Because of the copyright restrictions concerning the above material, it is not possible to describe it in detail. However, the devised method replacing it is described. There are several variables that have to be calculated. These are listed as follows:

Helix angle.

Tool point diameter.

Tool head speed.

Work piece speed.

The helix angle is calculated from the mean value of the helix angle at the root diameter and the screw diameter. This value is used to set the angle of the tool head with respect to the bar and is calculated from the following relationship:

$$\alpha = Arctan\left(\frac{P}{(D-RD)*0.5}\right)*\pi$$

In the above relationship α is the helix angle, D is the screw diameter and RD is the root diameter.

At this stage, following the operations manual and using its recommended table, the tool path diameter to work ratio is chosen. This is carried out by entering the table values in a two dimensional array and extracting the appropriate value by a few logical manipulations.

Having picked the ratio concerned, by multiplying it by the screw diameter the tool point diameter will be calculated.

Tool point dia. = screw dia.(tool point dia. / work-piece dia)

Whirler head speed is then calculated from the tool point diameter using the following relationship:

$$W_s = V * \frac{1000}{(\pi * TPD)}$$

In the above formula, V is the material cutting speed, TPD is the tool point diameter. At this stage the calculated value is compared with the existing tool -head speeds and the closest speed is chosen. At the next stage the work piece speed is calculated using the following relationship:

$$J_s = \frac{CT * N * W_s}{\pi * RD}$$

In the above relationship CT stands for chip thickness and N for the number of the roughing tools. The whirling time is also calculated using a simple formula. This is something similar to the following relationship:

$$W_t = \frac{L}{J_s * P}$$

where L is the overall screw length.

Having calculated these values they are written to a data file called "job number" with the "SET" extension which could be printed for reference. The operator then uses these values to set different parameters of the system. At this stage the "set-up values" processor is completed and the data is ready to be transferred to the next stage, the "G-CODE" Processor.

4-5-2 THE G-CODE PROCESSOR

Three major elements form the basis of the G-CODE processor which are as follows:

1 - Cutting tool analysis.

2 - Process analysis.

3 - Tool-path determination.

These three are described in the following sections.

4-5-2-1 TOOL ANALYSIS

There are a range of tools that could be used in this operation but because of the nature of the operation they tend to be fairly similar in shape. According to the suppliers cutting tools are best replaced but in some cases re-grinding of the tool is acceptable. In order to automate the process the general shape of the tool should be parametrised. The general shape of the tools used in this operation is presented in figure 4.16 and this is the basis of the tool analysis.

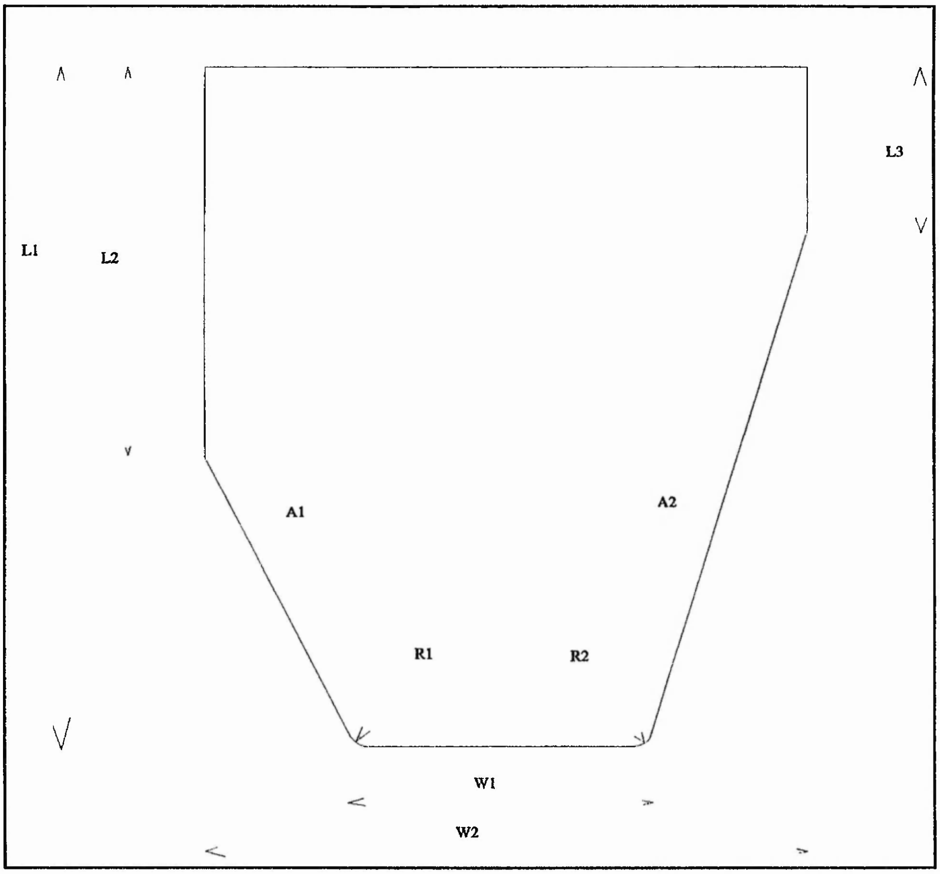


Figure 4.16
A typical cutting tool used in whirling.

As can be seen in figure 4.16, angles A1 and A2 can vary between zero and 90 degrees (square tools) the two radii R1 and R2 could also vary between negligible and a relatively large radius. W1 could vary between 0 and W2 giving a range between a fully curved tip and square tool. A1, A2 and A3 are variables where L1 cannot equal 0 and L2 and L3 could vary between 0 and L1. In this analysis L1 determines the maximum tool movement in the x direction before the tool holder and workpiece collision occurs, therefore the safe bid would be to consider a safety margin by reducing the L1 by the amount of that margin. Angles A1 and A2 are important when relative movement is taking place in the x direction. They determine the width of the cut in the z direction to each corresponding x movement value. This is particularly important when cutting three stage plasticating screws or variable pitch screws. The two radii on the tool tip will determine the curvature of the cut at each side. In practice tools available for this operation are usually a lot simpler than the one of figure 4.16. However, this information should be present before any other action is taken.

4-5-2-2 PROCESS ANALYSIS

It is obvious that more than one cut is required to finish the screw and they have to be planned carefully. The prime concern while developing the G-CODE processor has been to develop a tool for real manufacturing environments, therefore commercial considerations had an important role in the system initialisation. In real terms, this means that since each cut takes a certain time to complete and several cuts are required to complete each screw, it will take some considerable time to finish depending on the screw size and material. Since the required accuracy for the screw is not obtainable without a series of incremental cuts at each stage, it is not commercially viable to prolong the manufacturing process by concentrating on the finishing process while faster finishing methods are available. Besides, the actual cutting process is just the beginning of the screw manufacturing process and most screws undergo different treatments for hardening and chemical resistance.

At this stage, and after getting the tool data, the general procedure should be planned before the actual prediction of the tool paths. Each screw is formed by a number of cuts resulting in clearing the screw channel at the end of process. Figure 4.17 presents the succession of cuts within a pitch that completes a typical screw channel. In this particular screw it is apparent that 7 cuts are required to finish the screw channel but in principle, the number of

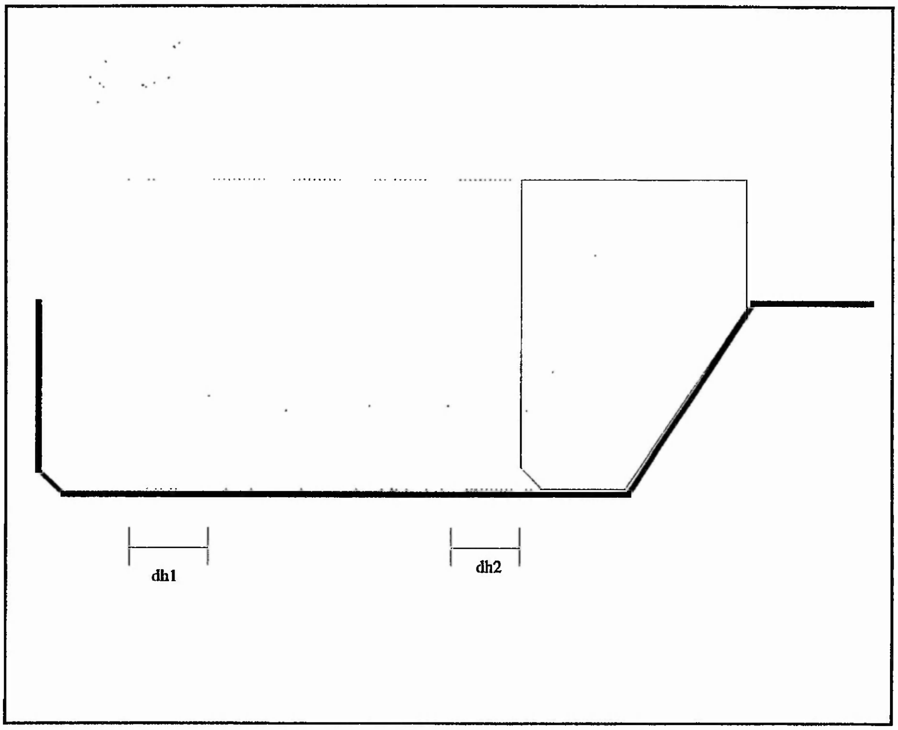


Figure 4.17
Cutter trace within the screw channel.

required cuts is a function of W2 (tool width) and W1 (width of the tip) as well as screw pitch and flight width. Since this operation is not a point tool cutting operation, figure 4.18 will reveal that if each cut starts where the previous cut finishes, unless the tool is square tipped, it leaves "cyclic uncut areas" that follow the tool profile and can cause a lot of problems.

Considering the direction of the x axis (figure 4.19), and accepting that the origin of the system is at the centre of the chuck, depending on the position of the tool tip and its relative position to zones A, B and C, the width of cut is defined by different formulae. If RB is the radius of the blank bar (in the chuck) and XT is the x coordinate of the tip of the tool and WC is the width of cut, then,

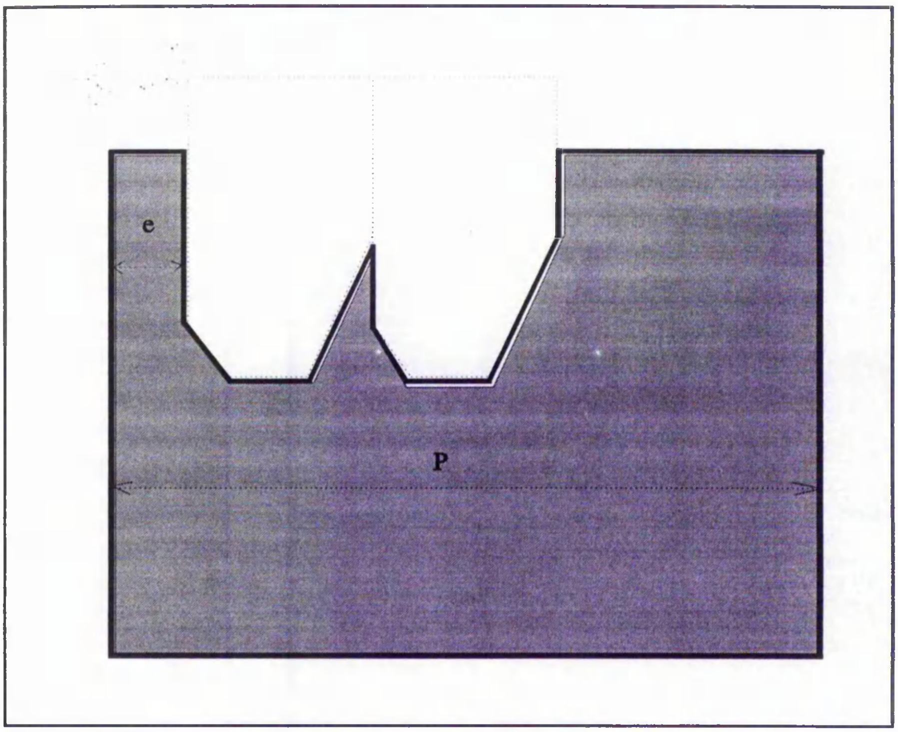


Figure 4.18
The uncut area between two successive cuts.

If (XT - RB) greater than zero, then WC = 0

and if (XT - RB) equal to zero, then WC = W1

and if (XT - RB) less than zero, then WC is calculated as:

$$\forall\ X \in A \quad WC = W1 + |(XT - RB)|\,(\sin(A1) + \sin(A2))$$

$$\forall\ X \in B \quad WC = W1 + (L1 - L2)\sin(A1) + |XT - RB|\,\sin(A2)$$

$$\forall\ X \in C \quad WC = W2$$

* symbol ($\in$) used above is called "in" and represents a subset or an interval.

* symbol ($\forall$) used above is called "for all" and represents all the values of the variable belonging to the described interval.

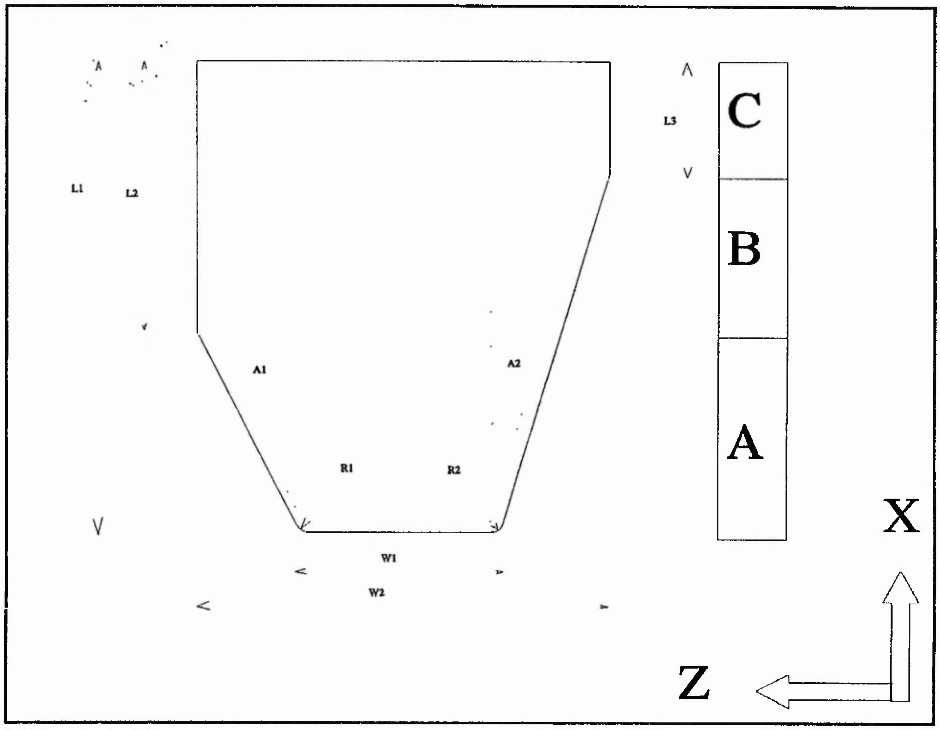


Figure 4.19
Machine coordinate system relative to the tool.

In the above relationships different zones correspond to different limits as follows:

zone A $RB \geq X > RB + (L1 - L2)$

zone B $RB + (L1 - L2) \geq X > RB + (L1 - L3)$

zone C $RB + (L1 - L3) \geq X > RB + L1$

All the variables used above are defined in figure 5.5. Because of commercial considerations the flight radii are formed by the actual tool itself and its profile instead of the tool passage hence the tool might have to be changed at the final cut where the radius at the leading flight is different from the one at the trailing flight.

The tool offset value is a function of the width of cut. Width of the cut itself is a function of its depth, due to the angle of the edge of the tool. The tool offset value is found by calculating the width of cut at the appropriate depth. Providing that the cut does not exceed the cutting area, the offset value will be " WC = W1 " whilst if it does, it should be reduced to prevent the over cut.

This procedure is carried out by programming simple logic statements and calculating different starting positions on the z axis relative to the required cutting offset. This method of offsetting is based on the fact that the CNC controller is applying 2.5D control in cutting screw threads. These axes are x, z and a marker which is used to detect a full pitch. The helical distance or its corresponding axial distance in the z direction will determine the starting angle (position) on a rotating cylinder or its relative position in the z direction. Other factors to consider are transient time before the velocity of the tool post reaches its intended value and engagement rate of tool to the workpiece.

5-2-2-3 TOOL PATH CALCULATIONS

The system is developed based on reading the screw geometry data and acquiring the tool data during an interactive session. Then in accordance with the machine capability, a tool path is predicted for each pass. Tool path creation is carried out within a loop which runs as many times as necessary to clear the screw channel.

The standard thread cutting command is similar to the following;

```
Nn G33 Xx Zz Kk
```

In the above format "n" is a program line number (positive) between 0 and 9999, "x" is the X coordinate of the destination point with format F4.3, and "z" is the Z coordinate of the destination point with format F4.3. K in this line represents the pitch value and is introduced to the machine by "k". It is useful to mention that F4.3 describes a real value (+ or -) with four figures before the decimal point and three digits after the decimal point.

Having calculated the value of each parameter, this is complemented by writing the predicted tool path data on a file named after the job number and with the "GCD" extension. The screw is parametrised based on figure 4.20 as follows.

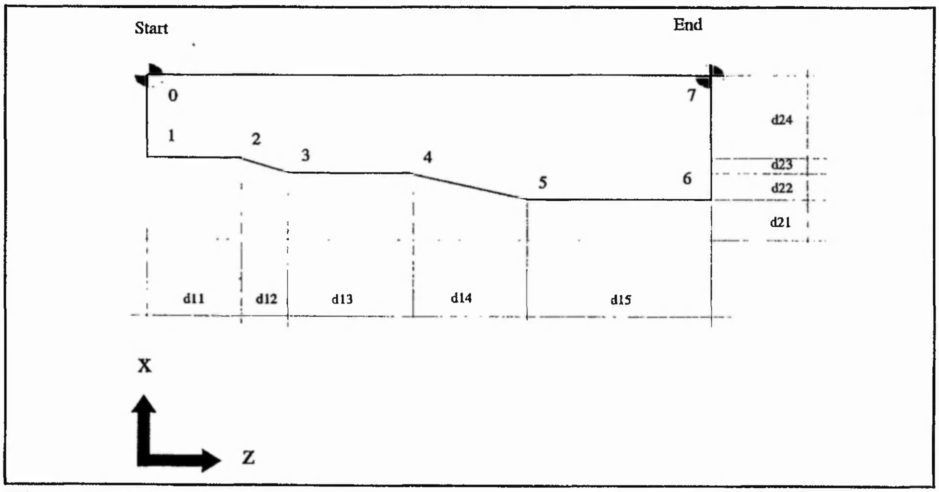


Figure 4.20
Parametrised cutter path.

Operation starts at the starting point (0) by setting up a few variables which are already calculated, such as spindle speed, rotational direction etc. This is followed by passing through the marked path in figure 4.20 for each cut. The centre-line shown in figure 4.20 is the centre line of the machine tool. Cutting starts at the metering section where the tool penetration is minimal and gradually increases with the cutting load. The first tapered section (2-3) reflects this gradual introduction of tool to the bar. Areas between points 2 and 4 form the metering zone. Areas defined between 4 and 5 and 5 and 6 correspond to the compression and feed zones respectively. By assigning different values to different "d" parameters a new path could be defined. Here variables between d10 and d20 are reserved for defining the z axis movement and variables d20 to d30 corresponds to different movements in the x direction. In the initialisation stage of the program the values acquired for different inputs are assigned to the right variable and start the process.

There are times when the compression angle or the rate of change in the x direction at the compression zone is too steep and there appears a sharp drop between each consecutive cut, as shown in figure 4.21.

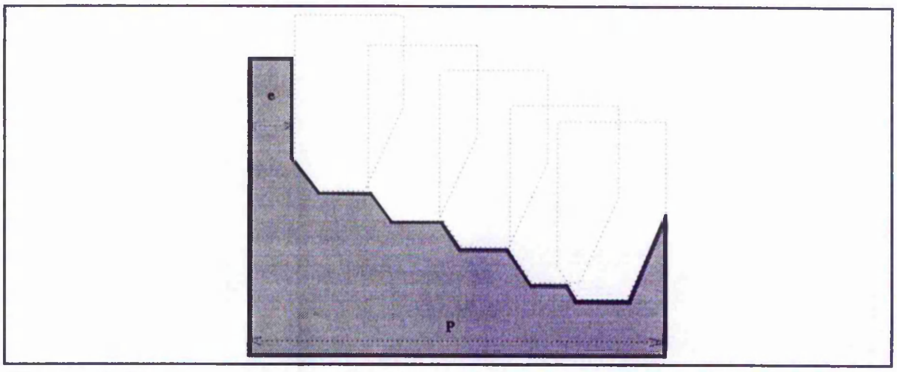


Figure 4.21
Cutter effect on a tapered section.

This will usually cause a change in the pitch value for there is generally an angle to the leading and trailing ends of the tool. To cure this problem, the compression section itself could be divided into smaller movements and reduce the pitch could be reduced in relation to the increase in width of cut.
Figure 4.22 represents the tool path for this screw. This technique could also be adopted when making variable pitch screws by virtually cutting over the previous cuts at the earlier pitches and gradually increasing the cutting width when approaching the later pitches.

Charts 4.1 parts 1,2 and 3 describe the main program, print subroutine and G-code calculator flow-charts, respectively.

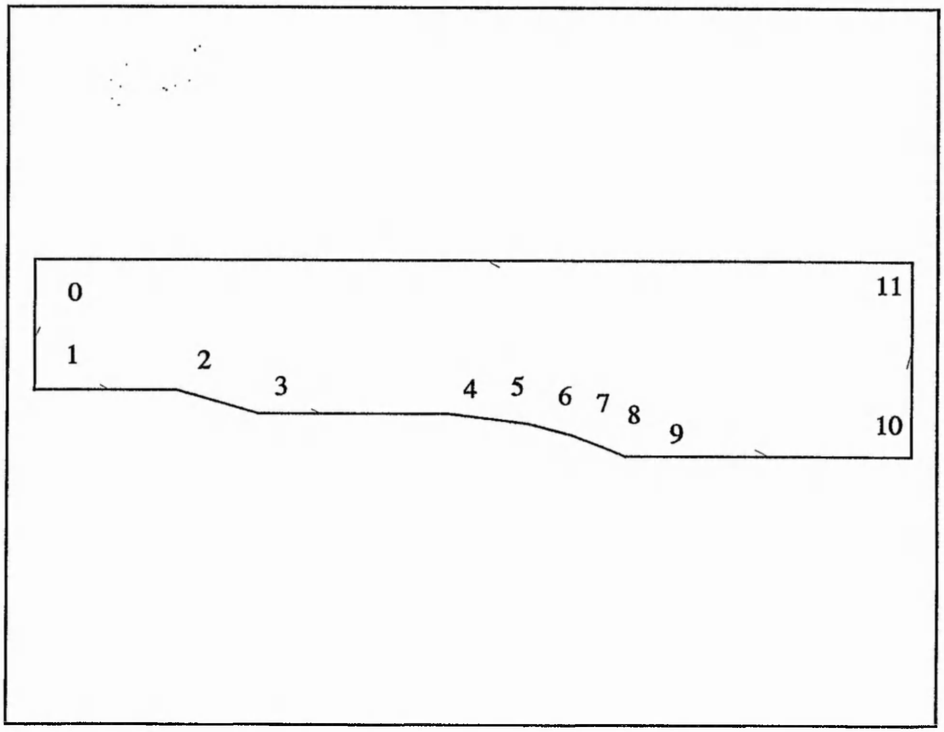


Figure 4.22
Revised cutter path for the tapered section.

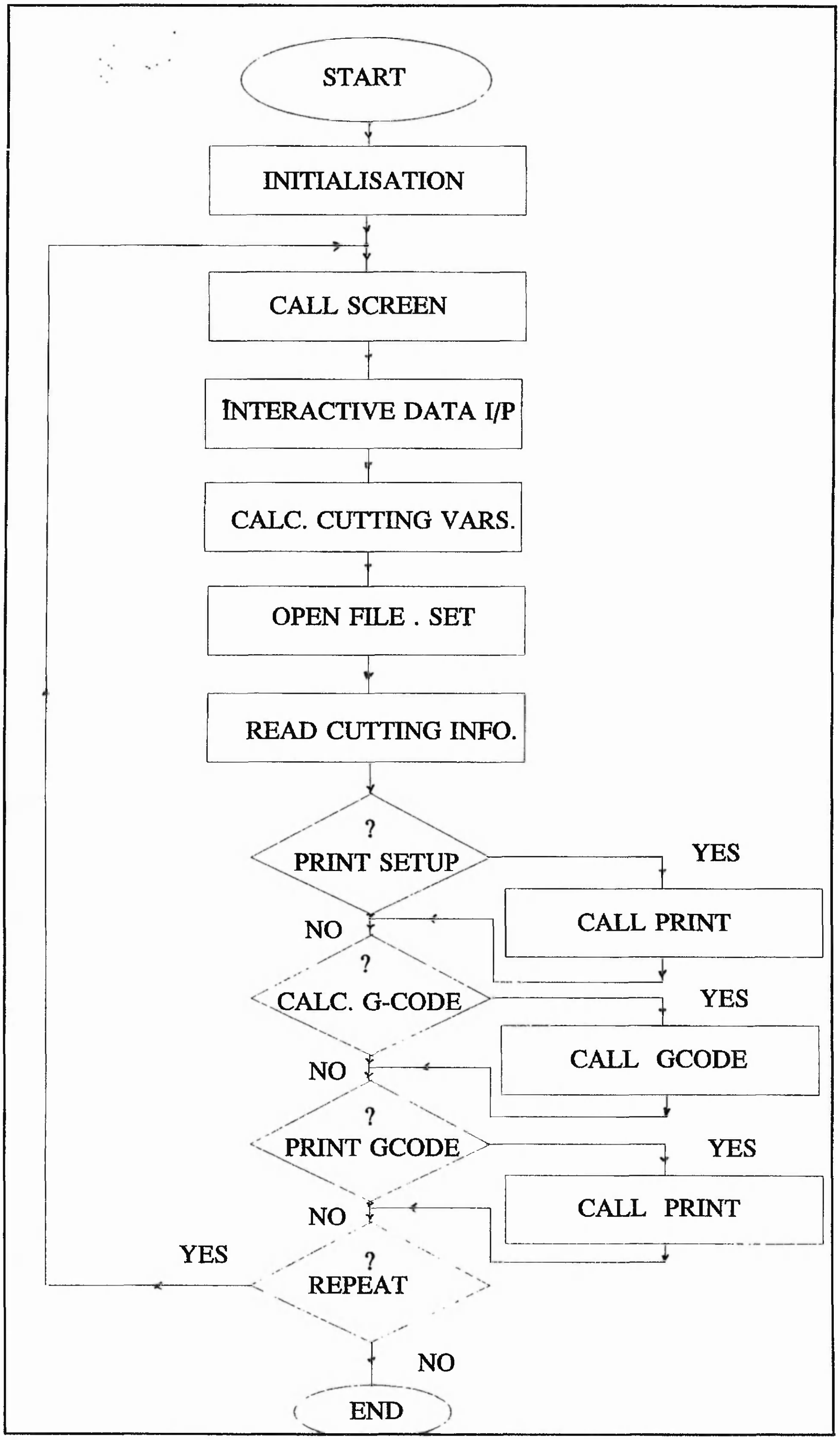


Chart 4.4 (part 1)
Main program flow-chart.

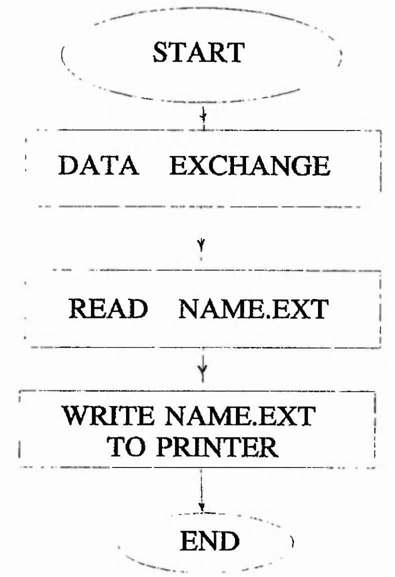


Chart 4.4 (part 2)
Print subroutine flow-chart.

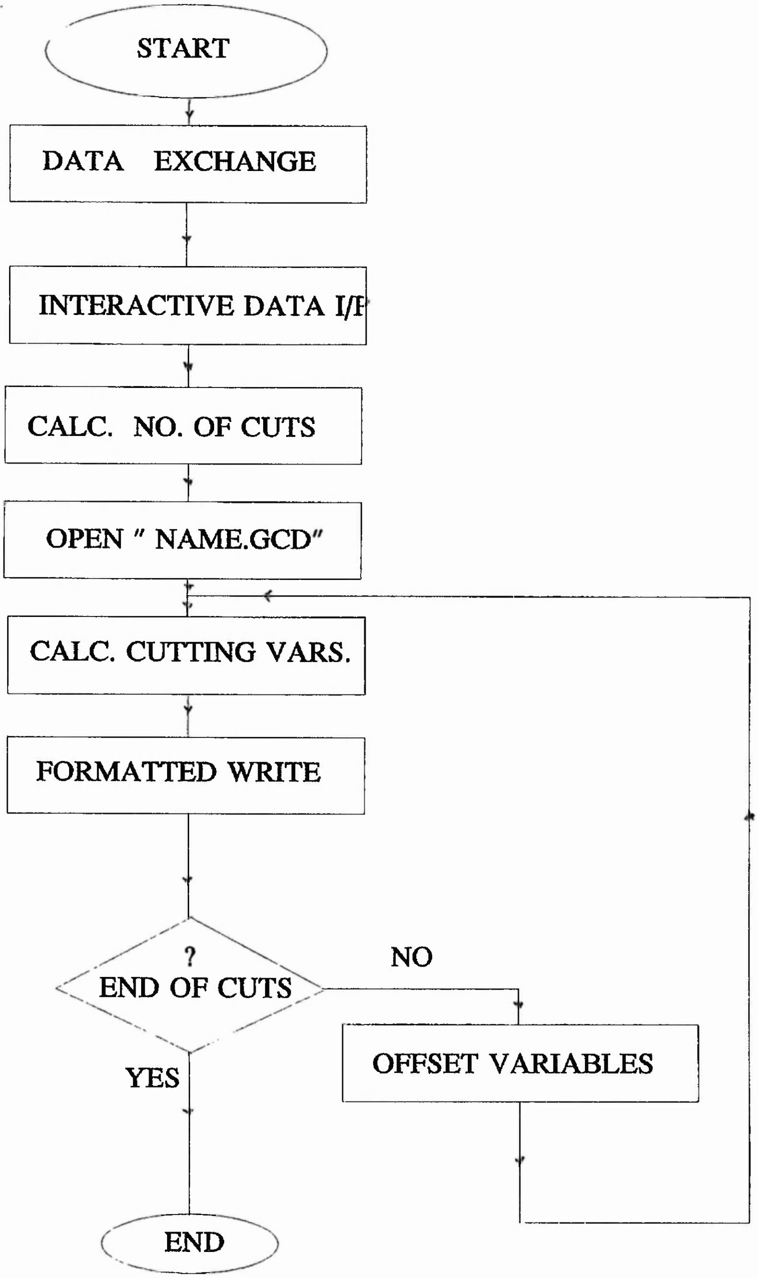


Chart 4.4 (part 3)
G-CODE subroutine flow-chart.

CHAPTER 5

TEST & EVALUATIONS

5-1 SYSTEM EVALUATION

At this stage of the work, the project as a whole should be assessed and the results should be analyzed. As in similar industrial research programmes, the findings should improve current techniques and demonstrate the merits (or otherwise) of the proposed methods.

During this chapter, the intention is not to repeat what has taken place and been achieved, unless in brief and except where necessary. This is because they have all been discussed in full during the previous chapters. Instead, an overall view of the whole problem and applicability of the proposed solution to the current problem is the major objective. Having outlined those factors, the system should be put to the test and its results should be examined.

The final system layout is similar to the one described in figure 5.1. As it could be seen from the system layout, there are several routes which could be followed to customize the system. These routes are basically the combination of system entry routes and outputs. As described previously, each user can define the system according to his special requirements and constraints by defining their preferred route. Obviously some of these combinations are less complicated than others and care should be exercised when defining the system for each environment. In figure 5.1 manufacturing equipment is illustrated as boxes, existing software systems as circle and developed software systems as ellipses.

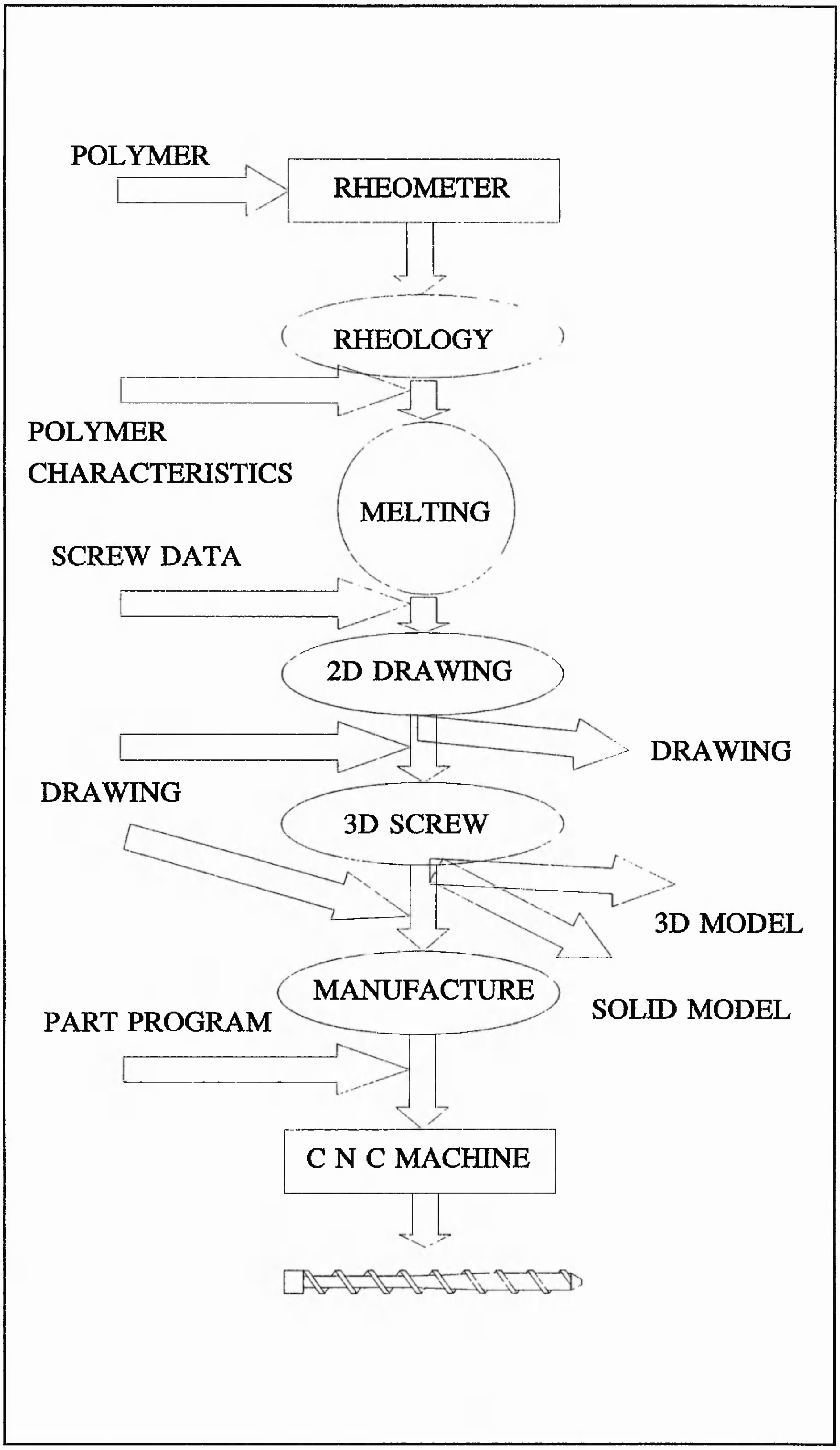


Figure 5.1
System layout.

To test the system, a demonstration was set on the 18th June 1991, at the premises of the collaborating company with the representatives of all supporting bodies present (Science and Engineering Research Council, Pitt Enterprises PLC.). An ordinary three stage screw was considered and scaled down to be designed and manufactured. The screw was scaled down because of the cost involved in terms of machine time, tooling and raw material. For the same reasons the material selected for the operation was mild steel instead of a nitriding steel. The screw was then designed and manufactured using the system.

The scaling process resulted in the omission of the optimisation process and its preceding operation namely the rheology test analysis unit. This in effect posed no threat to the credibility of the test. First of all, the optimisation software is an independent unit within the system and under constant development by our research partners at the University and it will be tested thoroughly in due course. The experimental results of the screws run in the test rig, their comparison with the program predictions and their usage in consultancy work to find the shortcomings in realistic situations have been more than adequate to test that particular unit. Secondly, the "Rheology" program has undergone the same test procedure and has been utilised by the project partners in research and indeed consultancy work and has passed the test.

With this in mind, the test process was planned with the following variables:

Screw Diameter : 50 mm.
Screw Pitch : 50 mm.
Flight Width : 8 mm.
Feed Length : 150 mm.
Compression Length : 200 mm.
Metering Length : 150 mm.
Feed Diameter : 30 mm.
Metering Diameter : 44 mm.

During the test process, the screw was cut in four passes of each less than 10 minutes duration. This is a remarkable achievement compared with the time it could take if the screw was cut manually. Figures 5.2, 5.3, 5.4, 5.5 and 5.6 illustrate the 2D drawing, 3D screw (print and photo), shaded model of screw and the manufactured screw respectively. Table T-5.2 presents the set-up values and information while T-5.3 is a print out of the G-CODES to cut the screw. Figure 5.7 represents a sample print-out of the "Rheology" program.

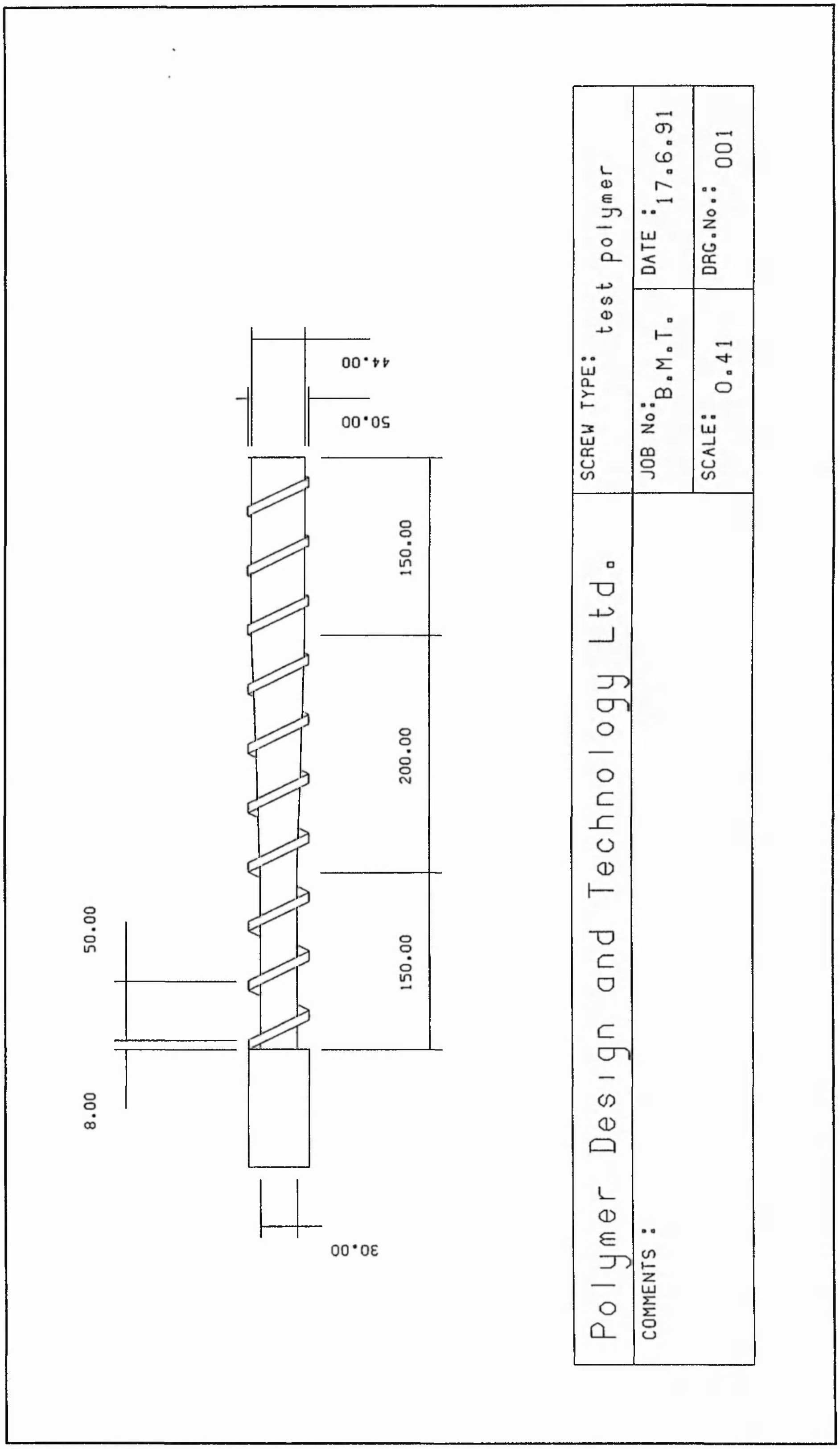


Figure 5.2
Automatic 2D screw drawing.

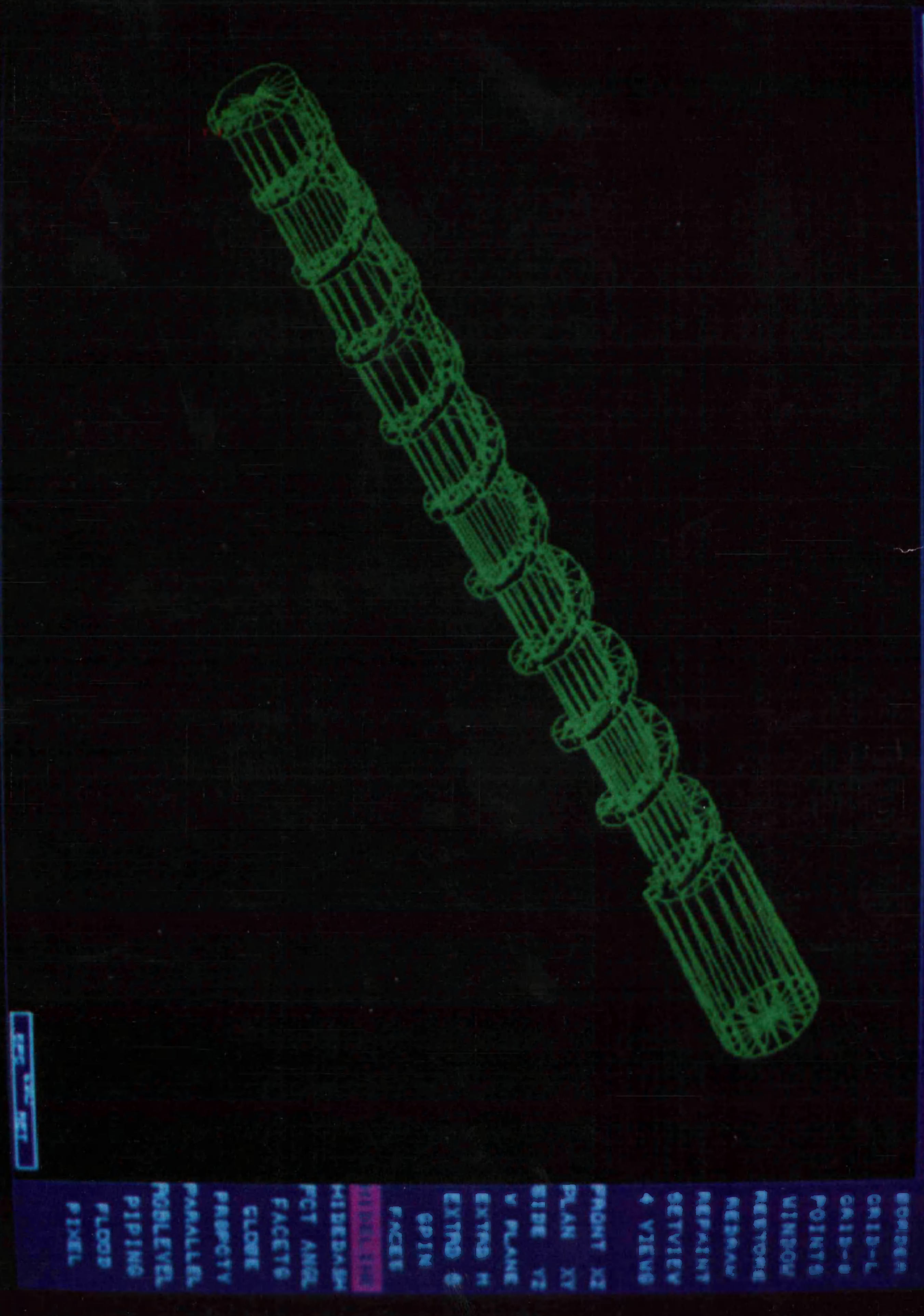


Figure 5.3
(screen phot

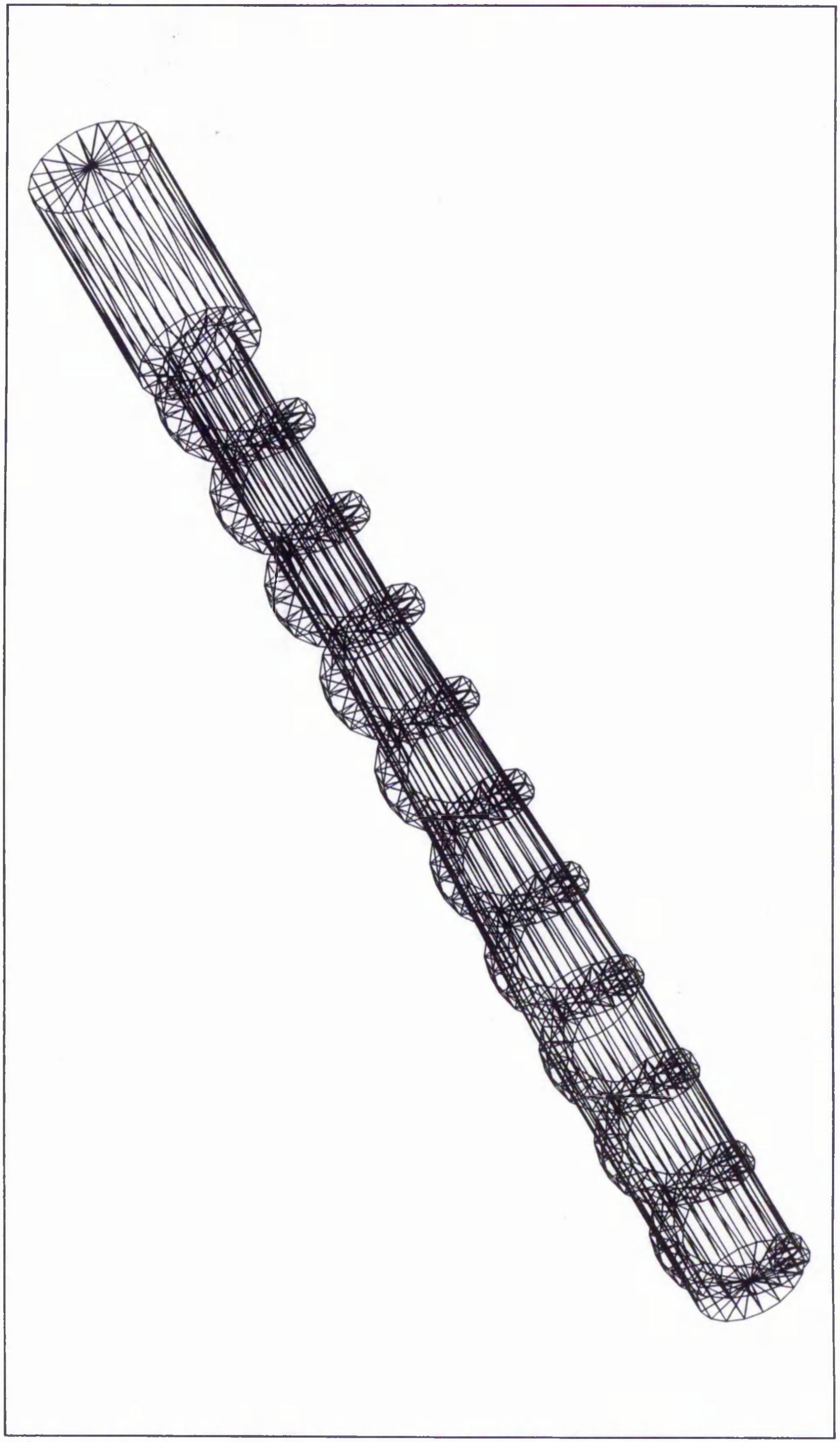


Figure 5.4
3D screw model.

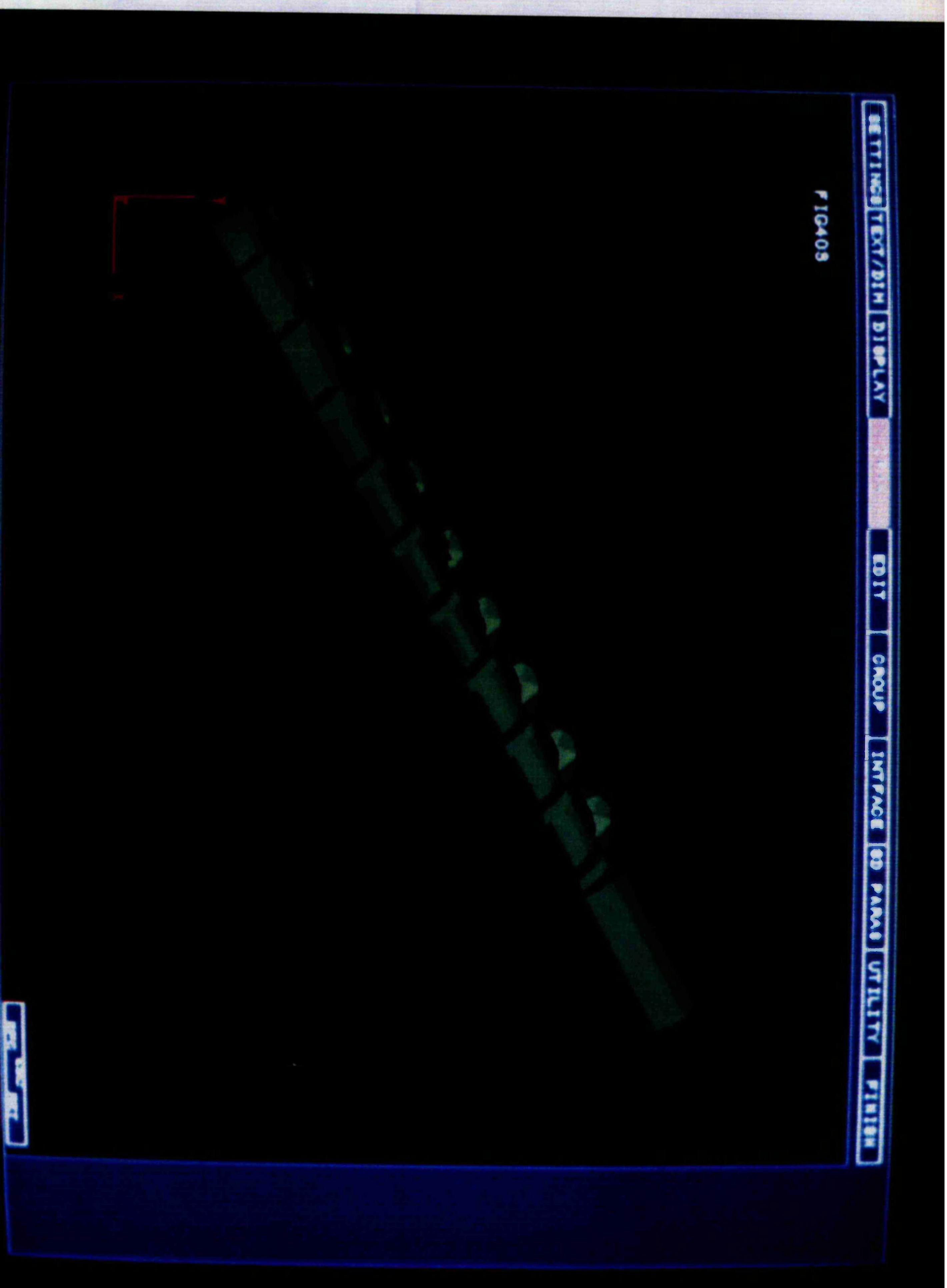
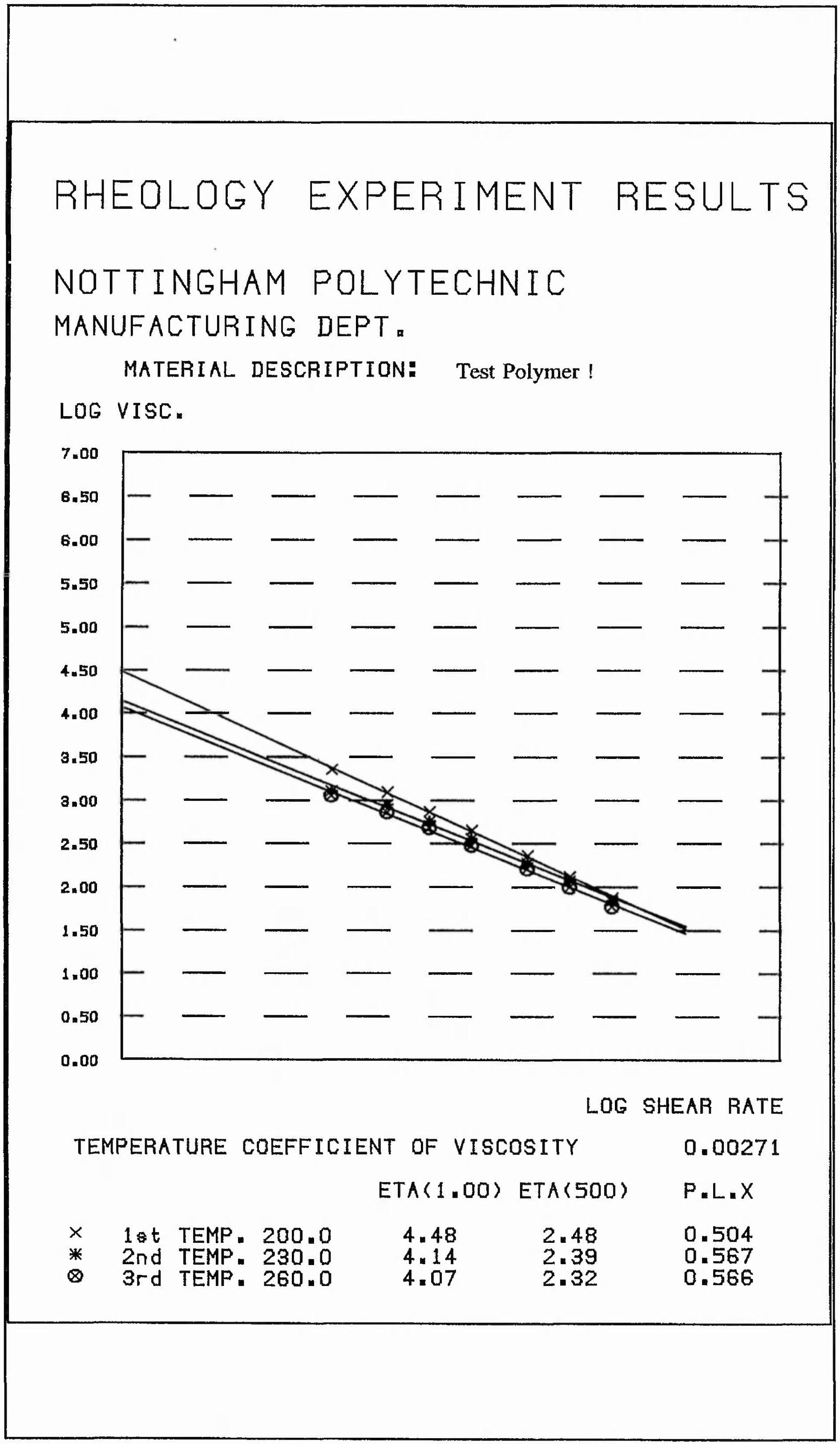


Figure 5.5
Shaded screw.

Figure 5.6
The actual screw.

```
                 POLYMER DESIGN AND TECHNOLOGY

         JOB NUMBER                               1000

         DATE                                     11 6 1992


*************************************************************


EXTERNAL DIAMETER (MM).                 =         50.00000
ROOT DIAMETER (MM).                     =         30.00000
PITCH (MM).                             =         40.00000
TOOL POINT CIRCLE DIAMETER (MM)         =         80.00000
T.P.C. DIA./ WORK RATIO                 =         1.60000
HELIX ANGLE (DEG.).                     =         21.69701
CHIP THICKNESS (MM).                    =          .15000
MATERIAL CUTTING SPEED (M/MIN).         =         97.33712
TOOL HEAD SPEED (RPM).                  =          310
WORKPIECE SPEED (RPM).                  =          1.97352
WHIRLING TIME PER PASS (MIN)            =          5.06708

             COMMENTS;
```

```
% 1000 RT
N   0 G71 RT
N   5 G97                            S    1.974 M 3 RT
N  10 G90 G00     X    93.000                       RT
N  15 G00                    Z   -44.000            RT
N  20 G91 G33 G05 X   -43.000 Z     4.000 K   50.000 RT
N  25             X   -20.000 Z    40.000 K   50.000 RT
N  30                         Z   162.000 K   50.000 RT
N  35             X      .000 Z   200.000 K   50.000 RT
N  40                         Z   138.000 K   50.000 RT
N  45 G90 G00     X    93.000                       RT
N  50                                        M 0 RT
N  55 G97                            S    1.974 M 3 RT
N  60 G90 G00     X    93.000                       RT
N  65 G00                    Z   -32.000            RT
N  70 G91 G33 G05 X   -43.000 Z    -8.000 K   50.000 RT
N  75             X   -20.000 Z    40.000 K   50.000 RT
N  80                         Z   162.000 K   50.000 RT
N  85             X      .000 Z   200.000 K   50.000 RT
N  90                         Z   138.000 K   50.000 RT
N  95 G90 G00     X    93.000                       RT
N 100                                        M 0 RT
N 105 G97                            S    1.974 M 3 RT
N 110 G90 G00     X    93.000                       RT
N 115 G00                    Z   -20.000            RT
N 120 G91 G33 G05 X   -43.000 Z   -20.000 K   50.000 RT
N 125             X   -20.000 Z    40.000 K   50.000 RT
N 130                         Z   162.000 K   50.000 RT
N 135             X      .000 Z   200.000 K   50.000 RT
N 140                         Z   138.000 K   50.000 RT
N 145 G90 G00     X    93.000                       RT
N 150                                        M 0 RT
N 155 G97                            S    1.974 M 3 RT
N 160 G90 G00     X    93.000                       RT
N 165 G00                    Z   -14.000            RT
N 170 G91 G33 G05 X   -43.000 Z   -26.000 K   50.000 RT
N 175             X   -20.000 Z    40.000 K   50.000 RT
N 180                         Z   162.000 K   50.000 RT
N 185             X      .000 Z   200.000 K   50.000 RT
N 190                         Z   138.000 K   50.000 RT
N 195 G90 G00     X    93.000                       RT
N 200                                        M 0 RT
%
```



RHEOLOGY EXPERIMENT RESULTS

NOTTINGHAM POLYTECHNIC
MANUFACTURING DEPT.

MATERIAL DESCRIPTION: Test Polymer !

```
TEMPERATURE COEFFICIENT OF VISCOSITY           0.00271

                            ETA(1.00) ETA(500)   P.L.X

×    1st TEMP. 200.0          4.48      2.48     0.504
✳    2nd TEMP. 230.0          4.14      2.39     0.567
⊗    3rd TEMP. 260.0          4.07      2.32     0.566
```

Figure 5.7
Sample Print out of the rheology results.

At this stage it could be claimed that with such a set up, a new tool has been developed which is capable of reducing the screw design and manufacture time. This tool could also be used by material manufacturers to advise their customers of the screw requirements for any new material.

To evaluate this tool, its performance should be compared with the best alternative available. At the same time, quantifying the improvement and efficiency is somehow difficult because the efficiency measure is a function of the system specification. However, considering just the manufacturing unit, the comparison could be made relatively easily. This comparison is made with the best available solution currently in use which is a system with a CAD support (CAD Assisted Part Programming). The two systems are compared and the result of comparison is presented in table T-5.1. The reason for not including design unit (including optimisation) is that there is at least another flow simulation program which is capable of producing results. A full comparison would require qualitative as well as quantitative measurement of results which is of course not the objective of our project. However, The indirect benefits and the measurement of the specific system benefits and its evaluation is left to the potential user to assess.

OPERATION	CAPP* system	Proposed system
Calculation of set-up parameters	10 - 20 mins.	< 1 min.
Calculation of the G-Codes	2 - 8 hrs.	< 1 min.
Data entry	30 - 60 mins.	< 1 min.
Hard copy creation	2 - 4 hrs.	< 1 min.

* CAD Assisted Part Programming

As can be seen, the efficiency measure in the new proposed system is much higher than in the old one. Completion of this system has provided an opportunity for screw manufacturers to design and manufacture single extruder screws according to their customer's requirements. These requirements could range from material characteristics to simply manufacturing a screw to a designed order. At the same time, it could enable the material manufacturers to identify or recommend the best design of screw for their new materials and supply their customers with a screw design on a floppy disc, ready for manufacture by suitably equipped vendor.

CHAPTER 6

CONCLUSIONS

6-1 CONCLUSIONS

The major stated aim of the work described in this thesis was to create and develop a system by which extruder screws can be made in a more efficient and cost effective manner. The screw optimisation program developed in a separate but related research programme has been used as an initial starting point to generate design parameters for plasticating extruder screws. To be able to use the data generated by the optimisation program it was necessary to create and develop a mathematical model of the extruder screw containing all the information regarding various surfaces of the extruder screw. This information was subsequently used by a parametric CAD package for the generation of 2-D parametric and a 3-D wire mesh drawings of the screw as well as generating the set-up data and G-Codes for the CNC machine control computer. Generation of the 2-D drawing, although not a critical part of the system, was included simply because it was requested by potential users of the system; it is difficult to change the habits of an industry which is used to having hard copies of their screw designs. The 3-D wire mesh diagrams and shaded models are useful additions for the designer since they give a feeling for the final product before any metal is cut.

With the information within the control computer it is a simple step to the manufacture of the screw. The set-up program defines the chip size, rotation speeds of the workpiece and the cutters of the Whirling machine used in the current study whereas the G-Code program along with the information regarding the tool in use provides all the information necessary to generate the tool path for each pass through the steel bar. Tool path generation takes place in a loop which runs as many times as is necessary to create the required helical channel. The great advantage of this system is that the programs have been written so that they can be applied to any CNC cutting machine with any control computer without the need for post processing of the code; it simply uses the standard ISO format codes to generate the control program. These ISO codes are common to all CNC controllers.

The proof of any pudding is in its eating and the proving test of this system took place on 18th June 1991 at the premises of Pitt Enterprises plc, the collaborating company, in the presence of a representative of the PEG (Polymer Engineering Group) who was appointed to oversee the project on behalf of the SERC (Science and Engineering Research Council). A steel bar was centred in the whirling machine and the design parameters of external diameter, screw pitch, flight width, the lengths of the feed, compression and metering sections and the root diameters of the feed and metering sections were all fed into the control computer and the cutting operation commenced. The screw was cut in four passes, each pass comprising of three cuts to form the full channel width, each pass taking no more than 10 minutes. This means that a complex helical screw with a tapering mid section -admittedly a scaled down version of the real thing - was produced from stock bar in less than 40 minutes. Compare this with the 2 - 3 days using part programming of a CNC machine, remembering that this exercise would not have even be attempted using a conventional manual cutting machine; manual cutting machines cannot be used economically to cut one-off pieces of this complexity.

The system has been exhibited at major international trade exhibitions - K '89 in Dusseldorf, November 1989 and Interplas '91 at the Birmingham NEC, November 1991 - and much interest was shown by many companies with interests ranging from raw material manufacturers to end users of plastic components. Parts of the system have been used successfully to produce commercial extruder screws. In the early days of screw design a common response was "that's fine, but how do you suggest we make it at a reasonable cost?". The use of this new system effectively removes this query.

6-2 Future Trends

At this stage it is possible to envisage future developments of the project. Firstly acquisition of polymer data could be improved. This could be achieved by integrating an automated rheometer into the system. This would eliminate operator error and speed up the operation. The results obtained could be transmitted via a serial communication port to the optimisation program. The optimisation program itself is currently being developed independently but thought might be given to the possibility of including parallel processing, object orientated and expert system concepts in the field of polymer processing. This would provide a faster, more reliable approach to optimisation with the incorporation of specialised expertise into an expert system removing the need for a specialist operator. An obvious need is the development of the program to enable the design of two stage vented screws.

Improvements in the manufacturing component of the system would arise from improvements in the optimisation process by devising sub-systems capable of cutting multistart and vented screws. This could be achieved by redefining the screw geometry model and incorporating it into the system.

The whole package is at present being developed to run on recently introduced parametric CAD packages which are faster and contain significantly more powerful features in addition to the fact that they are already widely used in industry.

APPENDIX A

CNC CONTROL CODES FOR TURNING OPERATION

A-1 PREPARATORY CODES

G00	Rapid traverse
G01	Linear interpolation
G02	Circular interpolation (CW)
G03	Circular interpolation (CCW)
G04	Dwell
G05	Round corner
G07	Square corner
G08	Arc tangent to previous path
G09	Arc programmed by two points(3 point arc definition)
G14	Activate C axis (in Degrees)
G15	Machining of the cylindrical surface of the part
G16	Machinning of the face of the part
G20	Call for standard subroutine
G21	Call for parametric subroutine
G22	Definition of standard subroutine
G23	Definition of parametric subroutine
G24	End of subroutine
G25	Unconditional jump
G26	Conditional jump/ call if equal zero
G27	Conditional jump/ call if it differs from zero
G28	Conditional jump/ call if it is smaller
G29	Conditional jump/ call if it is equal or greater
G30	Display error code defined by K
G31	Store present program's datum point

G32	Retrieve datum point stored by G31
G33	Thread cutting
G36	Controlled corner rounding
G37	Tangential approach
G38	Tangential exit
G39	Chamfering
G40	Cancellation of radius compensation
G41	Left hand radius compensation
G42	Right hand radius compensation
G50	Loading of tool offsets by program
G51	Modification of offsets of engaged tools
G53-G59	Zero offsets
G66	Pattern repeating
G68	Stock removal(X)
G69	Stock removal(Y)
G70	Imperical data input
G71	Metric data input
G72	Scaling
G74	Automatic search for machine reference
G75	Probing
G76	Automatic block generation
G81	Canned turning cycle with straight sections
G82	Canned facing cycle with straight sections
G83	Deep hole drilling
G84	Turning with arcs
G85	Facing with arcs

G86	Longitudinal thread cutting cycle
G87	Face threadcutting cycle
G88	Grooving cycle (X)
G89	Grooving cycle (Z)
G90	Absolute programming
G91	Incremental programming
G92	Presentation of coordinates and setting of max. S value
G93	Preselection of polar origin
G94	Feedrate F in In/min or mm/min
G95	Feedrate F in In/Rev or mm/Rev
G96	Constant surface speed
G97	Direct RPM programming

A-2 MISCELLANEOUS FUNCTIONS

M00	Programme stop
M01	Optional stop
M02	End of programme
M03	Spindle on forward
M04	Spindle on reverse
M05	Spindle stop
M08	Coolant on
M09	Coolant off
M80	Constant surface speed inhibit
M81	Constant surface inhibit off

APPENDIX B

UTILISATION GUIDE

B-1 INTRODUCTION

The diversity of this project and at the same time the interdependency of its elements was the prime factor in breaking it into smaller, more manageable parts. This has lead to different program development phases. Since the project was defined with a view to enable system customisation by end users, it was not possible to closely integrate the system. This meant that along with the loose integration of the different components of the system, an independent running structure was to be developed with each element. Therefore it was important to define and describe the system's different user interfaces for the maximum utilisation.

As described before, there are seven major elements to this system. Out of the seven, two of the programs were already available at the start of the project. The other five were however, produced to complete the system. In utilisation order, the seven programs constructing the system are:

Rheology program.
Rheology results manipulation (regression).
Optimisation program.
Solid modeller.
2D drawing program.
Manufacturing program.
3D screw design.

From the above list, The 3D screw design program would not be useful to the industrial users and hence is not available as a part of the system and has come at the end of the utilisation order and is only described here to assist any future research.

Despite the fact that the first two programs were developed by other researchers before the start of this project, yet, with their authors' permission, (Dr. P.Prentice and Mr. S.R.Wood), their programs operating guide is described out of necessity. The full description of the above programs and their operating guide are described later. At this stage it is useful to mention that due to the development rate in computer software, and the likelihood of system upgrades, the system commands used here are valid at the time of compilation and may not be relevant later. Consulting up to date system documentation is therefore recommended.

B-2 RHEOLOGY PROGRAM

As described before, this program was developed in Fortran using the equations described by N.Cogswell. This program is used to provide the rheological data for the optimisation program. In this program, the user will input the rheology test results as described in chapter two in the program. The results of the rheology test are in the form of a graph plotted on the testing machine, representing the measurement of the force vs the piston speeds. This program is called " Rheology" and is run by issuing the relevant commands at the root directory.

```
MODE BW80<return>    CD\<return>    RHEOLOGY<return>
```

The data is collected during an interactive question/ answer session. The questions start from the die dimensions to test code/name and temperature and progresses to the measured force for each piston speed. After accepting the data, the system then calculates shear stress, apparent shear rate, apparent viscosity and power law index for each piston speed and prints them in a table. The next screen presents the following graphs:

log shear stress vs log shear rate
log viscosity vs log shear rate
log viscosity vs log shear stress

The system then saves the information above in a sequential file and prints the program results upon the user's request.

B-3 REGRESSION PROGRAM

This is a program which uses the values calculated at the previous stage to draw the rheological flow curves log viscosity vs. log shear rate from the seven points calculated at the previous stage, at three different temperatures. It also calculates the three power law indices and the temperature coefficient of viscosity. This program is developed within the existing CAD system and is called VISC. The program is executed by running the CAD system.

The following commands activate the CAD shell and prepare the system for running the program. The command lines for activating the shell are:

```
CD\<return>
MODE MONO<return>
CD MCAD<return>
MCAD<return>
```

Having enabled the CAD program, the standard MCAD menu is displayed on the command monitor, with the cursor capable of moving between command and display monitors, using the mouse or the arrow keys.

The highlighted options are as follows:

```
SETTING    NEW DRWG   EDIT DRWG   FILING   HELP   FINISH
```

Using the mouse or arrow keys, the cursor is moved on the NEW DRWG icon and the space bar is depressed to select this option. Having selected to create a new drawing, the system will prompt for the name of the drawing. After entering the drawing name, the system will prompt for a comment message. This is a data field which could be interrogated by the user at any time to identify the contents of the respective drawing file, however, it could be left as blank. Having completed the message and upon depression of the return key, the system will then set the drawing parameters and displays the display menu on the display monitor. It also exhibits the drawing name at the top left side of the display monitor. To call the program there is two alternatives. First option is to use the screen menu where the MCAD reference manual should be consulted for detailed instructions, next, is a short cut using the key board. The program is run via the second option by pressing S on the keyboard to call a scalable detail (default 1:1). The system will then responds by prompting for a file name to be executed. Having entered the program name, VISC the system starts an interactive session for the data collection. The sequence is as following:

```
S        VISC<return>
```

Completing this session will result in appearing an standard A4 size drawing on the display screen. This drawing could then be printed at the user's discretion. This will herald the end of this stage and using the short cut and by typing F for finish and Y for yes to confirm the action, the drawing would be saved under the name identified before and the system returns to the standard MCAD menu. Repeating the latter keyboard input sequence, will log the user out of the CAD shell.

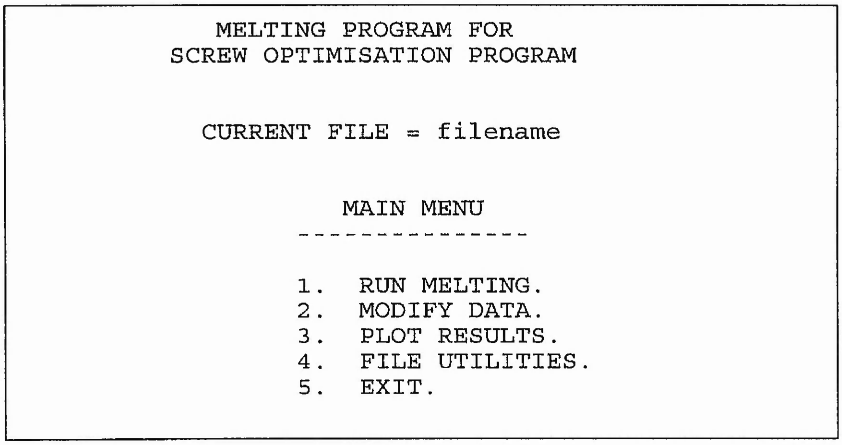
```
F    Y    F    Y
```

B-4 OPTIMISATION PROGRAM

This program as described before will utilise the results of the previous program to predict the flow properties of the polymer melt. the program is called MELTING and is been manipulated by a file handling system executable by the following sequence:

```
C:\<return>
MODE BW80<return>
RUN<return>
```

Following the above chain of command inputs, a display similar to figure B.1 will be displayed on the screen.

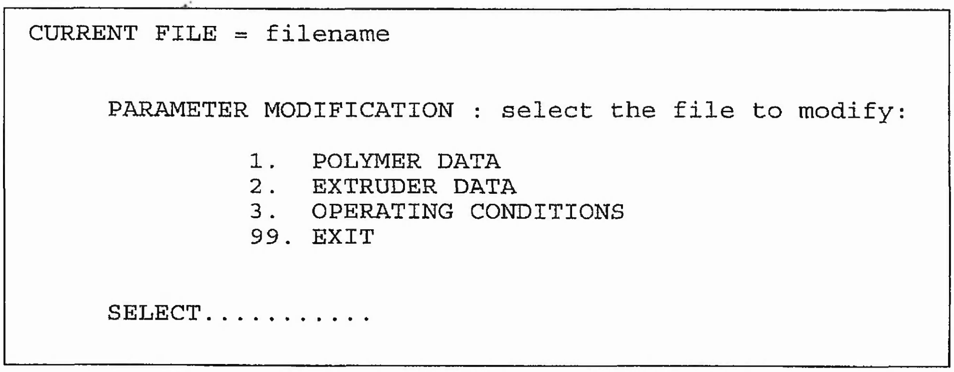


```
               MELTING PROGRAM FOR
           SCREW OPTIMISATION PROGRAM


             CURRENT FILE = filename


                      MAIN MENU
                   ---------------

                   1.  RUN MELTING.
                   2.  MODIFY DATA.
                   3.  PLOT RESULTS.
                   4.  FILE UTILITIES.
                   5.  EXIT.
```

Figure B.1

Obviously, inputting each number calls its respective function. Option 1 will cause the system to run the program with the current data files. Three data files are required for running the program. These three files determine the polymer data, extruder data and operating conditions for any specific simulated run and are filed under the same file name with different file extensions. The current file specifies the existing set of files in the memory and is displayed on the main menu.

The second option will provide the opportunity to edit any of the data files. Choosing this option will result in showing a menu similar to the figure B.2.



```
CURRENT FILE = filename


     PARAMETER MODIFICATION : select the file to modify:

              1.  POLYMER DATA
              2.  EXTRUDER DATA
              3.  OPERATING CONDITIONS
              99. EXIT


     SELECT..........
```

Figure B.2

Any of the data files could be edited by entering the appropriate option. Choosing options one to three will respectively display the following menus.

POLYMER DATA

```
  1. DESCRIPTION ....  filename
=================================================================
  2. DENSITY OF SOLID.............................(Kg/m3)  0.0
  3. DENSITY OF MELT .............................(Kg/m3)  0.0
  4. SPECIFIC HEAT CAPACITY OF SOLID.............(J/Kg oC)  0.0
  5. SPECIFIC HEAT CAPACITY OF MELT..............(J.Kg oC)  0.0
  6. LATENT HEAT OF FUSION..........................(J/Kg)  0.0
  7. MELTING TEMPERATURE..............................(oC)  0.0
  8. VISCOSITY POWER LAW INDEX..........................  0.0
  9. VISCOSITY AT UNIT SHEAR RATE..................(Ns/m2)  0.0
 10. DATUM TEMPERATURE OF VISCOSITY...................(oC)  0.0
 11. VISCOSITY TEMPERATURE COEFFICIENT..................  0.0
 12. THERMAL CONDUCTIVITY OF SOLID................(W/m oC)  0.0
 13. THERMAL CONDUCTIVITY OF MELT.................(W/m oC)  0.0
```

EXTRUDER DATA

```
  1. DESCRIPTION ....  filename
=============================================================
  2. INTERNAL BARREL DIAMETER..........................(m)  0.0
  3. LENGTH OF FEED ZONE...............................(m)  0.0
  4. LENGTH OF COMPRESSION ZONE........................(m)  0.0
  5. LENGTH OF METERING ZONE...........................(m)  0.0
  6. DEPTH OF FEED ZONE................................(m)  0.0
  7. DEPTH OF METERING ZONE............................(m)  0.0
  8. RADIAL FLIGHT CLEARANCE...........................(m)  0.0
  9. SCREW FLIGHT WIDTH................................(m)  0.0
 10. SCREW PITCH.......................................(m)  0.0
 11. NUMBER OF STARTS...................................    1.0
 12. NUMBER OF BARREL HEATER ZONES.......................  10.0
 13. BARREL HEATER ZONES   :
```

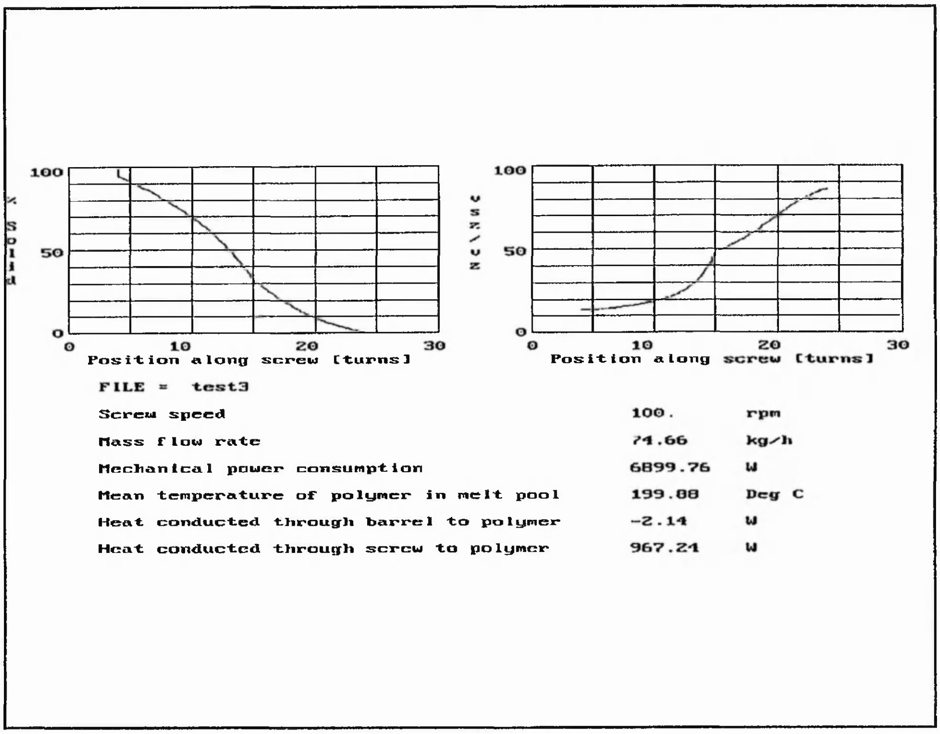
OPERATING CONDITIONS

```
  1. DESCRIPTION ....  filename
===========================================================
  2. SPEED OF SCREW..................................(rpm)  0.0
  3. INITIAL TEMPERATURE OF SOLID.....................(oC)  0.0
  4. SCREW TEMP. WHERE SCREW MELT FORMS...............(oC)  0.0
  5. BARREL MELT FILM START (helical dia)..............(m)  0.0
  6. SCREW MELT FILM START (helical dia)...............(m)  0.0
  7. BARREL TEMPERATURE ZONE OPTION............(1=Y, 0=N)   1.0

  9. BARREL HEATER ZONES   :
```

The 13th option of the extruder data table will display a table with each individual zone's number and distance from the centre of the feed hopper.

```
         Distance from the centre of the feed hopper to
            the centre of the barrel heater zone


               ZONE NUMBER      |      DISTANCE (m)
            =======================================
                     1          |           0.0
                     2          |           0.0
                     3          |           0.0
                     4          |           0.0
                     5          |           0.0


          99. RETURN TO MAIN MENU:

              SELECT BY NUMBER       :
```

The third option of the main menu (figure B.1) will display the results on the screen and a typical result is demonstrated in figure B.3.

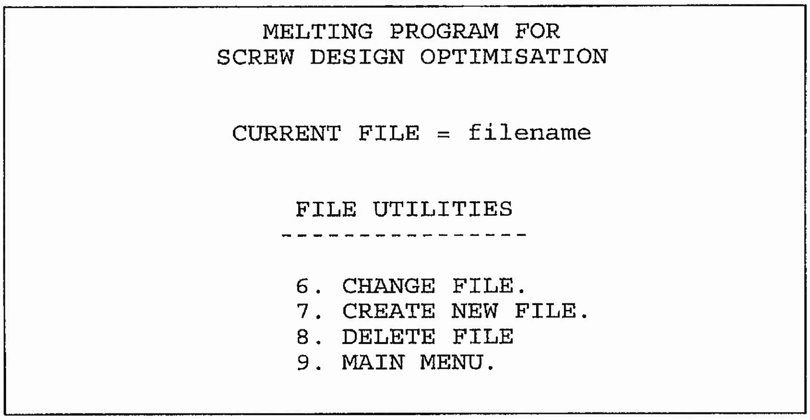


```
FILE =  test3
Screw speed                                        100.      rpm
Mass flow rate                                     74.66     kg/h
Mechanical power consumption                       6899.76   W
Mean temperature of polymer in melt pool           199.88    Deg C
Heat conducted through barrel to polymer           -2.14     W
Heat conducted through screw to polymer            967.24    W
```

Figure B.3
Optimisation program results.

"File utilities" or the fourth option of the main menu, will provide the user with the facility to create new files from scratch or mixing the existing data files. The screen in that case looks like figure B.4.

For a new material the file utilities should be called by entering 4 from the keyboard at the main menu. By calling the file utilities, another menu will be displayed on the screen which is the extension of the main menu.



```
                MELTING PROGRAM FOR
             SCREW DESIGN OPTIMISATION


              CURRENT FILE = filename


                  FILE UTILITIES
                 ----------------

                  6. CHANGE FILE.
                  7. CREATE NEW FILE.
                  8. DELETE FILE
                  9. MAIN MENU.
```

Figure B.4

B-5 DRAFTING PROGRAM

This part of the system as discussed before is developed to create automatic drawings. The program is developed within the CAD shell and to run the program first the CAD shell should be executed. This is done similar to the steps covered previously within this section (B.2). The succession of command lines are as follows:

```
MODE MONO<return>
C:<return>
CD MCAD<return>
MCAD<return>
NEW DRWG<space>
{filename}<return>
{comment}<return>
```

At this stage, after creating a file called {filename} and commenting on its contents for reference, and in order to generate the drawing the following steps should be taken to draw the screw. First the parametric program concerned should be called from the memory and executed. This is done again similar to the previous section (B-2) by the single key punch approach by entering "S" (scalable drawing) and the program name "DRAWING".

```
S
DRAWING<return>
```

Having entered the above, the system starts an interactive session and asks for a data file name and a series of questions regarding the geometry of the screw. Having generated the screw, it is then printed at the users discretion or saved as a file. A sequence of F,Y,F,Y will get the user out of the drawing and the CAD shell.

B-6 SHADED MODEL

This module is constructed within the CAD environment as well and will utilise the parametric facilities of the system to build the 3D structure of the screw. It would then use the system functions to remove the hidden lines and shade the image at the same time. The executing sequence is similar to the drafting module in principal. First of all the CAD shell is run as described previously and a file name is chosen for the operations. Then the parametric detail is called and the interactive data input session is followed. The name of the parametric detail in this case is "SOLID". After the system completes the 3D screw, it will display it in the default system view which is the plan view. This view is best to be changed to give a better presentation of the screw. In order to change the view to the required angle, the option "DISPLAY" is chosen from the menu options at the right hand side of the display monitor. This is done by clicking the mouse or pressing the space bar when the option is highlighted. Choosing this option will display another menu on the display monitor and a massage on the command monitor reading:

Give viewpoint or [I]sometric.

The user should either press I for an isometric view, or alternatively choose the option "GLOBE" and indicate the required view identified by spotting a point on a globe using the mouse.

Having viewed the screw at the desired angle it has to be shaded. This is done by using the flood option of the main menu displayed at the right hand side of the display monitor.

In CAD operations, usually the line removing and shading routines are very computer intensive and take a long time. In this system in order to notify the user of the system state, a rectangle is displayed at the bottom of the display monitor reminding the user that calculations are taking place. This rectangle is gradually painted as the operation approaches its end. Also another feature of the system is that it can grab and save the contents of the display buffer and show or retrieve them at a later stage as appropriate. This is done by entering D for display at the system prompt. The system will then respond by printing a message reading:

[R]ead film file, [S]ave film file

Choosing S will result in the system asking for a name and consequently saving an image file under that name. Choosing R will instead asks for a file name which is already saved and should be retrieved from the library.

B-7 3D SCREW DESIGN (RESEARCH VERSION)

It was described before that a 3D program was initially developed to establish the feasibility of the design and its problems. At this stage it is intended to describe the operation procedure for the benefit of the future research. The program is called 1270 and is run by first logging into the polytechnic VAX mainframe (Cluster).

```
<break> <return> <return>
CLUSTER<return>
[Username]<return>
[Password]<return>
```

Successful logging will be acknowledged by a " $ " prompt on the screen. While in the system, the CAD environment is called by entering UGRAF at the system prompt.

```
UGRAF<return>
```

This will take the user through the logging procedure of the CAD system which asks for the username and password to let the user get into the software shell. At this stage, the system will display a menu on the screen. From the above menu a new drawing has to be created. Having created the new drawing and initialised the working area, the option "GRIP" is to be chosen. Upon choosing the GRIP option, a new menu will be displayed. The options in this menu will consist of four major options.

These four are considered:

-Write a GRIP program.

-Compile GRIP program.

-Edit a GRIP program.

-Run a GRIP program.

By choosing the fourth option the system will prompt for the file name. Entering 1270 (the program name) will run the program.

Running the program in turn leads to an interactive session enquiring about the screw parameters. At the end of the interactive session, the system will draw the required screw.

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