An Integrated Design and Manufacture Methodology for Injection Moulded Components

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This work is dedicated to my Grand-Mother, Parents and Fiancée.

I certify that I have read this dissertation and that in my opinion it is fully adequate, in scope and quality, as a Masters of Engineering dissertation.

(Lead Supervisor)

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ABSTRACT

Traditionally, the uncertainties associated with the development of plastic injection moulded components resulted in a product development cycle of design, built and break. This sequential process adds considerable time and cost which in today's marketplace can be more detrimental than beneficial. Over the past ten years it is estimated that approximately 2800 different combinations of tools have emerged which can help eliminate these problems. The research study contained hereunder identifies the most suitable of these tools which can be applied to the design and manufacture of such components and proposes an alternative product development cycle.

The proposed cycle begins at the Design For Manufacturability phase, where the customer requirements are fully integrated into the design at the earliest possible stage. Following this is the design phase, which utilizes both Computer Aided Design and Engineering technique's to create a detailed product designs and virtually test them. Rapid Prototyping and Tooling procedures are also adopted to create functional prototypes from the end run material which can be tested using Accelerated Testing procedures. These six phases of this cycle are presented and examined, through action research and case studies.

Adopting such an approach has the potential of considerably improving the quality of any new injection moulded component and reducing both the time and cost associated with its development. Costs incurred through the application of these alternative tools and implementation of this new ***product development cycle*** can be regarded as being negligible when compared with the overall development of the product.

ACKNOWLEDGMENTS

Initially, I would like to thank my project supervisor, Mr. Daniel G. Boyle, who gave me the opportunity to pursue this course of study. I am grateful for his continuous support and encouragement that helped me to overcome the many disappointments encountered.

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NOMENCLATURE

A_0	Original Cross-Sectional Area
A	Constant
B	Constant
E_1	Young's Modulus Maxwell Model (Spring)
E_2	Young's Modulus Kelvin Model (Spring)
E_c	Creep Modulus
I'_j	Importance Value
K'_j	Raw Contribution
L_0	Original Length
P_i	Applied Load at Time Interval
Q	Activation Energy
R	Boltzmann's Constant
T	Absolute Temperature
W'	Contribution Value
W'_j	Contribution Percentage
a	Real Number
a_0	Empirical Constant
b	Real Number
c	Real Number
m	Empirically Derived Constant
n	Empirically Derived Constant
q	Error
t	Time Value
ΔL	Change in Length
ε_0	Initial Strain
ε_1	Strain (Spring Element)
ε_2	Strain (Dashpot Element)
ε_{cr}	Creep Strain
ε_k	Strain Kelvin Model

ε_t	Strain at Time t
η_1	Constant Assigned to Dashpot Maxwell
η_2	Constant Assigned to Dashpot Kelvin
σ	Stress
σ_1	Stress Associated with Kelvin Model (Dashpot)
σ_2	Stress Associated with Kelvin Model (Spring)

INTRODUCTION

This chapter is divided into a number of sections, the first of which establishes that the subject of this research study, Integrated Methodology for the Design and Manufacture of Injection Moulded components, is a valid and worthwhile area of research. The next two sections set out to define the scope and methodology, while the last, outlines each chapter contained within the thesis.

1.1. PROJECT BACKGROUND

The principles of both Concurrent Engineering and Computer Integrated Design and Manufacture have been well established at this stage [1, 2, 3]. These methodologies are about integrating fully all the design, analysis, engineering and manufacturing functions of any product or process and results in reduced costs, decreased development time and improved quality [4, 5, 6, 7, 8, 9, 10].

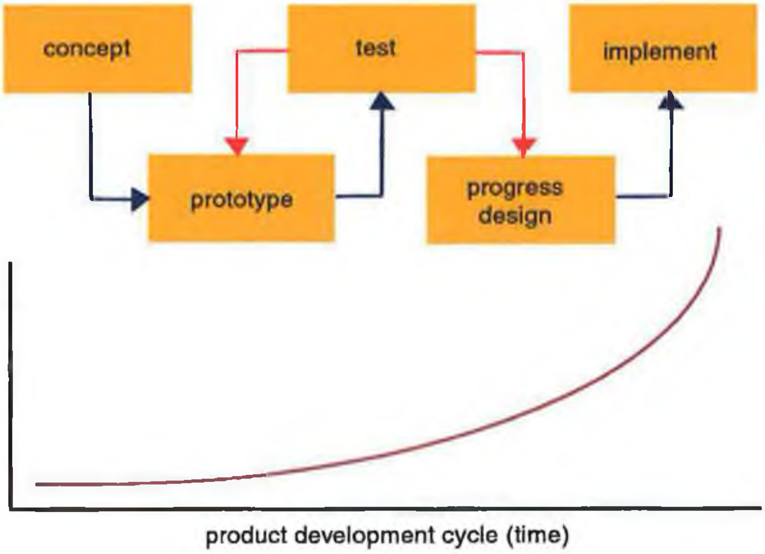


Figure 1.1: Traditional Product Development Cycle (CIDM)

The Traditional CIDM, which is represented by figure 1.1, starts with the identification of a market opportunity. This proceeds to concept generation and selection (the Design For Manufacturability stage) where the customer requirements are integrated into cycle. Following this, the product is designed, analysed and tested before proceeding to manufacture. Collectively this process is known as the Product Development Cycle. In more recent times, Rapid Prototyping and Tooling have also been included, normally in the testing phase.

If each individual area is examined, it becomes apparent that there has been ***a huge increase in options or choices with regards the various technologies while a corresponding decrease in there cost*** is evident. This applies to both software and hardware. Each of the individual areas is introduced hereunder.

Conceptional design tools are more commonly known as Design For Manufacturability tools [11]. These tools emerged in the early 90's and have gained widespread acceptance within many of the large multinational organizations [4]. The more common of these tools comprise mainly of Value analysis and graphs, Quality Functions Deployment, Tanaka's Cost Worth Analysis and Failure Modes and Effects Analysis. While these tools have been accepted by the larger organizations, many of the smaller to medium sized companies have not.

Computer Aided Design tools have been around since the mid 1960's, however it was not until the early 80's that 3D modeling began to emerge. At this point approximately 15 vendors provided such capabilities along side there 2D options. With the advent of the 90's, systems such as Computervision, UNIGRAPHICS, I-DEAS, PRO-ENGINEER, CATIA and AutoCAD had become the driving forces within the sector. Radical new developments, such as parametrics and advanced surfacing technology, spawned an explosion of activity in term of usage from concept through to production. By the end of this 1990's, a number of mid-range systems, including, SolidWorks, PRO-Desktop, and Solid Edge had also emerged.

As the number of commercially available systems increased dramatically, and as more systems battled for supremacy within the market place, a corresponding decline in price of approximately 60% became apparent [7].

In 1992, the average price of implementing a 3D solid modeling system was ≈ \$15000, whereas in 2002 this had been reduced to ≈ \$6000. This can be best accounted for, by the increase of both systems availably and the amount of user's adapting these technologies.

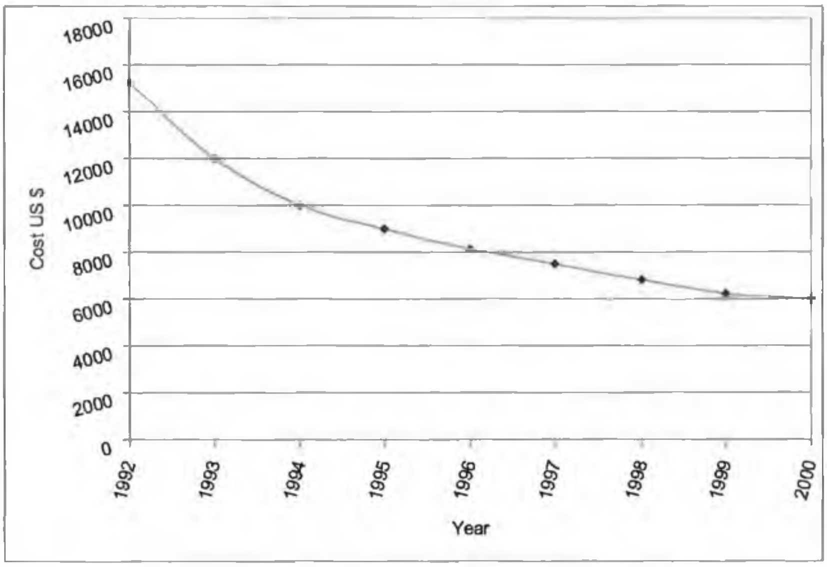


Figure 1.2: Average Cost of Implementing a CAD Systems

Computational Analysis Techniques have moved from the realm of the supercomputer to desktop of the design engineer as a result of the rapid decline in the cost of computers and the exceptional increase in computing power [2]. A number of vendors including ANSYS, NASTRAN, COSMOS, SDRC I-DEAS, and PATRAN have remained the key players within the sector over the past 15 year's. Little or no real extra competition has entered this sector, except for a number of pre-processors, or post-processors, which integrate into both the CAD systems being used, and the solver of choice [2]. Much in the same context as CAD systems, FEA has experienced a significant decline in cost over the past decade as the systems became more popular. Plastic flow analysis can also be grouped into this category. MoldFlow is the most notable of these, with costs similar to most FEA systems.

Rapid prototyping is an automated process which quickly builds physical prototypes from the 3D CAD dataset. This process offers a quick and easy route to obtaining both prototypes and tools at considerable time and cost saving [12, 13]. 3D Systems unveiled the first RP system at the November 87 Autofact Expo in Detroit, and made it commercially available in May of 1988. It was over the next four years that other techniques from vendors, Helisys (91), Stratasys (91), and DTM (92), emerged. The second generation of RP process based on inkjet techniques emerged towards the end of 1995.

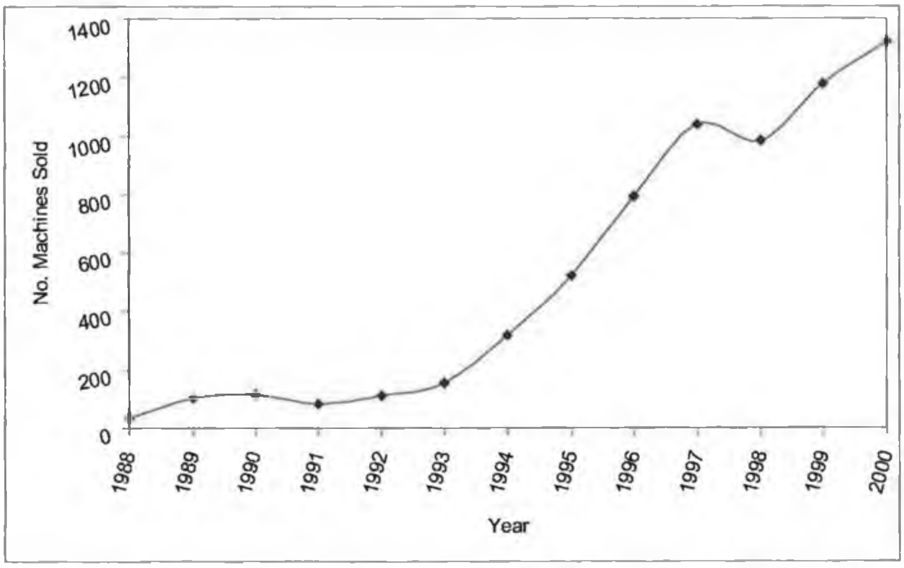


Figure 1.3: World-Wide RP Sales [14]

On an international basis over the period of 1988 to 2000, the unit sales of RP systems, has risen from 34 units per year to approximately 1320 [14]. Over this period the approximate cost of these systems can be assumed to have declined roughly by 50%. Doing some long division on figures in the Wohlers Report 2001 yields an average selling price of about €188,000 for 2001 Vs €352,000 for 1993.

The problems associated with effectively conveying a concept has been alleviated by the introduction of both RP and concept modelers. The Concept Modelers are ideally suited to production of prototypes which are used for visualization and communication purposes. Since there introduction the cost of these systems has remained static at €68K. In recent weeks however, both Stratus and Z-Corp have unveiled machines which will retail in the region of €34K.

Approximately 10 different rapid tooling processes have emerged in tandem with RP over the past ten years [10, 12, 15, 16]. In the early 90's, only three were available. These techniques offer a quick and easy route to the creation of functional prototypes, constructed from the end run material which can be tested under actual operating conditions.

If one considers all of the technologies discussed above including DFM, CAD, FEA, RPT which were available in 1993, it can be deduced that 120 different combinations could be utilized in the product development cycle. In 2000, this number had increased to approximately 2800 technologies. This research study, aims to ***indicate the most suitable combination of tools available for development of plastic components***.

	DFM	CAD	FEA	RP	RPT	Total
1993	1	4	5	3	2	120
2000	1	7	5	8	10	2800

Table 1.1: Tools availability according to year

Extensive research, into Design For Manufacturability Techniques has been conducted by both Stanford and Ohio State Universities under the guidance of K. Ishii and K. A. Beiter. Both authors have published a considerable amount data on the tools, techniques and their applications at various conferences [17, 18, 19, 20, 21, 22, 23]. Within the area of injection moulding, both the afore mentioned have also published papers dealing with 'Dimension Analysis and Fillability, Material Selection, and the Balance of Mechanical Requirements, Manufacturing Costs and Material Selection". The research activities of these respected groups continue within these areas.

Also at Stanford University, the Knowledge Systems Laboratory has been developing a knowledge-based technology to offer intellectual assistance in all stages of the life cycle of engineered products. One outcome of this group thus far is a Device Modeling Environment (DME), i.e. system that assists in model formulation, simulation, and documentation of designed artifacts. This tool will offer considerable benefits to all disciplines in years to come.

The Engineering Design Research Center at CMU has been actively involved in the development of fundamentals for design science, cross-disciplinary methodologies for the creation of products and processes, and computational tools for improved design practice. The activities of this group are extremely beneficial to many areas, however with regards plastic injection moulded components, nothing has been examined.

Nanua Singh of the Department of Industrial and Manufacturing Engineering at Wayne State University has published extensively in the areas of design, manufacture and integration of systems. Presently his research centre is actively investigating a number of areas including, Intelligent Design of Products and Processes in a Concurrent Engineering Environment, CAD/CAM, Robust Design and Reliability Engineering [24].

At Lancaster University, the Engineering Design Centre specializes in the development of software for Engineering Conceptual Design. Considerable developments have been reported for Mechatronics products however work within the plastics sector seems to be very limited at present. This work is some what similar to that on going at the Knowledge Systems Laboratory at Stanford.

Finite Element Analysis Research is conducted through various industrial groups and a wide variety of Universities with there findings published at each of the respected software vendors annual conferences. The Semi-Conductor division of Motorola, in the states has published a number of papers through the ANSYS Conference on Non-linear FEA.

A number of research groups investigating Rapid Prototyping and Tooling are readily identifiably worldwide. These include Dave Wimpenny's Warwick University group, Ian Gibsons research centre at the University of Hong Kong, Georgia Institute of Technologies Rapid Prototyping Laboratory, The Rapid Prototyping Laboratory at Stanford University (mostly concerned with embedded sensors), and the Institute for Plastics Innovation at the University of Massachusetts Lowell. Each of these groups has been actively involved in the development and application of these technologies over the past number of years. Considerable research into mechanical properties of both RP parts and moulds has been conducted and published by the vast majority of these. MIT has been actively involved in the development of new RP systems, an area that Georgia Tech is also investigating. Sources for obtaining such publications are the Society of Manufacturing Engineers Rapid Prototyping division, Wohler Associates or the Global Alliance of Rapid Prototyping Associations.

Assistant Professor Kuang-Hua Chang, of the Concurrent Design and Manufacturing Research Lab. at the University of Oklahoma has been actively involved in the development of Concurrent Design and Manufacture techniques applicable to Mechanical Systems for some time. This group has published many papers at various conferences most notably the ASME Design Engineering Technical Conference. The research activities of this group come closest to the research topic undertaken in this thesis, with the main difference being that plastic systems rather than mechanical systems are examined here. The tools and techniques while similar in some instances (namely, DFM and CAD) often differ considerably in others (FEA, RP and RT).

The following journals were also reviewed; International Journal of Advanced Manufacturing Technology, Concurrent Engineering - Research and Applications, Computers in Industry, International Journal of Machine Tools and Manufacture, Computers and Industrial Engineering, Integrated

Manufacturing Systems, Proceedings of the Institution of Mechanical Engineers –British Journal of Engineering Manufacture, Robotics and Computer Integrated Manufacturing, International Journal of Production Research, Journal of Materials Processing Technology (Science Direct search), Computer Integrated Manufacturing Systems, Computer-Aided Design.

This extensive journal search produced a total of 11 papers which only addressed fragmented aspects of this study. Researchers at the Hong Kong Polytechnic University, the University of Warwick and the Hong Kong Technical College developed a knowledge based system capable of simultaneously handling large volumes of data which are most relative early in the PDC in order to streamline process development [25]. This work was taken a step further by a Taiwan research group who integrated a planning system into new and emerging mould manufacturing techniques [26], in order to reduce development times, and costs incurred. Benefits such as these will establish these tools. The development of An Integrated Graphical User Interface for Concurrent Engineering Design was undertaken by a group operating out of the State University of New York and Chao Yang University of Technology in Taiwan [27]. This tool accesses product data contained within different computational systems and evaluates it based on criteria of DFM and DFA, for a variety of different constraints. A Product Data Management system which incorporates computational tools into a concurrent methodology was developed by researchers at Wroclaw University of Technology [28]. At the National Cheng Kung University, Shih-Wen Hsiao developed a customer oriented concurrent design methodology [29] which focused on DFM tools and there integration into the design cycle, while Yuh-Min Chen and Jang-Jong Liu highlighted that performing cost analysis at the start of the design cycle reduces any risk of cost-ineffective design in their study [30]. Both these studies illustrated the importance of performing DFM early in the PDC. Research conducted at Korea's Advanced Institute of Science and Technology comes closest to the topic of this Thesis. One group indicated the validity of integrating CAD/CAM/CAE/RP into a design methodology for metal forming [31], while another developed a concurrent engineering system for composite designs [32]. The latter integrates effectively the computational design and analysis tools in order to reduce both time and cost associate with the PDC.

Nothing was located that has been written on the area of Integrated Design and Manufacture of Injection Moulded components. The majority of research thus far has focused on individual areas such as DFM, Mould Balancing, and Rapid Prototyping for injection moulded components by the groups and centers indicated above. It can be concluded, that while some research has been conducted within the various fragmented sections, very little has been conducted when all techniques are considered together.

1.2. SCOPE

This study is concerned with the product development cycle of ***plastic injection moulded*** components from concept up until prototyping and testing. The constantly evolving topics of DFM, CAD, FEA, RP, RT etc..., are examined in an attempt to identify the most suitable tools currently available which are applicable to design of such components. These tools are integrated into the traditional PDC, thereby spawning a new cycle. The project does not examine production tooling though in some cases RT processes can be used to obtain such tools for short run items most notably DirectAIM and RapidTOOL.

1.3. METHODOLOGY

Because of the very large number of technologies and systems it is obviously not possible to evaluate them all, however it is felt that conclusions drawn from the literature with no practical experience may be of limited benefit. For this reason it was decided through action research and case studies to use the most promising 1 or 2 technologies, techniques, or software's in each category of this study in order to make the understanding more comprehensive and thus the conclusions of the report more useful.

1.4. THESIS OUTLINE

This research study examines the Product Development Cycle from concept through to testing. The study commences at the concept phase where the most common tools available which accurately identify the customer requirements are examined. These tools are presented in chapter 2, where their application to the design of a computer mouse is established.

Chapter 3 introduces the key issues which must be addressed when designing with plastic materials. An overview of top down and bottom up design as well as design features for plastic components is presented. The chapter also covers solid modeling, surfacing, master modeling techniques and parent child relationships, all of which are essential in the design of plastic products. These techniques are introduced through there application to the design of a computer mouse. This chapter concludes with the presentation of a chart representing the various CAD systems available in today's market place.

Chapter 4 addresses computational analysis tools and there application. These tools form the backbone of virtual prototyping and offer a significant advantage to users in determining the ability of a design to be manufactured and withstand various loading conditions. The finite element method, for both static and non-linear analysis is presented through the examination of a snap fit found on the computer mouse. The fill characteristics of the various components of this design are also examined, and there results presented. The chapter concludes with a comparison chart, representing the various tools available.

Rapid Prototyping technologies are introduced through chapter 5. The various techniques are outlined and the advantages and disadvantages of each process are presented. Other issues, such as file transfer form CAD systems to these machines, and build characteristics are also outlined. The chapter again concludes with a comparison of these systems in a tabular form.

The next chapter is concerned with the use of Rapid tooling. This chapter outlines ten of the more common tooling techniques available, dividing them into both soft and hard tooling for direct and indirect processes. A table outlining the RPT process Vs. Number of components concludes this chapter.

Sources for material data and the various testing techniques applicable to plastic components are presented in chapter 7. These form an essential tool in the design of any new product, in so far that they help to establish manufactures confidence in the design. They also help to establish if the product will operate over its intended life.

The Thesis concludes with the presentation of a revised Product Development Cycle, i.e. An Integrated Design and Manufacture Methodology (figure 1.4) which is applicable to Injection Moulded components. Topics for further research are also identified.

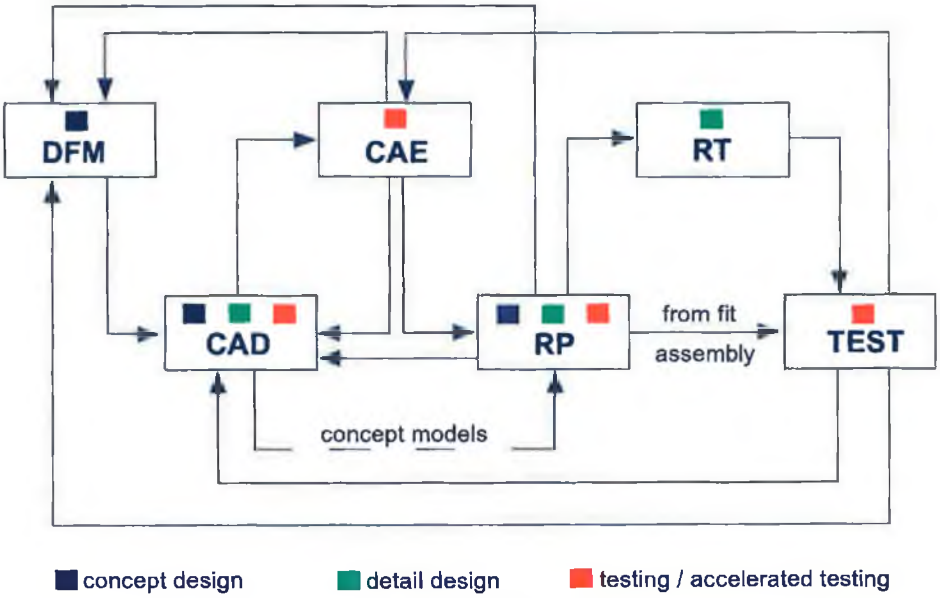


Figure 1.4: Integrated Design and Manufacture Development Cycle

INTRODUCTION

The concept of DFM refers to the practice of incorporating the important values of quality into the design process of a product or system at as early a stage as is possible during its development. These values address the entire life cycle of the product and incorporate the primary functions including producability, assembly, testability and environmental compatibility.

It is well documented that approximately 75% to 85% of life cycle costs are established at the design stage and therefore the key to successful design is the optimization of the life cycle [2, 3, 4, 9, 10, 14]. The introduction of structured design reviews and the exploitation of a close link between both the designers and the engineers can best achieve this. The implementation of tools such as Benchmarking, Value Analysis, Quality Function Deployment, Tanaka's Cost Worth Analysis, and Failure Modes and Effects Analysis often leads too much greater returns on an initial investment [11, 35, 37].

2.1. BENCHMARKING

This is a standard of excellence or achievement used by many organizations to compare and measure their activities with others within and outside that industry. The process compares the practices, processes and outcomes to standards of excellence, typically *"Best Practice or Best in Class"*, in a systematic manner [9, 36].

Generally speaking the best practice indicators are standards of excellence, which for the most part are based on surveys, interviews and other sources which are not freely available in the public domain. These help to identify and plan a program of attack, which focuses on both weaknesses and strengths. The examination of the success of others is possibly the most beneficial of all.

The benchmarking process can easily be applied to the design of a new product, the re-design of an old, or the development of system. In order to accomplish this, or for that matter the application of the process to any discipline, requires that a number of systematic phases be followed.

2.1.1. BENCHMARKING, THE PROCESS

As with many effective management tools, benchmarking has no clear start and finish. The process follows the concept of Plan-Do-Check-Act, PDCA, thus ensuring that it is continually contained within a repeated loop. Best in Class organizations are continually striving to be better, more successful and therefore have embraced the process, e.g. Xerox.

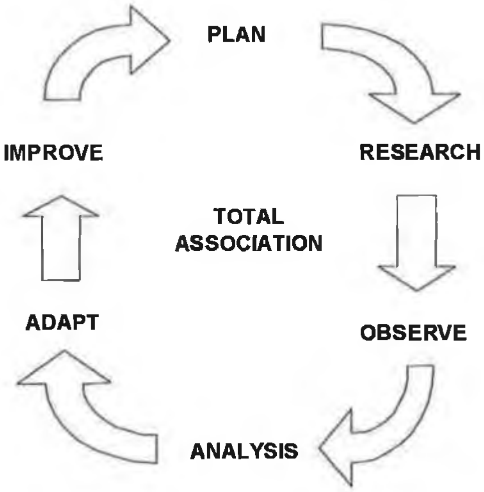


Figure 2.1: Benchmarking Process

The key phases in the process are identified in figure 2.1. Often it is found that the activities, of research, observation and analysis are grouped together in the one category.

2.1.2. PRODUCT BENCHMARKING

This method of benchmarking examines how a competitor's product operates, performs, functions and costs, in order to identify its strengths and weakness. As a result of conducting such a study, a more efficient solution can and often is obtained.

In the case of any product design, studies are conducted in order to identify the features and characteristics that make those designs good. Designers then attempt to improve these features and incorporate some element of them into their own design. Table 2.1, presented here under is one such study. Further information regarding this study can be viewed in Appendix A.

Mice / *Characteristic*	*Microsoft*	*IBM 3*	*IBM 1*	*Spurious*	*Hewlett Packard*	*IBM 2*
Easy to Operate	5	1	1	4	5	1
Aesthetics	5	2	2	5	5	1
Ergonomics	5	2	1	5	5	1
Percentiles Suitability	5	1	1	3	5	1
Weight	3	1	1	3	5	1
Manufacturability	1	3	5	5	5	5
Cost	3	2	2	5	3	2
Technology	5	1	1	3	3	1
Economic Material	4	2	2	4	4	2
Easy Dismantle & Clean	4	3	3	5	5	5
Reliable	5	4	4	5	5	4
Left Vs. Right Hand	1	5	5	5	4	5
TOTAL	46	27	28	52	54	29

Table 2.1. Benchmarking Analysis Results

It is evident from this table that the Hewlett Packard mouse scoured the highest. Factors such as its ergonomic and aesthetic design, weight, overall all quality and its ecological factors contribute to its high rating. The Spurious mouse scoured the next highest result, and Microsoft's mouse came in third. These results indicate that these mice posses the best characteristics, therefore these should become the main driving characteristics of any new design.

2.2. CAUSE & EFFECT DIAGRAM

The cause & effect diagram is the brainchild of Kaoru Ishikawa, who pioneered quality management processes in the Kawasaki shipyards [38]. This diagram is used to explore all the potential or real causes (or inputs) that result in a single effect (or output). Causes are arranged according to their level of importance or detail, resulting in a depiction of relationships and hierarchy of events. This can help you search for root causes, identify areas where there may be problems, and compare the relative importance of different causes.

Causes in a cause & effect diagram are frequently arranged into four major categories. While these categories can be anything, you will often see:

- Personnel, methods, materials, and machinery (recommended for manufacturing)
- Equipment, policies, procedures, and people (recommended for administration and service).

The categories used should be appropriate to the task being undertaken. The C&E diagram is also known as the fishbone diagram because it is drawn to resemble the skeleton of a fish, with the main causal categories drawn as "bones" attached to the spine of the fish. The fishbone diagram for the assembly of the mouse is illustrated in figure 2.2.

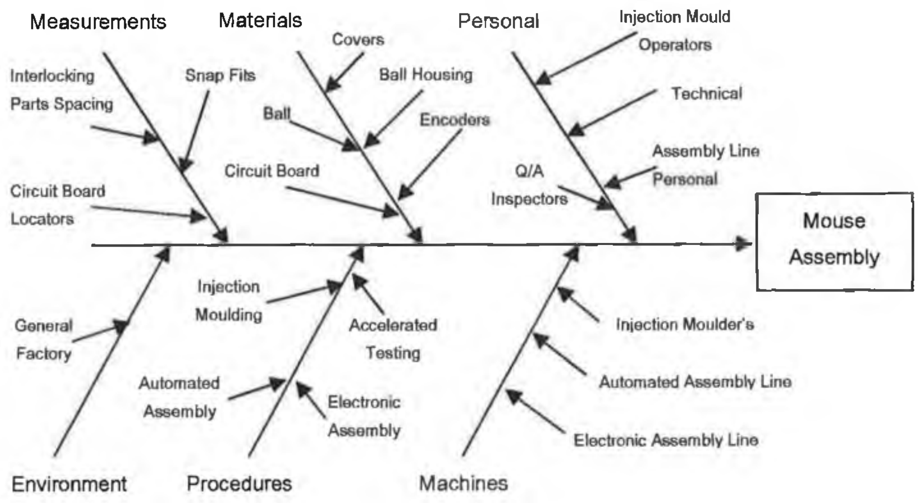


Figure 2.2: Cause and Effect Analysis

This diagram shows all the categories necessary for a manufacturing analysis of the computer mouse, it shows all the necessary information to be taken into account when production personnel are in the early stages of putting a design plan for a computer mouse into action.

2.3. VALUE ANALYSIS

Value engineering or analysis is a special application of creative problem solving techniques which was first applied by Lawrence D. Miles of General Electric in 1949 [36]. The main purpose of this technique is to create functionally equivalent or improved product designs at a reduced cost [9].

The purpose of the value analysis is to assign an approximate cost to each of the components that make up the end product. Special attention is given to each of the functions that a specific component must fulfill and what, if any contribution it makes to the overall cost. It also ascertains the percentage of the total functional cost contributed by each individual component, data which is essential for Tanaka's Cost Worth Analysis.

Value Analysis

Component #	Identification	Function Costs					Approximate Cost (€)	Percentage of Total Cost
		Hold Parts Together	Highlight Items	Control Items	Provide Interface	Provide Handle		
1	U. Cover	0.03	0.02	0.02	0.02	0.05	0.14	12.069
2	L. Cover	0.05	0.01	0.01	0.02	0.01	0.1	8.62
3	C. Board	0.025	0.1	0.175	0.16	0	0.66	39.65
4	Button	0	0.03	0.03	0.02	0.02	0.1	8.62
5	Ball	0	0.025	0.025	0.03	0	0.08	6.89
6	B. Housing	0.04	0.02	0.02	0.02	0	0.1	8.62
7	Rollers	0.01	0.04	0.04	0.04	0	0.13	11.20
8	Screws	0.05	0	0	0	0	0.05	4.31
Function Cost		0.205	0.245	0.32	0.31	0.08	1.16	100
Function Percent		17.67	21.12	27.58	26.72	6.89		100

Table 2.2: Value Analysis

Table 2.2., establishes that part numbers 1,3 & 7 contribute the highest cost. It is clear that the Motherboard is by far the most expensive component in

the mouse & the functions that contribute the most cost to the finished product are all associated with communication between this device and the computer. A graph which relates the cost of the parts to the cumulative cost of the product can also be constructed from this data (figure 2.3).

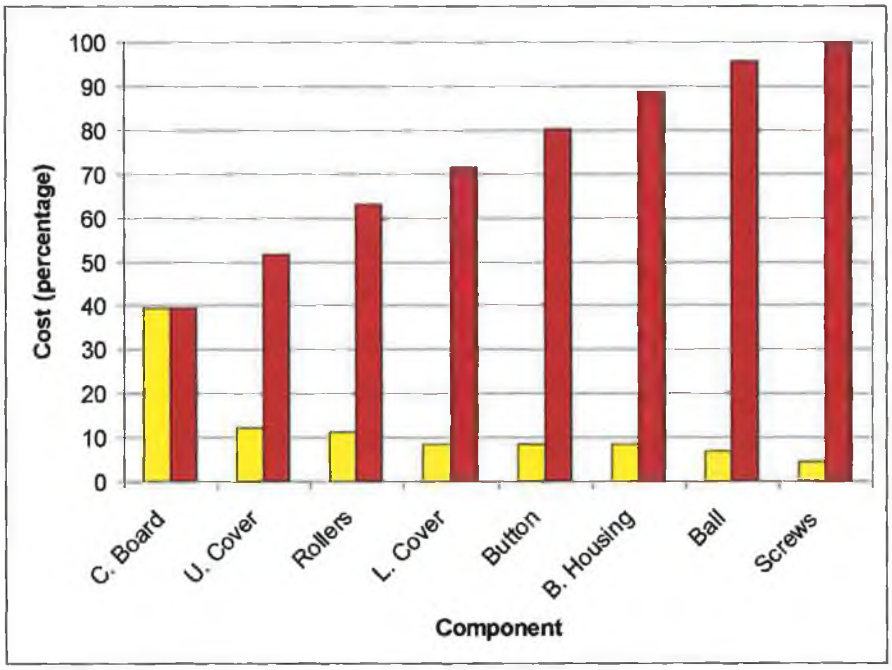


Figure 2.3: Graph of Relative Costs

Figure 2.3., illustrates the Part cost (in Yellow) against the cumulative cost of adding that component to the product (in Red). It shows graphically which of the product parts clearly cost more, in this cast component 3 which is the circuit board.

2.4. VALUE GRAPH

Design for value (DFV) is a very powerful technique which allows design teams to systematically review their objectives and the proposed design at various stages during the product development phase. From the earliest stage in the cycle designers clearly identify the necessary values which are required by the product and incorporate these into their designs. The *values* of a product come in various forms: functionally, performance, aesthetics, manufacturability, portability, assembly, inspectability, serviceability, reliability, etc.... The primary objective is to design a product that embodies all the necessary values or an appropriate combination.

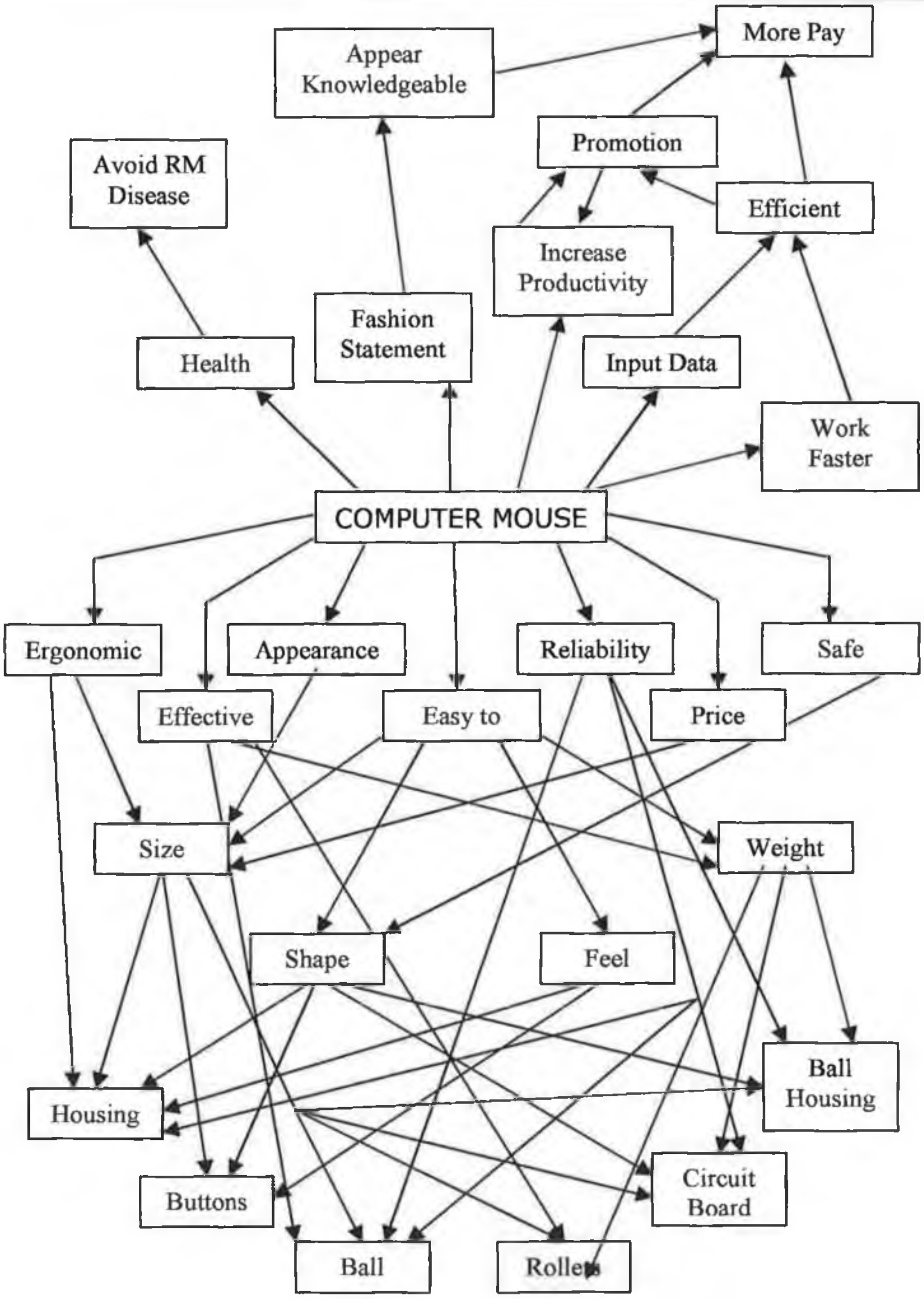


Figure 2.4: Value Graph

A very effective method of achieving this is to prepare a value graph. These graphs have both an upper and lower portion. The origin of these is there center, where a labeled box consisting of the name of the product is situated. A series of questions needs to be then asked in order to generate both the upper and lower portions. In the case of the upper region, why is asked repeatedly in order to break down the reasons for using the product. Alternatively at any node the question, Is there another way of achieving the same result, can also be asked. This results in a tree shaped figure which encourages lateral thinking. Also alternative solutions to the problem emerge.

Questions are also posed in order to generate the lower region. Asking what the customer values for this product are generates the first level below the start node of the product. These are generally established by conducting a number of customer surveys. Below this level another level consisting of product characteristics is constructed. These are pointed to by the customer values in the above row. The final row is the product structure, consisting of a list of physical assemblies or components on the product that realize the boxes in the rows above, particularly in the product characteristics row.

2.5. QUALITY FUNCTION DEPLOYMENT

Quality Function Deployment was first developed in Japan by Yoji Akao and is a derivative of Value Engineering. The process is a cross functional planning technique which ensures that the voice of the customer is clearly identified and maintained throughout the development and design phases of any product, process or system [3, 4, 9, 35, 36]. Implementing a QFD strategy facilitates concurrent engineering, which in turn encourages teamwork in order to achieve a common goal and ensure that customer satisfaction is incorporated.

A number of studies, involving surveys and meeting with the customer in order to discuss the proposed product so as to obtain in descriptive terms how the costumer feels about what is being proposed are conducted to facilitate the establishment of their needs. The outcome of these studies is then translated into design requirements and deployed through each phase of the manufacturing cycle in order to ensure that what is delivered is actually reflective to the needs and requirements of the costumer [3].

The customer needs and requirements are translated into process specification through the development of a series of interaction matrices. These can be identified by four distinct categories, which involve identifying the following parameters:

Problem Definition	*Leads Towards*	*Solution Definition*
Customer Requirements	→	Product Characteristics
Product Characteristics	→	Part/System Characteristics
Part/System Characteristics	→	Process Characteristics
Process Characteristics	→	Production Controls

Table 2.3: Phases of QFD

In Phase one the customer requirements are given a weighting depending on importance of 3, 6 or 9. The engineering metrics are given a weighting of 0, 1, 3, or 5 depending on their importance in relation to the customer requirements. These two values are multiplied and the value for each engineering metric is summed to give a raw score and hence a relative weight is calculated.

In phase 2 the engineering metrics are transferred from phase 1 along with the relative weights and the process is repeated as for phase 1, this time using part characteristics.

In phase one, seven customer requirements were compared with five engineering characteristics. This concluded that providing an interface and handle are the most important aspects of the mouse design (due to it having a higher relative weight). Phase two concluded that practically all the components with the exception of the screws are of equal importance to the mouse assembly. Combined these components allow the mouse to fulfill the functions for which the customer intends.

QFD Phase I

Customer Requirements	Customer Weight	Engineering Matrices					
		Hold Parts Together	Highlight Items	Control Items	Provide Interface	Provide Handle	
Ergonomic	6	1	0	3	3	5	
Effective	9	3	5	5	5	5	
Aesthics	6	5	0	0	3	5	
Ease of Use	6	1	5	5	5	5	
Reliable	9	3	5	5	5	3	
Cost	6	1	3	3	3	3	
Safety	9	5	5	5	5	5	Total
Raw Score		147	183	201	231	240	1002
Relative Weight		0.15	0.18	0.2	0.23	0.24	1

QFD Phase II

Engineering Matrices	Relative Weight	Part Characteristics							
		Upper Cover	Lower Cover	Circuit Board	Ball	Ball Housing	Rollers	Screws	
Hold Parts Together	0.15	5	5	3	0	3	0	5	
Highlight Items	0.18	1	1	5	5	3	5	0	
Control Items	0.2	1	1	5	5	3	5	0	
Provide Interface	0.23	3	3	5	5	5	5	0	
Provide Handle	0.24	5	5	0	0	0	0	1	Total
Raw Score		3.02	3.02	3.5	3.05	2.74	3.05	0.99	19.37
Relative Weight		0.16	0.16	0.18	0.16	0.14	0.16	0.05	1

Table 2.4: QFD Phase I and II for Computer Mouse

2.6. LIFE CYCLE COST AND FUNCTIONAL WORTH

Manufactures develop new and innovative products in order to generate profits. The difference between the production cost and the sales price is the determining factor, which governs the magnitude of these. The sales price is essentially determined by the market place and not the manufactures themselves therefore the overall production cost must be kept to a minimum in order to maximize their profits.

The cost of a product cannot be looked at in isolation. The other key factor associated with production is that of worth. If a product costs too much when it is considered in the context of the functional value, then it will not generated sufficient sales in order to make significant profits for the firm.

2.6.1 RELATIVE WORTH

Providing customers with what they want at an acceptable cost is the key to generating profits. Designers must ensure that they include the concepts of cost and worth in their designs at as early a stage in the product development cycle as is possible. It is of vital importance that the customer perceives value within a product, which is consistent with the manufacturing cost [4, 9, 37]. Either the Relative Worth Method or Tanaka's Cost Worth Method can achieve this.

The Relative Worth method has been widely adapted by Japanese companies and is very simple in its concept. Typically, the design is sub divided into various sections, to which a relative worth weighting is assigned. This weighting value reflects the overall contribution of that sub section to the complete product and is generally normalized into a percentage. A Cost breakdown is also generated for each sub section, which when combined with the relative worth value, yields a ratio. Priorities are then assigned to these subsections and addressed as the need arises.

2.6.2 TANAKA'S COST WORTH ANALYSIS

A much more comprehensive analysis technique, known as Tanaka's Cost Worth Analysis has been developed and introduced in 1989 [35]. The procedure calculates the relative worth and relative cost of each component and helps establish the best direction for the designer to concentrate their efforts, so as to maximize all improvements.

With this procedure, the product functions are identified and assigned a raw importance valve (I'_j). Typically $I'_j = 1, 3, 5$, where 1 is assigned for slight, 3 for moderate, and 5 for great. From these and equation 2.1, a relative importance value for each function is obtained.

$$I_i = \frac{I'_i}{\sum I'_i} * 100 \qquad 2.1$$

The components of the design are now identified. Relative costs for each of these components are assigned and then a raw contribution (K'_j) for each is estimated. Typically $K'_j = 0, 1, 3, 5$, where 0 is assigned for none, 1 for slight, 3 for moderate, and 5 for great. Next a relative contribution of each component (j) to function (i) needs to be calculated. This is accomplished by equation 2.2

$$K_j = \frac{K'_j}{\sum K'_j} * 100 \qquad 2.2$$

Finally, for each components contribution to each function and their relative cost, values need also be calculated. This is achieved by applying equations 2.3, and 2.4 respectively. The results for these calculations are then plotted.

$$W' = \sum K_j * I_i \qquad 2.3$$

$$W_j = \frac{W'_j}{\sum W'_j} * 100 \qquad 2.4$$

The Cost / Worth analysis for the mouse examines whether the component parts provide enough worth to the design functions to justify their cost. Each of the design functions is assigned a relative percentage based on the importance that function plays on the overall function of the mouse. This percentage is then multiplied by the relative cost for each individual component depending on whether that component contributes to the design function in question or not. This gives the relative worth for that component for that design function. The worth values for each component can then be summed to give the total relative worth for that part.

Tanaka's Cost Worth Analysis

Design Function		Highlight Images	Provide Interface	Control Items	Hold Parts Together	Provide Handle	Relative Worth	Cost Worth Ratio
Relative Cost %	Components	Relative Importance (%)						
		18	23	20	15	24		
12.07	Upper Housing	0 0	5 1.15	0 0	20 3.0	35 8.4	12.55	0.96
8.62	Lower Housing	0 0	5 1.15	0 0	15 2.25	35 8.4	11.8	0.73
39.66	Circuit Board	45 8.1	55 12.65	45 9.0	10 1.5	0 0	31.25	1.27
8.62	Buttons	10 1.8	10 2.3	10 2.0	5 0.75	15 3.6	10.45	0.82
8.62	Ball Housing	10 1.8	7.5 1.73	15 3.0	25 3.75	0 0	10.28	0.84
6.9	Ball	15 2.7	7.5 1.73	15 3.0	5 0.75	0 0	8.18	0.84
11.21	Rollers	20 3.6	10 2.3	15 3.0	0 0	0 0	8.9	1.26
4.31	Screws	0 0	0 0	0 0	20 3.0	15 3.6	5.5	0.65
	Totals	100	100	100	100	100	100	

Table 2.5: Tanaka's Cost Worth Analysis for the Computer Mouse

Finally the ratio of cost over worth is calculated, the ideal value being 1. This allows us to graph the cost / worth table using Tanaka's method. It is important to note that components with high relative cost to worth ratio must have their cost reduced in order for the product to be viably manufactured. From the above analysis it is clear the Upper housing is the closest to the ideal cost / worth ratio of 1. In order to gain a better picture of the ratio a graph of Cost Vs. Worth ratio should be constructed (figure 2.5). It is clear upon examination of this that all components fall within the bands of the analysis, except the circuit board. To make this component viable, its cost should be reduced, or alternatively its worth increased. It is not uncommon for electrical components similar to this to exhibit such a Cost/Worth Ratio.

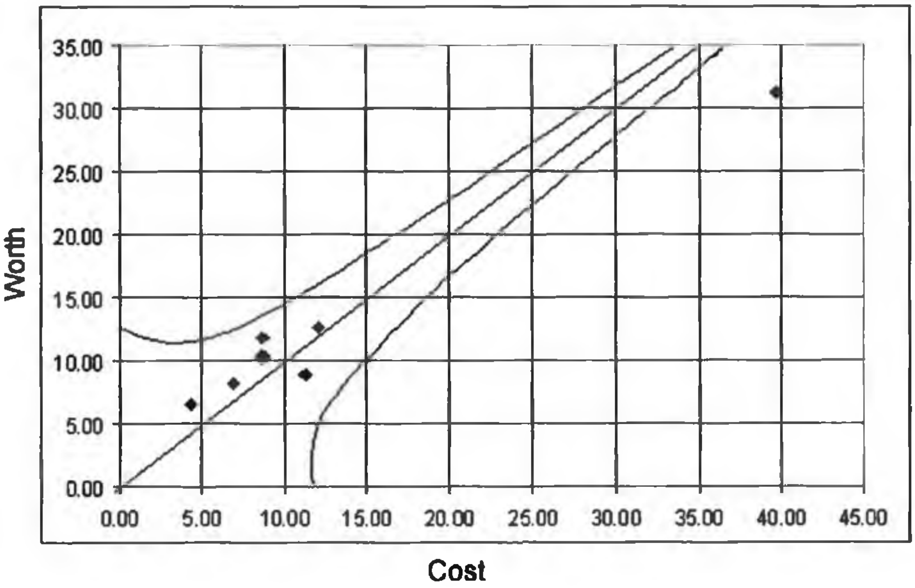


Figure 2.5: Cost Vs. Worth Analysis

2.7. FAILURE MODES EFFECTS ANALYSIS

Failure modes and effects analysis helps to identify how a product, system or service may fail during its operation [35, 36, 38]. Ideally someone removed from the design team should conduct this analysis, in order to reap the greatest benefit.

This work often has a significant impact on the overall design, safety and implementation of a new design or product. As a result of conducting such a study, it is not uncommon that considerable design changes may be necessary, hence, the ideal time to implement it, is during the preliminary design phase.

The concept behind the FMEA process is to identify any components of a design or system whose failure will have an undesirable effect on the operation and safety and hence, can lead to overall poor performance or failure of that design or system.

Prepared by: Keith Vaugh				**Failure Mode & Effects Analysis Design (FMEA)**				**Product Name: Computer Mouse**					
Part No	*Part Name*	*Part Function*	*Failure Location Characteristic*	*Failure Type*	*Failure Consequence*	*Failure Cause*	*Current Situation*	*Proposed*	*O*	*S*	*D*	*Rn*	*Suggested Action*
1	Upper Housing	To provide a grip for the user	Crack On Surface	Crack	Appearance Flawed	Impact	Cracked	Replace Cover	3	3	1	9	Replace mouse
2	Lower Housing	To provide a flat surface for the mouse to move on	Crack On Surface	Crack	Effect Mouse Movement	Impact	Cracked	Replace Cover	3	8	3	72	Replace mouse
3	Motherboard	Converts movements of the mouse into digital signals	Electrical Failure	Part Malfunction	Catastrophic Failure	Impact / Power Surge	shorted Out	Replace Motherboard	2	10	10	200	Replace mouse
4	Buttons	Cause Actions	Crack On Surface	Crack	Appearance Flawed	Impact	Cracked	Replace Button	1	1	1	1	Replace mouse
			Button Limit Switch Broken	Part Malfunction	Effect On-Screen Control	Impact	Inoperative	Replace Limit Switch	6	6	9	324	Replace mouse
5	Ball	Transfer movements to rollers	Shape Altered	Incorrect Translation Of Movement	Catastrophic Failure	Substantial Impact	Warped	Replace Ball	1	10	10	100	Replace mouse
6	Ball Housing	To support the ball	Cracked Or Broken	Crack	Catastrophic Failure	Substantial Impact	Cracked	Replace Housing	3	10	6	180	Replace mouse
7	Rollers	To relay information from the ball to the motherboard	Impregnation By Foreign Impurities	Part Malfunction	Altered Mouse Communication	Poor Environmental Surroundings	Dirty	Remove Housing & Clean Rollers	10	3	10	300	Clean Wheel
			Crack or break	Crack	Altered Mouse Communication	Impact	Cracked	Replace Roller	1	10	6	60	Replace mouse
8	Screws	To hold the assembly together	Thread warpage or Break	Break	Parts Disassemble	Shear	Broken	Replace Screws	3	10	1	30	Replace mouse

Table 2.6: Computer Mouse FMEA Analysis

The components or systems are recognized from the top down and the failures and their consequence are identified from the bottom. A value representative of the severity of that failure occurring, and a probability factor that it will actually occur, are assigned to each of these identifiable modes of failure. The severity rating is the first identifiable conclusion that can be drawn.

The F.M.E.A for the computer mouse indicates that the areas that must be focused on are:

- The limit switch for the buttons
- Electrical failure on the motherboard
- Dirt impregnating the rollers

These area's have the highest risk number and thus are the most likely to occur and cause failure, it is also shown that in most cases of failure it makes most economic sense to simply replace the mouse instead of repairing faulty parts.

INTRODUCTION

The majority of Computer Aided Design packages available to the design engineer are moderately easy to operate with respect to the design of any complex component. Most CAD systems offer the user, accurate creation of complex geometries in a relatively short timeframes. With regards plastic component design, large feature lists are created.

The following discussion aims to address the vital issues of designing plastic components in order to minimize modification difficulties. Key considerations, such as design planning, design features, surfacing and information tools associated with selecting a suitable CAD system for plastic component design are addressed. The implementation of these options is presented through the design of a computer mouse which forms the backbone of the later end of the discussion.

3.1. PROJECT DESIGN PLANNING

When designing with plastics, the designer should consider all the limitations imposed. For example, drop test, or impact test requirements, could drive the designer to select a specific material, and, or include strengthening features, such as ribs and webs which he/she would not select in the normal chain of events [1, 2, 10, 39, 40, 41]. Another key consideration, which can constrain or complicate the design, is the rheology rate of the material [19, 20].

The designer must also consider the limitations that exist in the conventional manufacturing techniques. Practically any component can be designed using a conventional CAD system, however not all can be manufactured [42]. The onus is therefore on the designer to consider any material and manufacturing limitations as early in the process as is possible.

Having some form of product specifications, or design limitations, can aid the direction the designer takes a new product [1]. Often similar product types are reviewed or benchmarked, to establish a good design. Decisions made at this early stage in the process often have an adverse effect on the product design later in the design cycle.

3.2. CONSIDERATION OF THE PARTING PLANE

In the case where the plastic components are to be moulded and then assembled, the inclusion of drafts, rounds, ribs, tweaks, etc. are a necessity [1, 39, 40, 41]. Plastic component design generally requires that each individual component be mated. This necessitates the requirement for some form of a mating surface to exist. In the majority of cases, the parting plane or surface acts as this, and hence the norm is model each component with this plane as the starting basis of the design.

Before any new design can be considered, the designer must determine the technique of manufacture and contemplate any design requirements of the product. To this end, he must consider where to place the parting plane and also how to best design the product so as to fulfill the design requirements. Often, it proves advantageous to design the product a number of different ways in order to determine the best approach to the design. This can be facilitated quite easily by modeling the component without any of the additional features of the design, i.e. draft angles, rounds, etc [42, 43, 44].

In the majority of cases, the parting surface is a shaped surface and not a simple plane. The designer need not restrict themselves to considering this surface as a planar surface, but rather a complex surface. The direction of separation between the core and cavity can be referred to as the parting plane direction.

3.3. PLASTIC DESIGN FEATURES

The ability of any CAD system to create plastic component features such as, shells, ribs, webs, bosses, etc... is essential for a successful design.

Another key factor that is essential is the ability to create surfaces which vary in section in the X, Y, and Z planes.

3.3.1. UNIFORM WALL THICKNESS

Plastic components should be designed with a minimum and constant wall thickness, which is consistent with the function and mould filling considerations of the component. Thinner wall sections help reduce the cycle times and reduce the cost of the part as the part both fills and cools much faster [39, 40, 41]. These thinner sections also result in a considerably lighter component.

Thinner wall sections cool much faster than thick sections, therefore they solidify first. This un-homogeneous cooling of the component, results in shrinkage of the thicker sections. As a result stresses near the boundary of the thin and thick sections often arise. As the thin section has solidified, it cannot yield so therefore the thick section must, which often leads to warpage or twisting. A typical example of both shrinkage and warpage is illustrated in figure 3.1.

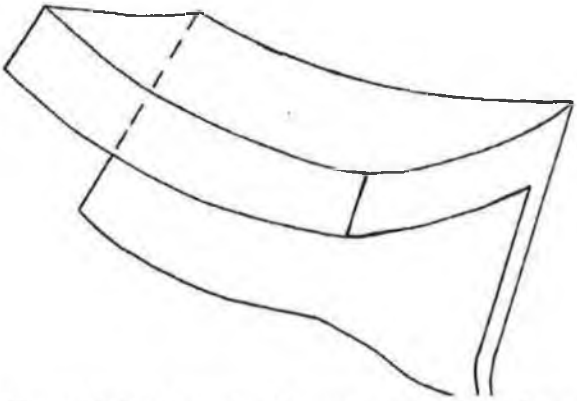


Figure 3.1: Example of warpage and shrinkage.

The shell option found in all systems allow for the creation of a constant wall thickness in a very easy manner. The component is modeled as a solid object, including all external features such as rounds. The engineer then decides on the surface to remove and defines a constant wall thickness. Sometimes a design requires that the wall thickness varies at different sections. This does not pose a major problem, but it is essential that the change in thickness is gradual rather than sudden.

3.3.2. DRAFT

This is a modification to the surfaces of a component so that it can be easily removed from the mould as illustrated in figure 3.3 [39, 40, 41]. Draft is essentially a small angular rotation of a surface about a pivot axis. The neutral plane or curve, determines the location of this pivot axis [43]. In the case where this axis is placed in the middle of a surface, a split draft on either side of the axis can be created. Alternatively a sketch can be projected onto the surface to define which will define two separate regions, thereby allowing for the creation of a different pivot axis and draft angles for each respective region [43].

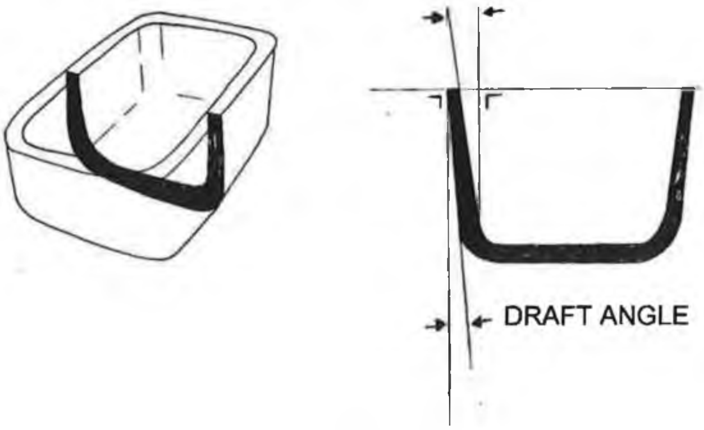


Figure 3.2: Draft Example

3.3.3. ROUNDS

Sharpe corners seriously increase the stress concentration in a particular area, thereby possibly resulting in the failure of the component under heavy loading conditions or as a result of a sudden shock [1, 45, 46]. Regions, such as these are generally found where bosses are attached to surfaces, at strengthening ribs, or at snap fits. In order to reduce these stress concentrations, rounds need to be included in the design. Rounds located in these areas, also helps the flow of plastic material thereby increasing the manufacturability of the component.

3.3.4. STRENGTH OF SHAPES

Plastic components can be used as safety barriers and thermal insulators when the necessary strengthening features are included in the design. Ribs can be placed in such a manner so as to resist bending, twisting and torsional effects [10, 39, 40, 41]. Wall height modifications, rounded corners, and curved ribs can also contribute to increasing the strength of the design.

The greatest problem faced by designers, is designing a component to withstand a sudden impact load such as when a device is dropped onto a hard surface [47]. Shock occurs at the instant of impact and for a few milliseconds afterwards causing bending throughout the structure. Also, internal components, such as circuit boards or battery's will contribute further to the shock. Such components need to be designed so that shock can be minimized in all directions. Often ribs or protrusion features are included not as strengthening features, but as internal component supports, i.e. a support to hold a battery in position.

The best design practice in minimizing shock is to include supporting features which can absorb some of this shock, but also to design the housing so that it itself can absorb some by bending and recovering thereby releasing what otherwise would be destructive energy. Rounds located at the exterior corners of the component help reduce the stress of impact.

3.4. TOP DOWN VS. BOTTOM UP DESIGN

The most common approaches that a designer may take when designing a new product may be either top down, or bottom up design [1, 48]. In the case of top down design, the designer has the freedom to do whatever it takes to get the job done. The part can be modeled by whatever means he wishes. He is not limited by certain design criteria. On the other hand, bottom up design, begins with, a design criteria. This drives the designer to pursue certain avenues. Often times existing components and guidelines are included.

3.4.1. TOP DOWN DESIGN

When the top down design approach is adapted, the designer has the freedom to model the complete exterior shape of the product under consideration without been driven by the internal components, or sub-assemblies. In the majority of cases, very few restrictions do exist. However, given the design criteria, the designer is able to establish the key restrictions by simply reviewing the intended function of the product.

Concurrent design methodology may be adapted when working on the layout of any such product. In this instance the product and the various component designs would be kept up to date with each other as the design evolves. The advantage associated with this approach is that, as design conflicts arise, they are dealt with.

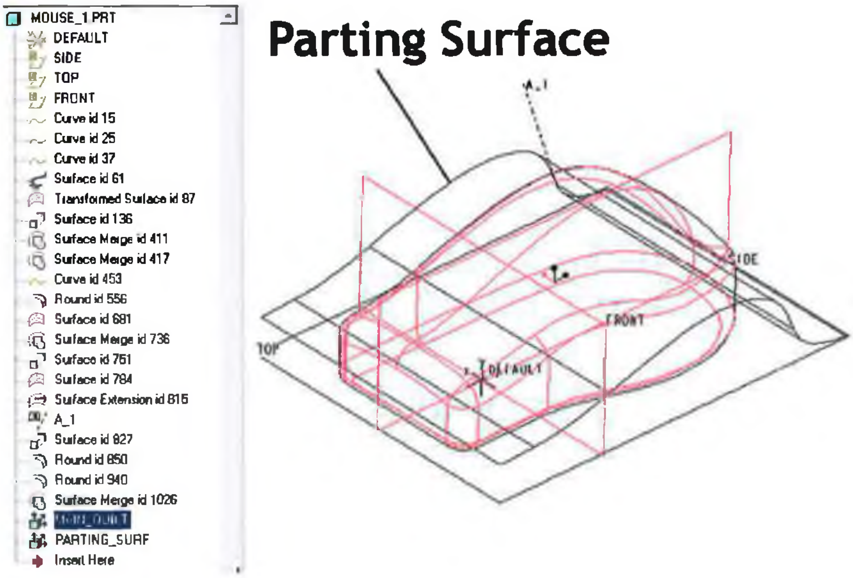


FIGURE 3.3: Parting Plane definition for a Computer Mouse

Considering the design of the computer mouse, and adapting the top down approach, the designer must first off model the overall exterior shape and size. It is advisable to make this profile modifiable in relation to the parting plane (In most CAD systems this is established by defining a datum curve and plane.

Given the external profile of the product it can then be established if the internal components will fit into the design by a framework which represents the space claims of each internal component, Surface models which represent the actual components, or modeling each component individually.

Very little time has been invested in the design and therefore major changes can be made inexpensively. The design can be modified easily, as there has been a very low feature count created and hence very few parent child dependencies to contend with when these modifications are made.

3.4.2. BOTTOM UP DESIGN

In this case the inspiration for a new product is drawn from existing components which are to be included in the design. The inclusion of components that have been used in previous designs have the major advantage of allowing for volume purchasing and therefore lowering the costs of the design, manufacture, inventory control and warehousing. Additionally, since off the shelf components are being used, tooling costs are avoided.

With this form of design, the existing components are assembled to form a sub-assembly around which the new design can be constructed. Alternatively, a subassembly used in a different design may be used, another potential cost saving,

3.5. SOLID MODELING

Essentially a solid model is a true representation of an actual component and contains all the information of this component. Generally due to the parametric nature of most CAD systems, the model will have volume, a centre of gravity and a mass.

A wide variety of features are used so that a solid model can be generated. These may include, extrusions, revolves, sweeps, blends, rounds, holes, cuts, surfaces, etc. Any combination of these can be used to generate the desired model. Figures 3.4., & 3.5., presented hereunder are true representations of the ball and encoder locator for the mouse design under consideration in this report. This component is generated by a first producing a solid extruded profile, creating a shell adding holes and cuts where necessary and any other protrusions as needed. As this is a moulded component a draft angle is also incorporated so as to facilitate the easy extraction from the mould.

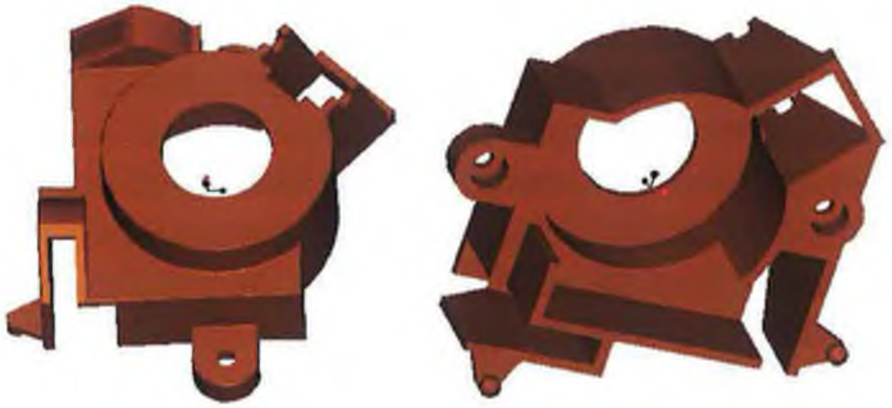


Figure 3.4 & 3.5: Ball and encoder housing. (Upper and Lower sides)

This component is relatively simple to create as it can be defined as a solid object initially. This is not true for the exterior profile of the mouse. These profiles vary in all three directions, i.e. the plan view of the mouse is curved as is both the elevation and end view, hence surfacing techniques must be utilised.

3.6. SURFACING

Surfaces have a specific area as well as defined boundaries, however are infinitely thin, hence are only suitable for visual purposes. These features can be generated in variety of ways, but all have the same general characteristics. Generally, surfacing is used as the tool of choice for the generation of all exterior profiles of a component. After their definition has been completed they are given some thickness thereby creating a solid part from which drawings can be obtained. Another procedure is to completely "close" up all the surfaces and then create a solid model from the sealed boundaries.

Generally speaking the exterior profile of the mouse is created by firstly defining datum curves, which define the boundaries of the surface. These curves are then used to sweep a profile through, resulting in a surface definition as illustrated in figure 3.6. This surface can then be mirrored through a datum plane (in this case the plane of the end curve) resulting in two surface which are then joined to form just one.

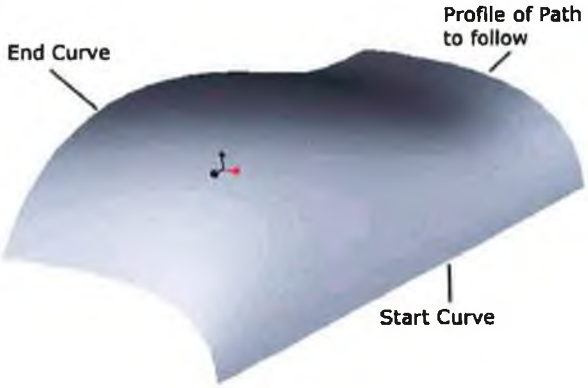


Figure 3.6. Initial Surface generation

A surface defined by a datum curve located on the plan datum (in this case the start curve is also located here) of the mouse is extruded vertically upwards. At the location where this surface interfaces the above, another joined is formed, which defines a rough exterior of the mouse.

Figure 3.7: Merged (joined) surfaces

A final flat surface and additional features, such as rounds and drafts can now be added in order to complete the exterior profile definition. This exterior profile can be used to create a solid model. It is also advantageous to create a parting surface which will be used as both the parting plane for the mould, and the separation surface of both the upper and lower components.

Figure 3.8: Exterior Surface and parting Surface.

3.7. MASTER MODELING TECHNIQUE

In the majority of cases the designer creates parts using complex surface geometries. This, results in several parts being created that contain numerous features involving different surfacing techniques. It is necessary that each of these parts mates perfectly together, a task that in itself is not difficult to achieve. In the event where design changes are necessary the designer must change each individual part. Afterwards it is necessary to ensure that the final assembly mates up correctly, which can prove to be very difficult. This can be the case with such consumer products as cellular phones, remote controls, and computer mice.

The Master Modelling Technique overcomes these problems. This technique generates a single model (master model) that drives the overall design of the product, rather than a number of individual components that have the necessary features. In the event of any design changes the designer only needs to update one model.

The process is relatively simple to incorporate. Initially, the designer generates the master model of the outside surfaces of the complete product (i.e. surfaces). The model itself would consist only of the exterior surfaces, and no solid components.

Figure 3.9: Master Assembly incorporating initial components

Initial components need also to be created. These are usually nothing more than the default datum planes saved as the component. These are then assembled into a master assembly as illustrated above. This is not the final assembly, but rather a working assembly to which additional geometries of the various components can be added as is required.

The geometry of the master model must now be published. Publishing the geometry is the process of generating geometrical features such as surfaces, datum curves, and points available to the various other components. Each of these individual components contains references to the master model. In the event that the master model changes, then the components will change also.

All the components contain the necessary information about the geometry, which has been copied from the master assembly to each of the components of the assembly. The designer can now create the solid models from the surface geometry and any other features such as bosses, holes, etc, that is required. The final step is to generate a new top level assembly with the solid components.

Figure 3.10: Solid Components and Additional Features

The process outlined above works well in the majority of cases, but, certain circumstances do arise where this does not hold through. One such instance is in the generation of the step feature where the upper and lower halves of the mouse meet. Ideally, a solid of the complete external profile of the mouse is first created. This solid is then cut, by the parting plane into the two respective halves of the upper and lower sections, each of which is then shelled using the shell feature. This should be sufficient and provide a profile through which a protrusion or a cut can be swept, in order to create the step. However, tangency between both does not hold for all sections, and a hump results. An alternative approach is required.

Rather than publishing just the external surface, extra surfaces, such as the interior, the surfaces of the step as well as surfaces associated with the button should also be published. These surfaces are merged as is required, resulting in a complete definition of the exterior and interior geometries of each individual component. Additional features such as the ribs and bosses can now be added as before.

Figure 3.11: Exploded View of Mouse Assembly

This results in a considerable amount of extra effort on the part of the design engineer, as the model becomes considerably more difficult to identify and understand. Extra attention must be invested when adapting this approach.

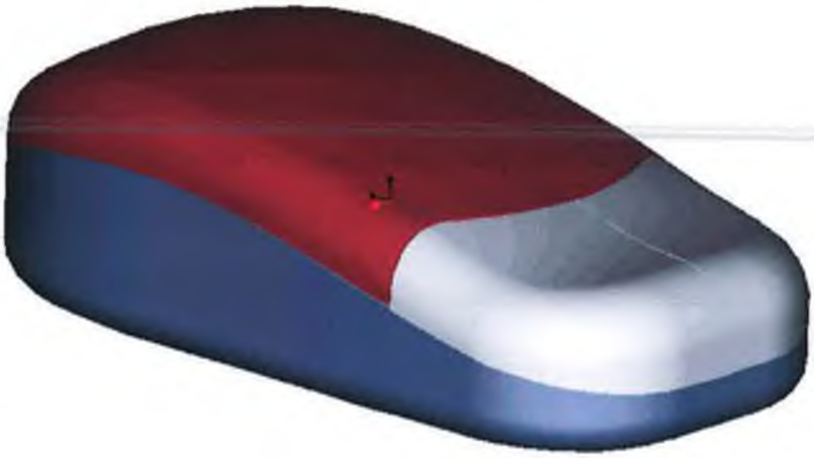


Figure 3.12: Completed Assembly

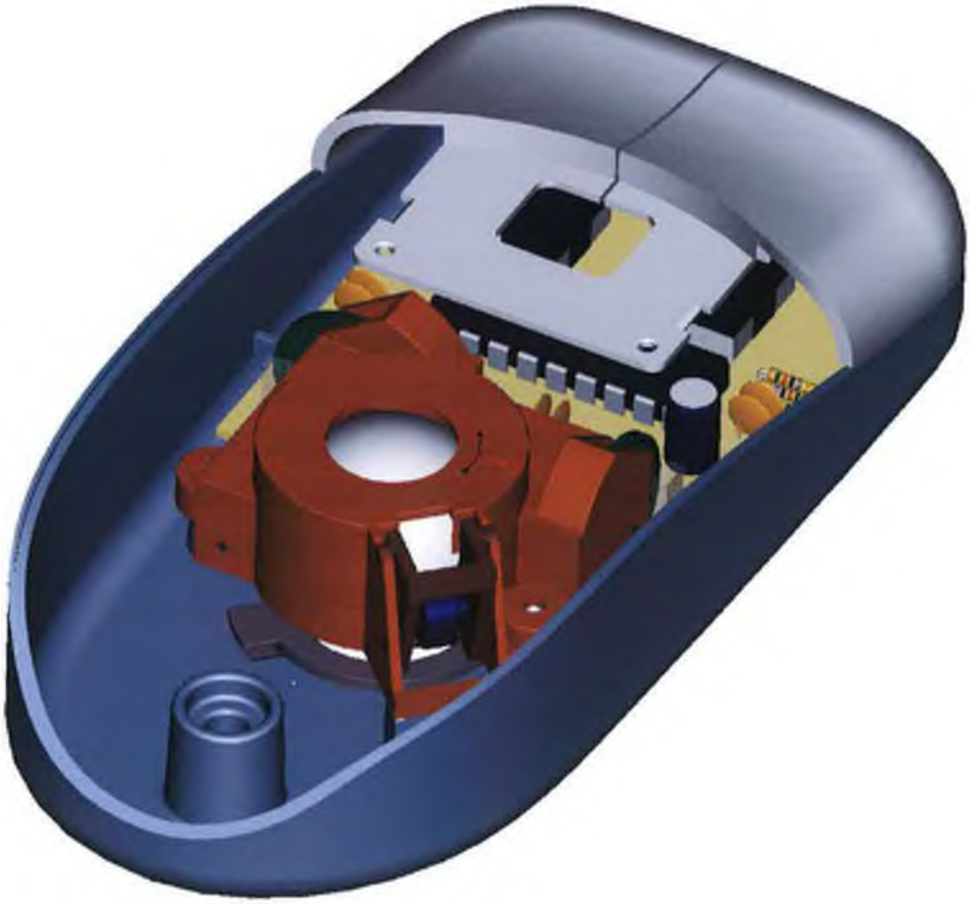


Figure 3.13: Internal View of Assembled Components

3.8. VOLUME CALCULATIONS

Some packages offer the ability to determine both the quantity of material that is required to manufacture a particular component and the volume of space contained within it. In order to determine the volume of a particular component, that component must be in a solid form. Surfaces will not suffice. The surface area parallel to the parting plane of the mould is what governs the clamping forces required for the components manufacture. Such tools help to reduce the cost of the design and give the designer added confidence in his design.

3.9. INFORMATION AND CLEARANCE/INTERFERENCE TOOLS

These tools can be subdivided into two categories, numerical, and visual tools. The exception to these two categories is the Draft Check. This is a numerical tool, which displays its results in a graphical format.

The suite of numerically based information tools can be used for the verification of wall thickness, positions, tangent conditions, draft angles, and other measurement quantities. These tools can be used to verify dimensional relationships, and also in the conformation that the geometry has been created as it was intended.

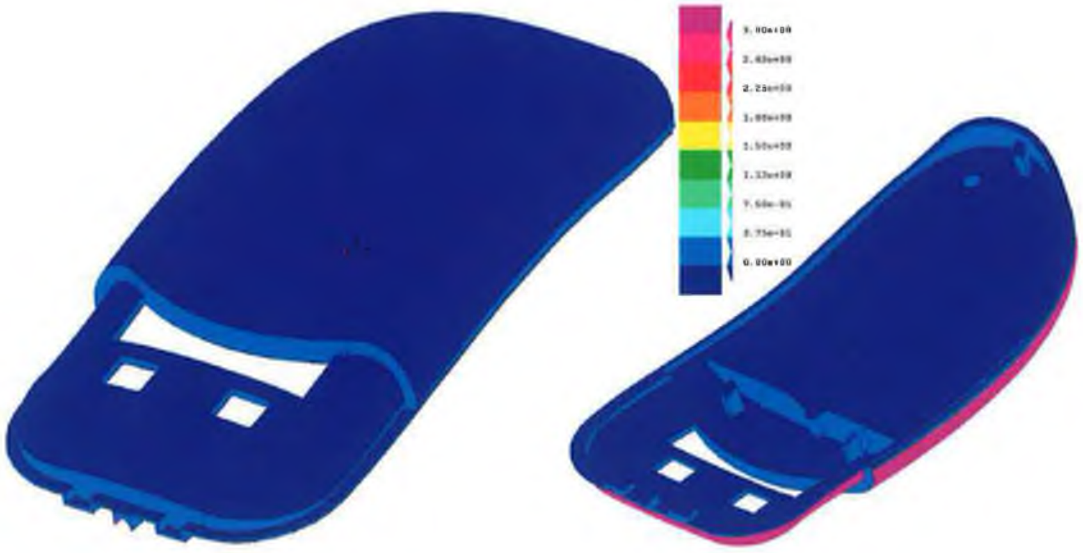


Figure 3.14: Top Cover Draft Analysis

The Draft Check tool is used frequently in the design of plastic components to verify the manufacturability of it (figure 3.14). The interpretation of the results obtained through this numerical visual tool requires a certain level of user expertise. This tool aids in identifying surfaces or portions of them which deviate outside the anticipated design specifications.

Other visual tools provided by the various packages are generally used in the analysis of the curvature of the surface. This form of analysis is often used when complex surfaces are generated. These tools identify bad curvature or breaks in the tangent condition of surface boundaries. Tools such as these are also a very effective means of examining imported geometries.

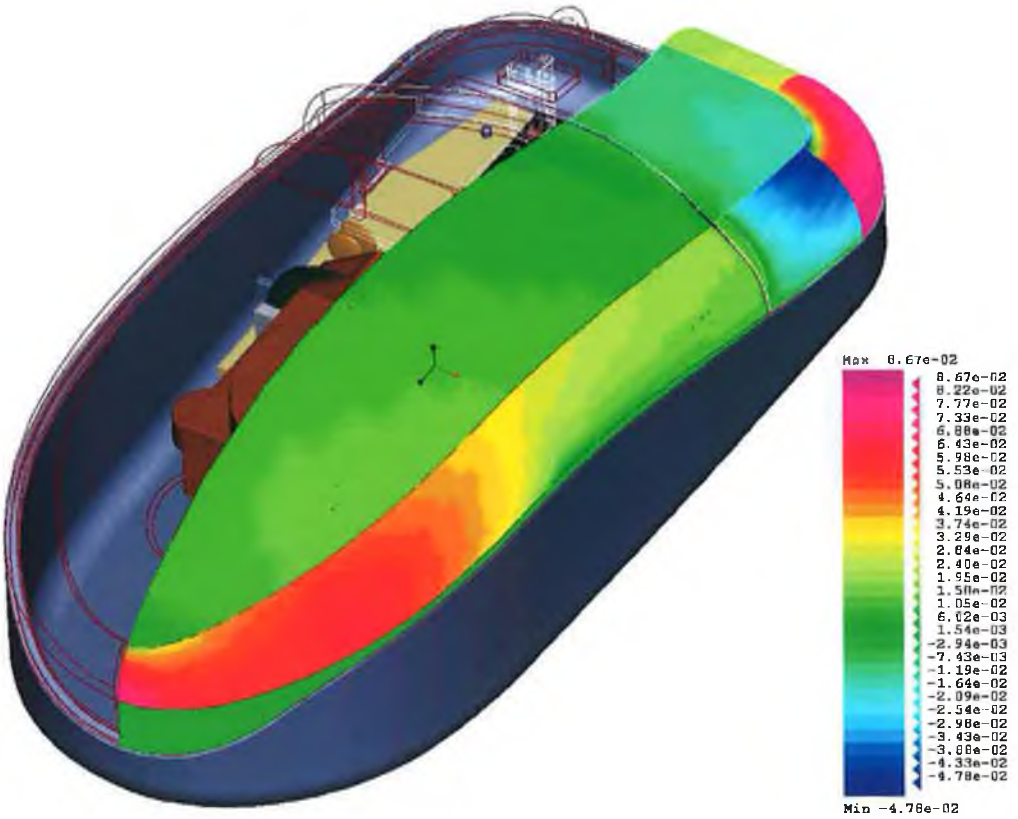


Figure 3.15: Top Cover Surface Curvature Analysis

Other evaluation tools such as clearance/interference checks are also available in most systems. These can be applied to the examination of individual surfaces as well as the surfaces of different components contained in an assembly. These tools operate in a similar manner to that of the distance tool, which measures the distance between two points.

INTRODUCTION

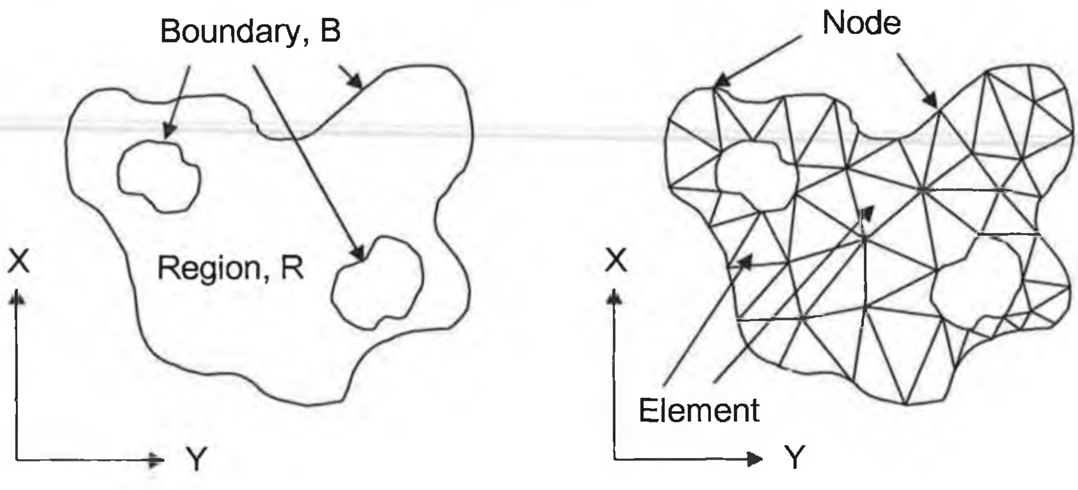
Computational techniques such as the Finite Element Method and Moldflow Analysis have established themselves as two of the most effective tools available to the modern design engineer [49, 50, 51, 52]. Any continuum the designer generates can efficiently be modelled and analysed using either or both of these means.

The chapter contained here under, aims to introduce the reader to the concepts and techniques associated with each of the individual methods. A study on a snap fit, which examines static, sensitivity, optimisation and non-linear analysis, presents the techniques associated with the Finite Element Method. Moldflow analysis is introduced through the examination of the fill characteristics of the upper and lower halves of the mouse design presented in the previous chapter.

4.1. FINITE ELEMENT METHOD

The development of this technique has been driven by ever increasing desire for much more accurate design computations in increasingly complex situations. As a result vast improvements were made in both the design procedures and the actual product design. The availability of much more powerful workstations which are capable of handling the immense quantity of calculations associated with conducting any FEA analysis has allowed the technique to migrate from the realm of the supercomputer to the desktop of the designer.

The ethos behind this technique, subdivides a complex problem into a series of interrelated sub-problems which can be solved by conventional means on a computational engine [50, 51, 52, 53, 54, 55]. Consider for example the 2 dimensional physical domain illustrated here under in figure 4.1, where some physical variable is governed by a physical law within the region R and is subjected to some known conditions at the boundary B.



a. Physical Domain b. Discretized Domain

Figure 4.1: Problem to be Solved.

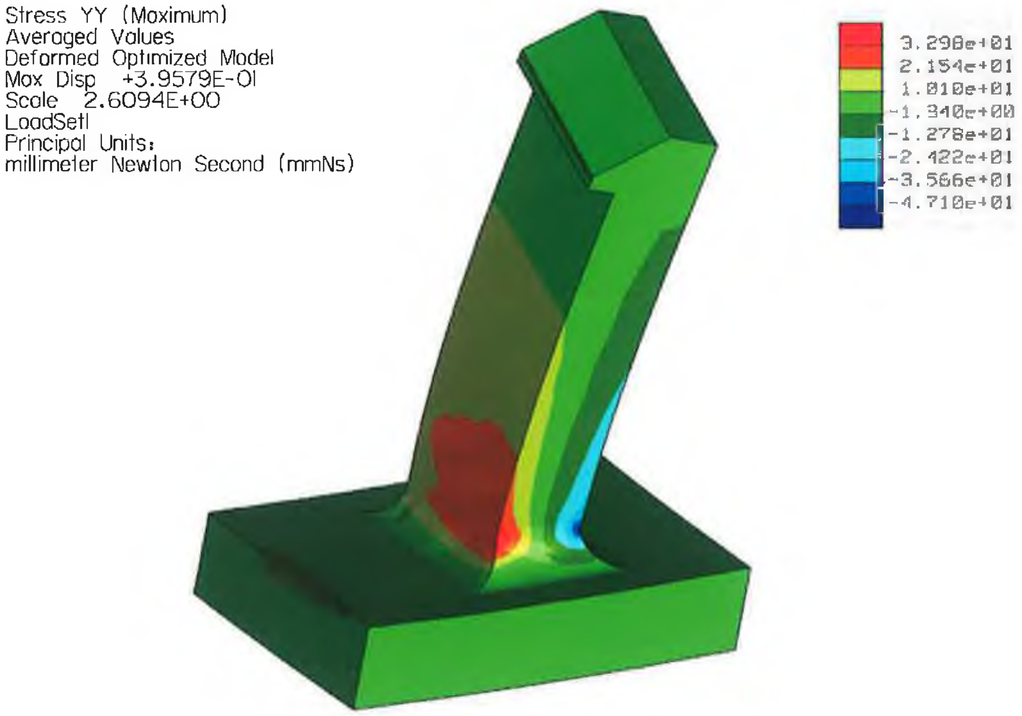
In the case of a two dimensional problem as presented in the figure above, the governing physical law might be expressed by the partial differential equation;

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}=0$$

which represents the temperature within a solid body which is governed by the conduction of heat within that body, where the temperature at the boundary of the entity is known [47]. The solution to this equation must satisfy some constraints on the boundary. Generally speaking such an equation is a simplified form of the actual entity where assumptions regarding the material being homogenous with constant linear properties, etc. are made.

In order to conduct the analysis of the region R, this area needs to be subdivided into a number of divisions as illustrated in the figure 4.1.(b). This subdivision, known as meshing can be either achieved manually or automatically. The mesh comprises of a number of elements which are mapped to the profile as accurately as possible. Each element which can be either triangular or quadrilaterals in the case of 2D problems, or as tetrahedral, bricks, or hexagonal prisms in the case of 3D problems, are bounded by nodes. These nodes are the connecting points of each element, and it is at these locations that all the solutions for the relevant variables are established which satisfy[1] the partial differential equation. These results are then transferred from that element to next.

The combination of the individual elements, the boundary conditions, and the interpolation procedures result in the transformation of the problems solution from a continuous differential equation into a large set of simultaneous linear algebraic equations. The solution of these simultaneous equations represents an approximation to the continuous solution of the initial partial differential equation and can be presented on a graphical contour plot similar to figure 4.2. The accuracy of this approximation needs to be considered.



Max Compressive and Tensile Stress in the Y Axis

Figure 4.2: Graphical Representation of a Solution (Optimised Mechanica Result)

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[1] In order to satisfy the PDE, the nodal values must satisfy a set of conditions which are represented by several linear algebraic equations. One way in which these PDE may be satisfied is to use interpolating polynomials.

4.1.1 P-Elements Vs. H-Elements

The classical approach to ensuring an accurate solution is to adapt the h-method [2, 45, 50, 51]. In this case the mesh size is continuously redefined until each successive analysis results in a similar solution. Ideally, if the mesh was approximately close to zero, an accurate solution would result. This however is not achievable.

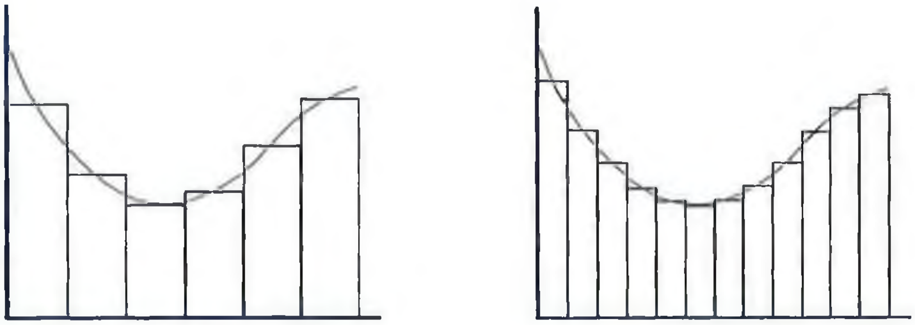

Figure 4.3: H-Element Approximation of Stress function in a Model

An alternative element technology is that of the p-method [50]. In this instance the element edge order is increased up to a maximum of nine, in order to approximate more accurately the desired geometry and hence reduce any error's that may arise. Accuracy is deduced by establishing the difference that exists between the last two sets of results, the result of which is compared to a user defined value of convergence, which is typically between 5-15%. If the solution has not converged by the last set of results, then the mesh must be redefined using smaller elements and the analysis run again.

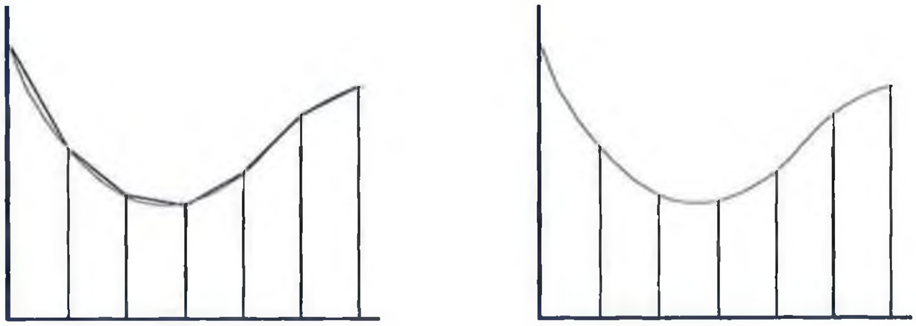

Figure 4.4: P-Element Approximation of Stress function in a Model

4.1.2 CONVERGENCE

Convergence is the process of obtaining the optimal set of results for the problem under consideration when the geometry, boundary conditions and properties are all considered [2, 50, 51, 53, 56]. For any given problem, the accuracy is controlled primarily by the mesh, but a converging solution may not represent the most accurate solution in the real world. The accuracy of the solution is dependent upon both the initial goals of the analysis and the confidence that is placed in all the simplifying assumptions.

In order to demonstrate exactly what is happening with convergence, an analogy between it and basic calculus can be used. The area under any curve can be established by the using integrals and a series of rectangles, the height and width of each is known. As the number of rectangles increase, the accuracy of the solution improves when the problem is solved.

An increase in the number of elements or nodes contained within the physical domain yields a similar result for the finite element method. A graphical illustration of stress vs. number of Nodes for a snap fit is presented in figure 4.5.

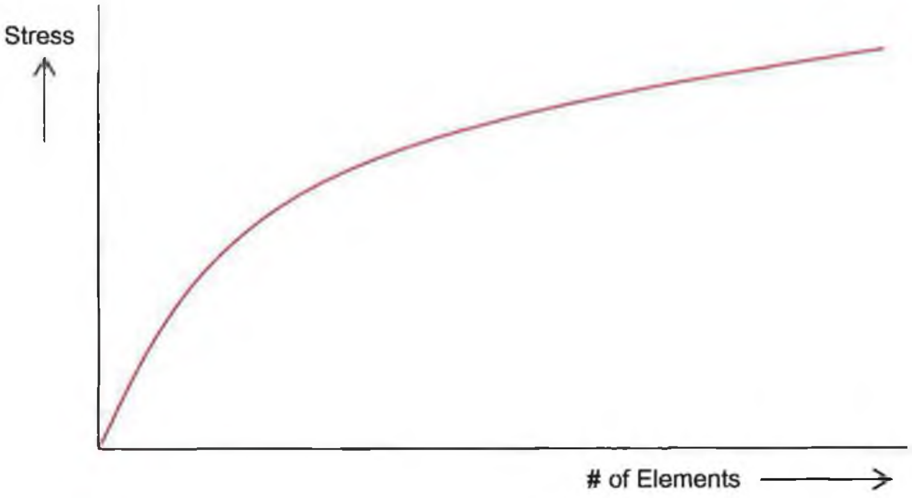

Figure 4.5: Graphical Illustration of Stress Vs. Number of Nodes

In the case of a linear analysis, as the number of nodes increase, the geometry becomes less rigid and more flexible [50, 51, 53, 56]. For a given load the stress will rise as the mesh density increases up to a maximum level, where any further increase in this mesh will result in a negligible effect on the results obtained [51, 53, 56]. This is in accordance with Young's Modulus, where stress is directly proportional to strain.

The degree of convergence of an h-method model is best expressed as the percentage difference between the two most recent mesh refinements. Convergence in the case of the p-method is established at the commencement of the analysis, where the user defines it as a percentage. The order of the governing differential equation is increased and solved until the solution converges within the limits defined. Refer to Appendix B for a P-method Analysis summary file.

4.2. COMPUTATIONAL MODELS

In an ideal world the seamless transfer of a solid model from a vendors CAD system to another's FEA system is often proclaimed. This however is a not practical option for most instances in the real world. Solid models are usually generated to provide a significant database of information (which includes all minor features as well as dimensions, surface finishes, processing procedures, etc), for the complete manufacturing process.

FEA is generally concerned with determining if the component design is capable of functioning within in its intended environment when all external conditions such as boundary and loading conditions are considered [50, 51, 54]. This can be established quite effectively by considering a simplified representation of the actual component or solid model. Factors such as symmetry, thickness and the removal of minor features which are incorporated only for aesthetic purposes can all contribute to the generation of such a representation.

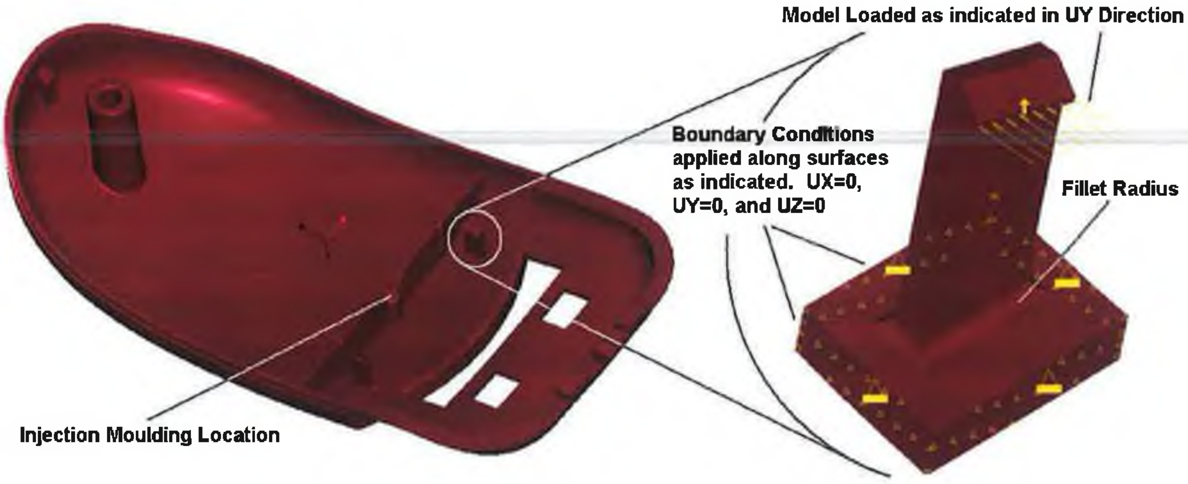

Figure 4.6: Moldflow Analysis and Idealised FEA Models

The models for both the FEA and moldflow analysis differ as indicated in the illustration above. In the case of the FEA analysis the model is idealised so that features that will have no effect on the analysis at hand are removed. The actual moldflow analysis model is the same as that of the solid model.

4.2.1. STATIC LINEAR ANALYSIS

Static linear analysis is probably the most common of all FEM procedures implemented by designer the world over. It essentially calculates the effects of steady loading conditions on the model at hand, while ignoring inertia[2] and damping effects [2, 50, 51, 56]. The procedure determines displacements, strains, stresses and forces within the design caused by the various loading configurations. It is assumed in such an analysis that the loads and designs structure vary slowly with respect to time.

A static analysis can be applied in order to determine if the snap fit design as illustrated in figure 4.6, is sufficient enough to withstand the maximum stress induced on it when it is deflected by the assembly of the button. This analysis is conducted by applying a deflection equivalent to the amount that it will deflect during the assembly processes.

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[2] NOTE: Steady inertia loads, i.e. rotational velocity and gravity, as well as time varying loads which can be approximated as static equivalent loads, i.e. wind etc.

The solution to such an analysis may indicate that the design is inadequate and needs refinements which can be as simple as increasing the thickness of the cantilever section and or increasing the radius of the fillet. Additional studies, such as sensitivity and optimisation, can be conducted in tandem with a static analysis in order to automate this process.

The sensitivity study, examines how the modification of a particular dimension over a specific range (defined by the user) will affect the overall analysis without having to actually modify the dimension manually. An optimisation study on the other hand will identify a specific value for a dimension which will be sufficient to withstand a user defined value of, stress, strain, deflection, etc. The application of either or both these studies can reduce the time involved in conducting any analysis.

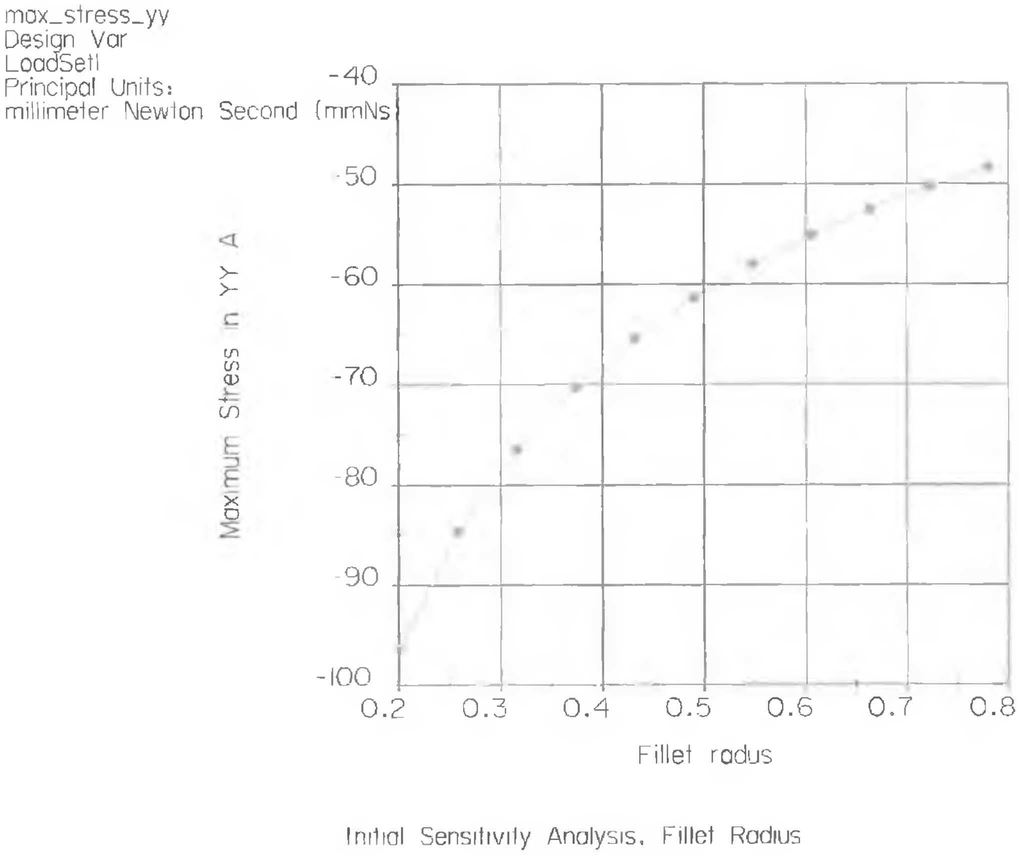


Figure 4.7: Sensitivity Analysis for Fillet Radius

For the case of the snap fit introduced above, each of these studies was conducted in order to the determine the optimum value for the fillet radius, which would result in both the compressive and tensional stress being kept within the limits defined by the material vendors data sheet. The static analysis Results obtained from both Pro-Mechanica and ANSYS, are presented in figures 4.2., and 4.8. respectively. The optimisations and sensitivity analysis were conducted through Pro-Mechanica solely as mesh refinement was not necessary. It was observed that the initial results obtained from ANSYS, did not concur with those obtained from Mechanica. This can be best explained by examining figure 4.5 (ANSYS employs the H-Method, and the initial model only contained 215 elements). The element density was increased to maximum allowable (educational ANSYS limits). As the fillet radius increases in size, the stress level found in the region decreases figure 4.7. An actual size of fillet was obtained by specifying a stress level, and then conducting an optimisation analysis.

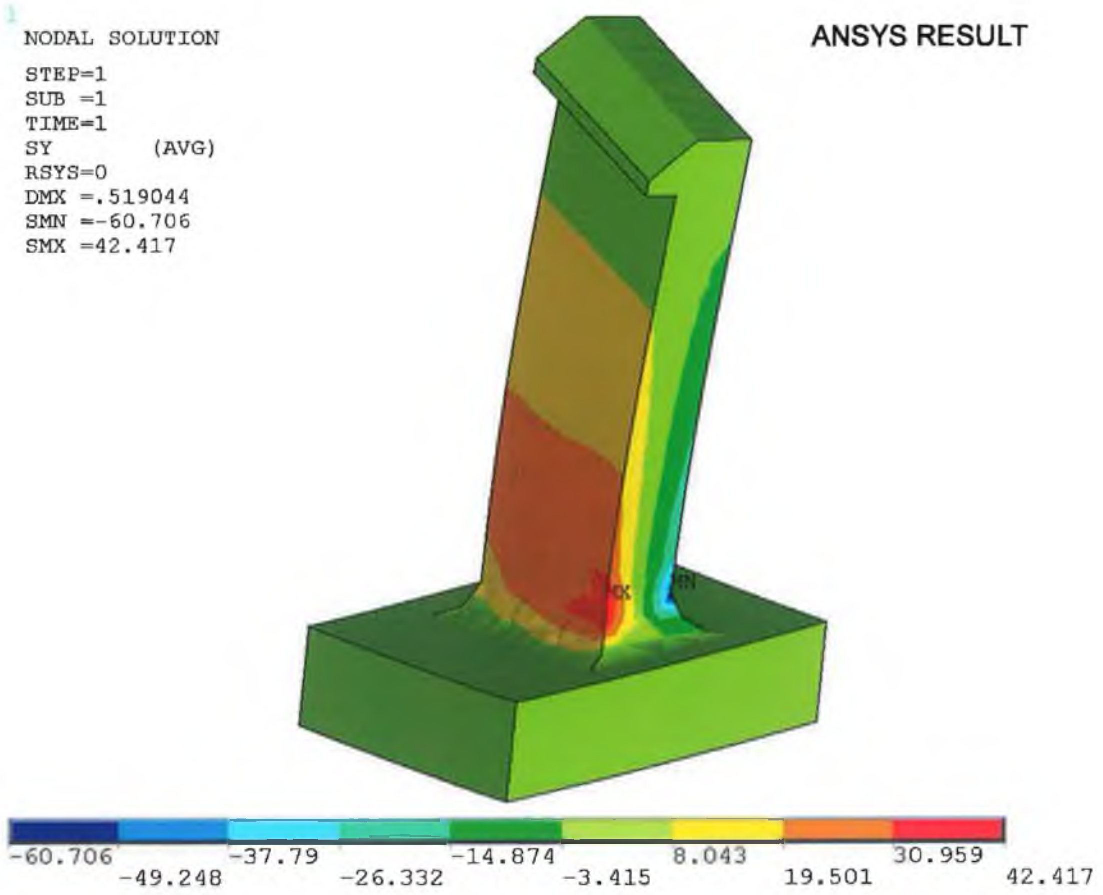


Figure 4.8: ANSYS Result (units=mmNs)

4.2.2. NON-LINEAR ANALYSIS

"A nonlinear solution will be as accurate as a linear solution, if not more so" state Vince Adams and Abraham Askenazi in their book, Building Better Products with Finite Element Analysis. They continue by stating "*If nonlinear analysis were as fast, easy to set up, and inexpensive as linear analysis, the 'to use or not to use' questions would not arise*". The fact remains however that nonlinear procedures require considerably more effort in their preparation and take considerably longer to solve than similar linear studies. Implementing such a procedure adds considerable time and cost, so why use it and what exactly is it?

Nonlinear analyses involve interdependent interactions, which sometimes result in abrupt changes in the system's behavior [57]. The algorithms associated with the procedure breaks the problem down into many smaller piecewise-linear solution increments in order to mathematically deal with large changes or singularities involved. The solution of each increment is totally dependent upon the results obtained from the previous increment, with the appropriate nonlinear properties updated along the way.

Principal engineer Walter Schmidt of CAE Applications explains, "Instead of solving a problem in one step, we solve the problem in, let's say, 100 steps of 1% of load applied in each step. Whereas in linear analysis, we can use the 1% results and multiply by 100 to obtain the 100% results. In nonlinear analysis, the results are not scalable." Thus, the 1% results are used as new inputs for the 2% analysis, and so on". [58]

The long term integrity of a snap fit (such as presented earlier), is one of the key considerations which should be addressed when designing such a feature. Its primary function is to hold two components firmly together. In the event that a feature such as this is deflected over an extended period of time, it will experience stress relaxation, which may result in unacceptable permanent deformations or loss of assembly preload. Stress Relaxation, which is similar to creep, is a time dependent plastic deformation under a sustained deflection (load in the case of creep). This phenomenon can be modeled by various material models, the constants for which can be derived from material property data [59, 60].

Non-linear material models are the most difficult type of nonlinear problem, as they tend to increases in complexity with the degree of increasing plasticity versus elasticity. Material vendors test data should always be verified before its incorporation in any non-linear procedure, and ideally one's own material data should be obtained by conducting material tests. Creep data is usually presented in terms of creep modulus versus time, the creep modulus, consolidating the applied stress and total measured strain. This information must be converted into empirical mathematical creep functions or models which can be applied to the various FEA solvers.

The majority of FEA solvers offer to the user a number of material models which describe the creep behavior of viscoelastic materials. These material models generally explicitly separate variables as functions of stress temperature and time. Time and stress are typically given the form of a power relation i.e. σ^n and t^m where n and m are empirically derived constants. The temperature function normally takes the form exp(-Q/RT), where Q is the activation energy, R is the Boltzmann's constant, and T is the absolute temperature. These various parameters can be combined to form the creep function:

where a_0 is an empirical constant. This formula can be simplified

$$\varepsilon_{cr} = (a_0)\sigma^n t^m e^{\left(-\frac{Q}{RT}\right)} \qquad \{4.1\}$$

further in the instance where a constant temperature is present;

$$\varepsilon_{cr} = (a_0)\sigma^n t^m \qquad \{4.2\}$$

Or

$$\ln\varepsilon_{cr} = \ln a_0 + n\ln\sigma + m\ln t \qquad \{4.3\}$$

This formula can take the form of $y=ax+bz+c$, and the error q can be determined:

$$q \equiv error \equiv \sum \left[y_i - \left(ax_i + bz_i + c\right)\right]^2 \qquad \{4.4\}$$

for which the error can be minimized by a process of linear regression;

$$\begin{aligned} \frac{\partial q}{\partial a} &= 0 = \sum \left[x_i y_i - ax_i^2 - bz_i x_i - cx_i\right] \\ \frac{\partial q}{\partial b} &= 0 = \sum \left[z_i y_i - ax_i z_i - bz_i^2 - cz_i\right] \\ \frac{\partial q}{\partial c} &= 0 = \sum \left[y_i - ax_i - bz_i - c\right] \end{aligned} \qquad \{4.5\}$$

These can be written in matrix format where $y=\ln\varepsilon_{cr}$, $ax=m\ln t$, $bz=n\ln\sigma$, and $c=\ln a_0$, as;

$$\begin{bmatrix} \sum t_i^2 & \sum \sigma_i t_i & \sum t_i \\ \sum \sigma_i t_i & \sum \sigma_i^2 & \sum \sigma_i \\ \sum t_i & \sum \sigma_i & n \end{bmatrix} \begin{Bmatrix} a \\ b \\ c \end{Bmatrix} = \begin{Bmatrix} \sum t_i \varepsilon_{cr_i} \\ \sum \sigma_i \varepsilon_{cr_i} \\ \sum \varepsilon_{cr_i} \end{Bmatrix} \qquad \{4.6\}$$

The parameters a, b, and c can be determined so that;

$$\varepsilon_{cr} = e^c \sigma^b t^a \qquad \{4.7\}$$

where $a_0=e^c$, $n=b$, and $m=a$

given this equation, the creep strain function based on the average parameter values derived from GE-Plastics own material data, can be written as;

$$\varepsilon_{cr} = \left(3.42716E-09\right)\sigma^{4.321843622} t^{0.5372264} \qquad \{4.8\}$$

for time (days), stress (MPa) and constant temperature. Finally, the majority of FEA solvers use an incremental form and in the case of ANSYS, a numerical time stepping procedure based on the incremental strain rate. This strain rate can therefore be determined by partial differentiation;

$$\dot{\varepsilon}_{cr} = \frac{\partial \varepsilon_{cr}}{\partial t} = ae^{c}\sigma^{b}t^{(a-1)}$$

therefore {4.9}

$$\dot{\varepsilon}_{cr} = \frac{\partial \varepsilon_{cr}}{\partial t} = 1.84116e-09\sigma^{4.321843622}t^{-0.46277356}$$

FEA solvers which support this form of equation can accept these parameters as material constants in a creep table. This formula can be applied to the non-linear analysis of the snap fit presented in figure 4.6, with a similar loading and constraint configuration. A time stepping algorithm can also used with the total duration being 320 days and 730 intervals. The results of such an analysis are presented hereunder.

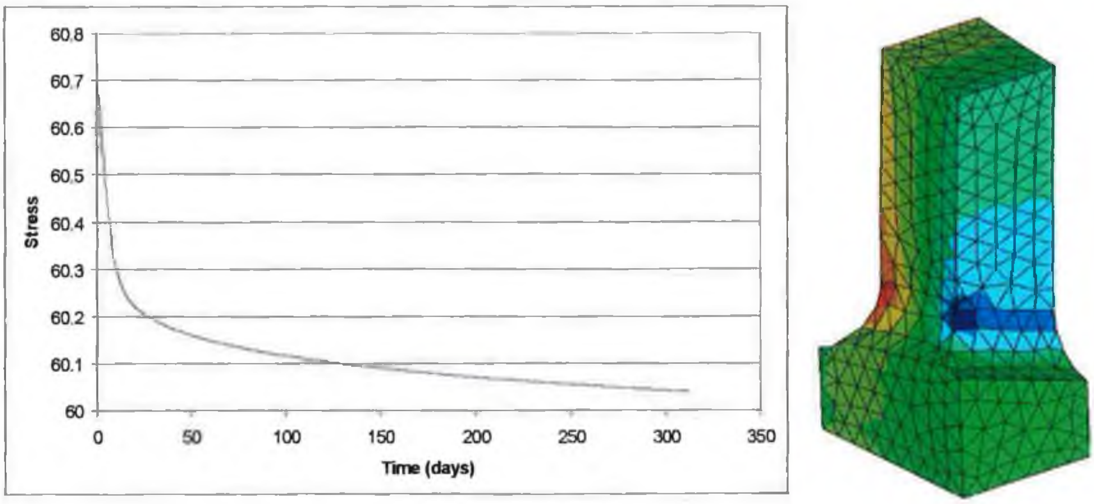


Figure 4.9: Stress Relaxation Analysis of a Snap Fit Submodel

4.3. PLASTIC FLOW SIMULATION

The determination of the flow characteristics of any plastic material and how it conforms to the component design has remained the domain of the mold design specialist for many years. Recently however, simulation software which automates and conceals the finite element operations has emerged which allows the product designer to make these determinations in a relatively short time frame and at a considerable cost saving [52, 61, 62, 63]. These tools seamlessly integrate into the most prominent CAD packages and require only background knowledge of plastic engineering and an ability to interpret the results obtained.

The development of these tools has been primarily focused towards the design engineer hence they do not take into account matters such as feeding systems. It is not possible therefore to balance a family mould. Essentially the analysis commences from the injection point, which is the point immediately downstream of the gate. Each individual component design can be optimized for the most suitable injection point, or points.

A 3D solid model of the actual component design is the initial input that is required in order to conduct an analysis. In the majority of cases the tool will accept a native file format from the CAD system, or failing this a Surface Tessellation Language (refer to section 5.2., chapter 5) format will suffice. In the past, the remodeling of such designs was necessary in order to generate a mid-plane mesh, which the flow analysis software could work with. This was a very laborious task which required considerable skill, extensive practice and above all else lots of time. The new generation of tools employs a technique developed by moldflow known as Dual Domain.

Implementing a flow analysis is simplicity in itself. Within the solid model that appears on the screen, the injection moulding point('s) is located (figure 4.6), a material is selected from a database of approximately 4500 grades, and finally the analysis is started. If the user selects an injection point which may be not unsuitable, then the system flags up a series of warnings and makes recommendations. Upon completion of the analysis, the results can be view as a series of contour plots.

The results presented below include confidence of fill, fill animations, air traps, weld lines, injection pressure, pressure drop, fill time and temperature at the flow front. Technical help files known as advisers can be obtained by right clicking on any of the result widows. The actual contour plots can be viewed in Appendix D.

Flow Analysis Results			
	Components		
	Top	Bottom	Button
Material Supplier	GEPlastics	GEPlastics	GEPlastics
Material Grade	Cycolac X37	Cycolac X37	Cycolac X37
Confidence of Fill	High	High	High
Fill Time	0.4 sec	0.4 sec	0.41 sec
Injection Pressure	72.72 MPa	74.39 MPa	70.24 MPa
Pressure Drop	73.92 MPa	83.61 MPa	70.24 MPa
Flow Front Temp	261.28 Deg C	260.48 Deg C	262.25 Deg C
Weld Lines	Yes	Yes	Yes
Air Traps	Yes	Yes	Yes

Table 4.1: Plastic Flow Simulation Results for Various Components

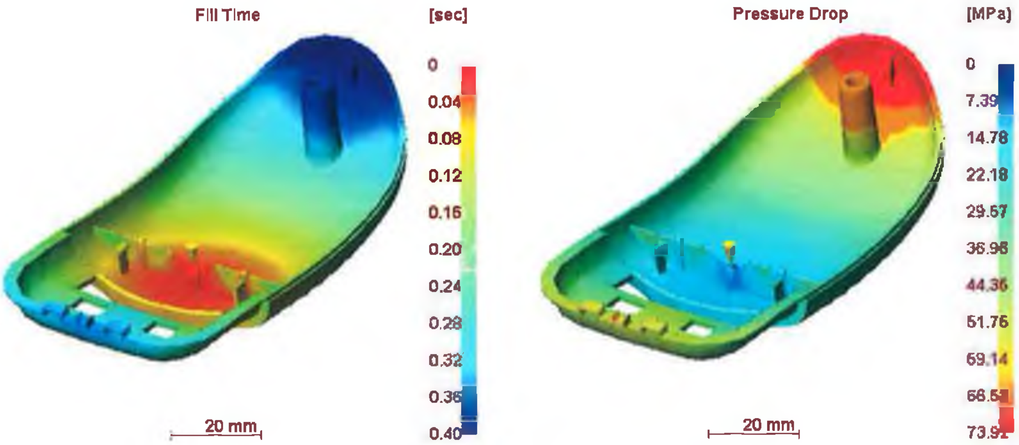


Figure 4.10: MoldFlow Contour Plots

INTRODUCTION

In today's highly competitive market place, manufacturers can no longer afford to spend years designing, prototyping, testing and tooling a product that may have a very limited life span [2, 3, 9, 10, 12]. This is none the more evident in the mobile phone industry, where a new product has an effective shelve life of less than 12 months. In order to keep pace with this fast changing market, manufactures need to embrace new technologies.

Rapid prototyping is one such emerging technology that is rapidly becoming a necessity rather than a novelty. The process significantly impacts the way these products are being designed, manufactured and tested [9, 10, 12, 14, 55]. This technology has now become the most important tool available to the modern design engineer since the advent of Computer Aided Design packages. When both these technologies are married together, they yield a strong and competitive edge to design and manufacturing.

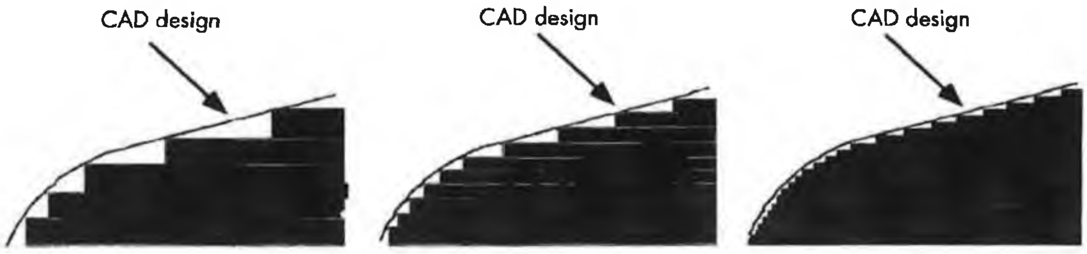
A multitude of Rapid Prototyping technologies now exist, arming the design engineer with a much greater choice of materials and processes. Each of these technologies have there own advantages and disadvantages, and their selection is very dependent on the job at hand. The following discussion aims to introduce each of these rapid prototyping technologies, their benefits to the design and how to implement a successful RP design strategy.

5.1. RAPID PROTOTYPING

In the past several terms have been used to describe this process including, Solid Freeform Fabrication (SFF), Computer Automated Manufacturing, and Layered Manufacturing Techniques (LMT), to name but a few. However, the term Rapid Prototyping (RP) seems to have become the standard.

The Process can probably be best described as a means of creating a scale model of a component or assembly using a three-dimensional CAD dataset. Conventional techniques generally require the subtraction of material by some form of cutting tool, which has the net result of producing either a part or a tool to manufacture many parts. However in the case of one of the rapid prototyping processes, the opposite is the norm. This is to say that rather than removing material, the material is added layer by layer, in a process similar to printing.

Models, which have been generated on one of the many processes available, inherently do have some limitations. One such limitation arises from the layering technique, in that it tends to produce a stepping or a staircase type surface finish as is illustrated in figure 5.1 below [16]. This problem can be somewhat reduced by selecting a process with a smaller layer thickness and/or employing some form of a post processing procedure. Another limitation is that the choice of material is still very limited [64]. Models created by one of the many different machines are not suitable for end run components due to limited range of materials.



Large layer thickness Medium layer thickness Fine layer thickness

Figure 5.1: Stair Stepping Effect Vs. Layer Thickness [16]

In the past many manufacturers have been put off using these technologies, due to the fact that they have experienced rather expensive, fragile, and very inaccurate models [9, 10]. The past decade however has seen some major advances in materials, and accuracy. This coupled with the fact that products can now be brought to the market place at a much greater pace, and that the amount of costly mistakes can be decreased by a significant amount has merited a review by many of the various processes at their disposal [3, 9, 10, 44].

5.2. CAD SOLID MODELING AND FILE TRANSFER

Both Rapid Prototyping and solid modeling are two technologies, which are mutually compatible. Solid modeling benefits from RP in that a three dimensional representation of the end product can be obtained with relative ease, while RP benefits from solid modeling in so far that it provides the data to be modeled [9, 10, 16, 44, 64] . Without a CAD model, it's impossible to produce an RP component except in the case where other mediums such as CT scanners and 3D digitizing systems, are utilized.

The most common method of creating a CAD model is either by solid or Surface Modeling. The Latter is much more acceptable to the polymer industry in so far that it allows for complex geometries to be created with relative ease. The main draw back with this surface definition approach is that the external boundary must be completely closed in essence forming an external skin, which is watertight [13, 16, 44, 64]. In the case where solid modeling is utilized, a solid geometry, which can include material information, mass, density, etc. can be defined. This ensures that the geometry is completely closed, as it creates a solid entity.

The majority of RP machines cannot interpret the CAD file in its native form. A pre-processing step, which converts this file to a format that the RP machine can interpret, is necessary. This is achieved by exporting the CAD dataset, as a Stereolithography or Surface Tessellation Language (STL) file format [13, 16, 44, 54, 64].

This STL file format generates a mesh of triangles over the complete surface of the part as illustrated in figure 5.2. This meshed surface is a true representation of the surface geometry of that model. Needless to say, the smaller the triangles used to define the shape, the closer to the real part the eventual prototype will be.

FIGURE 5.2: Mesh of Triangles

Another key to the generation of a good quality prototype is that of the build orientation [13, 16, 64]. As mentioned previously, all rapid prototyping process have the unique characteristic of creating objects having a stair or step type surface finish. By orientating the model it may be possible to minimize this effect.

The majority of Rapid Prototyping processes require some form of supporting structure. The necessity of such a structure can be some what minimized by correctly orientating the model. Once a suitable orientation has been established, the software program analysis the STL file and endeavors to identify any overhangs that may require some form of support during the build process. If adequate support is not provided during the build process, then the part may collapse, or de-laminate during layering [64].

The final phase in the preparation of the model for manufacture on the RP machine is carried out within the software provided with the RP system. It is here that both the STL CAD and support files are sliced into the various layers representing a section through both files, and therefore a new slice file is generated. The thickness of each of these layers is dependent on the RP process being employed, but in general can range from 0.05 mm to 25 mm. This new slice file contains all the positional data that is required for scanning or plotting of each on top of one another.

5.3. RAPID PROTOTYPING TECHNOLOGIES

The concept behind all rapid prototyping techniques is that an actual three dimensional model is constructed layer by layer from the cross-section profiles taken through the CAD model which has been converted to the an STL file as outlined above. This is an additive, rather than a subtractive process hence there is no need for any machining.

Up until recently all RP processes could have been categorized as Machine Room Technologies [14]. These machines produce prototype parts, which are more that acceptable as either patterns for rapid tooling or as rapid tools themselves. The newest category of RP processes, which has emerged are those of the concept modelers. These machines do not have the same choice of materials, the accuracy or even the reproducibility but they do offer a valuable tool early in the design phase in so far that evaluation models can be obtained easily. These models can aid in the effective communication of design ideas.

5.4. MACHINE ROOM TECHNOLOGIES

5.4.1. STEREOLITHOGRAPHY

Stereolithography was the first RP process to be made commercially available in 1988. Since then it has established itself as the most widely used process, with a wide variety of machines utilizing different resin and laser combinations for each individual application. The smallest machine available in the range has en effective work envelope of 250*250*250 mm and uses a 40 mW helium-cadmium laser, while the largest machine has an effective work envelope of 500*500*600 mm, and is fitted with a solid state laser which can deliver up to 1 W of power [13, 64].

The system employed by this process is relatively simple and has been made to produce excellent results by careful development and careful process control. The liquid polymer, resting on an elevator tray, is stored in a vat. The elevator tray starts just (>0.1mm) below the surface of the liquid. Located above the vat are two galvanometer-controlled mirrors. These mirrors direct a fine laser beam onto the surface of the liquid contained within the vat. At the location where the laser strikes the surface, and only within the diameter of the beam, the liquid polymer solidifies. The laser is directed onto the surface of the liquid polymer, so as to trace out the profile of that section on that layer. Upon completion of that layer, the elevator, and the existing model are lowered into the liquid. A fresh layer of the liquid flows over the top of the layer just lowered, and the process is repeated. The next layer is built on top of the previous and so on until the model is completed and fully submerged. The model is then raised and removed.

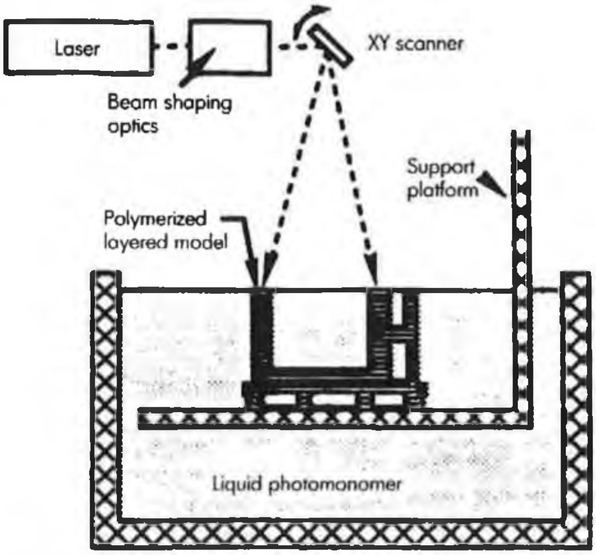


Figure 5.3: 3D Systems Stereolithography RP Machine. [13]

A wide variety of photo curable polymer resins are now available which can be used with this process. For general purpose prototypes, both DuPont and Vantico (formerly Ciba Specialty Chemicals) produce acrylic and epoxy based resins, while a specialized bi-colored acrylic resin which can be utilized in the medical sector, is produced Zeneca Specialities [13, 16, 64]. Resins are also available which can be used for production of prototype components which can used, in high temperature applications up to 200° C, or as mould tools for limited production runs.

Main Advantages	*Main Disadvantages*
▪ The machine can run virtually unattended. It is advisable however to have an operator on hand, in event of unforeseen problems arising ▪ Components can be as detailed as necessary ▪ Components are suitable for a wide variety of applications ▪ Accuracy of (0.1 mm can be obtained refer to Computer Mouse Case study) ▪ The surface finish is of an excellent standard (refer to computer Mouse)	▪ Machines are extremely expensive, typically of the range €150K-€1M ▪ Supports are required when building overhangs (additional material required) ▪ Some Resins are very hazardous and require careful handling and storage. ▪ Components are prone to warpage if not handled correctly ▪ Machine needs to be installed in a sealed room (i.e. toxic Resins)

5.4.2. SELECTIVE LASER SINTERING

The general principle of Selective Laser Sintering is very similar to that of Stereolithography, except that rather than depending on UV radiation emitted from the laser to cure the material, this process depends on the heat generated from the laser to fuse particles together. To this end, the process requires a much higher powered, laser, generally of magnitude of 50 W and 200 W of power for plastic and metal components respectively [13, 16, 64].

The process utilizes a powder, either plastic or metal, rather than a photo curable polymer. A thin layer of this powder is spread over the surface of the build support table. The laser is then directed onto this surface and the particles of this powder is fused together while the laser traces out the profile of the cross-section to be generated. Once this layer has been created, the table is lowered, and a new layer of powder is spread on top of it. The laser is once again directed onto this new surface, and it traces out the next cross-sectional profile. This layer is fused to the layer preceding it by the heat generated by the laser. This process of sintering, re-coating and sintering is repeated until the complete prototype is created. The powder acts as the supporting structure for each successive layer.

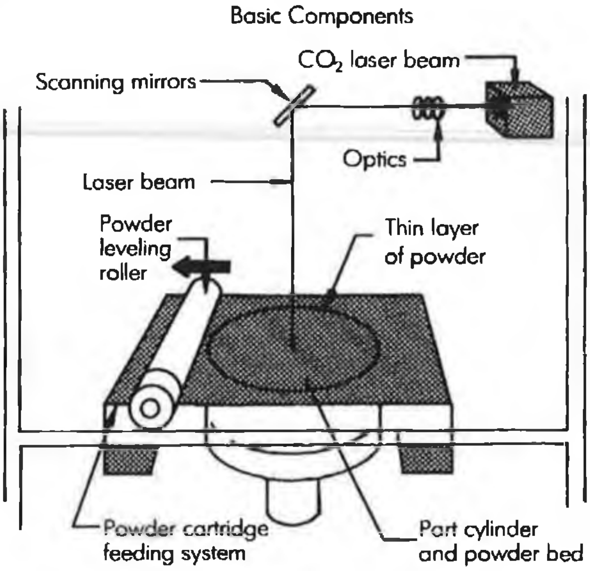


Figure 5.4: Selective Laser Sintering System. [13]

Main Advantages	*Main Disadvantages*
▪ The need for supports is completely removed by the build material ▪ No post curing is required ▪ Large range of materials to select from ▪ The process can use metals, or ceramics ▪ More and More Rapid Tooling process are emerging which utilize this process ▪ Rapid Tools can be created directly on this system	▪ The surface's of the prototypes are usually porous and may require some post processing to minimize this ▪ Copper and steel parts require some form of post-processing ▪ Some materials require supports as the build progresses ▪ The machines can take considerable long periods of time to heat up and cool down

The main advantage of this process is the fact that there is a wide variety of materials to choice from. For the more conventional prototypes, these include, nylon, polycarbonate, glass filled nylon or rubbery flexible materials. Metallic components can also be manufactured with this process quite simply. The process can also be used to manufacture cores and cavities for the gravity casting industry.

5.4.3. LAMINATED OBJECT MANUFACTURING (LOM)

The method employed by the LOM differs considerably from those already discussed. A sheet of material normally paper is laid down on a worktable.

A laser or a blade, which only cuts to the depth of a single layer, is then directed by an XY plotter, which traces out the outside profile of the layer to be built. Any unwanted material is also crosshatched at this stage. A second layer of paper, the underside of which has a bonding attached, is then laid down on top of the first and a heated roller is passed over the two. This roller squeezes the two sheets together, thereby bonding them. This process is repeated until the whole model has been built. The unwanted material needs to be removed manually.

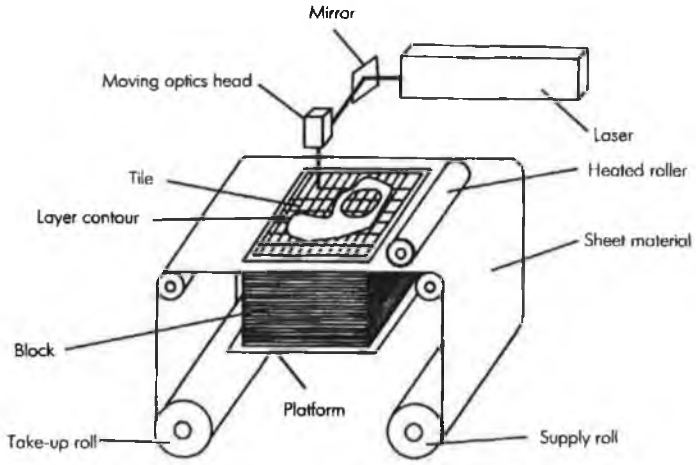


Figure 5.5: LOM System Arrangement. [13]

This process has been around for almost as long as the Stereolithography. The process has not really been improved upon since its inception. The materials available are still very limited, but can accommodate much larger prototypes than any of the process available.

Main Advantages	*Main Disadvantages*
▪ The supports is completely eliminated ▪ Very large components can be catered for (refer to discussion chapter for typical work envelope) ▪ The process is very simple and clean ▪ No post curing of the prototypes is required	▪ The prototype parts when constructed from paper and therefore will absorb moisture ▪ The surface finish is rather poor, where the stair-stepping effect is very evident ▪ The machine design is very crude ▪ The software is reported to be not very user friendly

5.4.4. FUSED DEPOSITION MODELLING

This process differs somewhat from processes discussed above. In this case either a molten polymer material or an investment casting wax is extruded out through a fine nozzle. This nozzle is positioned in both the X and Y, axes by means of a drive screw coupled to a stepper motor. The material is extruded onto a build table, which is positioned in the Z, axis by a similar arrangement [10, 13].

The extrusion head consists of two nozzles, one for the build material, and the other for the support material. The prototype is built layer by layer by depositing both the build and support material onto the build platform outlining the cross-sectional profile for that layer. Once that layer is complete, the platform is lowered, the extrusion head is positioned, and the extrusion process is repeated for this new layer. This layer is built on top of the previous layer hence creating a three dimensional prototype.

Upon completion of the build process, all support material required during the build process must be removed manually. This can be a very laborious task and often results in damage to the part. The advent of water-soluble support materials has made the process much more acceptable.

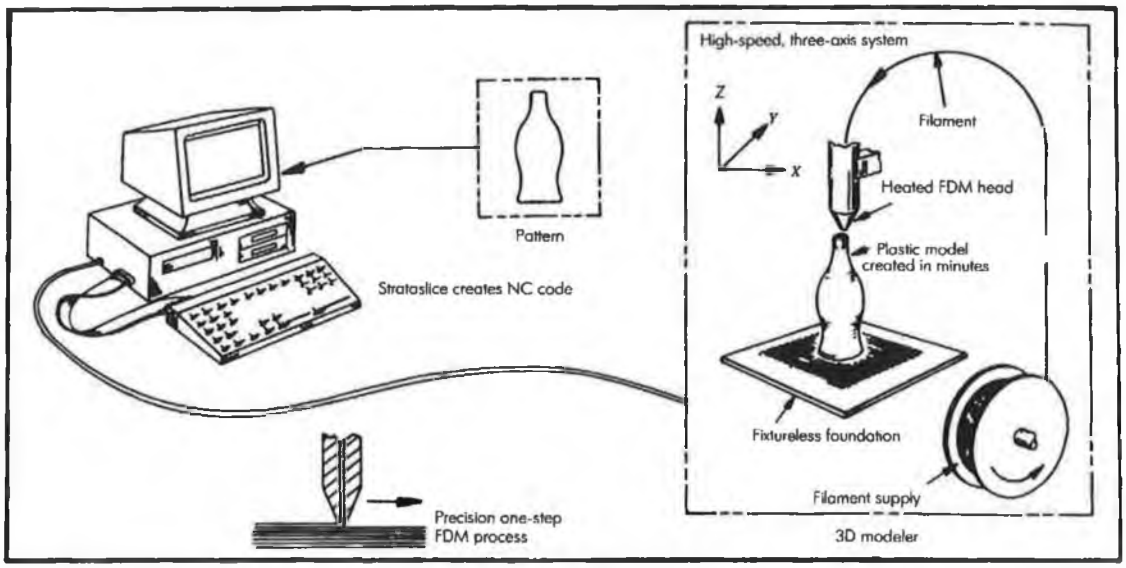


Figure 5.6: FDM System Arrangement. [13]

A number of different materials can be used with this process, including acrylonitrile-butadiene-styreneterpolymer (ABS), Investment Casting Wax, Methyl methacrylate/ABS and an elastomer with mechanical properties similar to polypropylene. Other materials are also available for specialist applications. The work envelope is similar to that of the Stereolithography process in that prototypes ranging from 200*200*200 mm up to 600*500*600 mm depending on the machine can be accommodated.

Main Advantages	*Main Disadvantages*
▪ The machine is basic ▪ Supported structures are extruded at the same time as the build material ▪ The process is fast for thin walled or hollow components ▪ Materials can be changed very easily. ▪ The machine can be used in a Design Office, (i.e. no toxic fumes) ▪ The prototype possesses very good strength characteristics in the vertical build direction (reported from University of Limerick Studies)	▪ Support structures are required for all builds (additional cost incurred from a material view point) ▪ Large volume parts results in a very slow build time (can be reduced by building hollow models) ▪ Some prototypes can be prone to de-lamination

5.4.5. SOLID GROUND CURING

Cubital Inc. of Israel, first developed solid Ground Curing, or the Solider Process. In essence this process is a combination of Computer numerical Control, Stereolithography, and some might argue Fused Deposition Modeling. Unlike the Stereolithography process where a single dot of the photo curable polymer resin is solidified at any one time, this process covers the polymer with a mask, exposing only the surface to be solidified, which is then flooded with a UV light. The mask is manufactured by a laser scanner, which prints the profile of the layer with a toner onto a glass sheet. Once photopolymerisation has occurred the mask is removed, and a vacuum type device removes any excess un-cured polymer. A molten wax is then poured into the cavities that remain and allowed to set. When the wax has set a milling cutter removes the excess wax and mills the polymerized section to the correct layer thickness. The wax provides support for the next layer of polymer resin. The process is now repeated and the next layer is built [65].

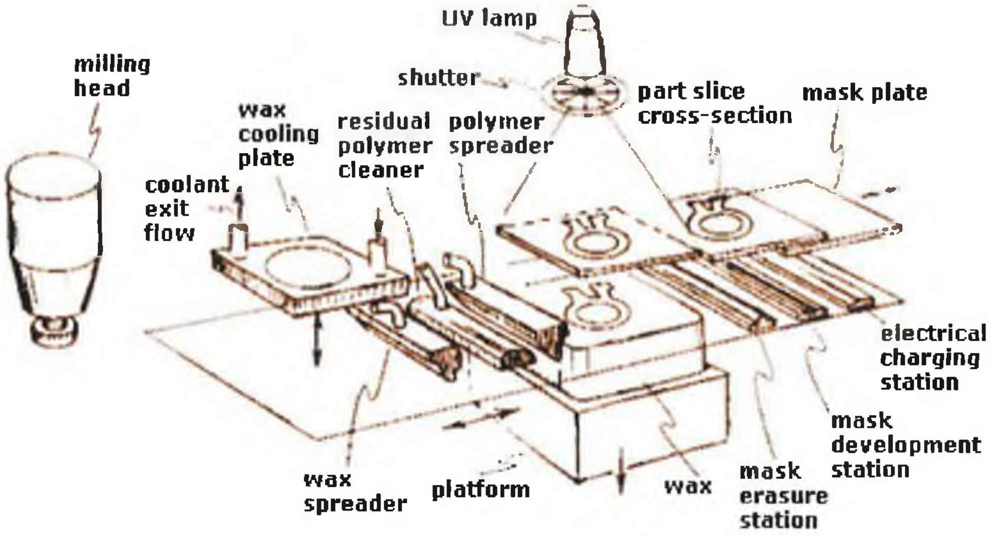


Figure 5.7: Solid Ground Curing Process [efunda.com]

This process offers one of the largest work envelopes of the all RP processes, however it is also the most limited in so far that very few materials are available. The process also has one of the best built times available. In the case where a number of components can be nested together on the built platform, excellent times can be achieved, being only limited by the vertical height of the tallest component.

Main Advantages	*Main Disadvantages*
▪ Build times can be easily predicted ▪ The wax provides the support structure ▪ It is a high output device ▪ Nesting of multiple parts is allowed	▪ A full time operator is required ▪ There is a considerable amount of waste of both the resin and the wax therefore incurring additional costs ▪ Considerable downtimes have been reported

5.5. CONCEPT MODELERS

All the process outlined in the preceding discussion, are all either to big, require to much attention or are very expensive to operate. For the majority, these processes do more than is required and therefore having such a system is not justified in their high cost.

Several companies identified this void in the market and began to manufacture machines, which in general preformed as the above but on somewhat of a limited scale. At an early stage in the design process, when a design needs to be evaluated or the design intent needs to be communicated, these processes gained a foothold. They can fabricate a hard copy three-dimensional prototype from an STL file in a matter of hours, which requires little or no post processing or clean up. This coupled with the fact that all these machines can be purchased for less than €80K has established them as a true office companion.

5.5.1. THERMOJET MODELING

This system comprises of an array of 352 nozzles, which extrude a bead of molten wax onto a build platform. The machine operates at very high speeds with the multiple jets printing approximately 12*0.033 mm strips at a time with each pass of the print head. The need for a second support material is eliminated by the fact that the process constructs very thin pillars in areas where support is needed from the actual build material. It requires a small foot print of office space, and is inherently safe as it does not require any chemicals or solvents [65].

Main Advantages	*Main Disadvantages*
▪ The process employed is very simple ▪ Supporting structures are easily removed and do not damage the final part ▪ No post curing is required ▪ The upper surface finish is excellent ▪ No hazards chemicals or solvents are used ▪ The machine is small and easily moved	▪ The underside surfaces are of a poor quality ▪ The material employed in the process is very expensive, typically in the region of £140-£160/kg. ▪ Parts are reported to have very limited mechanical strength

5.5.2. 3D PRINTING

Z-Corporation, Z402 3D Printer has established itself as the fastest rapid prototyping machine available. The system operates by spreading a layer of starch and cellulose powder from a feeder box onto the build surface. A print head containing 128 jets then transverses over the powder and deposits a binding solution onto it, forming the first cross-section. Where the binder is printed, the powder is glued together. The powder left over remains and is used as the supporting structure for the next layer. Upon completion of the first layer, the build platform is lowered, a new layer of the powder is spread, and the process is repeated. When the part has been completed, it is completely encased by the loose powder, which must be vacuumed away [65].

The parts that are produced by this method are both relatively weak and are porous. In the case where these parts are only required just for communicating the design intent, no further process is required. However, if a robust part is required, then some form of post processing must be implemented. The most common approach to this is to dip the part in a low temperature wax, which infiltrates the part through capillary action. If greater strength is required another similar infiltration process where a two-part, low viscosity epoxy resin can be employed.

Main Advantages	*Main Disadvantages*
▪ The process is extremely fast ▪ The build materials are relatively cheap	▪ Rough or grainy surface finish ▪ Parts require additional infiltration process, hence additional equipment, time and cost investment ▪ Parts are very weak prior to infiltration ▪ The process can be extremely messy

5.5.3 DROP-ON-DEMAND INK JET

This process is a combination of two machine room technologies, the Solid Ground Curing and Fused Deposition Modeling processes. Similar to the

FDM, the process makes use of two extrusion nozzles, one for the build material and the other for the support material. The part is built onto a build table by depositing molten build and support material. Once one layer is complete, a cutter is passed over the surface of the layer to smoothen it. The build table is now lowered, and the next layer is build on top of the previous. Upon completion of the process, the part is completely encased in the support material. This support material is easily dissolved away by placing the built part into a dissolving agent. This solvent leaves the finished parts undamaged. However, this agent may be hazardous, therefore the process cannot be operated in an office environment.

Main Advantages	*Main Disadvantages*
▪ Small machine footprint ▪ Surface finish is excellent ▪ Low cost machine ▪ Useful for investment casting patterns	▪ The use of hazardous solvents in the washing process (therefore post processing must be carried out in a controlled environment ▪ Parts have a poor mechanical strength ▪ Extremely small build envelope ▪ The process is slow and very noisy

INTRODUCTION

Rapid prototyping offers the engineer a quick and easy route to a real representative model of a design. These models however cannot be used for functional testing as they are usually fabricated from materials, which have rather poor mechanical and thermal properties [9, 12, 13, 14, 15, 16, 44, 64, 65, 66]. In general the majority of engineers require that these prototypes be fabricated from the end-run material, by a process that is similar to the process, which will be used for production of that product. Rapid tooling provides one avenue towards obtaining such prototypes.

Implementing a rapid tooling strategy for a product can be quite expensive. Bureaus currently involved in providing such services are endeavoring to reduce the costs and lead times, and as a result new and exciting tooling processes are constantly emerging. The discussion contained here under aims to introduce the more common processes available and how they are implemented.

6.1. RAPID TOOLING

The process of Rapid Tooling uses a rapid prototyping model as a pattern to manufacture a mould quickly. Alternatively the rapid prototyping process can be used directly to fabricate a tool for a limited volume of prototypes. The manufacturing processes associated with the Plastics, Metals and Ceramics sectors, all can benefit from this process.

The applications associated with rapid tooling can generally be divided into the categories of soft and hard tooling, as well as the subgroups direct and indirect tooling. With regards to direct tooling, the necessity of preparing a master pattern is removed, as the tool cavity is manufactured directly on the rapid prototyping system. Indirect rapid tooling on the other hand requires some form of master pattern. These patterns can be manufactured either by conventional means or on one of the many rapid prototyping systems discussed in the previous chapter.

In order to achieve any benefit from the indirect tooling approach the manufacturing lead times of the pattern must be reduced as much as possible. This can best be achieved by adapting one of the rapid prototyping processes available, which are additive rather than subtractive in their mode of operation. The subtractive approach of conventional processes tends to be very time consuming and wasteful in nature. The elimination of the need to remove material, results in both the cost and product development lead times, being reduced considerably.

6.2. SOFT TOOLING

The definition of soft tooling varies, as there are many different ways of considering the applications and techniques used in the process. More commonly the definitions may include [13, 64]:

- Tools which are produced by soft tooling techniques are generally produced at very low costs, hence both the terms soft tooling and low cost are interchangeable.
- As a method of manufacture. In the case where hard tooling is the choice, the tool is generally produced by conventional machining techniques (Aluminum Moulds).
- The material used can be considered another definition. Tools fabricated as hard tools are often referred to as those made from tool steels. Any materials therefore with a lower hardness level can be considered soft. Materials included within this category are, aluminum, low melting point alloys, zinc alloys, epoxies, silicone and rubber.
- The most obvious definition however, maybe regarded as; tools that are required for small production quantities. In industries such as either the Aerospace or defense, a large production run would be considered as being a few thousand, whereas in others, such as consumer industry, it would be regarded as many millions. In this case a few thousand would be regarded as a prototype quantity.

Company policy, still requires a prototype component or assembly, to be manufactured by both the intended process and the end run material. This is owed to the fact that existing RPTM techniques make use of a very limited selection of materials, which have poor mechanical and thermal properties when compared with the end-run material. Prototypes produced by such RPTM techniques do offer some benefit, in so far that they can give a quick and initial evaluation of the design. If a component survives testing after being constructed from such materials and processes employed in these RPTM processes, then the chances are that it will function within its intended environment without incident.

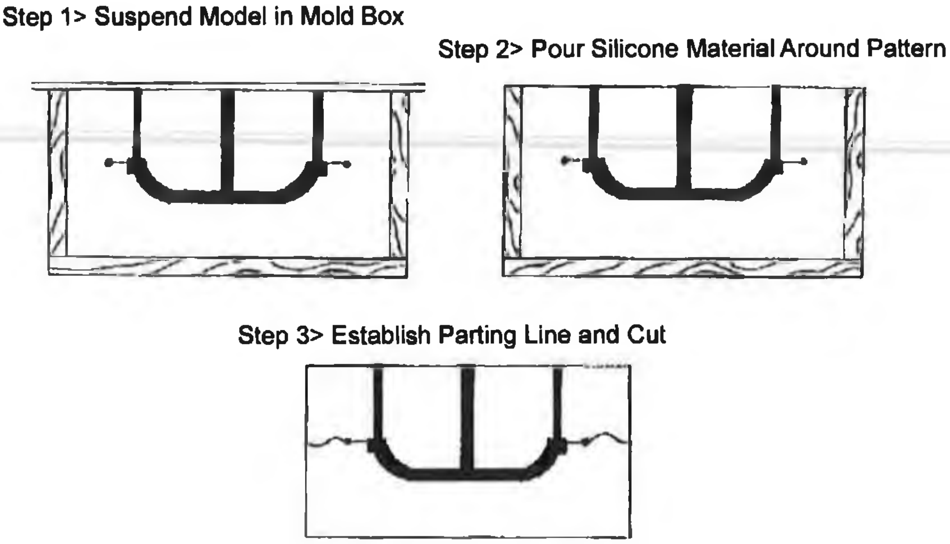
6.3. INDIRECT SOFT TOOLING TECHNIQUES

The following section aims to introduce some of more common indirect soft tooling techniques.

6.3.1 SILICONE RUBBER TOOLING

Room Temperature Vulcanizing (RTV) silicone rubber is an exceptionally flexible, simple, and fast, as well as relatively inexpensive material which can be used for the construction of [67]. The material can be quiet easily moulded around a pattern in order to produce a cavity. Two different types of silicon rubber exist, each of which has a different fabrication technique can be used to produce the moulds [10, 12, 44, 64]. These two materials differ in so far that one is opaque, while the other is transparent, the latter being the more expensive of the two.

In the case of the transparent material, the pattern, which is produced by one of the several different Rapid Prototyping techniques, is suspended in a mould box. The silicone rubber is then poured into this box until the pattern is completely submerged. After the mould has been given sufficient time to solidify, a parting line is established and then cut with a scalpel. The master is now removed, hopefully without breaking it. This pattern can then be used at a later time to produce a second mould if need be.



Step 1> Suspend Model in Mold Box

Step 2> Pour Silicone Material Around Pattern

Step 3> Establish Parting Line and Cut

Figure 6.1: Basic Silicone Rubber Tooling Process

The cavity, which has been created, can now be used to mould a number of prototypes from a variety of different materials. Polyurethane is the most popular choice, as it is available with a variety of mechanical properties, which can replicate the mechanical and thermal properties of most elastomers, nylon, ABS, acrylic, etc. In order to avoid air bubbles in the moulded component, the polyurethane is poured into the silicone tool under vacuum conditions.

It is not uncommon to obtain in excess of 20 complex polyurethane components from a silicone rubber tool. The two most common contributors to the break up of these moulds would be the level of detail and the grade of the material being used. Longer post cure times are required for flexible polyurethane's, which are usually placed in an oven at approximately 60°C. As a result, the polyurethane at this elevated temperature is contact with the surfaces of the cavity for a considerable amount of time, tending to dry out these surfaces and thereby rendering it brittle.

Opaque silicones can also be mould in a similar manner. The major problem associated with this method however is that, it is more difficult to cut to the parting line around the pattern, as it is not possible for the operator to visualize it within the mould. The norm when adapting this approach is for the operator to begin at the spruce and make there way around the parting line of the object with the aid of photograph of the pattern suspended within the mould box.

An alternative is to produce the mould in two stages. This can be achieved by initially setting up the model with the parting line constructed from plasticine. It is then possible to produce one half of the mould. After the silicone has been given sufficient time to solidify, it is inverted and the plasticine is removed. The second half of the mould can now be poured. This method incur considerable time in the production of a mould contributing to extra cost. Opaque silicon is much less expensive.

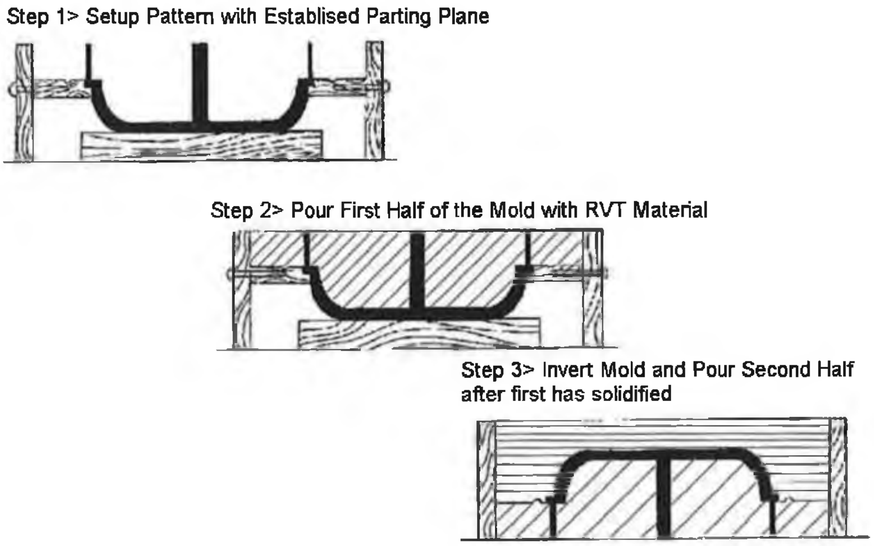


Figure 6.2: Two Stage RVT Mould Creation

Silicone rubber tools can typically be used on four different manufacturing processes [13, 64].

- Reaction Injection Moulding (RIM): This process uses a relatively simple injection system with two pressured chambers. An injection nozzle is used to fill the silicone tool at atmospheric pressure until the mould is completely filled. This is indicated by a series of risers, which are strategically placed. This process does not rely on expensive mixing and vacuum chambers. The major advantage of this approach is that there is no thermal cycling therefore that tools can last for up to 100 shots.

- Spin Casting (Metal Parts): This process requires a number of silicone rubber tools, located radially around a disc. The tool takes advantage of centrifugal force to pressurize the cavities, as it is spoon around. This helps to fill the cavities efficiently. If handled with care this tool can produce upwards of 100 prototype components. Adapting this process, it is possible to cast polyurethane or zinc based alloys.
- Wax Injection Tooling (Wax Parts): Silicone rubber tools can quite easily be used for low-pressure injection moulding of waxes for investment casting. Semi molten wax is forced into the tool using a low-pressure injection moulding system. Sufficient time must be provided so as to ensure that the wax has fully solidified. It is not uncommon to chill the cavity in order to speed up the process. Extreme care must be exercised when removing the wax from the cavity due to its fragile nature.
- Vacuum Casting (Plastic Parts): In this case the silicone tool is placed in a vacuum chamber with normally a two part polyurethane resin. This two part resin is first mixed and de-gassed before it is eventually poured into the silicone cavity. Once the mould has been poured, the vacuum is released, the tool removed and placed into a post-curing oven for a period of time to allow the pour to cure fully. Upon completion the part is removed form the mould and the process is repeated. Tool life is dependent on the complexity of the mould and the material being poured. Various materials are available and can mimic production polymers such as heat resistant acetyl, ABS and nylon. Typically each cavity can produce between 10 and 20 components before the thermal cycling of the cavity destroys it.

6.3.2. SPRAY METAL TOOLING

This process involves coating a pattern, which we have obtained from one of the rapid prototyping systems, with a thin metal shell, which is typically 2mm thick. The shell is then backed with an epoxy, and often a cooling system is embedded within this. As with most rapid prototyping techniques, the material used to produce the pattern has a low glass transition temperature[3]. During the application of the metal coat, it is important to keep the pattern temperature as low as possible. An elevated temperature would cause the pattern to distort and soften thereby producing an inaccurate tool [10, 13, 64].

Figure 6.3: Spray Metal Tooling Example

The most popular spray metal techniques involve low melting point alloys (lead/tin – based). These alloys are distributed with either a gun similar to a paint sprayer, or else a Tafa process[4] [64].

In the case of the Tafa arc system, two wires are feed into a gun and an electric arc is struck between them which cause's the material in the wire to melt. The exhaust jet from the compressed gas atomizes the molten material and sprays it onto the pattern. It is more difficult to keep the pattern cool with a wire material that has a higher melting point. To this end it is customary to spray zinc or aluminum based alloys directly onto the rapid prototype model as these have a relatively low melting point. The model can

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[3] i.e. the temperature at which the material starts to change to a soft amorphous structure.

[4] Metal deposition with an arc system

now be removed and a higher melting point material can be sprayed into the cavity. This method could be repeated indefinitely however the process can become very expensive.

Spray Metal Tooling is particularly suitable for models having gradually curving surfaces. The process is not suitable to models having small diameter holes or slots, put inserts fabricated from brass can positioned in the model and the metal can then be sprayed around them. These inserts are permanently fixed into the shell and are considerably stronger than it. As a result the shell can break very easily.

Up to 10 K components can be obtained from tools produced in this manner [64]. As these tools are relatively fragile, they need to be handled with a considerable amount of care. It is not uncommon that the mechanical properties of the injection-moulded components are affected, due the fact that the clamping and injection pressures used with these tools are normally less than their steel or aluminum equivalents. Also the thermal conductivity properties of these tools are not as high, therefore increasing the cycle time.

6.3.3. CASTABLE RESINS

This technique consists of positioning a pattern in a mould box, setting up a parting line, and then pouring the resin over the pattern until there is a quantity of resin sufficient enough to form half the tool. Many different resins are available which are often impregnated with aluminum powder or pellets. These additions to the resin can improve the thermal conductivity of the tool. This also has the added advantaged of reducing the cost of the resin. Without a doubt this is probably the simplest and least expensive process available.

6.3.4. CASTABLE CERAMICS

Castable Ceramics has emerged as a viable process for the production of injection mould tools. The cheapest and best materials for these moulds are based around a sand/cement mixture, which is poured over the master pattern. The water content in the mixture should be kept to a minimum so that any shrinkage as the material sets is avoided. In order to render the material fluidic for easy pouring and complete filling of the cavity requires some form of plasticiser to be added. To effectively mix all the constituents, a mixing machine, and in order to pact the material after pouring, a vibratory table is reqiured. This adds unwanted cost to the process.

6.4. INDIRECT HARD TOOLING

The following section aims to introduce some of more common indirect hard tooling techniques.

6.4.1. THE KELTOOL PROCESS

This process was first described by Arie Ruder in a paper presented at the First European Conference on Rapid Prototyping in 1992 [12, 13, 16]. Tools are fabricated from bronze or stellite, therefore it can be argued that this is a process that can fit into the soft tooling category. A mixture of powder, binder and solvent are poured around a master pattern. The solvent contained in the mixture eventually evaporates and at this point the part, which is held by the binder, is fired at a temperature sufficient enough to burn off this binder and sinter the powder particles together. The resulting structure is normally porous and copper is infiltrated into it. The resulting surface finish is excellent. The major drawback associated with the process is that shrinkage must be allowed for and that the process is limited to small tools.

6.4.2. INVESTMENT CAST TOOLING

The master pattern, obtained from the one of the RP processes, is first treated with a light coat of wax so as to improve the surface finish of the finished mould. This pattern is then coated with a first layer of ceramic and allowed to cool. A second coat and a stucco mixture are then applied. This is repeated until the desired thickness is achieved. Once the ceramic coating has completely dried the invested part, i.e. the pattern and the ceramic coating, is fired in an oven, which sinters the ceramic shell and burns out the RP model [68]. The result is a sintered ceramic mould. The temperature of this mould is first elevated to a temperature close to the melting point of the material to be poured in the pouring chamber. The molten material is then poured into the void left by the pattern. Once sufficient time has been allowed for the material to solidify and cool, the ceramic shell is fractured and the new part is removed for post-processing.

This tooling process has been used in the past for both die casting tools and injection mould tools. The process is limited in so far that it is difficult to predict the contraction of the casting process. A high level of accuracy with this tooling process is difficult to maintain.

6.4.3. ALUMINUM AND ZINC KIRKSITE TOOLING

Due to high production volumes and the rather aggressive nature of many polymers, it is of vital importance that any material used in the manufacture of a mould must poses a significantly higher mechanical hardness value than any ceramic or silicone cavity. For this reason alone, a process that could provide such a tool, cast form either zinc or aluminum had to be developed. Such a process would require a pattern, which could withstand the high temperatures of a molten casting technique.

When the temperature of the casting material is considered, it becomes apparent that the initial pattern must be replicated from a material capable of withstanding these temperatures. By employing silicone tooling as discussed earlier, a cavity of the pattern can be produced quite easily. From this cavity, a new replica of the initial pattern can be produced from a ceramic material. This is given sufficient time to solidify, and is then placed into a bolster and covered with the molten material [64].

6.5. DIRECT TOOLING

All of the above techniques have proven themselves as effective means of producing a tool rather cheaply and in a relatively short period of time. Each process produces the tool from a master pattern fabricated on one of the many rapid prototyping processes. The major concern associated with adapting one of these tooling techniques is that inaccuracies can be introduced at any stage and therefore reproduced at successive stages.

Up until recently, the only other method of producing a tool without the necessity of producing a master pattern was to adapt a traditional machining technique. The main advantage associated with adapting this technique, is that tools can be produced under highly controlled conditions, which result in highly accurate dimensions.

It is now possible to produce tools directly from a rapid prototyping process such as stereolithography, or Selective Laser Sintering. Tools produced in such a manner poses significant advantages over conventional tooling techniques [14]. The most significant of these is that cooling or heating channels, which allow for cooling or heating of the tool, at points or locations where they are most required, can be incorporated quite easily. Conventionally these needed to be drilled and often could not be located where desired.

6.5.1. STEREOLITHOGRAPHY TOOLING

This is the longest established rapid prototyping process at the disposal of the modern engineer. The selections of materials available for use with this process have expanded considerably, and are finding new applications everyday. Considerable research has been undertaken by many material manufactures in the hope of identifying a material that can be used in the manufacture of moulds directly.

Conventionally, a master pattern is fabricated around which a material is cast in order to fabricate a cavity. Rather than taking this some what round about approach, manufactures are fabricating mould cavities directly. These cavities are less robust than the cast cavity, but it has been reported that up 500 components can be moulded from a single tool. At present, only lower melting point, less abrasive polymers are being injected into such tool cavities. This method of fabrication will not find wide spread usage, until such time that new high temperature and more structurally robust resins are available.

6.5.2. LAMINATED TOOLING

This process is still very much in the development phase. The method employed in the manufacture of such tools is very similar to that of the LOM process discussed in the previous chapter, however, rather than using paper or plastic material, a metal is used.

In order to produce a mould tool in this manner, the mould cavity must first be generated by a CAD system. The mould is then sliced as if a model was being fabricated. Each slice is then cut out of a sheet of material, stacked on top of one another in a layering process and bonded together using a suitable bonding agent. It is possible to fabricate a pseudo-solid cavity in hardened tool steel, without the requirement of complex post process cutter planning in this manner.

The major limitation associated with this approach is that relatively tick laminates, typically 1 mm are only available, thereby resulting in a very poor surface finish, which generally needs some form of post machining to improve. Tools manufactured in this manner have found application in many fields, including, injection moulding, blow moulding, vacuum forming, and press tooling. Tool life is a function of the material used and can be increased by hardening the material after cutting and lamination.

The process does have one major advantage in so far that component geometry can be changed quite easily. This is achieved by de-laminating the tool, i.e. breaking the bonds, and then replacing the unwanted sheet with a new one. The tool is then rebounded and ready for the next run. Conformai cooling channels are very easily incorporated into the tool design.

6.5.3. LASER SINTERED TOOLING

Laser sintered tools can be fabricated in much the same manner as the Stereolithography process. In this case however, two alternative methods can be utilized.

- A steel powder matrix can be used within the laser sintering machine to produce a sintered tool directly.
- Polymer coated metal powders can be infiltrated with cooper after sintering.

The tool cavities fabricated in this manner are much more durable that those cavities produced with the Stereolithography process, and have been used quite successfully to injection mould various different polymers. Considerable interest also exists in using cavities produced in such a manner for the production of die cast components.

6.6. SILICONE RUBBER TOOLING APPLICATION

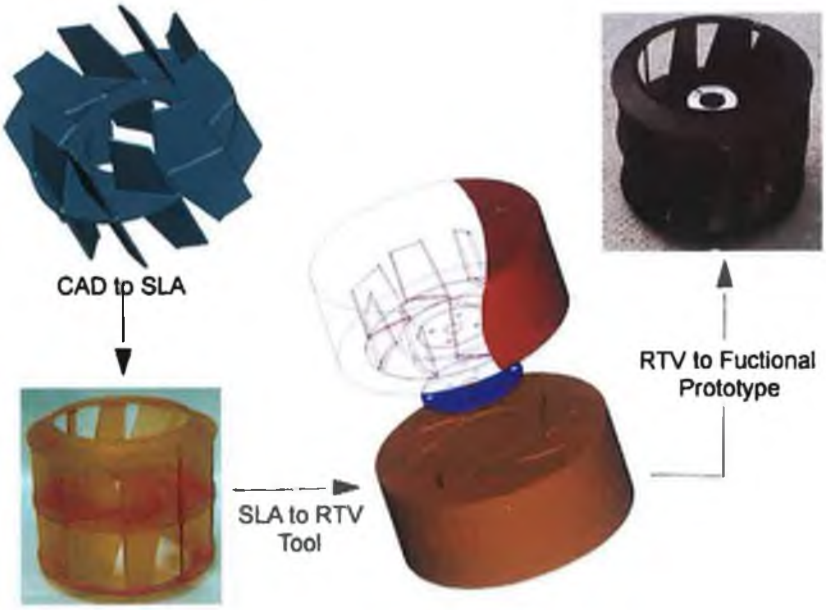


Figure 6.4: Design to Tooling example.

A functional prototype of an evaporator blower was obtained from the Silicone Rubber Tooling process outlined above. This blower was first modeled in a 3D solid modeling system and output as an STL file (refer to section 5.2, chapter 5). The stereolithography process was employed to generate the master pattern, which was then suspended in a mould box. Molten Silicone Rubber was poured over this pattern until it was completely submerged. After sufficient time was allotted for solidification, a parting line was established and the two mould halves separated. The centre plate for the blower was now positioned between these two mould halves, and polyurethane was cast into the cavity [44]. This complete process is illustrated in figure 6.4.

INTRODUCTION

Plastic components fail for two primary reasons: too much deformation due to creep or stress relaxation or they crack. When they deform too much while not cracking they may cause the product too partially or totally malfunction. When they crack (which may be due to combined creep and fatigue), the product will probably cease to function. Testing is performed for two reasons; (1) to identify material properties if they do not exist and, (2) to ensure that under rigorous conditions the product will continue to perform its intended function throughout the warranty period. Because warranty periods can be tens of years obviously it is important to know this in much less time (typically before the product leaves the factory) and hence the necessity of accelerated testing.

The following chapter firstly introduces to the reader the most appropriate sources of Plastic Material Property data. Secondly, issues such as creep, stress relaxation, fatigue and suitable test procedures are presented. Finally an introduction to concepts and techniques of accelerated testing is offered.

7.1. SOURCES OF PLASTIC MATERIAL PROPERTY DATA

The selection of a suitable plastic material is driven by the matching of performance requirements of the end-use component with the property profile of the material [10, 69]. At present, thousands of different material grades are available to choose from, which makes the selection a rather overwhelming task. A variety of different approaches for the selection of a suitable material can be adapted.

7.1.1. BOOKS, BROCHURES, AND SUPPLIER DATA SHEETS

Due to the vast quantity of material grades now available it is virtually impossible to obtain and catalogue all the different grades [10]. Any library specialising in providing such information has an enormous task is keeping up to date with respect to new grades, grades no longer available and the varying cost. These sources can be beneficial in so far as providing data regarding pure grades, or grades impregnated with 10, 20, 30% etc... filaments of another material. One key consideration which must be considered when selecting a suitable grade from such a sources, is the time availability.

7.1.2. MATERIAL SUPPLIER

Consultation with a material supplier or a suppliers database, limits the designer to that suppliers material grades. In general a number of different suppliers should be consulted in an attempt to identify the most suitable grade for the design under consideration. On the up side, the quantity and quality of data available from such sources is of an excellent standard. These sources often provide additional information such as processing and design data. On the downside however, as must suppliers use data formats and test specimen preparation procedure methods unique to themselves, a direct comparison of data obtained from the separate suppliers is often inappropriate.

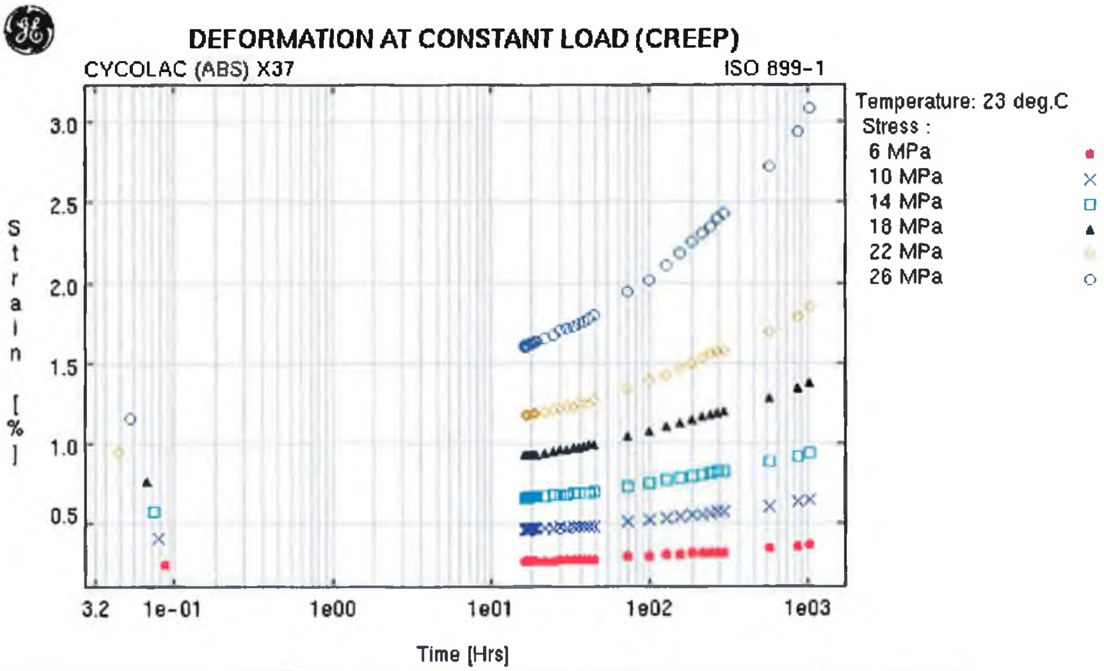


Figure 7.1: Creep Curves for Cycolac X37

7.1.3. INTERNET

Many material suppliers have embraced the internet as a means of easily distributing their unique material data to a much wider engineering community. The majority of suppliers now have very user friendly online databases which can yield a wide variety of test data. GE Plastics – Visualizer is one such sources. Extensive data is available pertaining to their unique material grades. It is from this source that the material data used to prepare the computational FEA model presented in chapter 4, was obtained.

7.1.4. MATERIAL LABORATORIES

Independent or in house material test laboratories can be contacted in an attempt to identify a suitable material. It is not uncommon for these sources to have tested a number of different grades of material from different suppliers. These can therefore render accurate and independent advice, given that they are not associated with the supplier, and they have prepared test specimens under tightly controlled and similar conditions. If information is sought for a specific grade which these laboratories do not have, then they can be commissioned to test it.

7.1.5. MATERIAL DATABASES

Universal plastic material databases provide a valuable tool to the selection process. Generally these are computerised databases compiled from existing data from a wide variety of material suppliers which can be searched based on different input criteria. In 1988 a standardised database was introduce under the name, Computer Aided Material Pre-selection by Uniform Standards (CAMPUS) [10]. This database format provides an internationally accepted system of testing and data presentation, based on the International Standard Organisation (ISO) test methods. Some flexibility still exists in terms of specimen manufacturing conditions. The datasets obtained from this system however are more appropriate for direct comparisons between the various suppliers.

PLASTICS MATERIAL DATABASES

Company	Product	Materials	Data Types	Formats
ASM International Materials park, OH	Mat.Db	8,000 + plastics and other materials	Properties	PC and Publication
BASF Corp. Parsippany, NJ	CAMPUS	BASF Materials	Properties, Ratings, Chemical Resistance.	PC
D.A.T.A. Business Publishing, Englewood, CO	D.A.T.A. Plastics Digest	10,000 + thermoplastics, thermosets, elastomers	Properties, Ratings	Publication
Dow Plastics Midland, MI	591 Ways to Succeed	Dow Materials	Properties, ratings, and chemical Resistance	PC and Publucation
GE Plastics, Pittsfield, MA	Engineering Design Database	GE thermoplastics and foams	Properties, ratings, Design data	Online
Hoechst Celanese Corp. Chatham, NJ	Fast Focus	Hoechst Materials and equivalents	Properties, ratings, and chemical Resistance	PC
IDEAS, Inc. Laramie, WY	Prospector	10,000+ thermoplastics, thermosets, elastomers, films	Properties, ratings, design data, a chemical Resistance	PC and Mac
Information Indexing Inc. Garden Grove, CA	CenBase Materials	10,000+ plastics and other materials	Properties, design data, and chemical Resistance	PC, Workstation and Publication
LNP Engineering Plastics Exton, PA	EPOS	LNP Materials	Properties, ratings, design data, a chemical Resistance	PC
McGraw Hill Inc./Polydata New York, NY	DataPlas	7,000 engineering thermoplastics	Properties, ratings, and chemical Resistance	PC
Miles Pittsburgh, PA	CAMPUS	Miles Materials	Properties, ratings, and chemical Resistance	PC
Plaspec Yardley, PA	Plaspec	10,000+ thermoplastics, thermosets, elastomers	Properties, ratings, and chemical Resistance	Online
Plastics Design Library New York, NY	Chemical Compatibility and ESCR	60 Families+ of plastics	Chemical Resistance	Publication
Prime Alliance Des Moines, Iowa	Prime Alliance Database	Over 700: BASF, Miles, Mobil, Monsanto, Rexene	Properties, ratings	PC
Rapra Technology Ltd., Shropshire, England	Plascams	Contains generic Materials	Properties	PC and Publication

Table 7.1: Available Plastic Material Databases [10]

7.2. MECHANICAL BEHAVIOR OF PLASTIC MATERIALS

The vast majority of material property data is obtained by adapting either the International Standard Organisation (ISO) or American Society of Testing and Materials (ASTM) procedures [10, 47]. Factors such as temperature, stress or strain, the environment, and time influences the mechanical behaviour of all Plastics.

Mechanical and physical properties of most materials are determined from short term loading conditions. These values will not represent the characteristics of that material when subjected to long-term loads. When loading is more that momentary, creep data, must be considered for purposes of both material selection and design [2, 10, 39, 45, 56, 57, 58, 59, 60, 69, 70, 71]

7.2.1. DETERMINATION OF MECHANICAL PROPERTIES

Creep Data which is used in design must correlate with the type of stress and environmental conditions which the part is subjected to during its service life. For this reason, the designer must adapt a modulus which represents the material at a given stress level and temperature over a specified period of time [10, 44, 57, 60, 69, 70]. This Creep Modulus is expressed as:

$$E_c = \frac{\sigma}{\varepsilon_t} \qquad 7.1.$$

Where:

E_c = Creep Modulus
σ = Stress
ε_t = Strain at time t

This form of creep data can be generated by subjecting moulded samples to a series of loads, or stresses and monitoring the change in length, or strain over time (refer to figure 7.2). In the unlikely instance that creep data is not readily obtainable, the designer can conduct his/her own test in this manner.

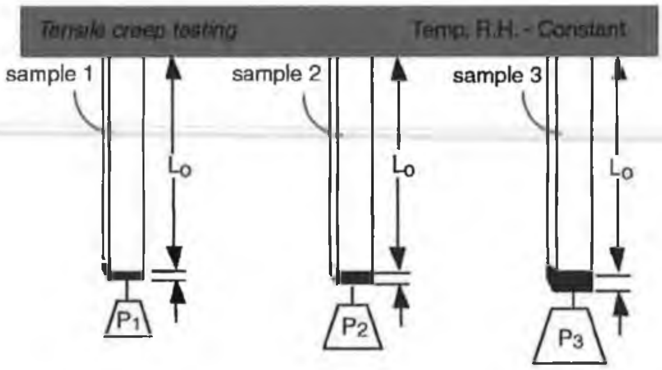


Figure 7.2: Determination of Creep Data

The force which is necessary to maintain a constant deformation decreases with time. This behaviour is known as stress relaxation and much like creep is both time and temperature dependent [59]. The Relaxation Modulus can be defined as:

$$E_{relax} = \frac{Pl_t \big/ A_o}{\Delta l \big/ l_o} \tag{7.2.}$$

Where:

A_o = Original Cross-Sectional Area
L_o = Original Length
ΔL = Change in Length
P = Load at time

Both the relaxation and creep modulus are essentially equal in the same service conditions, therefore only one of these, modulus is necessary for all calculations, the creep modulus being the preferred.

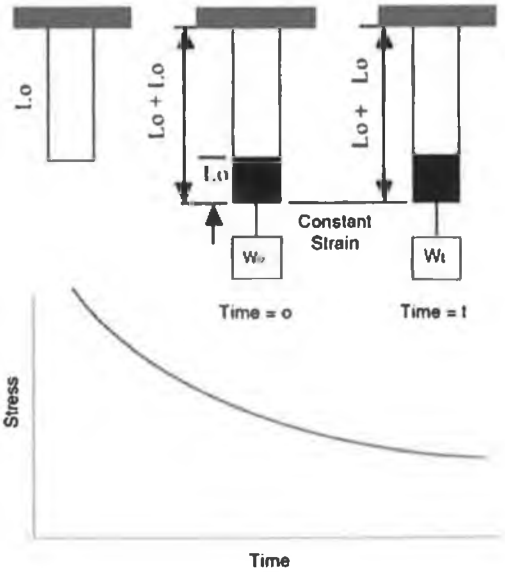


Figure 7.3: Determination of Relaxation Modulus

The creep and stress relaxation behavior of plastic materials are often modeled using elastic and viscous elements. One such arrangement, figure 7.4, is a Maxwell and Kelvin model in series. For the instance of stress relaxation, such a model can be solved by the adapting the approach presented in [59]. Alternatively in the instance of creep, this model can be solved by the approached presented in [60].

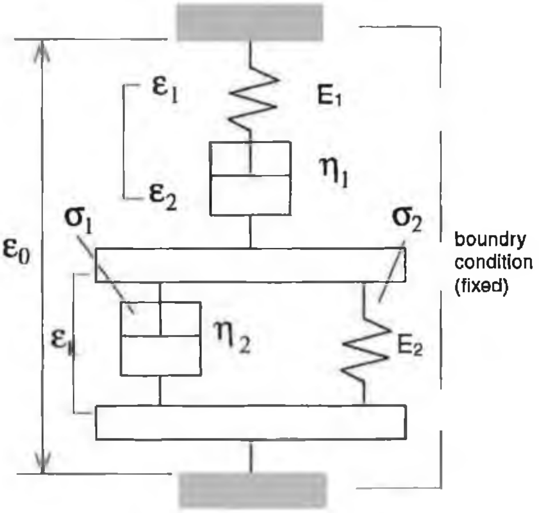


Figure 7.4: Maxwell and Kelvin Model in Series

The fatigue characteristics of plastic materials are required when designing parts which will be subjected cyclic loads. Parts subjected to such loading conditions develop micro-cracks or other physical/chemical defects over time that lead to a decrease in the overall toughness of the material and eventual failure [45, 47, 59, 72, 73, 74].

Tests for fatigue are performed by subjecting a moulded test specimen to alternating stresses between equal and positive stress values. These tests are normally conducted in the presence of bending, torsion or torsion at a given frequency, temperature, and amplitude of loading. The stress at which a test specimen fails will decrease as the number of cycles increase. Most materials exhibit a fatigue endurance limit which indicates that a failure at a stress value below this limit is unlikely. Results from fatigue tests are generally presented as indicated in figure 7.5.

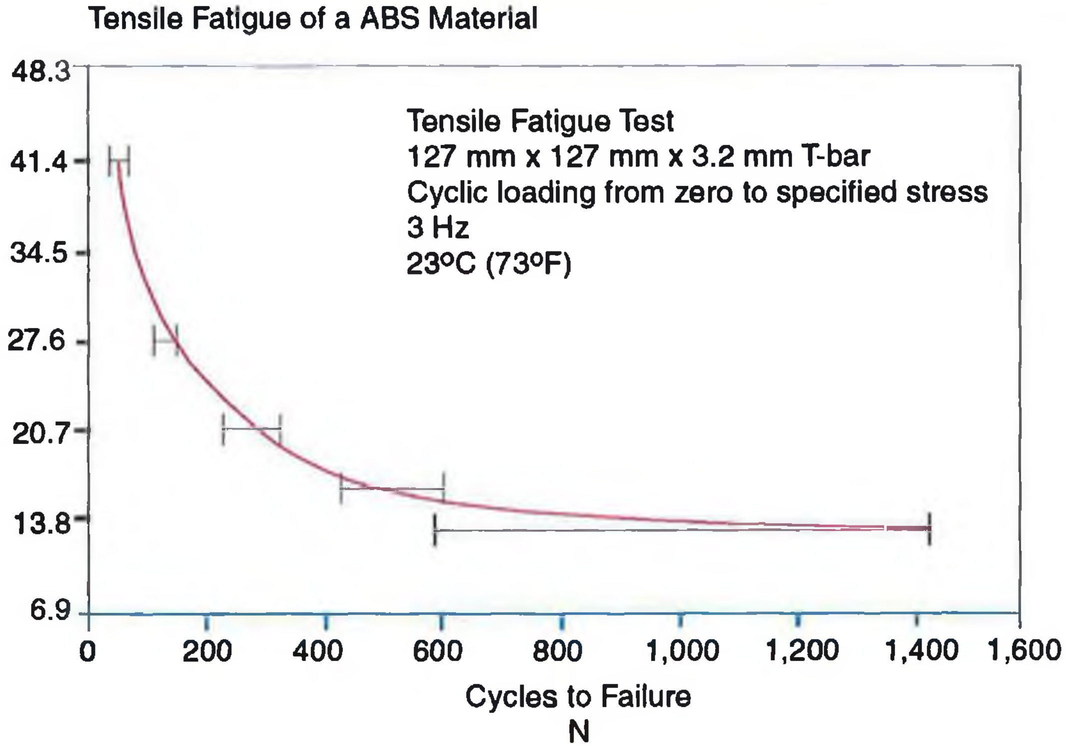


Figure 7.5: Tensile Fatigue of an ABS Material [Dow Plastics]

All plastic materials are viscoelastic in nature and therefore their fatigue properties are significantly affected by the test frequency, amplitude, specimen geometry and temperature [10, 45, 69]. For design purposes it is advisable to conduct tests using injection moulded test specimens (to account for residual stresses) at conditions which are representative of the end-use application.

7.2.2. CREEP RUPTURE

Under a sustained loading condition, plastic materials exhibit a failure mode which is associated with the creep deformation. Sometimes this is referred to as static failure, but more commonly creep rupture [45]. In general this failure mode can be easily identified as a number of visible indicators such as whitening, necking or crazing become evident prior failure. Any of these indicators on there own can terminate the useful life of the component. Typical creep failure data is illustrated in figure 7.5.

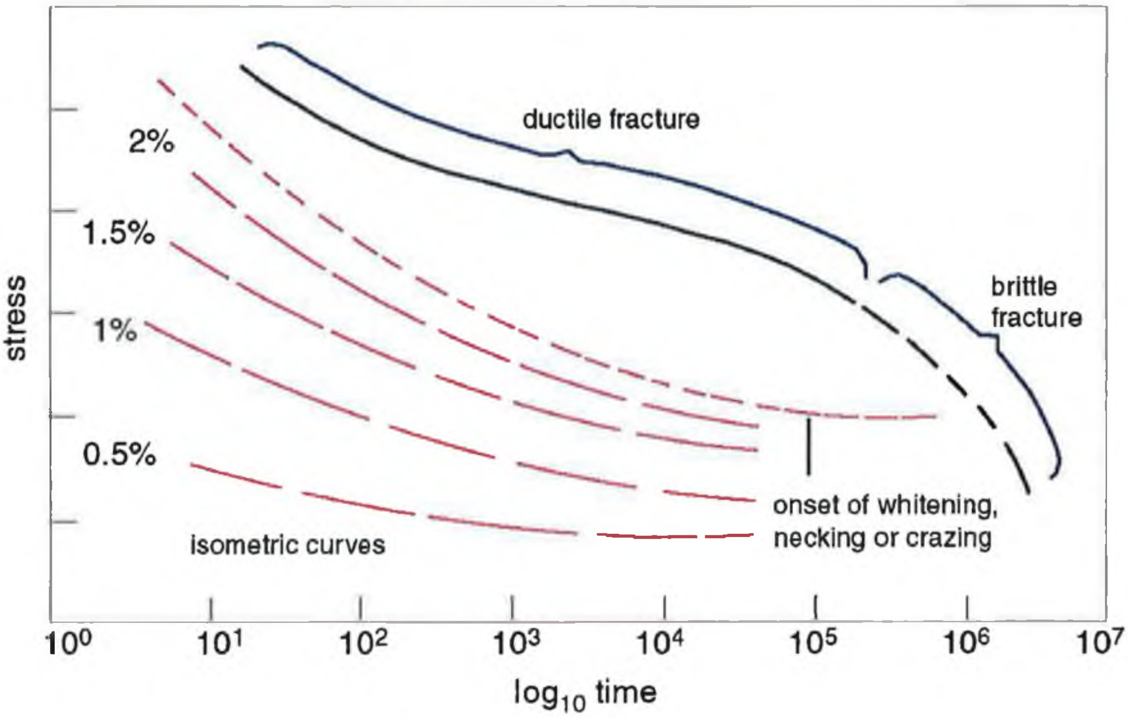


Figure 7.5: Creep Rupture Behavior of a Plastic Material [45]

7.2.3. CREEP-FATIGUE RELATIONSHIP

Creep is a time dependent behavior, whereas fatigue is a cyclic dependent mechanism. The most appropriate manner for presenting combined data from both these sources is in the form of a diagram of alternating stress against steady or mean stress [45, 69]. Results from creep tests, which lead to creep rupture are plotted along the abscissa, while results from fatigue tests are plotted along the ordinate.

Tapsell [69] prepared such a study (figure 7.6) for 0.26% carbon steel for various amounts of total creep strain occurring within 100 hours at 400(C under different combinations of cyclic steady stresses. Theoretically predicted curves for creep strains of 0.002 and 0.005 are also illustrated. It is important to stress that all plastic materials exhibit a similar behavior at room temperatures, and therefore any elevation in temperature will result in failure much quicker.

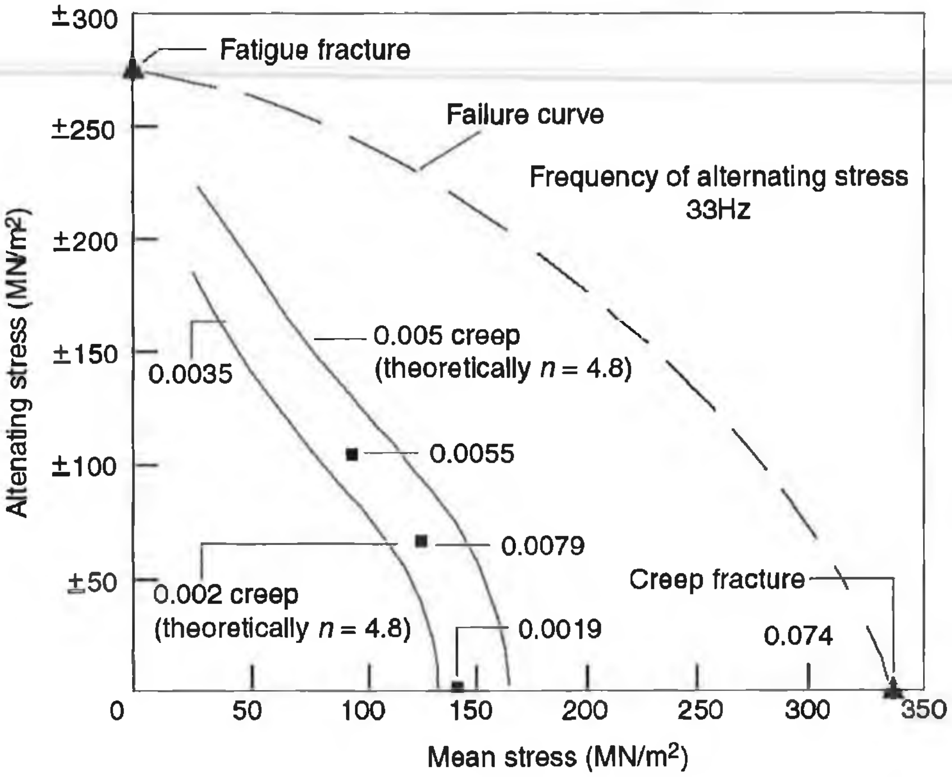


Figure 7.6: Creep-Fatigue Relationship of Carbon Steel [45]

7.3. ACCELERATED TESTING

Accelerated testing procedures are often employed to establish a suitable warranty period for a product, or in the event where a number of products have failed from what appears to be similar factors, a cause [10, 70, 71]. The latter often results in production facilities being shut down until the cause has been establish, thereby reducing the risk of producing defective products. The process of accelerated testing establishes quickly how a component has failed or will perform throughout its intended service life.

7.3.1. BRITTLE COATING

Brittle coatings are strain sensitive lacquers which are used to determine the surface strains in plastic components. These lacquers (available in a series of strain sensitivities) are sprayed over the entire surface of the component to be tested. When an external force is applied to the component, cracks which are parallel to each other and run perpendicular to the direction of the largest principle stresses will appear. These cracks provide an indication of the overall strain distribution, magnitude and directions. This technique is a quick and convenient method for obtaining areas of high stress or pinpointing locations for more extensive gauge testing. Residual stresses introduced in the moulding process are not easily determined using this technique.

7.3.2. STRAIN GAUGES

Strain gauges are strain sensitive electrical resistors which are useful for quantitative analysis of surface strains arising from external loading. These instruments are bonded to region of interest (indicated by the brittle coating) of part under test. The surface strains caused by stresses resulting from external loading are transformed into electrical resistance charges, which can be interpreted by a measurement device. The physical architecture of the most common strain gauges can be obtained from many books [10].

Unlike brittle coating, strain gauges can determine quite easily the residual stress introduced at the moulding stage. These stresses often lead to environmental stress cracking, warpage at elevated temperatures or contribute to failure in service [10].

7.3.3. CHEMICAL TESTING

Internal or external stresses within a plastic component can reduce the solvent resistance of the part. The test is conducted by placing the component under test into a solvent of appropriate strength, and monitoring the time until crack initiation. Pre-stressed control samples are often added, so that a correlation of results can be obtained. Elevating the temperature can accelerate the test.

This testing procedure offers a quick and partially quantitative set of results which are useful for determining residual stress levels in moulded plastic components. Load induced stresses can also be evaluated in this manner.

The major drawback associated with this procedure is that proper safety precautions and ventilation must be provided.

7.3.4. PHOTOELASTIC TESTING

Plastic materials of an isotropic nature can exhibit a temporary double refractive index when stressed. An increase in the level of stress or strain will change the refraction index, thereby forming an optical property which can be viewed as colour fringe pattern under polarized light. These fringe patterns provide an accurate indication of the magnitude and direction of the stress within the test specimen.

Three dimensional models can be evaluated by this method by loading them at an elevated temperature and allowing sufficient time for them to cool back to room temperature, so that the photoeleastic pattern is frozen into the model. This model is then sliced into two dimensional thin sections and analysed using a light transmission polariscope or polarizer equipped microscope and a variable intensity light source.

This technique is very a attractive potion, as parts of virtually any size material or shape can be analysed easily. Prototype parts obtained from one of the tooling process discussed in the previous chapter, and moulded from the end run material can be coated and evaluated as outlined. It is important to note that not all plastic materials are of photoelastic nature, therefore must be coated with a thin layer of material that is.

INTRODUCTION

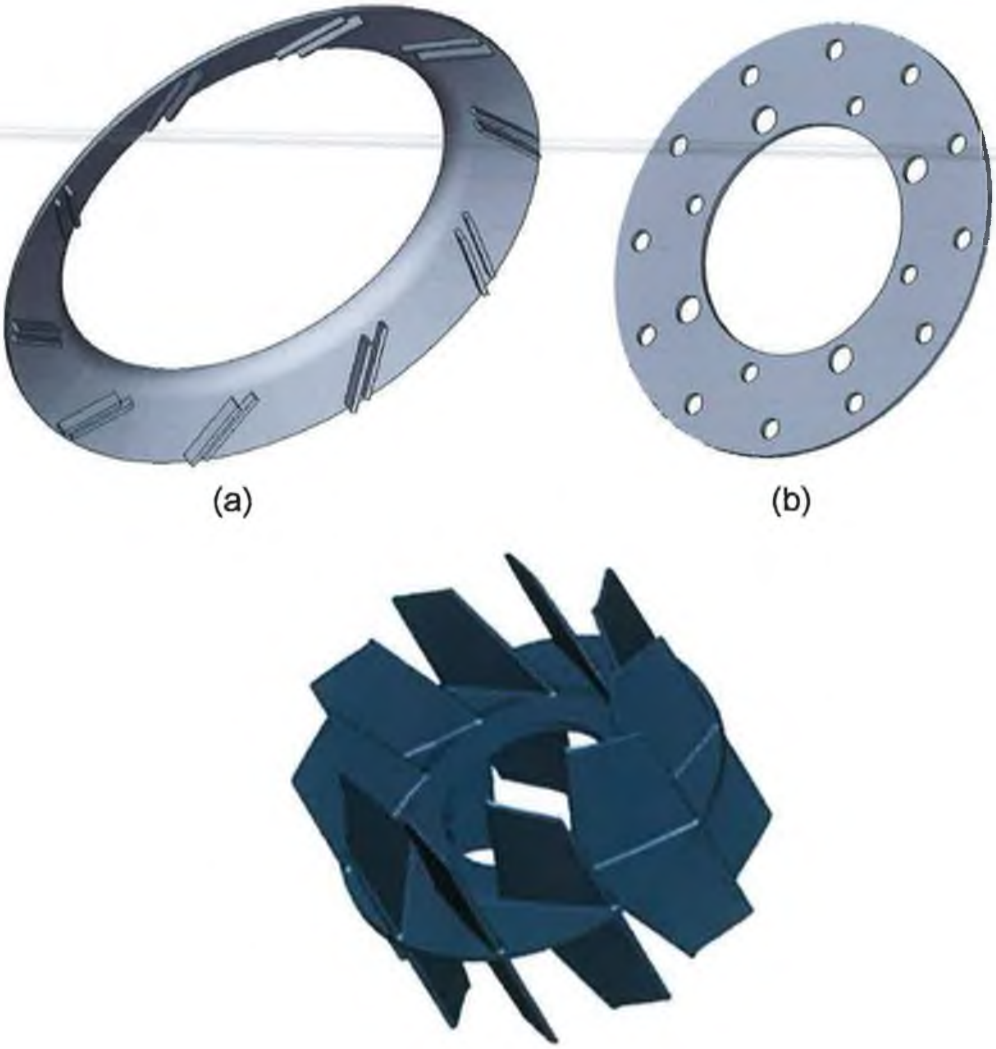
The purpose of the following chapter is to present two case studies which utilize the tools discussed in the preceding chapters. Each of these studies have been prepared in order to validate and improve the proposed product development cycle. The first study presents the design, one of manufacture of a functional prototype plastic evaporator blower, and subsequent testing. The second study presented details the design, analysis and generation of a functional rapid prototype of a computer mouse.

8.1. CASE STUDY I

This study involves the rapid prototyping, tooling and functional testing of a centrifugal blower which is part of a transport refrigeration system. The original design consisted of 83 parts, which when broken down results in a centre plate, 20 blades, 2 shrouds (top and bottom), approximately 20 rivets used to secure the blades to the centre plate and 40 welds to secure both shrouds to the top of the blades.

The tools first presented in chapter two where utilized in order to identify design alternatives and any limitations that existed with the original design. One of the key outcomes of conducting these studies was that considerable time and money was wasted during the assembly process, as repeatability was hard to achieve, and jigs and fixtures, as well as a skilled workforce were required. An alternative plastic component option presented itself and when examined with these tools resulted in a more attractive option.

Pro-Engineer, Version 20 was used to create the 3D Solid Model Assembly. This model consisted of an aluminum centre plate (for attaching the blower to the spindle) containing a series of holes to secure it within the plastic component structure, the required amount of blades (the bottom end of which are thicker therefore resulting in a blended profile), and both the top and bottom shrouds. The various components of this model are presented figure 8.1.


(a) (b)

(c)

Figure 8.1: Blower Assembly Components

The Finite Element Method was employed to ensure that the assembly operated as intended and would not fail in its working environment while under test. The blower rotates at approximately 2400 rpm and therefore would pose a significant danger to personal within the test vicinity. A complete FEA analysis was performed on the assembly to pin point the highest stresses. These were determined to occur at the roots of the vanes as indicated in the figure 8.2. The radius was increased within this region to improve the long term performance of the blower by minimizing both creep, and creep rupture failure. Such an increase also has the knock on effect of allowing easy extraction from a mould cavity. Non-linear FEA analysis was not performed on this part.

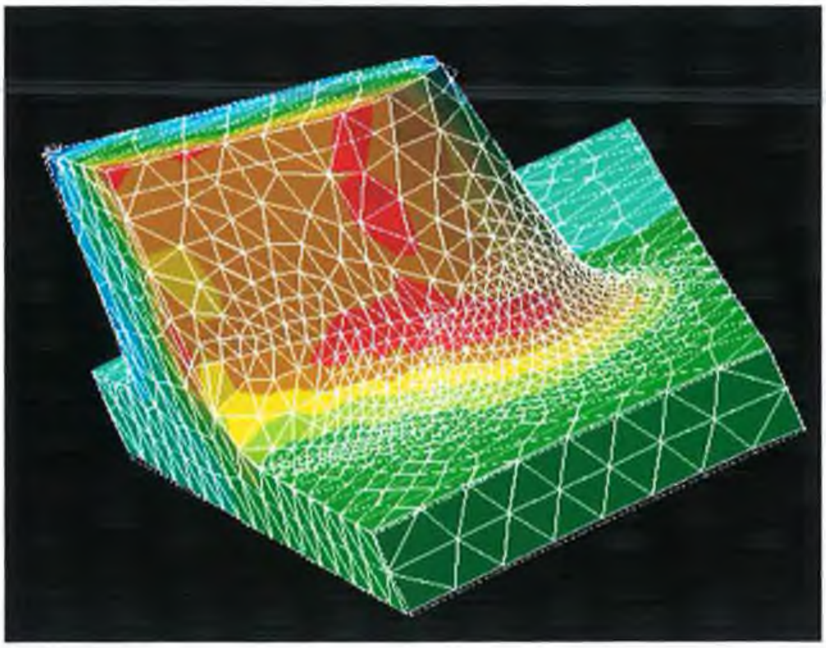


Figure 8.2: Detailed Sub-model of Blade Root

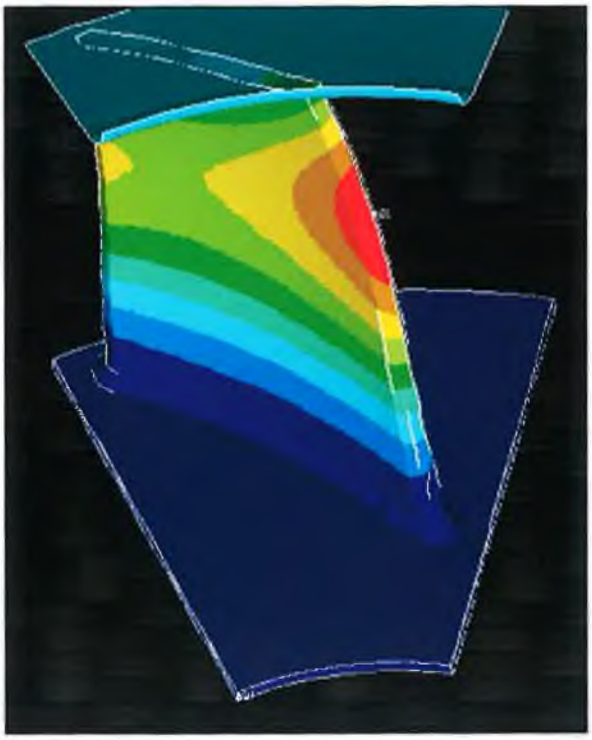


Figure 8.3: FEA of the Shroud and Blade illustrating deflection

Once the FEA modeling was complete, and all modifications made to the design resulting from this analysis, the CAD files where converted to a STL file format (applicable to virtually all RP systems). A chord height of 0 (this field is generally replaced by a minimum acceptable value) and an angle control of 1 were set in Pro-Engineer when preparing the file. These values resulted in a rather large, but extremely accurate file size, which was transferred to ARRK Prototype's in the UK by an ftp sever. It was this bureau that generated the SLA patterns which can be seen in figure 8.4 (additional pictures are contained in appendix E).

Figure 8.4: SLA Patterns of Blower Components

Stereolithography was chosen as the RP process as the machine, an SLA5000, yields relatively accurate patterns with a good surface finish at a reasonable cost. Other processes were also considered and quotes obtained. These alternative processes could not cater for size of pattern required, or in the event where they could proved to be rather expensive.

Silicone Rubber Tooling with the final part produced using a vacuum casting process, was chosen as the tooling process as only one prototype was required. This process offered the most economical option with more than adequate accuracy. Each tool was created independently of each other, thereby reducing the cycle time to approximately 24 hours. High quality polyurethane was cast into the cured tools. The complete design to tooling cycle is as depicted in figure 6.4.

Some post processing was necessary in order to improve the final component. Each of the individual parts was sanded at the service bureau to reduce drag on the air moving through the blades. All parts were assembled as shown in Figure 8.5. This was done using 2 part epoxy which formed a strong rigid bond.

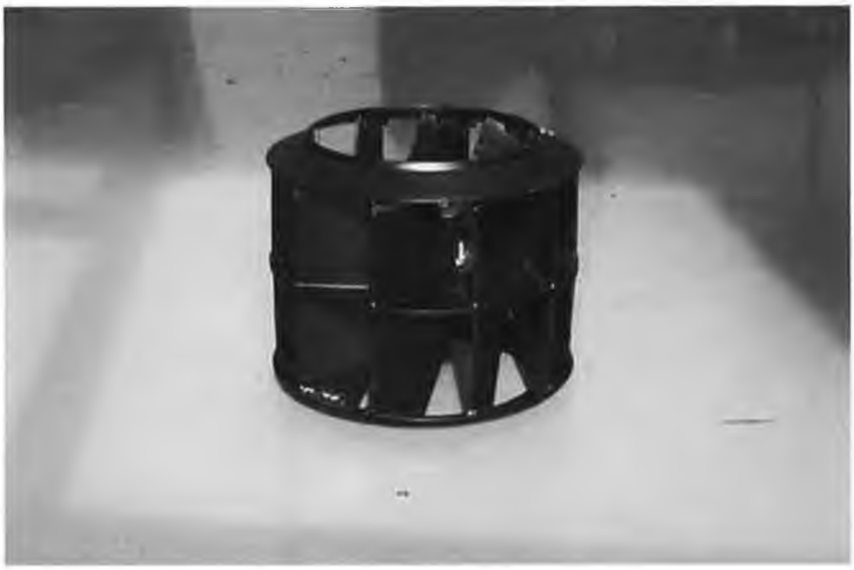


Figure 8.5: Complete Polyurethane Assembly

It was vital that the blades obtained from this tooling process were geometrically accurate and similar to an injection moulded alternative (in order to ensure that such an alternative would be applicable to generation of many thousand components). It was also important that the tops of the blades accurately mated with the under side of shroud. This was the case, even though there were slight gaps. These were easily filled using an epoxy adhesive when the components were assembled (refer to figure 8.6).

Figure 8.6: Blades and Shroud mating

Additional balancing of the blower was also required. The balance weights are shown as lead rivets in the shroud, figure 8.7. ThermoKing has special equipment for balancing blowers that indicate the precise location where these lead rivets should be placed.

Figure 8.7: Located Balance Weights

The assembly was installed in a large transport refrigeration unit. Functional testing identified a problem with the trailing edge blade tips which resulted in a performance limitation. In a redesign this was addressed and it was calculated that approximately 3% to 4% efficiency was subsequently achieved. Another contributing factor to the efficiency losses was that the blades were not perfectly smooth. Extra care should have been taken to polish them and perhaps a coating of clear smooth resin should have been employed.

Both the SLA and vacuum cast parts were very accurate. A jib should have been created for centering and locating the shrouds on the blade tips. In this case more weights were used to balance the blower than would have otherwise not been necessary.

The costs associated with obtaining this functional prototype are summarized in table 8.1. These costs do not include post processing (namely, polishing, balancing etc.).

Component	*Process*	*Cost (Stg)*
Blower Blades	SLA	£1,494.00
Blower Blades	Vacuum Casting	£1,224.00
Shroud Top	SLA	£431.00
Shroud Top	Vacuum Casting	£377.00
Shroud Bottom	SLA	£431.00
Shroud Bottom	Vacuum Casting	£377.00

Table 8.1: SLA Pattern and RTV Costings

8.2. CASE STUDY II

The design, analysis, and subsequent generation of a prototype computer mouse is present through this study. Each of the phases with the exception of rapid tooling, presented in figure 1.4, where examined with regards there usefulness to the product development cycle of injection moulded components. Considerations originally omitted from this methodology where identified and subsequently incorporated, the most notable of which is the linkage between design and concept modeling.

This study commenced at the Design For Manufacturability phase, where the various tools discussed and presented in chapter 2 where adapted. The process of benchmarking a number of different computer mouse's (refer to appendix A), identified key features that should be incorporated into any new design. Value analysis established the approximate cost that each component within the mouse should incur (table 2.2.), while the Value Graph identified the components, product requirements and some alternative approaches. Quality Function Deployment ensured that the requirements of customer where incorporated into the design, while Tanaka's Cost Worth Analysis ensured that no component's cost exceeded its worth in the overall design. Failure Modes Effects Analysis proved to be the most powerful of all the tools on an individual basis, in so far that it identified possible failure modes before the detail design phase began. When combined the results (refer to the various table's and figure's in chapter 2), of these tools provided a very clear product specification for the design phase.

The exterior profile of the mouse was the primary customer requirement. This profile had to be suitable for both left and right handed people, while also being comfortable. Older mouse designs reviewed as part of the benchmarking process, possessed a very unique characteristic hump which fitted the human hand, but due to the limited moulding capabilities of that era, these design proved to be uncomfortable. Incorporating these key features into the new design configuration would result in a very effective and attractive design.

In order to successfully achieve this, advanced surfacing techniques and a top down design approach was adopted. The design was not driven by the space constraints of any existing internal components, hence the top down approach. The surfacing capabilities of Pro-Engineer provided an easy and more than adequate definition of the exterior surface of the mouse, and formed a master profile. Additional surfaces were added to identify the parting planes of the top and bottom halves, as well as the buttons (refer to figure 3.3).

Each of the external components of the mouse was created by the Master Modeling Technique outlined in chapter 3. The master profile was used to create the individual components by this procedure coupled with conventional modeling techniques. Modification's which were subsequently made to any of these parts did not have an adverse effect on the others as these were updated with changes corresponding the modifications made.

Upon close examination of each component it was identified that internal components of an existing computer mouse (considered in the benchmarking study) would fit this revised design. The dimensions of these components were established using a CMC machine, and subsequently each was modeled with the CAD system using conventional modeling techniques. These where then assembled and the exterior components placed around them. Working within assembly mode, it was easy to identify where the necessary locators and supports needed to be placed in figure 8.8.

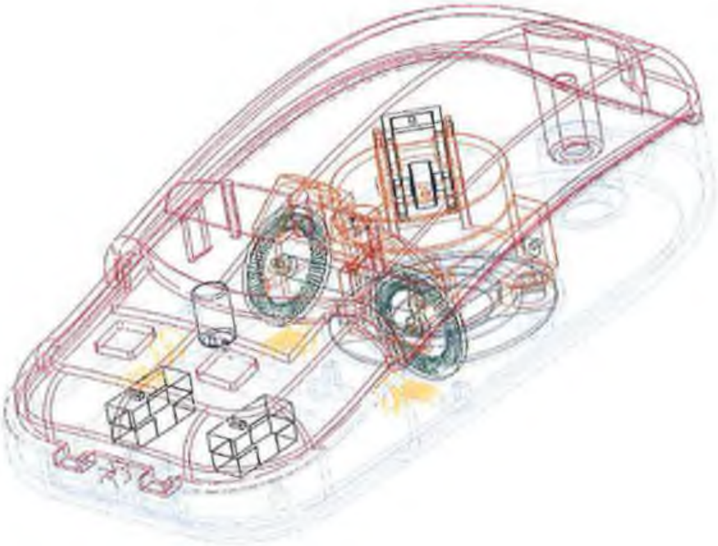


Figure 8.8: Wireframe Model of Computer Mouse Depicting Locators and Supports

Both Finite Element Analysis and MoldFlow studies were performed on the final design. In the case of Finite Element Analysis, static, sensitivity, optimization and non-linear studies of the snap fit which secures the button to the top half were conducted. The static results (figure 4.2 and 4.8) indicated that this design was within the UTS of the material and adequate. The sensitivity study illustrated how varying the fillet radius affected the results (figure 4.7), while the optimization study indicated that a fillet radius of 0.56 mm was acceptable to tolerate the working stress. The non-linear analysis results indicate that over a period of 300 days, the stresses relax by approximately 50% (figure 4.9), thus suggesting that the snap fit would be compromised, therefore resulting assembly failure. To avoid this, the cross-sectional area of the cantilever section of this snap fit should be increased and the study revised.

The MoldFlow studies (presented in appendix D) illustrates that each component can be filled easily with a high confidence level. The results also indicate the expected temperatures and injection pressures that are required. Weld lines are evident therefore residual stresses will be apparent in these regions. Additional venting will also be required as a number of air traps are evident. These results are summarized in table 4.1 (reproduced hereunder).

Flow Analysis Results

	Components		
	Top	Bottom	Button
Material Supplier	GEPlastics	GEPlastics	GEPlastics
Material Grade	Cycolac X37	Cycolac X37	Cycolac X37
Confidence of Fill	High	High	High
Fill Time	0.4 sec	0.4 sec	0.41 sec
Injection Pressure	72.72 MPa	74.39 MPa	70.24 MPa
Pressure Drop	73.92 MPa	83.61 MPa	70.24 MPa
Flow Front Temp	261.28 Deg C	260.48 Deg C	262.25 Deg C
Weld Lines	Yes	Yes	Yes
Air Traps	Yes	Yes	Yes

Table 4.1 (reproduction)

Stereolithography and Fused Deposition Modeling were chosen as the Rapid Prototyping techniques for the production of rapid models. In the case of the FDM model, the stair stepping effect of the layering processes was very evident (refer to figure 8.7), and therefore required considerable post processing. The model was also limited in so far that the tolerances were relatively poor. This is not problem with the machine, but rather the use of a relatively large extrusion head. Smaller heads are available which could elevate some of the problems encountered. The SLA model was produced on a SLA7000 system. This model (figure 8.8) posses very high tolerances and a very good surface finish (even with no post processing). The assembly of each component with the existing parts (figure 8.9) required only minimum alterations for an accurate fit.

Figure 8.9: FDM Model with supports (before post-processing)

Figure 8.10: SLA Model (before post-processing)

Figure 8.11: Complete RP Assembly

The functional prototype obtained from this study performed well when connected to a PC. A number of users where also asked for their opinion on the design and functionalability. All remarked that the device was very comfortable to operate and fitted the hand well. The only drawback that was identified was that the overall width of the design needed review. An increase of 4-5 mm in the width would make the device much more comfortable to hold. This can be achieved easily by the modifying the overall width parameter of the master CAD profile, but if the locators and supports for the internal components are not dimensioned from a central reference datum then the modified design will not assembly correctly. This could be avoided by obtaining a concept model after the profile was defined.

DISCUSSION

The Product Development Cycle proposed at the end of chapter one has proved to be of significant benefit to the development of any new injection moulded plastic component design. This cycle identifies weakness in the proposed design by examining it at more frequent intervals, and earlier in the development cycle. The most recent tools available to the design engineer are integrated into this cycle, thereby yielding an Integrated Design and Manufacture Methodology applicable to Injection Moulded Components.

Each of the techniques falling under the banner of Design For Manufacturability are primarily used as product development tools. Benchmarking is employed when things are not going as well as they should be, when it is perceived that the competition is gaining an advantage or when the organization wishes to leverage an advantage over the competition in terms of quality, service, cost, profitability, etc.... Value Analysis, provides a means of establishing the cost of each component, when the functions that it provides are all considered. Value Graphs, are used as a means of identifying both customer requirements, and product architecture. Q.F.D. ensures that the voice of the customer is clearly identified and maintained throughout the development and design phases. Tanaka's Cost Worth Analysis calculates the relative worth and relative cost of each component. While, F.M.E.A. identifies how a product, system or service may fail during its operation.

On an individual basis the three techniques of benchmarking, value analysis and F.M.E.A. are of most benefit. Benchmarking is easy to implement and can help gain a significant advantage over the competition. Both Value Analysis and F.M.E.A. offer considerable benefits to the design process by identifying costs and failure modes respectively. The Minimization of both these characteristics is the key to any successful product development cycle.

The remaining three techniques, namely, Value Graphs, Q.F.D. and Tanaka's cost Worth Analysis, are of little or no real benefit on their own, and in reality cannot even be implemented. When these techniques are combined however, a very different picture becomes apparent. These tools marry both the customer and product requirements together in order to ensure that the voice of the customer and product characteristics as well as the cost to worth ratio is clearly established. This ensures that the product design concept will be successful.

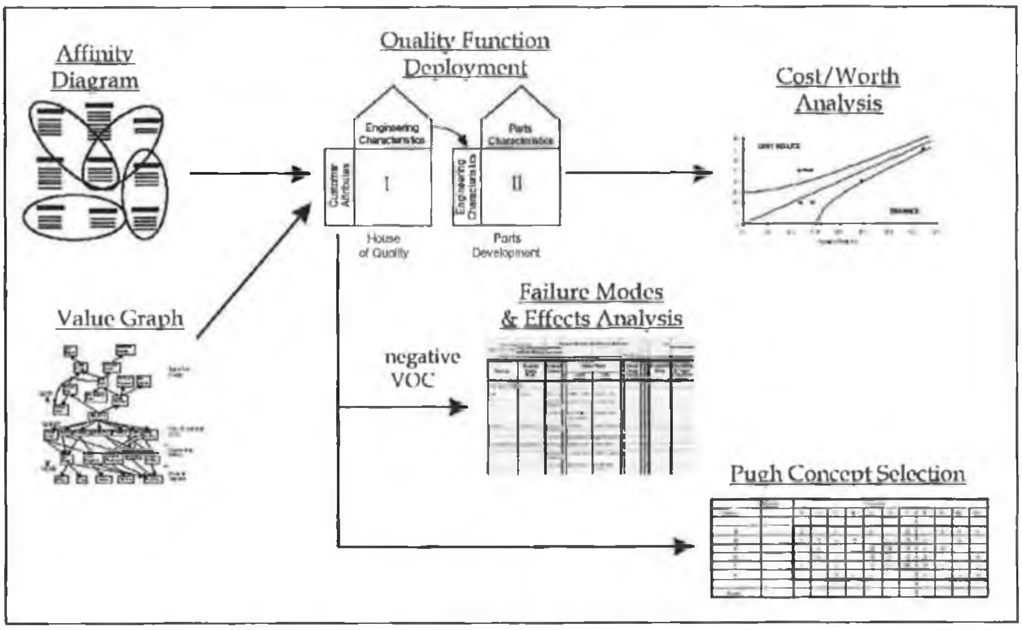


Figure 9.1: D.F.M. Tool Integration [35]

The majority of Computer Aided Design systems available within today's market place are more than capable of handling the majority of features that plastic components require. Some of these systems offer much more enhanced capabilities than others, but generally speaking all offer the basics. Table 9.1, which has been complied after discussing these capabilities with other users of the various systems, illustrates the capabilities found within the most common systems.

SolidWorks and Pro-Engineer seam to be the most accepted systems for plastic design. Catia, Unigraphics, and Pro-Engineer, are the more expensive of these systems. SolidWorks, while only being around for the past seven years or thereabouts is posing a significant challenge to the more dominant systems. Within its next three derivatives, it will probably attain the number one spot, even though it does not have the same functionality as others. With time these capabilities will emerge.

When considering Pro/E, one should consider the future of the company, which at present looks pretty bleak from a financial view point. I-DEAS will probably not be around much longer since it has been bought out by EDS, the company behind Unigraphics. In the case of Unigraphics and Catia, one should be aware of the cost, learning curve, and affordable talent pool. Solid Edge (also owned by EDS) lacks most of the complex shape tools, and is looked at by some as bait-and-switch for Unigraphics when the user's needs become more advanced.

	CAD Systems						
Features	Unigraphics	Pro-Engineer	Catia	SolidWorks	SolidEdge	I-Deas	Pro-Desktop
Wall Thickness	Y	Y	Y	Y	Y	Y	Y
Rounds	A	A	A	Y	Y	Y	Y
Draft	Y	Y	Y	L	Y	Y	Y
Webs/Ribs	Y	Y	Y	Y	Y	Y	Y
Surfacing	Y	A	Y	Y	L	Y	L
Master Modeling	Y	Y	Y	L	L	Y	L
Top-Down Design	Y	Y	Y	Y	Y	Y	Y
Info Tools	Y	Y	Y	Y	Y	Y	L
Draft Check	Y	Y	Y	Y	Y	Y	N
Surface Check	Y	Y	Y	N	L	L	L
Y=Yes, N=No, L=Limited, A=Advanced Capabilities							

Table 9.1. CAD System Comparison

Performing a static FEA analysis, as well as sensitivity and optimization studies, can be achieved easily and conducted in a relatively short timeframe. Results obtained from these, can increases the confidence associated with the actual design.

FEA System Comparison					
	Pro-Mechanica	ANSYS	COSMOS/M	NASTRAN	SDRC I-DEAS
Solution Types					
Linear Static	Y	Y	Y	Y	Y
Modal	Y	Y	Y	Y	Y
Buckling	Y	Y	Y	Y	Y
Nonlinear					
Large Deformation	Y	Y	Y	Y	Y
Contact	L	Y	Y	L	Y
Buckling	Y	Y	Y	Y	Y
Materials	N	Y	Y	Y	Y
Dynamic					
Transient	Y	Y	Y	Y	Y
Frequency	Y	Y	Y	Y	Y
Random Response	Y	Y	Y	Y	Y
Modal Method Solution	Y	Y	Y	Y	Y
Direct Method Solution	N	Y	L	Y	Y
Design Improvement Options					
Geometry Optimization	Y	Y	Y	Y	Y
Size Optimization of Plate or Beam Properties	Y	Y	Y	Y	Y
Sensitivity Studies	Y	Y	Y	Y	Y
Element Technology Supported					
P-Element	N	Y	Y	Y	Y
H-Element	Y	L	Y	L	L
Geometric element definition of p-elements	Y	N	N	L	N
Increased p-order of existing H-element mesh	N	Y	Y	N	Y
Other					
Automatic Adaptive Mesh Refinement	Y	L	Y	Y	L
Sub-modeling Support	N	Y	Y	N	Y
Super-element support	N	Y	Y	Y	Y
Asymmetric Loading of Axi-symmetric Models	N	Y	Y	N	Y

Table 9.2: FEA System Comparison

Non-Linear FEA analysis is the most difficult of all techniques to implement. Conducting such a study requires a considerable time investment, and a high level of skill. Any such study should not be undertaken by a novice FEA user. In the circumstances where is deemed such an analysis is necessary, it should be outsourced to a specialized consultation agency.

The Plastic Flow Analysis tools presented can be utilized by both experts and novices alike. Extensive expertise knowledge is not essential but beneficial for result interpretation. These tools are limited in the information they provide.

Two distinct categories exist when discussing all Rapid Prototyping Processes, these being the Machine Room Technologies and the Concept modelers. The concept modelers provide a quick, cheap and easy path to rapid prototyping. These have their limitations however, in that they all have a limited work envelope. These devices are an ideal tool for the production of visual aids and are finding a place in the surgeries of many surgeons who are faced with complicated and delicate operations. These surgeons can model their patient's internal organs and any tumors that may be infecting them from data obtain by either a Magnetic Resonance Imaging (MRI) or a Computed Tomography (CT) machine. Now rather than spending hours studying the two-dimensional scan data, the surgeon can produce an actual three-dimensional model of that patient's unique architecture.

These concept modelers have also become a vital tool in the design office. More radical and adventurous designs are beginning to emerge as designers now have the freedom to explore many design iterations. The machine room technologies are limited in this regard in so far that they present time and cost implications.

Rapid Prototyping Comparison Table

Company	Model	Build Technology	Materials	Build Volume	Price €
3D Systems 26081 Avenue Hall Valencia CA 91355 www.3dsystems.com	SLA 250	Stereolithography	Epoxy, acrylates	254*254*254	165,000
	SLA 3500	Stereolithography	Epoxy	355.6*355.6*406.4	370,000
	SLA 5000	Stereolithography	Epoxy	508*508*584.2	560,000
	SLA 7000	Stereolithography	Epoxy	508*508*609.6	900,000
	Viper SI2	Stereolithography	Epoxy	254*254*254	200,000
	ThermoJet	Thermoplastic Jet	Thermoplastic	254*203.2*203.2	56,000
	Sinterstation 2500Plus	Powder Sintering	Polyamide, Polystyreme, Elastomers, Foundry sands, Stainless Steel	203.2*254*355.6	540,000
Cubic Technologies (formerly Helisys) 1000 E. Dominguez St. Carson, CA 90746-3608 310-965-0006 www.cubictechnologies.com	LOM-1015Plus	Paper lamination	Paper	381*254*355.6	78,000
	LOM-2030H	Paper lamination	Paper	812.8*558.8*508	200,000
EOS GmbH Pasinger Strasse 2 D-82152 Planegg/ Munich, Germany +49-0-89-856-85-0 www.eos-gmbh.de	EOSINT P 360	Laser sintering	Polystyrene, polyamides	330.2*330.2*609.6	365,000
	EOSINT P 700	Laser sintering	Polystyrene, polyamides	711.2*381*584.2	900,000
	EOSINT M 250 Xtended	Laser sintering	Bronze-based metal powders	254*254*152.4	365,000
	EOSINT S 700	Laser sintering	Resin-coated sand	711.2*381*381	700,000
Kira America 4133 Courtney St. Unit 3 Franksville, WI 53126 262-835-9272 www.cs.com	PLT-A4	Paper lamination	Paper	279.4*203.2*203.2	62,000
	PLT-A3	Paper lamination	Paper	406.3*279.4*304.8	82,000
Objet 1199 Route 22 East Mountainside NJ 07092 908-228-5400 www.2objet.com	Quadra	Ink jet	Acrylate photopolymer	279.4*304.8*203.2	79,000
Optomec 3911 Singer NE Albuquerque, NM 87109 505-761-8250 www.optomec.com	LENS 750	Laser fused metal deposition	Stainless steel, tool steel, titanium, inconel, tungsten, copper, aluminum	304.8*304.8*304.8	605,000
	LENS 850	Laser fused metal deposition	Stainless steel, tool steel, titanium, inconel, tungsten, copper, aluminum	457.2*457.2*1066.8	720,000

Rapid Prototyping Comparison Table Continued….

Company	Model	Build Technology	Materials	Build Volume	Price €
Schroff Development P.O. Box 1334 Mission, KS 66222 913-262-2664 www.schroff.com	JP5 Standard	Adhesive paper lamination	Adhesive paper	76.2*76.2*76.2	8,500
	JP5 Premier	Adhesive paper lamination	Adhesive paper	101.6*101.6*101.6	12,000
Stratasys 14950 Martin Dr. Eden Prairie, MN 55344 952-937-3000 www.stratasys.com	FDM2000	Fused deposition	ABS, casting wax, elastomers	254*254*254	90,000
	FDM3000	Fused deposition	ABS, casting wax, elastomers	254*254*254	140,000
	FDM8000	Fused deposition	ABS	457.2*457.2*609.6	170,000
	Prodigy	Fused deposition	ABS	203.2*203.2*304.8	75,000
	FDM Titan	Fused deposition	Polycarbonate, ABS, polyphenylsulfone	355.6*406.4*406.4	215,000
	FDM Maxum	Fused deposition	ABS	609.6*508*609.4	325,000
	Genisys Xs	Fused deposition	Polyester	304.8*203.2*203.2	50,000
Z Corp. 20 North Ave. Burlington, MA 01803 781-852-5005 www.zcorp.com	Z400 3D Printer	Ink jet	Starch and plaster	203.2*254*203.2	55,000
	Z406 System	Ink jet	Starch and plaster	203.2*254*203.2	76,000

Table 9.3: Rapid Prototyping Comparison

System	Accuracy	System	Accuracy	System	Accuracy
SLA Viper	0.05 mm	EOSINT P700	0.15 mm	FDM Titan	0.25 mm
SLA 7000	0.00125 mm	EOSINT P360	0.1-0.2 mm	Prodigy	0.178-0.33 mm
SLA 5000	0.0035 mm	EOSINT M250	20-100 μm	Z 400	0.076-0.254 mm
SLA 3500	0.0035 mm	EOSINT S700	0.2 mm	Z406	0.076-0.254 mm
SLS 2500	Material Dependent	FDM 3000	0.178-0.356 mm	LENS 750	0.020 in
LOM 1015 plus	0.08-0.25 mm	FDM Maxum	0.178-0.25 mm	LENS	0.02 in
LOM 2030	0.076-0.254	FDM8000	0.178-0.356	JP5	4.33-5.4 mil

Table 9.4: RP Machine Layer Thickness Comparison

Virtually all the rapid prototyping processes discussed operate automatically without any operator intervention. Some, with the exception of the concept modelers, do require some nursing due to a lack of reliability within the machine make up. This is non-the more evident in the case of the laser based LOM processes where a number malfunctions within the hardware have resulted in fires. The SGC process has also been reported has having a number high proportion of downtime.

Operation of all rapid prototyping machines does require some level of operator skill. Slice thickness, the orientation of the part, and the placement of the supports needs to be carefully considered when preparing the STL file for modeling.

Given the growing need for rapid tooling, a wide variety of process, which can accommodate the production of rapid tools has been established in recent times. The selection of a suitable process necessitates the need to identify the specification upon which of the processes is finally chosen. Generally two points should be considered:

- The quantity of end components required
- And, the material they are to be fabricated from

When these two criteria are considered, it should be possible to identify a process, which can fabricate the required tool quickly and easily in a very cost effective manner.

Tools fabricated from one of the many rapid tooling process remain quite fragile and therefore are limited in the usage when compared with hard tools. Also RPTM cavities are not suitable for complex geometries, with fine details and high aspect ratios. Another point worth considering is that these tools generally are only suitable for the production of straight pull geometries, as they cannot accommodate sliding cores.

Each of the rapid prototyping processes currently available has advantages and disadvantages with respect to manufacturing lead times and its performance. The choice of process must be considered early on, and must be based on the points identified above. The key consideration in selecting the process can therefore be established as the longevity of the tool surface for a given production run. For example, if a large number of components are required, which are to be manufactured from a relatively soft material, such as ABS or polypropylene, then the tool face and tool material should be required to be significantly harder than that production material. If on the other hand, small volumes of parts are required, produced from a material such as metal or glass filled polymer, then the tool face should be an order of magnitude harder.

Another point worth considering when selecting a process is any time limitations. A general rule of thumb, is that the softer the tool material, the quicker the tool can be fabricated. In the case of silicone rubber tools, the tool can be fabricated and ready for use in a matter of hours, ceramics can take a few days, while non-ferrous alloy's and powder metallurgy tools can take a number of weeks to prepare.

Commercially Available INDIRECT Tooling Processes

	RTV Silicone Rubber Mould	Aluminum-Filled Epoxy	Sprayed-Metal	Kirksite	3D Keltool™
Lead Time	0.5 to 2 wks	1 to 4 wks	2 to 4 wks	3 to 6 wks	1 to 6 wks
Relative Cost	$1K to $5K	typical $3K; range: $2.5 to $10K and up to $35K	$2 to $15K	$4 to $15K	$2K to $5K
Materials	urethanes, epoxies, acrylics	Thermoplastics	thermoplastics	Thermoplastics	thermoplastics
Tolerance (in/in) or as designated	+ - 0.005 w/ 0.020 walls	+ - 0.002 in/in	+ - 0.002 in/in	+ - 0.003 in/in	+ - 0.001, flatness + - 0.025mm/in; details0.04mm
Strengths	least expensive mould, (but fairly expensive piece parts)	Least expensive for true thermoplastics	large parts	Complex shapes	accuracy, high volume
Weaknesses	tool life; accuracy, better for simple parts; limited materials	long cycle times ; tool life; accuracy, better for simple parts	tool life; accuracy, better for simple parts; poor for narrow slots	Accuracy	part size, one supplier

Table 9.5: Indirect Tooling Comparison [sourced from RP worldwide report]

Commercially Available DIRECT Tooling Processes						
	Direct AIM™	Copper Polyamide SLS	Direct Metal Laser Sintering (DMLS) (Bronze alloy)	CNC Aluminum Tooling	RapidTool™ SLS (Steel)	DirectTool™ (Steel)
Lead Time	1 wk	1 to 5 days	1 to 4 wks	4 to 16 wks	2 to 5 wks might be typical range	1 to 2 wks
Relative Cost	$2K to $5K			$4K to $25K	$4K to $10K	
Materials	Low temp, unfilled thermoplastics	Thermoplastics	thermoplastics	thermoplastics	thermoplastics, metals	thermoplastics, metals
Tolerance (in/in) or as designated	+ - 0.002		+ - 0.002 overall	+ - 0.001 in/in	0.003 in layers; +/- most dims	+ - 0.001 to 0.002 in/in
Strengths	Direct fabrication of moulds	Close to hard tool cycle time and temp; conformal cooling; no burnout cycle	Conformal cooling, no burnout cycle	Excellent accuracy and finishes; long tool life	die casting; can take typ inj mould press and temp ; Largely unattended operation	no burnout; accuracy. surface finish are improving w/ new materials
Weaknesses	Severe materials and process limitations.	Limited tool life, lower pressures, conformal cooling channels have limitations due to powder removal	Limited tool life, lower pressures, conformal cooling channels have limitations due to powder removal	Slow, expensive for complex parts	Requires burnout and infiltration cycle; may require finish machining; conformal cooling channels have limitations due to powder removal	may require finish machining; conformal cooling channels have limitations due to powder removal

Table 9.6: Direct Tooling Comparison [sourced from RP worldwide report]

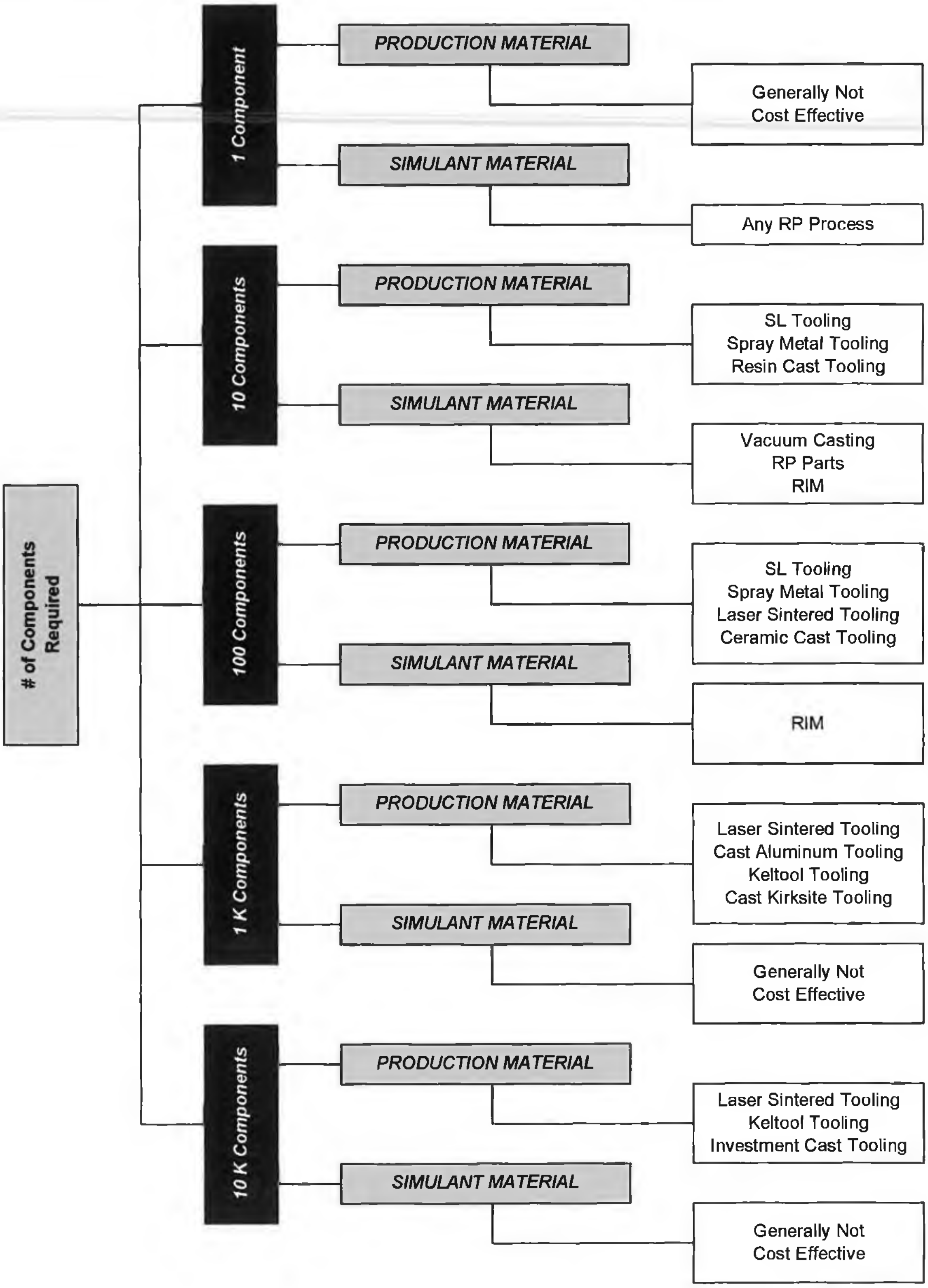


TABLE 9.7: RPT Process Vs. # of Components Required [64]

The choice of processes is very dependent on what is required. The selection of a suitable process needs to be carefully considered, taking into account, the end run material and the manufacturing lead time.

The identification of a suitable material for any plastic component design can be a daunting task for any designer. Most material vendors provide accurate and complete specification sheets for their specific material grades, but the selection of materials can be quite limited from any one vendor. Generally, as many vendors as possible should be consulted before a final decision is made. The most advisable approach is first consult one or two of the many universal databases available, identify the materials that are most suitable for the design and then consult with the respected vendors.

Material Data obtained from these vendors is generally prepared to conform to the specific standards of either the ASTM or ISO. The methods by which this data has been prepared however can vary from one vendor to another therefore a somewhat inaccurate picture can be obtained when comparing materials from different sources. It is advisable to conduct ones own material tests to verify the vendors data when more that one vendor is being considered. These material tests can be carried out with relative ease, with samples which have been prepared under the same processing conditions of the end-run product. Another advantage is that these tests can be conducted under the expected loading conditions to that product also.

Accelerated tests provide accurate and quantitative results to how a product will perform in real world situations. Ideally, these tests should be performed before a product is released to the public domain which is not always an option, as time constraints often dictate. All too often, this results in product recalls and modifications. Generally speaking endurance testing is mandatory though not performed intensively or at all in some facilities.

These tests are also applied in the event where a number of products have failed in what appears to be similar circumstances. Often a combination of different tests on various testing equipment is conducted in order to gain a more accurate picture of the failure. As tests conducted in such circumstances have time constraints imposed on them, the tests can be conducted at elevated temperatures to accelerate the procedures further. Computational Analysis Techniques, as presented in chapter 4, are also revisited in such circumstances. It is often determined that residual stresses, introduced at the processing stage, have contributed to the failure.

Brittle coating can be performed by a non-specialist within hours and will yield results accurate to within 10%. Such a test also identifies the location and direction of the maximum principal stress which is where the crack will occur. Strain gauging is mandatory though this is costly in terms of man-hours and personnel. Ideally, strain gauges should be applied in order to obtain a much more accurate picture of these stresses.

Clearly the most significant advantages, to any product development cycle is obtained when all these tools are combined as depicted in figure 1.4 (reproduced hereunder). Each technique uses the outcome of the previous, in order to obtain an outcome itself. Weakness of any phase are not allowed to proceed to the next phase, therefore each phase provides some from of feedback which highlights where limitations/weakness may exist in the design is.

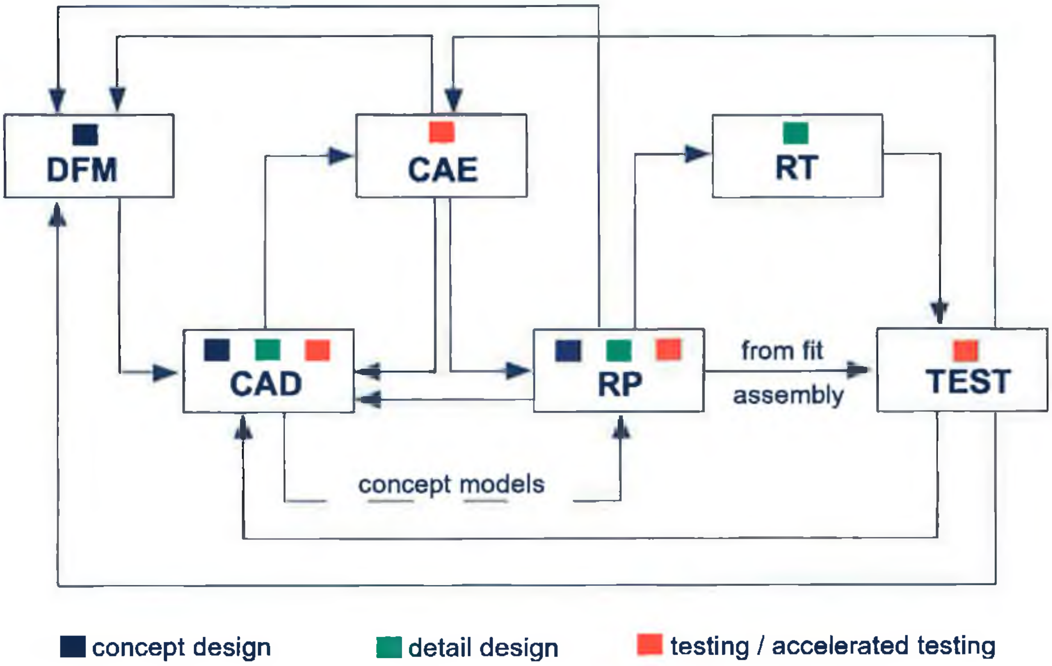


Figure 1.4: Proposed Product Development Cycle (reproduced)

Implementation of such a methodology, adds considerable value and confidence to the development of any new product by avoiding costly rework. Its adaptation is made more attractive by the virtue of the fact, that the systems and tools utilized have over the past ten years experienced considerable reductions in cost (approximately 50%), while also increasing in accuracy. My thesis is therefore represented by the proposed methodology and the tools which have been identified in each of the preceding tables which are applicable to this new PDC for Injection Moulded Components.

CONCLUSION

Extensive and exhaustive literary searches indicated that the areas addressed in this research thesis had never really been examined with regard to *plastic component design*. Some research, although limited, had been conducted in fragmented areas (i.e. DFM, CAD, RP, RT) by researches from most notably from North America, Europe and Asia [4, 5, 6, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 36, 47, 49, 64, 76, 77]. Combining all of this information together for the determination of the ***correct selection of technologies*** among the many choices available and illustrating the correct ***Product Development Cycle*** is what is new and relevant in this study.

Design For Manufacturability is a relatively new set of tools. These tools have been adapted and proven to be of considerable benefit to many manufacturing organisations. The implementation of these techniques yields a very significant competitive advantage to any industry adopting them. Benchmarking, Value Analysis, and Failure Modes and Effects Analysis, can all be used independently of each other. The inputs to Quality Function and Deployment and Tanaka's Cost Worth analysis, are generally the outcome of some other tools within this category. To benefit fully from these tools, it is recommended that benchmarking, Value Analysis, Value graphs, Quality Function Deployment, Tanaka's Cost Worth Analysis and Failure Modes and Effects Analysis are all adapted at the inception stage of any new product design, or service.

Virtually all CAD systems available to the designer can handle the features necessary for plastic component design. Having interviewed many users of the various systems, and from a review of the capabilities as shown in table 9.1, it appears that the packages of Solid Works and Pro-Engineer are the leaders within the plastic sector. Pro-Engineer offers a complete suite of software, from design to analysis, where Solid Works depends on a number of add-ins. The master modeling technique is of considerable benefit to any plastic component design, as it provides a very convenient method of creating components from an external definition. Solid Works trails in this department, but is rapidly catching up (envelopes).

Computational Analysis Tools are widely accepted in Today's world. They offer a quick approximation to the overall behavior of any component design in real world situations. The major drawback associated with most, is that they can be rather difficult to use, the exception being COSMOS and Pro-Mechanica. Both these systems are very user friendly and require little training but *the users must understand fully what they are doing*. The adoption of systems based on the P-Element technology is advised, as these systems require less tinkering with element selection, sizes, and mesh densities. Implementing linear analysis procedures is relatively straight forward. Non-Linearity's should be left to the expert. Plastic flow analysis with tools such as MoldFlows Plastic Adviser can be utilized by anyone once they can comprehend the results. MoldFlow Plastics Insight is a much more advanced system, which can determine where residual stresses will occur during the moulding process, and identify areas prone to shrinkage and warpage. Such a system requires a high degree of operator knowledge, and much like non-linear FEA should be left to the expert.

Two distinct categories of rapid prototyping machines can be readily identified, Concept Modelers and Machine Room Technologies. The later are generally used to produce prototypes of relatively high tolerance, which can be used as patterns for the production of rapid tools. In other instances a tool can be produced directly by the process. Both the SLA and SLS systems offer the best solution to the plastics sector, as the tolerances obtainable from such systems are very good, as evident from the computer mouse prototype. The concept modelers have gained substantial ground since there introduction in the mid 90's. These devices are ideally suited to the design office where concept models can be obtained for evaluation purposes early in the design cycle with ease. Either, 3D Systems Thermojet or a Z-Corp machine, are the most suitable. The Z-Corp machines offer the best build times, but do require a further post-processing phase, which adds time and effort to the process.

A gradual shift is beginning to emerge towards hard tooling as new processing methods for tools produced on RP systems emerge. Harder tool materials, result in less wear, and hence the tool lasts longer, making these approaches ideal for larger production runs. Due to the large volumes obtainable and the accuracy of the 3D Keltool process, it is ideally suited for injection moulded component designs. When only small quantities are required then a silicone rubber tooling process should be adopted. This process is limited however in so far that good accuracy is hard to achieve (refer to table 9.5). Referring to table 9.6, the process of RapidTool shows considerable benefit, as tools produced in this manner can be used for injection moulding purposes. These direct tooling approaches are changing and improving at an exponential rate, and therefore further study should be directed towards these.

The many universal material databases currently available provide significant time savings in the selection of a suitable plastic material. Once a material has been identified the material vendor needs to be consulted. Properties provided by such vendors are normally accurate and detailed. Discrepancies can arise due to differences in processing conditions hence one should always conduct their own material tests, as outlined in the previous chapter.

Accelerated testing procedure should always be performed on a new product design to ensure the results obtained from the computational analysis tools are accurate. Such tests increase the confidence in the design. They also a valuable tool in the instance where a number of products have failed while in service, and within the warranty period. Instances such as this can be avoided by conducting accelerated tests before the product is introduced to the market.

The combination of the tools discussed in the preceding chapters, and the adaptation of the Product Development Cycle represented by figure 1.4, will increase any organisations competitive advantage who are involved in the development of injection moulded components. The case studies presented in chapter 8 illustrates the key benefits associated with my thesis.

In conclusion, my thesis is that any organisation involved in the design and development of Injection Moulded components should adopt the tools and the methodology presented in the preceding chapters.

FURTHER RESEARCH

- The application of the proposed development cycle to other disciplines and products (this can be achieved through case studies)
- The selection of suitable tools for other products, e.g. for an engine design, DFM, CAD, FEA, RP and RT can be used, but different aspects of each must be considered. In the instance of FEA, vibration analysis and non-linear studies at elevated temperatures must be considered.
- The examination and application of computer based DFM tools.
- An extensive evaluation of the CAD industry should be conducted, as considerable changes are currently taking place, with vendors realigning themselves, and targeting different diverse sectors.
- The identification or subsequent development of a P-Element FEA tool capable of performing non-linear analysis.
- An extensive examination of MoldFlows Plastic Insight and subsequent comparison with FEA tools. In particular the inclusion of residual stresses in FEA models, Is there an automated approach?
- An extensive study of the new and emerging direct tooling techniques. Can such tools be applied to a short production run of 1K-10k components; which technique is most suitable?
- An examination of the tools available for the generation of production tools from solid models.
- A comparison study of accelerated testing procedures and FEA for plastic components. (probably an undergraduate project)
- Consideration of the manufacturing activities and their integration into the new PDC. How can knowledge based machining be leveraged to gain a greater competitive advantage?

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Mouse 1	
Item	***Description***
1	Upper Lid
2	Bottom Lid
3	Button
4	Chips & Cable
5	2 Encoders
6	2 Springs
7	2 Screws
8	Wire
9	Roller Wheel
10	Roller Support
11	Rubber Ball
12	Ball Lid

Mouse 2	
Item	***Description***
1	Upper Lid
2	Bottom Lid
3	Wheel
4	Wheel Support
5	Button
6	Electronics & Cable
7	2 Encoders
8	Ball
9	Ball Lid
10	1 Screw
11	1 Spring

Mouse 3	
Item	***Description***
1	Upper Lid
2	Bottom Lid
3	Electronics and Cable
4	Wheel
5	Wire
6	Button
7	2 Fixed Encoders
8	Ball
9	Ball Lid
10	3 Screws

Mouse 4	
Item	***Description***
1	Upper Lid
2	Bottom Lid
3	Support
4	Wheel
5	Wheel Support
6	2 Screws
7	2 Encoders
8	Button
9	Electronics and Cable
10	Ball Lid
11	Ball Lid
12	1 Spring

Mouse 5	
Item	***Description***
1	Upper Lid
2	Bottom Lid
3	Button
4	2 Encoders
5	Wheel
6	Wheel Support
7	Spring
8	Electronics & Cable
9	Ball
10	Ball Support
11	2 Screws

Mouse 6	
Item	***Description***
1	Upper Lid & Fixed Button
2	Bottom Lid
3	Wheel
4	Wheel Support
5	Spring
6	Electronics & Cable
7	4 screws (Lids)
8	2 screws (Elect)
9	Ball
10	Ball Support

A.1. BENCHMARKING ANALYSIS OF A COMPUTER MOUSE

The following is a description and discussion on a variety of various computer Mice which are currently on the market and have been in the past, The advantages and disadvantages of each type is also presented in order to determine the features which have made them successful.

A.1.1. MOUSE 1: Microsoft

This mouse is manufactured by Microsoft. The design of mouse has a very modern feature, the inclusion of the roller wheel for the vertical position of the cursor. The mouse itself is very aesthetically pleasing and very easy to use. However, the major disadvantage is that the mouse itself is designed specifically for right-handed users. Another disadvantage is that the mouse, due to its shape, requires a more complicated mould (including sliding inserts), hence is much more expensive to manufacture.

Advantages	*Disadvantages*
Easy to operate Extra roller ball feature. Comfortable. Aesthetic. Ergonomic. Original design. Suitably dimensioned for all percentiles.	Expensive to manufacture. Only suitable for right-handed person. Non-economical material.

A.1.2. MOUSE 2: IBM 1

This type of mouse, manufactured by IBM, does not have any extra features. The design is very basic in that it is essentially an extrusion. The result is an inexpensive functional mouse that is not very aesthetically pleasing, and is not all that ergonomic and hence uncomfortable.

Advantages	*Disadvantages*
Inexpensive Textured surface for extra grip. Light. Suitable for both right and left-handed people.	Non-ergonomic. Not aesthetically pleasing. Uncomfortable. Not suitable for all percentiles. Non-economic material.

A.1.3. MOUSE 3: IBM I

This is the oldest of all the mice as it is the original of the IBM I series. The disadvantages heavily out way the advantages.

Advantages	*Disadvantages*
Cheap. Easily manufactured. Suitable for both right and left-handed people. Hand can fit snugly onto this design (hence formed the base for many newer derivatives)	Ugly to look at, therefore not aesthetically pleasing. Not at all ergonomic. Heavy Not suitable for all percentiles. Uncomfortable to use.

A.1.4. MOUSE 4: Spurious

This design is not the most modern of the considered designs. It does however show some of the qualities that have being elaborated on since. For example it has a middle button for easy use of the cursor, which has being developed into a roller wheel. It is also curved to allow for improved comfort while operated.

Advantages	*Disadvantages*
Ergonomic. Comfortable to use. Slightly more attractive design, therefore aesthetically pleasing. Easy to dismantle and clean. Easy to manufacture. Relatively inexpensive. Light weight	Non-economical material. Middle button difficult to use to control cursor.

A.1.5. MOUSE 5: Hewlet Packard (HP)

This is by far the best design of all the mice under assessment as the advantages heavily out way the disadvantages. The only disadvantage is that it does not incorporate a roller wheel (which can be an advantage in some circumstances), for cursor control.

Advantages	*Disadvantages*
Ergonomic. Comfortable to use. Aesthetically pleasing. Easy to dismantle and clean It is directed more towards the right-handed user, but is also comfortable for the left-handed person. Light weight. Easy to manufacture. Suitable for all percentiles.	Expensive. No multiple features, eg. Roller wheel.

A.1.6. MOUSE 6: IBM II

Another original design in the IBM series, which is relatively old design and very outdated.

Advantages	*Disadvantages*
Easy to manufacture. Cheap. Suitable for both left-handed and right-handed persons. Easy to dismantle and clean.	Non-ergonomic. Not aesthetically pleasing Not suitable for all percentiles Uncomfortable to use

A.2. COMPARISON TABLE OF FEATURES

Mice *Characteristic*	*Microsoft*	*IBM 3*	*IBM 1*	*Spurious*	*Hewlett Packard*	*IBM 2*
Easy to Operate	5	1	1	4	5	1
Aesthetics	5	2	2	5	5	1
Ergonomics	5	2	1	5	5	1
Percentiles Suitability	5	1	1	3	5	1
Weight	3	1	1	3	5	1
Manufacturability	1	3	5	5	5	5
Cost	3	2	2	5	3	2
Technology	5	1	1	3	3	1
Economic Material	4	2	2	4	4	2
Easy Dismantle & Clean	4	3	3	5	5	5
Reliable	5	4	4	5	5	4
Left Vs. Right Hand	1	5	5	5	4	5
TOTAL	46	27	28	52	54	29

Benchmark Analysis Results

FEA SUMMARY AND LOG SAMPLES

```
------------------------------------------------
Pro/MECHANICA STRUCTURE Version
22.3(305)
Log for Design Study "Snap_fit_static"
Mon Nov 19, 2001   13:24:27
------------------------------------------------

Begin Creating Database for Design Study
Mon Nov 19, 2001   13:24:27
  Elapsed Time      (sec):      0.00
  CPU Time         (sec):      0.00
  Memory Usage       (kb):         0
  Work Dir Disk Usage (kb):         0
--------------------------------------------------
--------------------

Pro/MECHANICA External Database Interface -
MNF_TO_MDB Translator
Copyright(c) 2000PTC (tm) -
All Rights Reserved

--------------------------------------------------
--------------------


Global Information:

           Model Name:
.\Snap_fit_static\Snap_fit_static
           Product Name            Undefined
           Product Version          22.3

           Creation Date           11/19/01
           Creation Time           13:24:27
           Author               UNKNOWN


Header Information:

           MNF Version             22.3
           MNF Author              mechxfce
           Date of MNF Creation       Not
available
           Import Mode             ptc
           Name of Original Model      Not
available
           Comments               Not available
```

```
Error / Warning Reports :

        Translation Error/Warning Summary



                      Total errors: 0
                      Total warnings: 0
                      Total informational messages: 0


        **** Entity Creation Summary ****

         ---- Summary Information ----



          Description            Entities    Entities
                                 Found       Created


          Groups                  3           3
          Coordinate Systems      1           1
          Parts                   1           1
          Curves                  49          49
          Topological Edges       45          0
          Surfaces                18          18
          Surface Curves          90          0
          Surface Regions         18          18
          Volumes                 1           1



                      Translation Elapsed Time

                      *** 2 seconds ***


Checking the model before creating elements...
These checks take into account the fact that AutoGEM
will
automatically create elements in volumes with material
properties, on surfaces with shell properties, and on
curves
with beam section properties.

Not all of the materials assigned to the model contain
failure data. Failure Index measures will only be
```

```
calculated for materials with failure data.


Begin Generating Elements
Mon Nov 19, 2001   13:24:30
  Elapsed Time        (sec):      0.00
  CPU Time            (sec):      0.00
  Memory Usage        (kb):          0
  Work Dir Disk Usage (kb):          0

Copying elements from an existing study model
...
Successfully copied elements from an existing
study model.


A complete set of elements already exists.

OK


Checking the model after creating elements...

No errors were found in the model.

Description:
  Static Analysis of Mouse Snap Fit using ABS

  Step Elapsed Time  (sec):     0.89
  Step CPU Time      (sec):     0.00

Begin Engine Bookkeeping
Mon Nov 19, 2001   13:24:33
  Elapsed Time        (sec):      7.97
  CPU Time            (sec):      1.67
  Memory Usage        (kb):      16757
  Work Dir Disk Usage (kb):          0

  Step Elapsed Time  (sec):     0.89
  Step CPU Time      (sec):     0.22

Begin Analysis: "Snap_fit_static"
Mon Nov 19, 2001   13:24:34
  Elapsed Time        (sec):      8.86
  CPU Time            (sec):      1.89
  Memory Usage        (kb):      16757
  Work Dir Disk Usage (kb):          0

  Step Elapsed Time  (sec):     1.62
  Step CPU Time      (sec):     0.43

Begin Mass Calculation
Mon Nov 19, 2001   13:24:35
  Elapsed Time        (sec):     10.48
  CPU Time            (sec):      2.32
  Memory Usage        (kb):      16757
  Work Dir Disk Usage (kb):          0

  Step Elapsed Time  (sec):     2.32
  Step CPU Time      (sec):     0.00

Begin P-Loop Pass 1
Mon Nov 19, 2001   13:24:38
  Elapsed Time        (sec):     12.81
  CPU Time            (sec):      2.32
  Memory Usage        (kb):      16757
  Work Dir Disk Usage (kb):          0

  Step Elapsed Time  (sec):     1.09
  Step CPU Time      (sec):     0.01

Begin Element Calculations, Pass 1
Mon Nov 19, 2001   13:24:39
  Elapsed Time        (sec):     13.90
  CPU Time            (sec):      2.33
  Memory Usage        (kb):      30935
  Work Dir Disk Usage (kb):          0

  Step Elapsed Time  (sec):     0.64
  Step CPU Time      (sec):     0.13

Begin Global Matrix Assembly, Pass 1
Mon Nov 19, 2001   13:24:39
  Elapsed Time        (sec):     14.54
  CPU Time            (sec):      2.46
  Memory Usage        (kb):      34165
  Work Dir Disk Usage (kb):          0

  Step Elapsed Time  (sec):     0.37
  Step CPU Time      (sec):     0.00

Begin Equation Solve, Pass 1
Mon Nov 19, 2001   13:24:40
  Elapsed Time        (sec):     14.91
  CPU Time            (sec):      2.46
  Memory Usage        (kb):      34165
  Work Dir Disk Usage (kb):          0
```

```
  Step Elapsed Time  (sec):     0.53
  Step CPU Time      (sec):    0.01

Begin Load Calculations
Mon Nov 19, 2001   13:24:40
  Elapsed Time        (sec):    15.44
  CPU Time          (sec):    2.47
  Memory Usage        (kb):     81104
  Work Dir Disk Usage (kb):         0

  Step Elapsed Time  (sec):     0.39
  Step CPU Time      (sec):    0.00

Begin Post-Processing Calculations, Pass 1
Mon Nov 19, 2001   13:24:41
  Elapsed Time        (sec):    15.83
  CPU Time          (sec):    2.47
  Memory Usage        (kb):     81104
  Work Dir Disk Usage (kb):         0

  Step Elapsed Time  (sec):     0.76
  Step CPU Time      (sec):    0.12

Begin Displacement and Stress Calculation
Mon Nov 19, 2001   13:24:42
  Elapsed Time        (sec):    16.59
  CPU Time          (sec):    2.59
  Memory Usage        (kb):     81104
  Work Dir Disk Usage (kb):         0

  Step Elapsed Time  (sec):     2.04
  Step CPU Time      (sec):    0.37

Begin Reaction Calculation
Mon Nov 19, 2001   13:24:44
  Elapsed Time        (sec):    18.64
  CPU Time          (sec):    2.96
  Memory Usage        (kb):     82534
  Work Dir Disk Usage (kb):         0

  Step Elapsed Time  (sec):     0.94
  Step CPU Time      (sec):    0.01

Begin Convergence Check Pass 1
Mon Nov 19, 2001   13:24:45
  Elapsed Time        (sec):    19.58
  CPU Time          (sec):    2.97
  Memory Usage        (kb):     82534
  Work Dir Disk Usage (kb):         0
```

```
  Step Elapsed Time  (sec):     1.35
  Step CPU Time      (sec):    0.00

Begin P-Loop Pass 2
Mon Nov 19, 2001   13:24:46
  Elapsed Time        (sec):    20.93
  CPU Time          (sec):    2.97
  Memory Usage        (kb):     82534
  Work Dir Disk Usage (kb):         0

  Step Elapsed Time  (sec):     1.07
  Step CPU Time      (sec):    0.01

Begin Element Calculations, Pass 2
Mon Nov 19, 2001   13:24:47
  Elapsed Time        (sec):    22.00
  CPU Time          (sec):    2.98
  Memory Usage        (kb):     82534
  Work Dir Disk Usage (kb):         0

  Step Elapsed Time  (sec):     0.69
  Step CPU Time      (sec):    0.16

Begin Global Matrix Assembly, Pass 2
Mon Nov 19, 2001   13:24:48
  Elapsed Time        (sec):    22.69
  CPU Time          (sec):    3.14
  Memory Usage        (kb):     83253
  Work Dir Disk Usage (kb):         0

  Step Elapsed Time  (sec):     0.41
  Step CPU Time      (sec):    0.01

Begin Equation Solve, Pass 2
Mon Nov 19, 2001   13:24:48
  Elapsed Time        (sec):    23.10
  CPU Time          (sec):    3.15
  Memory Usage        (kb):     83253
  Work Dir Disk Usage (kb):         0

  Step Elapsed Time  (sec):     0.64
  Step CPU Time      (sec):    0.09

Begin Load Calculations
Mon Nov 19, 2001   13:24:49
  Elapsed Time        (sec):    23.74
  CPU Time          (sec):    3.24
  Memory Usage        (kb):     83253
```

```
  Work Dir Disk Usage (kb):      0

  Step Elapsed Time  (sec):    0.38
  Step CPU Time      (sec):    0.00

Begin Post-Processing Calculations, Pass 2
Mon Nov 19, 2001   13:24:49
  Elapsed Time       (sec):   24.12
  CPU Time           (sec):    3.24
  Memory Usage        (kb):   83253
  Work Dir Disk Usage (kb):      0

  Step Elapsed Time  (sec):    0.99
  Step CPU Time      (sec):    0.23

Begin Displacement and Stress Calculation
Mon Nov 19, 2001   13:24:50
  Elapsed Time       (sec):   25.12
  CPU Time           (sec):    3.47
  Memory Usage        (kb):   83253
  Work Dir Disk Usage (kb):      0

  Step Elapsed Time  (sec):    2.00
  Step CPU Time      (sec):    0.42

Begin Reaction Calculation
Mon Nov 19, 2001   13:24:52
  Elapsed Time       (sec):   27.12
  CPU Time           (sec):    3.89
  Memory Usage        (kb):   83622
  Work Dir Disk Usage (kb):      0

  Step Elapsed Time  (sec):    0.60
  Step CPU Time      (sec):    0.02

Begin Convergence Check Pass 2
Mon Nov 19, 2001   13:24:53
  Elapsed Time       (sec):   27.72
  CPU Time           (sec):    3.91
  Memory Usage        (kb):   83622
  Work Dir Disk Usage (kb):      0

  Step Elapsed Time  (sec):    1.37
  Step CPU Time      (sec):    0.02

Begin P-Loop Pass 3
Mon Nov 19, 2001   13:24:54
  Elapsed Time       (sec):   29.09
  CPU Time           (sec):    3.93
```

```
  Memory Usage        (kb):   83622
  Work Dir Disk Usage (kb):      0

  Step Elapsed Time  (sec):    1.10
  Step CPU Time      (sec):    0.01

Begin Element Calculations, Pass 3
Mon Nov 19, 2001   13:24:55
  Elapsed Time       (sec):   30.19
  CPU Time           (sec):    3.95
  Memory Usage        (kb):   83622
  Work Dir Disk Usage (kb):      0

  Step Elapsed Time  (sec):    2.28
  Step CPU Time      (sec):    0.33

Begin Global Matrix Assembly, Pass 3
Mon Nov 19, 2001   13:24:57
  Elapsed Time       (sec):   32.48
  CPU Time           (sec):    4.27
  Memory Usage        (kb):   83622
  Work Dir Disk Usage (kb):   3072

  Step Elapsed Time  (sec):    0.45
  Step CPU Time      (sec):    0.01

Begin Equation Solve, Pass 3
Mon Nov 19, 2001   13:24:58
  Elapsed Time       (sec):   32.93
  CPU Time           (sec):    4.28
  Memory Usage        (kb):   83622
  Work Dir Disk Usage (kb):   3072

  Step Elapsed Time  (sec):    1.38
  Step CPU Time      (sec):    0.41

Begin Load Calculations
Mon Nov 19, 2001   13:24:59
  Elapsed Time       (sec):   34.31
  CPU Time           (sec):    4.70
  Memory Usage        (kb):   83622
  Work Dir Disk Usage (kb):   3072

  Step Elapsed Time  (sec):    0.40
  Step CPU Time      (sec):    0.01

Begin Post-Processing Calculations, Pass 3
Mon Nov 19, 2001   13:25:00
  Elapsed Time       (sec):   34.71
```

```
  CPU Time         (sec):    4.71
  Memory Usage       (kb):    83622
  Work Dir Disk Usage (kb):     3072

  Step Elapsed Time  (sec):     1.65
  Step CPU Time      (sec):    0.51

Begin Displacement and Stress Calculation
Mon Nov 19, 2001   13:25:01
  Elapsed Time       (sec):    36.36
  CPU Time         (sec):    5.22
  Memory Usage       (kb):    83622
  Work Dir Disk Usage (kb):     3072

  Step Elapsed Time  (sec):     2.11
  Step CPU Time      (sec):    0.45

Begin Reaction Calculation
Mon Nov 19, 2001   13:25:03
  Elapsed Time       (sec):    38.47
  CPU Time         (sec):    5.67
  Memory Usage       (kb):    91814
  Work Dir Disk Usage (kb):     3072

  Step Elapsed Time  (sec):     0.72
  Step CPU Time      (sec):    0.03

Begin Convergence Check Pass 3
Mon Nov 19, 2001   13:25:04
  Elapsed Time       (sec):    39.20
  CPU Time         (sec):    5.70
  Memory Usage       (kb):    91814
  Work Dir Disk Usage (kb):     3072

  Step Elapsed Time  (sec):     1.51
  Step CPU Time      (sec):    0.06

Begin P-Loop Pass 4
Mon Nov 19, 2001   13:25:06
  Elapsed Time       (sec):    40.71
  CPU Time         (sec):    5.76
  Memory Usage       (kb):    91814
  Work Dir Disk Usage (kb):     3072

  Step Elapsed Time  (sec):     1.13
  Step CPU Time      (sec):    0.02

Begin Element Calculations, Pass 4
Mon Nov 19, 2001   13:25:07
```

```
  Elapsed Time       (sec):    41.84
  CPU Time         (sec):    5.78
  Memory Usage       (kb):    91814
  Work Dir Disk Usage (kb):     3072

  Step Elapsed Time  (sec):     5.30
  Step CPU Time      (sec):    1.20

Begin Global Matrix Assembly, Pass 4
Mon Nov 19, 2001   13:25:12
  Elapsed Time       (sec):    47.14
  CPU Time         (sec):    6.98
  Memory Usage       (kb):    91814
  Work Dir Disk Usage (kb):    10240

  Step Elapsed Time  (sec):     0.43
  Step CPU Time      (sec):    0.01

Begin Equation Solve, Pass 4
Mon Nov 19, 2001   13:25:13
  Elapsed Time       (sec):    47.57
  CPU Time         (sec):    6.99
  Memory Usage       (kb):    91814
  Work Dir Disk Usage (kb):    10240

  Step Elapsed Time  (sec):     4.19
  Step CPU Time      (sec):    1.69

Begin Load Calculations
Mon Nov 19, 2001   13:25:17
  Elapsed Time       (sec):    51.75
  CPU Time         (sec):    8.68
  Memory Usage       (kb):    91814
  Work Dir Disk Usage (kb):    10240

  Step Elapsed Time  (sec):     0.50
  Step CPU Time      (sec):    0.04

Begin Post-Processing Calculations, Pass 4
Mon Nov 19, 2001   13:25:17
  Elapsed Time       (sec):    52.25
  CPU Time         (sec):    8.72
  Memory Usage       (kb):    91814
  Work Dir Disk Usage (kb):    10240

  Step Elapsed Time  (sec):     2.62
  Step CPU Time      (sec):    0.94

Begin Displacement and Stress Calculation
```

```
Mon Nov 19, 2001   13:25:20
  Elapsed Time       (sec):    54.88
  CPU Time          (sec):    9.66
  Memory Usage       (kb):    91814
  Work Dir Disk Usage (kb):    10240

  Step Elapsed Time  (sec):    2.35
  Step CPU Time      (sec):    0.54

Begin Reaction Calculation
Mon Nov 19, 2001   13:25:22
  Elapsed Time       (sec):    57.23
  CPU Time          (sec):    10.20
  Memory Usage       (kb):    91814
  Work Dir Disk Usage (kb):    10240

  Step Elapsed Time  (sec):    0.84
  Step CPU Time      (sec):    0.10

Begin Convergence Check Pass 4
Mon Nov 19, 2001   13:25:23
  Elapsed Time       (sec):    58.07
  CPU Time          (sec):    10.30
  Memory Usage       (kb):    91814
  Work Dir Disk Usage (kb):    10240

  Step Elapsed Time  (sec):    1.77
  Step CPU Time      (sec):    0.15

Begin P-Loop Pass 5
Mon Nov 19, 2001   13:25:25
  Elapsed Time       (sec):    59.85
  CPU Time          (sec):    10.45
  Memory Usage       (kb):    91814
  Work Dir Disk Usage (kb):    10240

  Step Elapsed Time  (sec):    1.09
  Step CPU Time      (sec):    0.01

Begin Element Calculations, Pass 5
Mon Nov 19, 2001   13:25:26
  Elapsed Time       (sec):    60.94
  CPU Time          (sec):    10.46
  Memory Usage       (kb):    91814
  Work Dir Disk Usage (kb):    10240

  Step Elapsed Time  (sec):    15.02
  Step CPU Time      (sec):    4.30

Begin Global Matrix Assembly, Pass 5
Mon Nov 19, 2001   13:25:41
  Elapsed Time       (sec):    75.96
  CPU Time          (sec):    14.76
  Memory Usage       (kb):    91814
  Work Dir Disk Usage (kb):    25600

  Step Elapsed Time  (sec):    0.42
  Step CPU Time      (sec):    0.01

Begin Equation Solve, Pass 5
Mon Nov 19, 2001   13:25:41
  Elapsed Time       (sec):    76.38
  CPU Time          (sec):    14.77
  Memory Usage       (kb):    91814
  Work Dir Disk Usage (kb):    25600

  Step Elapsed Time  (sec):    12.80
  Step CPU Time      (sec):    5.38

Begin Load Calculations
Mon Nov 19, 2001   13:25:54
  Elapsed Time       (sec):    89.18
  CPU Time          (sec):    20.15
  Memory Usage       (kb):    91814
  Work Dir Disk Usage (kb):    25600

  Step Elapsed Time  (sec):    0.59
  Step CPU Time      (sec):    0.09

Begin Post-Processing Calculations, Pass 5
Mon Nov 19, 2001   13:25:55
  Elapsed Time       (sec):    89.77
  CPU Time          (sec):    20.24
  Memory Usage       (kb):    91814
  Work Dir Disk Usage (kb):    25600

  Step Elapsed Time  (sec):    5.64
  Step CPU Time      (sec):    2.32

Begin Displacement and Stress Calculation
Mon Nov 19, 2001   13:26:00
  Elapsed Time       (sec):    95.41
  CPU Time          (sec):    22.56
  Memory Usage       (kb):    91814
  Work Dir Disk Usage (kb):    25600

  Step Elapsed Time  (sec):    2.88
  Step CPU Time      (sec):    0.67
```

```
Begin Reaction Calculation
Mon Nov 19, 2001   13:26:03
  Elapsed Time       (sec):    98.29
  CPU Time           (sec):    23.23
  Memory Usage        (kb):    91814
  Work Dir Disk Usage (kb):    25600

  Step Elapsed Time  (sec):     1.19
  Step CPU Time      (sec):     0.26

Begin Convergence Check Pass 5
Mon Nov 19, 2001   13:26:04
  Elapsed Time       (sec):    99.48
  CPU Time           (sec):    23.49
  Memory Usage        (kb):    91814
  Work Dir Disk Usage (kb):    25600

  Step Elapsed Time  (sec):     2.32
  Step CPU Time      (sec):     0.40

Begin P-Loop Pass 6
Mon Nov 19, 2001   13:26:07
  Elapsed Time       (sec):   101.81
  CPU Time           (sec):    23.89
  Memory Usage        (kb):    91814
  Work Dir Disk Usage (kb):    25600

  Step Elapsed Time  (sec):     1.11
  Step CPU Time      (sec):     0.02

Begin Element Calculations, Pass 6
Mon Nov 19, 2001   13:26:08
  Elapsed Time       (sec):   102.92
  CPU Time           (sec):    23.91
  Memory Usage        (kb):    91814
  Work Dir Disk Usage (kb):    25600

  Step Elapsed Time  (sec):    43.76
  Step CPU Time      (sec):    13.10

Begin Global Matrix Assembly, Pass 6
Mon Nov 19, 2001   13:26:52
  Elapsed Time       (sec):   146.68
  CPU Time           (sec):    37.01
  Memory Usage        (kb):    91814
  Work Dir Disk Usage (kb):    53248

  Step Elapsed Time  (sec):     0.45
  Step CPU Time      (sec):     0.02

Begin Equation Solve, Pass 6
Mon Nov 19, 2001   13:26:52
  Elapsed Time       (sec):   147.13
  CPU Time           (sec):    37.03
  Memory Usage        (kb):    91814
  Work Dir Disk Usage (kb):    53248

  Step Elapsed Time  (sec):    64.49
  Step CPU Time      (sec):    17.92

Begin Load Calculations
Mon Nov 19, 2001   13:27:57
  Elapsed Time       (sec):   211.62
  CPU Time           (sec):    54.95
  Memory Usage        (kb):    92149
  Work Dir Disk Usage (kb):   134144

  Step Elapsed Time  (sec):     1.40
  Step CPU Time      (sec):     0.42

Begin Post-Processing Calculations, Pass 6
Mon Nov 19, 2001   13:27:58
  Elapsed Time       (sec):   213.03
  CPU Time           (sec):    55.37
  Memory Usage        (kb):    92149
  Work Dir Disk Usage (kb):   134144

  Step Elapsed Time  (sec):    16.32
  Step CPU Time      (sec):     5.93

Begin Displacement and Stress Calculation
Mon Nov 19, 2001   13:28:14
  Elapsed Time       (sec):   229.35
  CPU Time           (sec):    61.30
  Memory Usage        (kb):    92149
  Work Dir Disk Usage (kb):   134144

  Step Elapsed Time  (sec):     9.83
  Step CPU Time      (sec):     0.83

Begin Reaction Calculation
Mon Nov 19, 2001   13:28:24
  Elapsed Time       (sec):   239.17
  CPU Time           (sec):    62.13
  Memory Usage        (kb):    93606
  Work Dir Disk Usage (kb):   134144
```

```
 Step Elapsed Time  (sec):    1.94
 Step CPU Time      (sec):    0.61

Begin Convergence Check Pass 6
Mon Nov 19, 2001   13:28:26
 Elapsed Time       (sec):   241.12
 CPU Time          (sec):    62.74
 Memory Usage        (kb):    93606
 Work Dir Disk Usage (kb):    134144

 Step Elapsed Time  (sec):    15.54
 Step CPU Time      (sec):    6.11

Completed P-Loop
Mon Nov 19, 2001   13:28:42
 Elapsed Time       (sec):   256.66
 CPU Time          (sec):    68.85
 Memory Usage        (kb):    93606
 Work Dir Disk Usage (kb):    134144

 Step Elapsed Time  (sec):    0.68
 Step CPU Time      (sec):    0.01

Completed Analysis: Snap_fit_static
Mon Nov 19, 2001   13:28:42
 Elapsed Time       (sec):   257.34
 CPU Time          (sec):    68.86
 Memory Usage        (kb):    93606
 Work Dir Disk Usage (kb):    134144


----------------------------------------
Pro/MECHANICA STRUCTURE Version
22.3(305)
Log for Design Study "Snap_fit_static"
Mon Nov 19, 2001   13:24:27
----------------------------------------

Begin Creating Database for Design Study
Mon Nov 19, 2001   13:24:27
 Elapsed Time       (sec):     0.00
 CPU Time          (sec):     0.00
 Memory Usage        (kb):       0
 Work Dir Disk Usage (kb):       0

------------------------------------------
-----------------

Pro/MECHANICA External Database Interface -
MNF_TO_MDB Translator
```

```
Copyright(c) 2000PTC (tm) -
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--------------------------------------------------
----------



Global Information:

          Model Name:
.\Snap_fit_static\Snap_fit_static
          Product Name          Undefined
          Product Version       22.3

          Creation Date         11/19/01
          Creation Time         13:24:27
          Author              UNKNOWN



Header Information:

          MNF Version           22.3
          MNF Author            mechxfce
          Date of MNF Creation      Not available
          Import Mode           ptc
          Name of Original Model     Not available
          Comments              Not available


Error / Warning Reports :

       Translation Error/Warning Summary



                  Total errors: 0
                  Total warnings: 0
                  Total informational messages: 0


       **** Entity Creation Summary ****

       ----- Summary Information -----



          Description          Entities    Entities
                             Found      Created
```

```
Groups                 3        3
Coordinate Systems         1        1
Parts               1        1
Curves                49       49
Topological Edges         45        0
Surfaces               18       18
Surface Curves            90        0
Surface Regions            18        18
Volumes                1        1



            Translation Elapsed Time

            *** 2 seconds ***


Checking the model before creating elements...
These checks take into account the fact that
AutoGEM will
automatically create elements in volumes with
material
properties, on surfaces with shell properties,
and on curves
with beam section properties.

Not all of the materials assigned to the model
contain
failure data. Failure Index measures will only be
calculated for materials with failure data.


Begin Generating Elements
Mon Nov 19, 2001   13:24:30
  Elapsed Time      (sec):      0.00
  CPU Time          (sec):     0.00
  Memory Usage       (kb):        0
  Work Dir Disk Usage (kb):        0

Copying elements from an existing study model
...
Successfully copied elements from an existing
study model.


A complete set of elements already exists.

OK
```

```
Checking the model after creating elements...

No errors were found in the model.

Description:
  Static Analysis of Mouse Snap Fit using ABS

  Step Elapsed Time  (sec):      0.89
  Step CPU Time      (sec):     0.00

Begin Engine Bookkeeping
Mon Nov 19, 2001   13:24:33
  Elapsed Time      (sec):      7.97
  CPU Time          (sec):     1.67
  Memory Usage       (kb):     16757
  Work Dir Disk Usage (kb):        0

  Step Elapsed Time  (sec):      0.89
  Step CPU Time      (sec):     0.22

Begin Analysis: "Snap_fit_static"
Mon Nov 19, 2001   13:24:34
  Elapsed Time      (sec):      8.86
  CPU Time          (sec):     1.89
  Memory Usage       (kb):     16757
  Work Dir Disk Usage (kb):        0

  Step Elapsed Time  (sec):      1.62
  Step CPU Time      (sec):     0.43

Begin Mass Calculation
Mon Nov 19, 2001   13:24:35
  Elapsed Time      (sec):     10.48
  CPU Time          (sec):     2.32
  Memory Usage       (kb):     16757
  Work Dir Disk Usage (kb):        0

  Step Elapsed Time  (sec):      2.32
  Step CPU Time      (sec):     0.00

Begin P-Loop Pass 1
Mon Nov 19, 2001   13:24:38
  Elapsed Time      (sec):     12.81
  CPU Time          (sec):     2.32
  Memory Usage       (kb):     16757
  Work Dir Disk Usage (kb):        0
```

```
  Step Elapsed Time  (sec):     1.09
  Step CPU Time      (sec):     0.01

Begin Element Calculations, Pass 1
Mon Nov 19, 2001   13:24:39
  Elapsed Time       (sec):    13.90
  CPU Time          (sec):     2.33
  Memory Usage       (kb):    30935
  Work Dir Disk Usage (kb):       0

  Step Elapsed Time  (sec):     0.64
  Step CPU Time      (sec):     0.13

Begin Global Matrix Assembly, Pass 1
Mon Nov 19, 2001   13:24:39
  Elapsed Time       (sec):    14.54
  CPU Time          (sec):     2.46
  Memory Usage       (kb):    34165
  Work Dir Disk Usage (kb):       0

  Step Elapsed Time  (sec):     0.37
  Step CPU Time      (sec):     0.00

Begin Equation Solve, Pass 1
Mon Nov 19, 2001   13:24:40
  Elapsed Time       (sec):    14.91
  CPU Time          (sec):     2.46
  Memory Usage       (kb):    34165
  Work Dir Disk Usage (kb):       0

  Step Elapsed Time  (sec):     0.53
  Step CPU Time      (sec):     0.01

Begin Load Calculations
Mon Nov 19, 2001   13:24:40
  Elapsed Time       (sec):    15.44
  CPU Time          (sec):     2.47
  Memory Usage       (kb):    81104
  Work Dir Disk Usage (kb):       0

  Step Elapsed Time  (sec):     0.39
  Step CPU Time      (sec):     0.00

Begin Post-Processing Calculations, Pass 1
Mon Nov 19, 2001   13:24:41
  Elapsed Time       (sec):    15.83
  CPU Time          (sec):     2.47
  Memory Usage       (kb):    81104
  Work Dir Disk Usage (kb):       0

  Step Elapsed Time  (sec):     0.76
  Step CPU Time      (sec):     0.12

Begin Displacement and Stress Calculation
Mon Nov 19, 2001   13:24:42
  Elapsed Time       (sec):    16.59
  CPU Time          (sec):     2.59
  Memory Usage       (kb):    81104
  Work Dir Disk Usage (kb):       0

  Step Elapsed Time  (sec):     2.04
  Step CPU Time      (sec):     0.37

Begin Reaction Calculation
Mon Nov 19, 2001   13:24:44
  Elapsed Time       (sec):    18.64
  CPU Time          (sec):     2.96
  Memory Usage       (kb):    82534
  Work Dir Disk Usage (kb):       0

  Step Elapsed Time  (sec):     0.94
  Step CPU Time      (sec):     0.01

Begin Convergence Check Pass 1
Mon Nov 19, 2001   13:24:45
  Elapsed Time       (sec):    19.58
  CPU Time          (sec):     2.97
  Memory Usage       (kb):    82534
  Work Dir Disk Usage (kb):       0

  Step Elapsed Time  (sec):     1.35
  Step CPU Time      (sec):     0.00

Begin P-Loop Pass 2
Mon Nov 19, 2001   13:24:46
  Elapsed Time       (sec):    20.93
  CPU Time          (sec):     2.97
  Memory Usage       (kb):    82534
  Work Dir Disk Usage (kb):       0

  Step Elapsed Time  (sec):     1.07
  Step CPU Time      (sec):     0.01

Begin Element Calculations, Pass 2
Mon Nov 19, 2001   13:24:47
  Elapsed Time       (sec):    22.00
  CPU Time          (sec):     2.98
  Memory Usage       (kb):    82534
```

```
  Work Dir Disk Usage (kb):        0

  Step Elapsed Time  (sec):     0.69
  Step CPU Time      (sec):     0.16

Begin Global Matrix Assembly, Pass 2
Mon Nov 19, 2001   13:24:48
  Elapsed Time       (sec):    22.69
  CPU Time         (sec):     3.14
  Memory Usage       (kb):    83253
  Work Dir Disk Usage (kb):        0

  Step Elapsed Time  (sec):     0.41
  Step CPU Time      (sec):     0.01

Begin Equation Solve, Pass 2
Mon Nov 19, 2001   13:24:48
  Elapsed Time       (sec):    23.10
  CPU Time         (sec):     3.15
  Memory Usage       (kb):    83253
  Work Dir Disk Usage (kb):        0

  Step Elapsed Time  (sec):     0.64
  Step CPU Time      (sec):     0.09

Begin Load Calculations
Mon Nov 19, 2001   13:24:49
  Elapsed Time       (sec):    23.74
  CPU Time         (sec):     3.24
  Memory Usage       (kb):    83253
  Work Dir Disk Usage (kb):        0

  Step Elapsed Time  (sec):     0.38
  Step CPU Time      (sec):     0.00

Begin Post-Processing Calculations, Pass 2
Mon Nov 19, 2001   13:24:49
  Elapsed Time       (sec):    24.12
  CPU Time         (sec):     3.24
  Memory Usage       (kb):    83253
  Work Dir Disk Usage (kb):        0

  Step Elapsed Time  (sec):     0.99
  Step CPU Time      (sec):     0.23

Begin Displacement and Stress Calculation
Mon Nov 19, 2001   13:24:50
  Elapsed Time       (sec):    25.12
  CPU Time         (sec):     3.47
```

```
  Memory Usage       (kb):    83253
  Work Dir Disk Usage (kb):        0

  Step Elapsed Time  (sec):     2.00
  Step CPU Time      (sec):     0.42

Begin Reaction Calculation
Mon Nov 19, 2001   13:24:52
  Elapsed Time       (sec):    27.12
  CPU Time         (sec):     3.89
  Memory Usage       (kb):    83622
  Work Dir Disk Usage (kb):        0

  Step Elapsed Time  (sec):     0.60
  Step CPU Time      (sec):     0.02

Begin Convergence Check Pass 2
Mon Nov 19, 2001   13:24:53
  Elapsed Time       (sec):    27.72
  CPU Time         (sec):     3.91
  Memory Usage       (kb):    83622
  Work Dir Disk Usage (kb):        0

  Step Elapsed Time  (sec):     1.37
  Step CPU Time      (sec):     0.02

Begin P-Loop Pass 3
Mon Nov 19, 2001   13:24:54
  Elapsed Time       (sec):    29.09
  CPU Time         (sec):     3.93
  Memory Usage       (kb):    83622
  Work Dir Disk Usage (kb):        0

  Step Elapsed Time  (sec):     1.10
  Step CPU Time      (sec):     0.01

Begin Element Calculations, Pass 3
Mon Nov 19, 2001   13:24:55
  Elapsed Time       (sec):    30.19
  CPU Time         (sec):     3.95
  Memory Usage       (kb):    83622
  Work Dir Disk Usage (kb):        0

  Step Elapsed Time  (sec):     2.28
  Step CPU Time      (sec):     0.33

Begin Global Matrix Assembly, Pass 3
Mon Nov 19, 2001   13:24:57
  Elapsed Time       (sec):    32.48
```

```
  CPU Time          (sec):     4.27
  Memory Usage        (kb):    83622
  Work Dir Disk Usage (kb):      3072

  Step Elapsed Time  (sec):      0.45
  Step CPU Time      (sec):      0.01

Begin Equation Solve, Pass 3
Mon Nov 19, 2001   13:24:58
  Elapsed Time       (sec):    32.93
  CPU Time          (sec):     4.28
  Memory Usage        (kb):    83622
  Work Dir Disk Usage (kb):      3072

  Step Elapsed Time  (sec):      1.38
  Step CPU Time      (sec):      0.41

Begin Load Calculations
Mon Nov 19, 2001   13:24:59
  Elapsed Time       (sec):    34.31
  CPU Time          (sec):     4.70
  Memory Usage        (kb):    83622
  Work Dir Disk Usage (kb):      3072

  Step Elapsed Time  (sec):      0.40
  Step CPU Time      (sec):      0.01

Begin Post-Processing Calculations, Pass 3
Mon Nov 19, 2001   13:25:00
  Elapsed Time       (sec):    34.71
  CPU Time          (sec):     4.71
  Memory Usage        (kb):    83622
  Work Dir Disk Usage (kb):      3072

  Step Elapsed Time  (sec):      1.65
  Step CPU Time      (sec):      0.51

Begin Displacement and Stress Calculation
Mon Nov 19, 2001   13:25:01
  Elapsed Time       (sec):    36.36
  CPU Time          (sec):     5.22
  Memory Usage        (kb):    83622
  Work Dir Disk Usage (kb):      3072

  Step Elapsed Time  (sec):      2.11
  Step CPU Time      (sec):      0.45

Begin Reaction Calculation
Mon Nov 19, 2001   13:25:03
  Elapsed Time       (sec):    38.47
  CPU Time          (sec):     5.67
  Memory Usage        (kb):    91814
  Work Dir Disk Usage (kb):      3072

  Step Elapsed Time  (sec):      0.72
  Step CPU Time      (sec):      0.03

Begin Convergence Check Pass 3
Mon Nov 19, 2001   13:25:04
  Elapsed Time       (sec):    39.20
  CPU Time          (sec):     5.70
  Memory Usage        (kb):    91814
  Work Dir Disk Usage (kb):      3072

  Step Elapsed Time  (sec):      1.51
  Step CPU Time      (sec):      0.06

Begin P-Loop Pass 4
Mon Nov 19, 2001   13:25:06
  Elapsed Time       (sec):    40.71
  CPU Time          (sec):     5.76
  Memory Usage        (kb):    91814
  Work Dir Disk Usage (kb):      3072

  Step Elapsed Time  (sec):      1.13
  Step CPU Time      (sec):      0.02

Begin Element Calculations, Pass 4
Mon Nov 19, 2001   13:25:07
  Elapsed Time       (sec):    41.84
  CPU Time          (sec):     5.78
  Memory Usage        (kb):    91814
  Work Dir Disk Usage (kb):      3072

  Step Elapsed Time  (sec):      5.30
  Step CPU Time      (sec):      1.20

Begin Global Matrix Assembly, Pass 4
Mon Nov 19, 2001   13:25:12
  Elapsed Time       (sec):    47.14
  CPU Time          (sec):     6.98
  Memory Usage        (kb):    91814
  Work Dir Disk Usage (kb):     10240

  Step Elapsed Time  (sec):      0.43
  Step CPU Time      (sec):      0.01

Begin Equation Solve, Pass 4
```

```
Mon Nov 19, 2001   13:25:13
  Elapsed Time      (sec):    47.57
  CPU Time          (sec):    6.99
  Memory Usage      (kb):     91814
  Work Dir Disk Usage (kb):     10240

  Step Elapsed Time  (sec):     4.19
  Step CPU Time      (sec):     1.69

Begin Load Calculations
Mon Nov 19, 2001   13:25:17
  Elapsed Time      (sec):    51.75
  CPU Time          (sec):    8.68
  Memory Usage      (kb):     91814
  Work Dir Disk Usage (kb):     10240

  Step Elapsed Time  (sec):     0.50
  Step CPU Time      (sec):     0.04

Begin Post-Processing Calculations, Pass 4
Mon Nov 19, 2001   13:25:17
  Elapsed Time      (sec):    52.25
  CPU Time          (sec):    8.72
  Memory Usage      (kb):     91814
  Work Dir Disk Usage (kb):     10240

  Step Elapsed Time  (sec):     2.62
  Step CPU Time      (sec):     0.94

Begin Displacement and Stress Calculation
Mon Nov 19, 2001   13:25:20
  Elapsed Time      (sec):    54.88
  CPU Time          (sec):    9.66
  Memory Usage      (kb):     91814
  Work Dir Disk Usage (kb):     10240

  Step Elapsed Time  (sec):     2.35
  Step CPU Time      (sec):     0.54

Begin Reaction Calculation
Mon Nov 19, 2001   13:25:22
  Elapsed Time      (sec):    57.23
  CPU Time          (sec):   10.20
  Memory Usage      (kb):     91814
  Work Dir Disk Usage (kb):     10240

  Step Elapsed Time  (sec):     0.84
  Step CPU Time      (sec):     0.10

Begin Convergence Check Pass 4
Mon Nov 19, 2001   13:25:23
  Elapsed Time      (sec):    58.07
  CPU Time          (sec):   10.30
  Memory Usage      (kb):     91814
  Work Dir Disk Usage (kb):     10240

  Step Elapsed Time  (sec):     1.77
  Step CPU Time      (sec):     0.15

Begin P-Loop Pass 5
Mon Nov 19, 2001   13:25:25
  Elapsed Time      (sec):    59.85
  CPU Time          (sec):   10.45
  Memory Usage      (kb):     91814
  Work Dir Disk Usage (kb):     10240

  Step Elapsed Time  (sec):     1.09
  Step CPU Time      (sec):     0.01

Begin Element Calculations, Pass 5
Mon Nov 19, 2001   13:25:26
  Elapsed Time      (sec):    60.94
  CPU Time          (sec):   10.46
  Memory Usage      (kb):     91814
  Work Dir Disk Usage (kb):     10240

  Step Elapsed Time  (sec):    15.02
  Step CPU Time      (sec):     4.30

Begin Global Matrix Assembly, Pass 5
Mon Nov 19, 2001   13:25:41
  Elapsed Time      (sec):    75.96
  CPU Time          (sec):   14.76
  Memory Usage      (kb):     91814
  Work Dir Disk Usage (kb):     25600

  Step Elapsed Time  (sec):     0.42
  Step CPU Time      (sec):     0.01

Begin Equation Solve, Pass 5
Mon Nov 19, 2001   13:25:41
  Elapsed Time      (sec):    76.38
  CPU Time          (sec):   14.77
  Memory Usage      (kb):     91814
  Work Dir Disk Usage (kb):     25600

  Step Elapsed Time  (sec):    12.80
  Step CPU Time      (sec):     5.38
```

```
Begin Load Calculations
Mon Nov 19, 2001   13:25:54
  Elapsed Time       (sec):    89.18
  CPU Time           (sec):    20.15
  Memory Usage        (kb):    91814
  Work Dir Disk Usage (kb):    25600

  Step Elapsed Time  (sec):     0.59
  Step CPU Time      (sec):     0.09

Begin Post-Processing Calculations, Pass 5
Mon Nov 19, 2001   13:25:55
  Elapsed Time       (sec):    89.77
  CPU Time           (sec):    20.24
  Memory Usage        (kb):    91814
  Work Dir Disk Usage (kb):    25600

  Step Elapsed Time  (sec):     5.64
  Step CPU Time      (sec):     2.32

Begin Displacement and Stress Calculation
Mon Nov 19, 2001   13:26:00
  Elapsed Time       (sec):    95.41
  CPU Time           (sec):    22.56
  Memory Usage        (kb):    91814
  Work Dir Disk Usage (kb):    25600

  Step Elapsed Time  (sec):     2.88
  Step CPU Time      (sec):     0.67

Begin Reaction Calculation
Mon Nov 19, 2001   13:26:03
  Elapsed Time       (sec):    98.29
  CPU Time           (sec):    23.23
  Memory Usage        (kb):    91814
  Work Dir Disk Usage (kb):    25600

  Step Elapsed Time  (sec):     1.19
  Step CPU Time      (sec):     0.26

Begin Convergence Check Pass 5
Mon Nov 19, 2001   13:26:04
  Elapsed Time       (sec):    99.48
  CPU Time           (sec):    23.49
  Memory Usage        (kb):    91814
  Work Dir Disk Usage (kb):    25600

  Step Elapsed Time  (sec):     2.32
```

```
  Step CPU Time      (sec):     0.40

Begin P-Loop Pass 6
Mon Nov 19, 2001   13:26:07
  Elapsed Time       (sec):   101.81
  CPU Time           (sec):    23.89
  Memory Usage        (kb):    91814
  Work Dir Disk Usage (kb):    25600

  Step Elapsed Time  (sec):     1.11
  Step CPU Time      (sec):     0.02

Begin Element Calculations, Pass 6
Mon Nov 19, 2001   13:26:08
  Elapsed Time       (sec):   102.92
  CPU Time           (sec):    23.91
  Memory Usage        (kb):    91814
  Work Dir Disk Usage (kb):    25600

  Step Elapsed Time  (sec):    43.76
  Step CPU Time      (sec):    13.10

Begin Global Matrix Assembly, Pass 6
Mon Nov 19, 2001   13:26:52
  Elapsed Time       (sec):   146.68
  CPU Time           (sec):    37.01
  Memory Usage        (kb):    91814
  Work Dir Disk Usage (kb):    53248

  Step Elapsed Time  (sec):     0.45
  Step CPU Time      (sec):     0.02

Begin Equation Solve, Pass 6
Mon Nov 19, 2001   13:26:52
  Elapsed Time       (sec):   147.13
  CPU Time           (sec):    37.03
  Memory Usage        (kb):    91814
  Work Dir Disk Usage (kb):    53248

  Step Elapsed Time  (sec):    64.49
  Step CPU Time      (sec):    17.92

Begin Load Calculations
Mon Nov 19, 2001   13:27:57
  Elapsed Time       (sec):   211.62
  CPU Time           (sec):    54.95
  Memory Usage        (kb):    92149
  Work Dir Disk Usage (kb):   134144
```

```
  Step Elapsed Time  (sec):     1.40
  Step CPU Time      (sec):    0.42

Begin Post-Processing Calculations, Pass 6
Mon Nov 19, 2001   13:27:58
  Elapsed Time        (sec):    213.03
  CPU Time          (sec):    55.37
  Memory Usage       (kb):    92149
  Work Dir Disk Usage (kb):    134144

  Step Elapsed Time  (sec):    16.32
  Step CPU Time      (sec):    5.93

Begin Displacement and Stress Calculation
Mon Nov 19, 2001   13:28:14
  Elapsed Time        (sec):    229.35
  CPU Time          (sec):    61.30
  Memory Usage       (kb):    92149
  Work Dir Disk Usage (kb):    134144

  Step Elapsed Time  (sec):     9.83
  Step CPU Time      (sec):    0.83

Begin Reaction Calculation
Mon Nov 19, 2001   13:28:24
  Elapsed Time        (sec):    239.17
  CPU Time          (sec):    62.13
  Memory Usage       (kb):    93606
  Work Dir Disk Usage (kb):    134144

  Step Elapsed Time  (sec):     1.94
  Step CPU Time      (sec):    0.61

Begin Convergence Check Pass 6
Mon Nov 19, 2001   13:28:26
  Elapsed Time        (sec):    241.12
  CPU Time          (sec):    62.74
  Memory Usage       (kb):    93606
  Work Dir Disk Usage (kb):    134144

  Step Elapsed Time  (sec):    15.54
  Step CPU Time      (sec):    6.11

Completed P-Loop
Mon Nov 19, 2001   13:28:42
  Elapsed Time        (sec):    256.66
  CPU Time          (sec):    68.85
  Memory Usage       (kb):    93606
  Work Dir Disk Usage (kb):    134144
```

```
  Step Elapsed Time  (sec):     0.68
  Step CPU Time      (sec):    0.01

Completed Analysis: Snap_fit_static
Mon Nov 19, 2001   13:28:42
  Elapsed Time        (sec):    257.34
  CPU Time          (sec):    68.86
  Memory Usage       (kb):    93606
  Work Dir Disk Usage (kb):    134144

--------------------------------------------------


---------------------------------------------

Pro/MECHANICA STRUCTURE Version 22.3(305)
Summary for Design Study "Sensitivity"
Mon Nov 19, 2001   17:12:53

---------------------------------------------


Run Settings
  Memory allocation for block solver: 48.0
  Perform mesh smoothing after each parameter
update.
  Remesh after each parameter update.

Checking the model before creating elements...
These checks take into account the fact that AutoGEM
will
automatically create elements in volumes with material
properties, on surfaces with shell properties, and on
curves
with beam section properties.

Not all of the materials assigned to the model contain
failure data. Failure Index measures will only be
calculated for materials with failure data.

  Generate elements automatically.

Checking the model after creating elements...

No errors were found in the model.

Pro/MECHANICA STRUCTURE Model Summary

  Principal System of Units: millimeter Newton Second
(mmNs)

  Length:        mm
  Force:         N
```

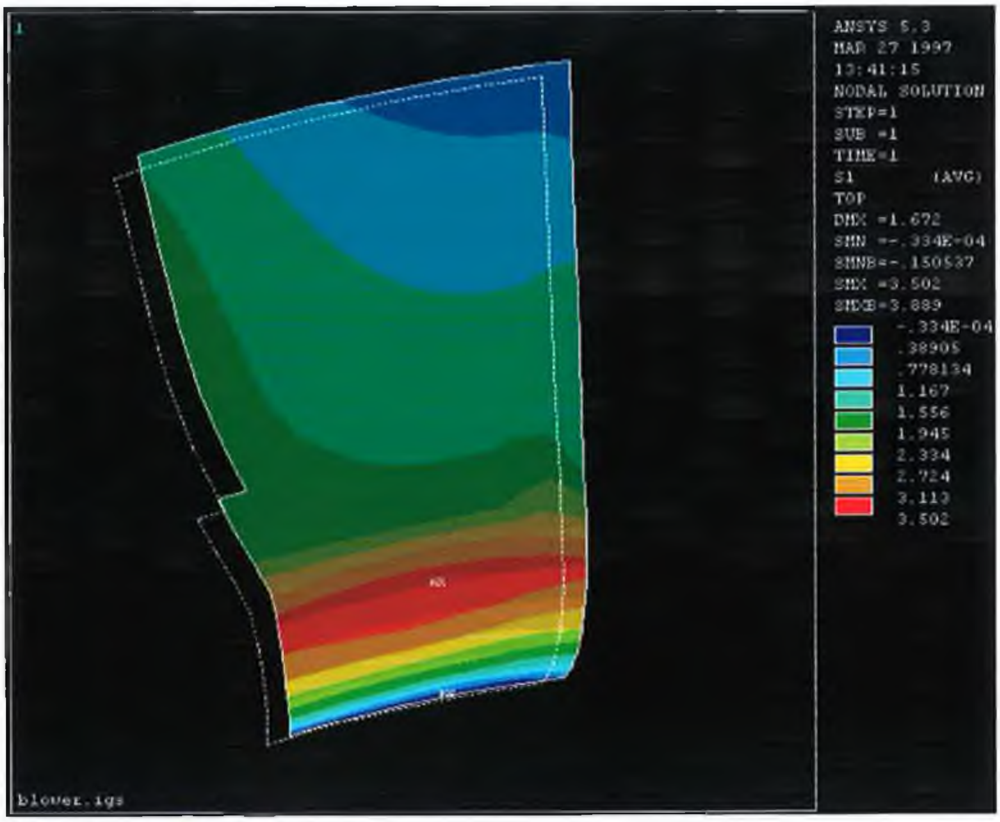
```
  Time:        sec
  Temperature:    C

  Model Type: Three Dimensional

  Points:      87
  Edges:       378
  Faces:       512

  Springs:      0
  Masses:       0
  Beams:        0
  Shells:      0
  Solids:      220

  Elements:    220

------------------------------------------

Global Sensitivity Design Study

Description:
  This study is concerned with the modification
of the
   radial round dimension from 0.18mm to
0.35mm

Parameter              Start        End
  d202               0.18        0.28

Sensitivity Step 1 of 11

Parameters:
  d202               0.18

Static Analysis "Snap_fit_static":

  Convergence Method: Multiple-Pass Adaptive
  Plotting Grid:    4

  Convergence Loop Log:
(17:13:18)

  >> Pass  1 <<
      Calculating Element Equations
(17:13:18)
        Total Number of Equations:    225
        Maximum Edge Order:           1
```

```
    Solving Equations                  (17:13:18)
    Post-Processing Solution             (17:13:18)
    Calculating Disp and Stress Results   (17:13:18)
    Checking Convergence                  (17:13:19)
      Elements Not Converged:      220
      Edges Not Converged:         378
      Local Disp/Energy Index:   100.0%
      Global RMS Stress Index:    100.0%
    Resource Check                       (17:13:19)
      Elapsed Time    (sec):     26.27
      CPU Time        (sec):     5.57
      Memory Usage     (kb):     82534
      Wrk Dir Dsk Usage (kb):        0

  >> Pass  2 <<
    Calculating Element Equations          (17:13:19)
      Total Number of Equations:   1284
      Maximum Edge Order:             2
    Solving Equations                  (17:13:19)
    Post-Processing Solution             (17:13:19)
    Calculating Disp and Stress Results   (17:13:20)
    Checking Convergence                  (17:13:20)
      Elements Not Converged:      158
      Edges Not Converged:          97
      Local Disp/Energy Index:   100.0%
      Global RMS Stress Index:    95.2%
    Resource Check                       (17:13:20)
      Elapsed Time    (sec):     27.70
      CPU Time        (sec):     6.88
      Memory Usage     (kb):     91814
      Wrk Dir Dsk Usage (kb):        0

  >> Pass  3 <<
    Calculating Element Equations          (17:13:20)
      Total Number of Equations:   3912
      Maximum Edge Order:             4
    Solving Equations                  (17:13:21)
    Post-Processing Solution             (17:13:22)
    Calculating Disp and Stress Results   (17:13:22)
    Checking Convergence                  (17:13:23)
      Elements Not Converged:      126
      Edges Not Converged:          25
      Local Disp/Energy Index:   100.0%
      Global RMS Stress Index:    39.4%
    Resource Check                       (17:13:23)
      Elapsed Time    (sec):     30.25
      CPU Time        (sec):     9.19
      Memory Usage     (kb):     91814
      Wrk Dir Dsk Usage (kb):     3072
```

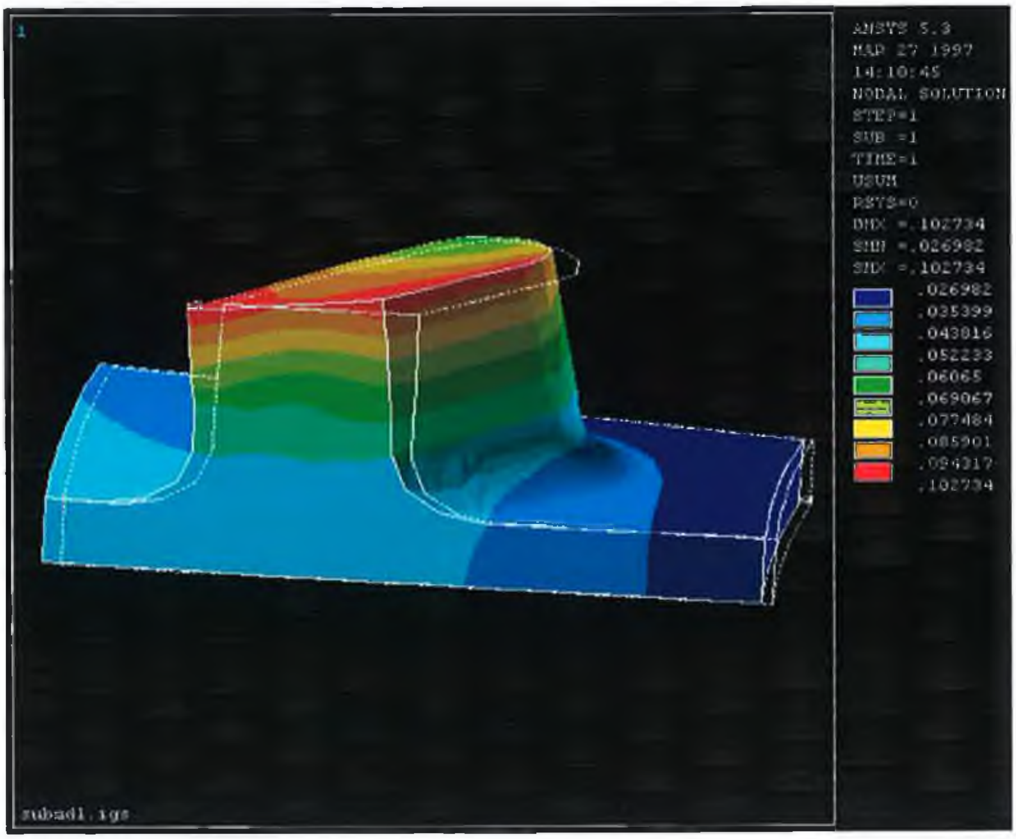
```
>> Pass  4 <<
    Calculating Element Equations
(17:13:23)
      Total Number of Equations:   8466
      Maximum Edge Order:          5
    Solving Equations
(17:13:25)
    Post-Processing Solution
(17:13:27)
    Calculating Disp and Stress Results
(17:13:29)
    Checking Convergence
(17:13:29)
      Elements Not Converged:      42
      Edges Not Converged:         0
      Local Disp/Energy Index:   15.8%
      Global RMS Stress Index:    7.2%
    Resource Check
(17:13:30)
      Elapsed Time    (sec):    37.05
      CPU Time        (sec):    15.13
      Memory Usage    (kb):     91814
      Wrk Dir Dsk Usage (kb):   10240

>> Pass  5 <<
    Calculating Element Equations
(17:13:30)
      Total Number of Equations:  15435
      Maximum Edge Order:          5
    Solving Equations
(17:13:37)
    Post-Processing Solution
(17:13:43)
    Calculating Disp and Stress Results
(17:13:51)
    Checking Convergence
(17:13:51)
      Elements Not Converged:       2
      Edges Not Converged:          0
      Local Disp/Energy Index:    6.1%
      Global RMS Stress Index:    5.2%
    Resource Check
(17:13:52)
      Elapsed Time    (sec):    59.42
      CPU Time        (sec):    33.83
      Memory Usage    (kb):     94185
      Wrk Dir Dsk Usage (kb):   25600
```

```
>> Pass  6 <<
    Calculating Element Equations           (17:13:52)
      Total Number of Equations:   24558
      Maximum Edge Order:            6
    Solving Equations                   (17:14:10)
    Post-Processing Solution              (17:14:37)
    Calculating Disp and Stress Results    (17:15:08)
    Checking Convergence                   (17:15:09)
      Elements Not Converged:        0
      Edges Not Converged:          0
      Local Disp/Energy Index:    2.5%
      Global RMS Stress Index:     3.2%

    RMS Stress Error Estimates:

    Load Set       Stress Error  % of Max Prin Str
    -----------  ----------  ------------
    LoadSet1       1.69e+06      2.9% of  5.83e+07

    Resource Check                      (17:15:18)
      Elapsed Time    (sec):    145.00
      CPU Time        (sec):    101.64
      Memory Usage    (kb):     109990
      Wrk Dir Dsk Usage (kb):    134144

 The analysis converged to within 5% on
 edge displacement, element strain energy,
 and global RMS stress.

Analysis "Snap_fit_static" Completed  (17:15:18)

Sensitivity Step 2 of 11

Parameters:
 d202                 0.19

Static Analysis "Snap_fit_static":

 Convergence Method: Multiple-Pass Adaptive
 Plotting Grid:     4

    Calculating Element Equations           (17:15:49)
      Total Number of Equations:   24558
      Maximum Edge Order:            6
    Solving Equations                   (17:16:04)
    Post-Processing Solution              (17:16:28)
    Calculating Disp and Stress Results    (17:16:58)

    RMS Stress Error Estimates:
```

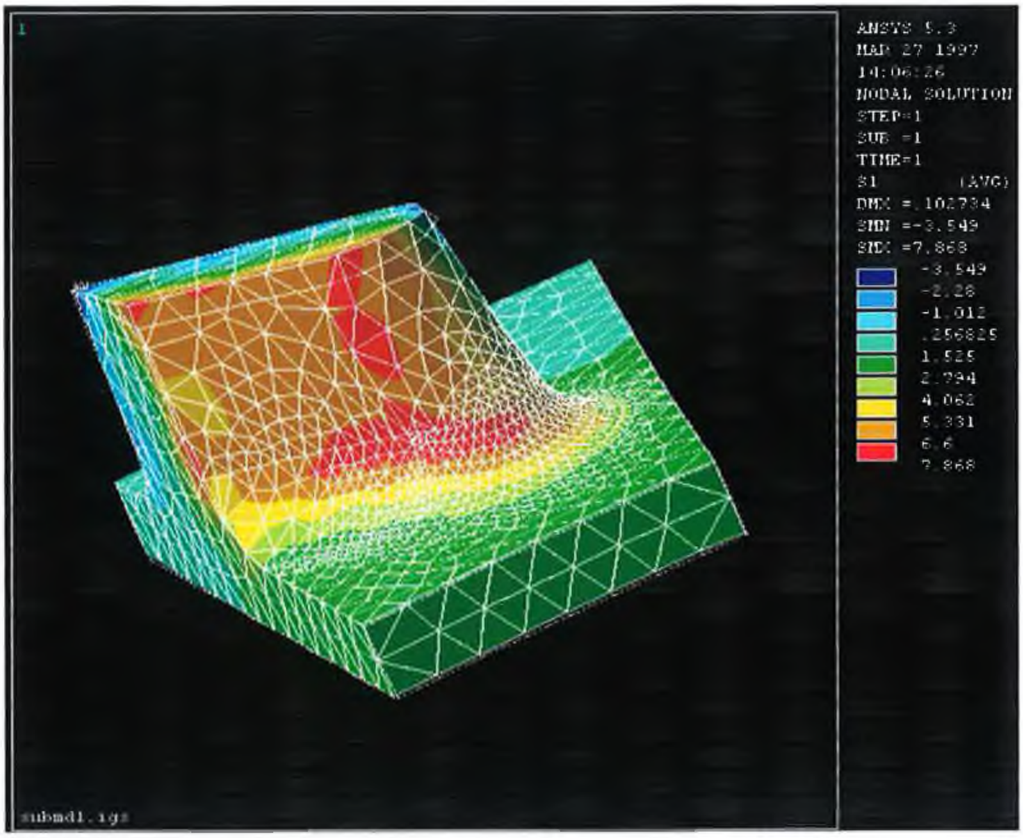
```
     Load Set        Stress Error  % of Max
Prin Str
     ------------  ----------  ------------
     LoadSet1         1.60e+06     2.8% of
5.66e+07

     Resource Check
(17:17:06)
       Elapsed Time     (sec):     253.24
       CPU Time         (sec):     168.17
       Memory Usage      (kb):     118122
       Wrk Dir Dsk Usage (kb):     134144

Analysis "Snap_fit_static" Completed
(17:17:06)
```



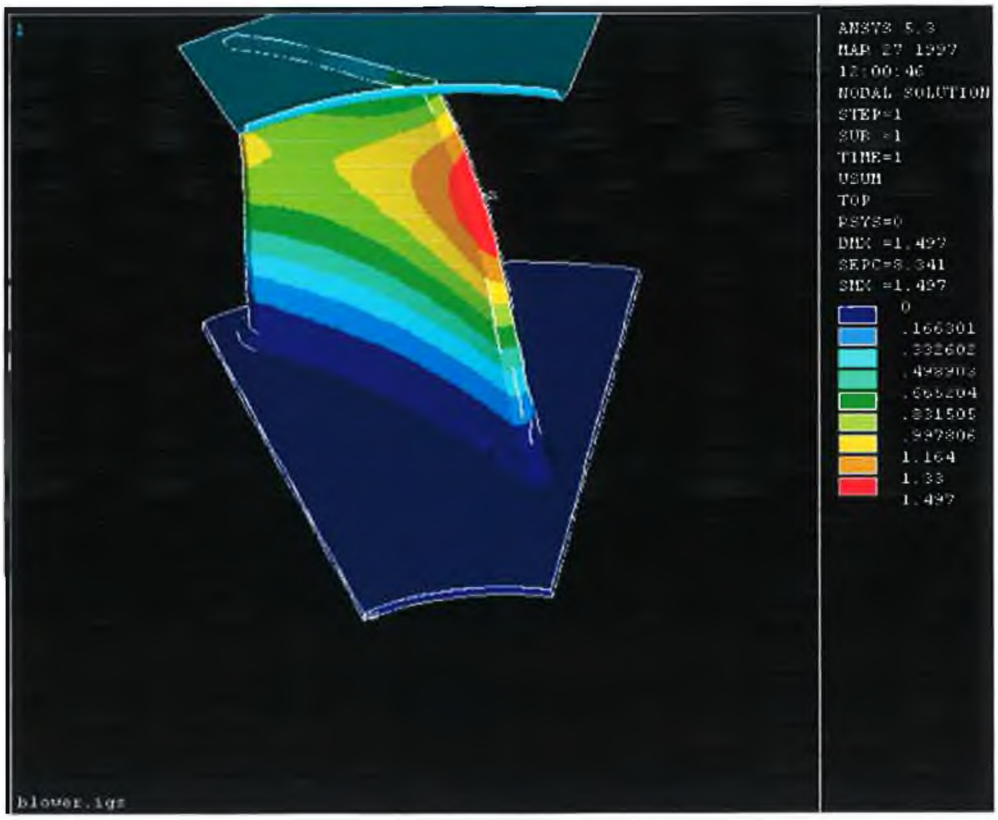
Blower Shroud FEA Stress



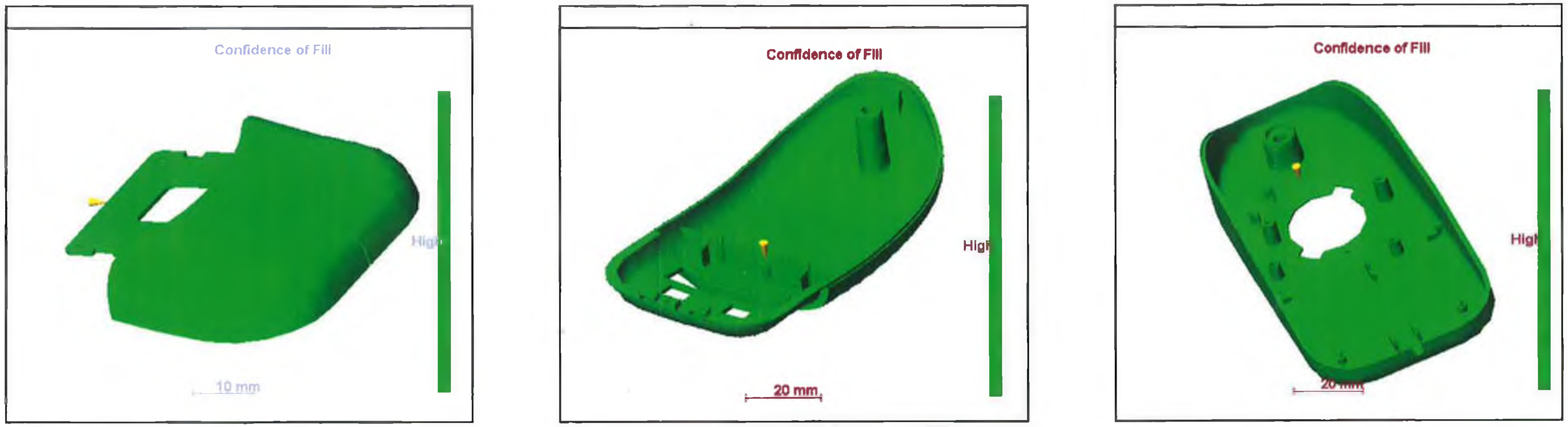
Submodel Deflection of Blower Design



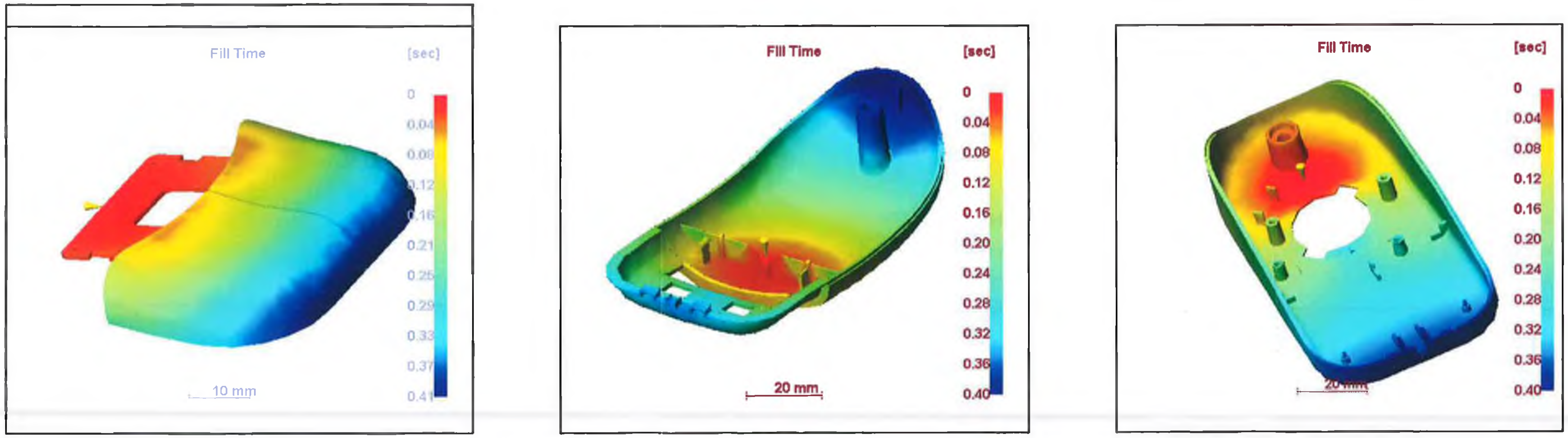
Submodel Stress for Blower Design



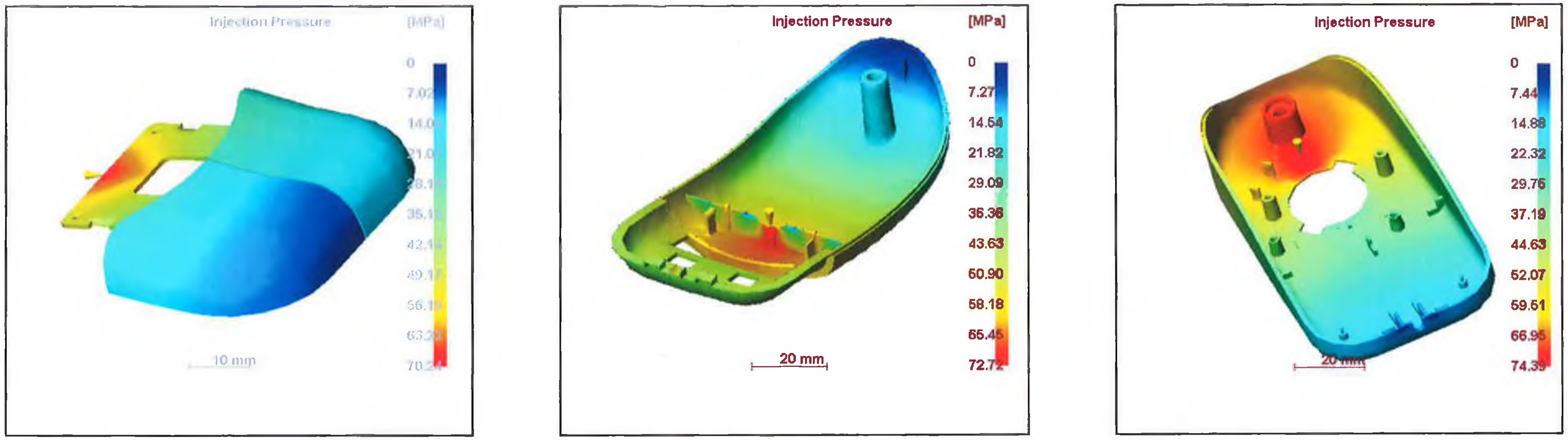
Blower Assembly Deflection Contour



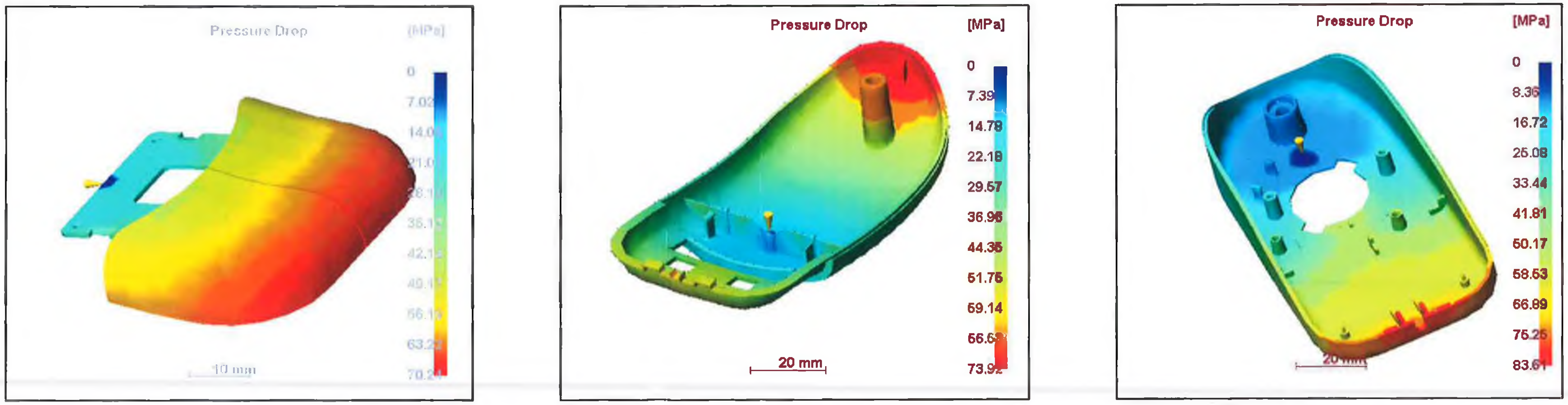
Confidence of Fill:



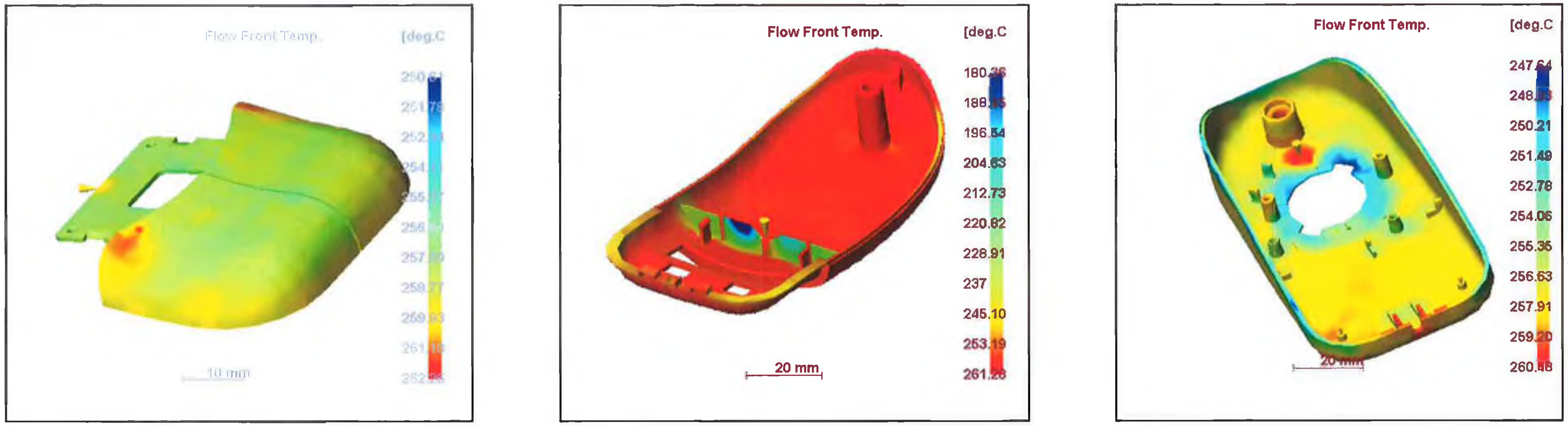
Fill Time:



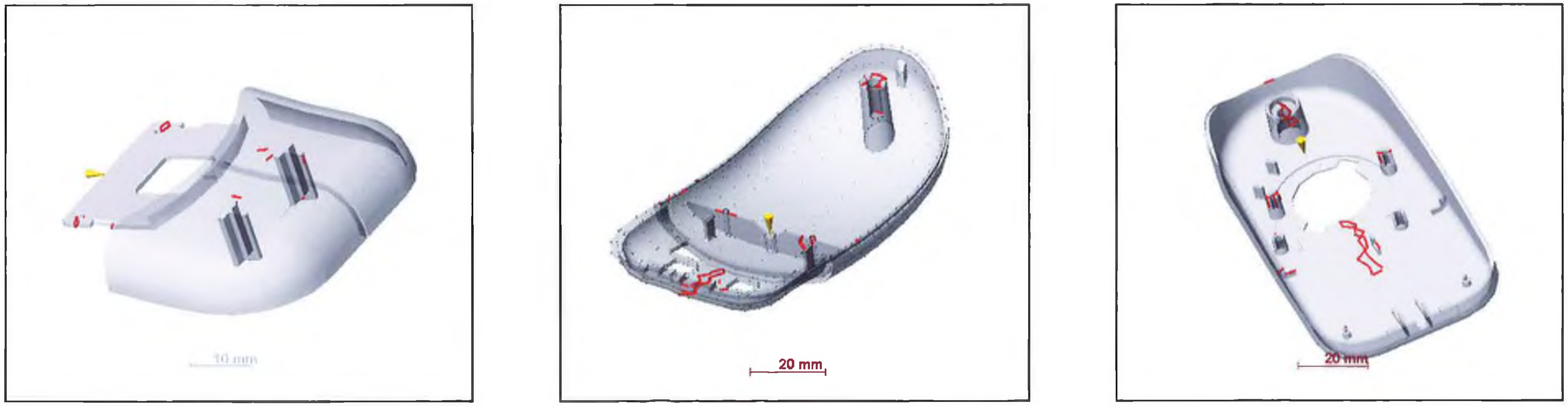
Injection Pressure:



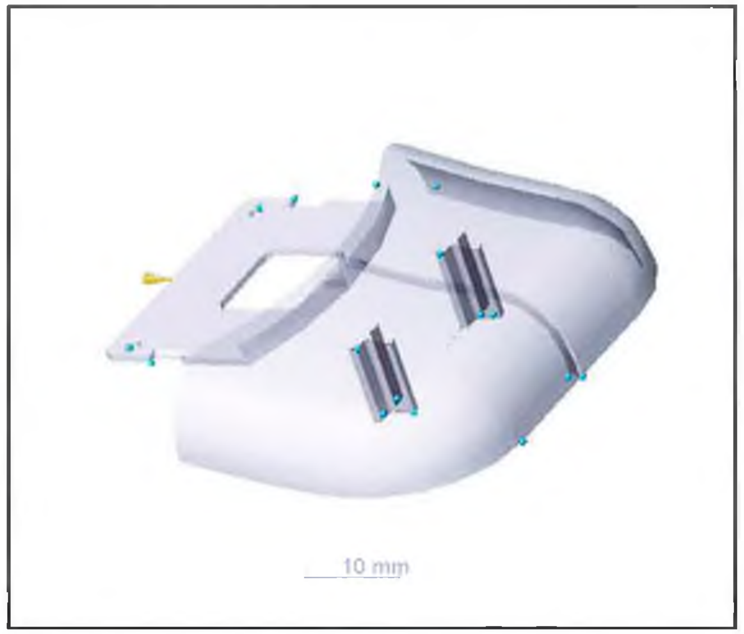
Pressure Drop:

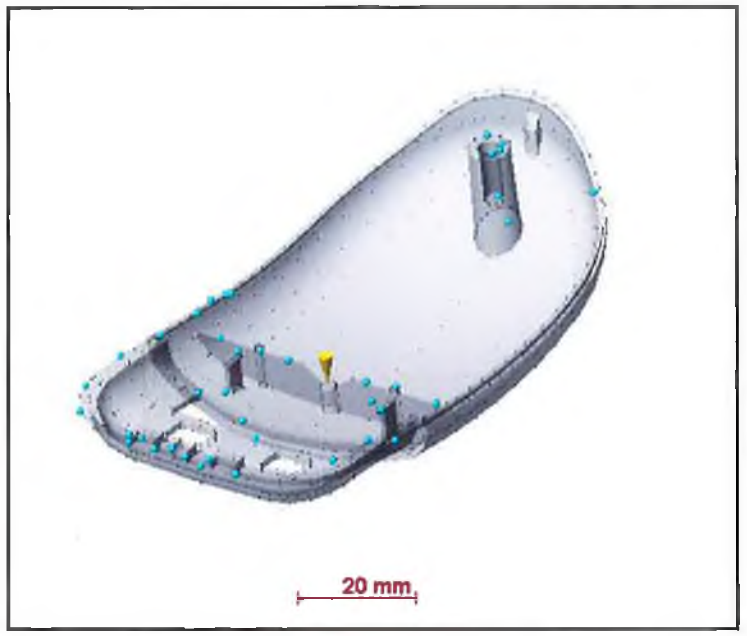


Flow Front Temperature:



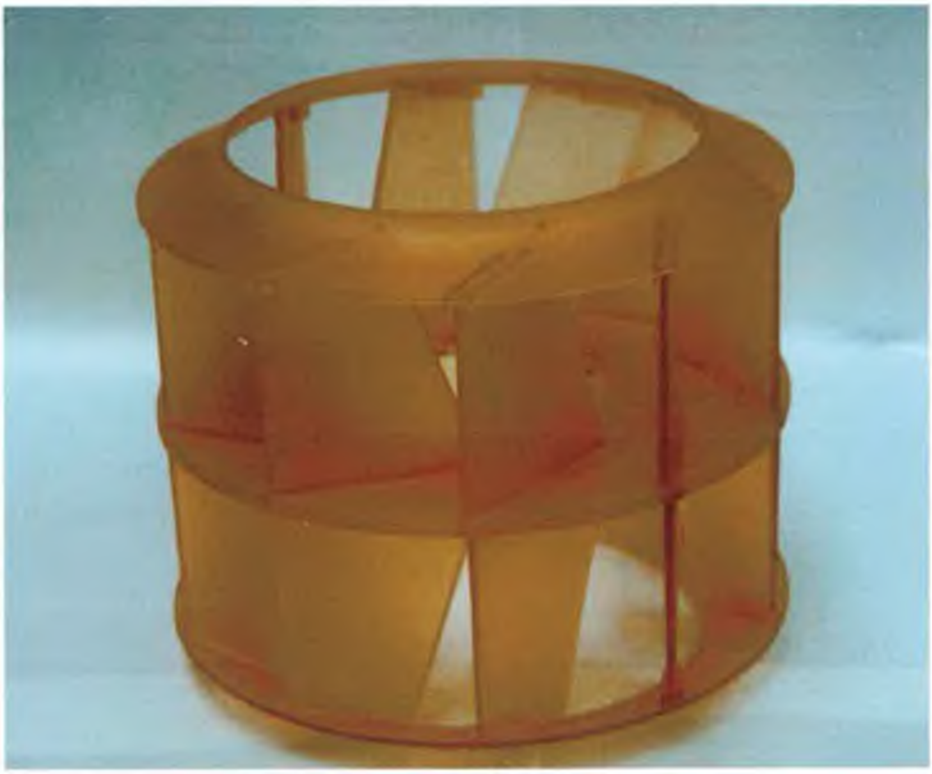
Weld Lines:





Air Traps:

SLA Prototype component of Blower



SLA Prototype Assembly

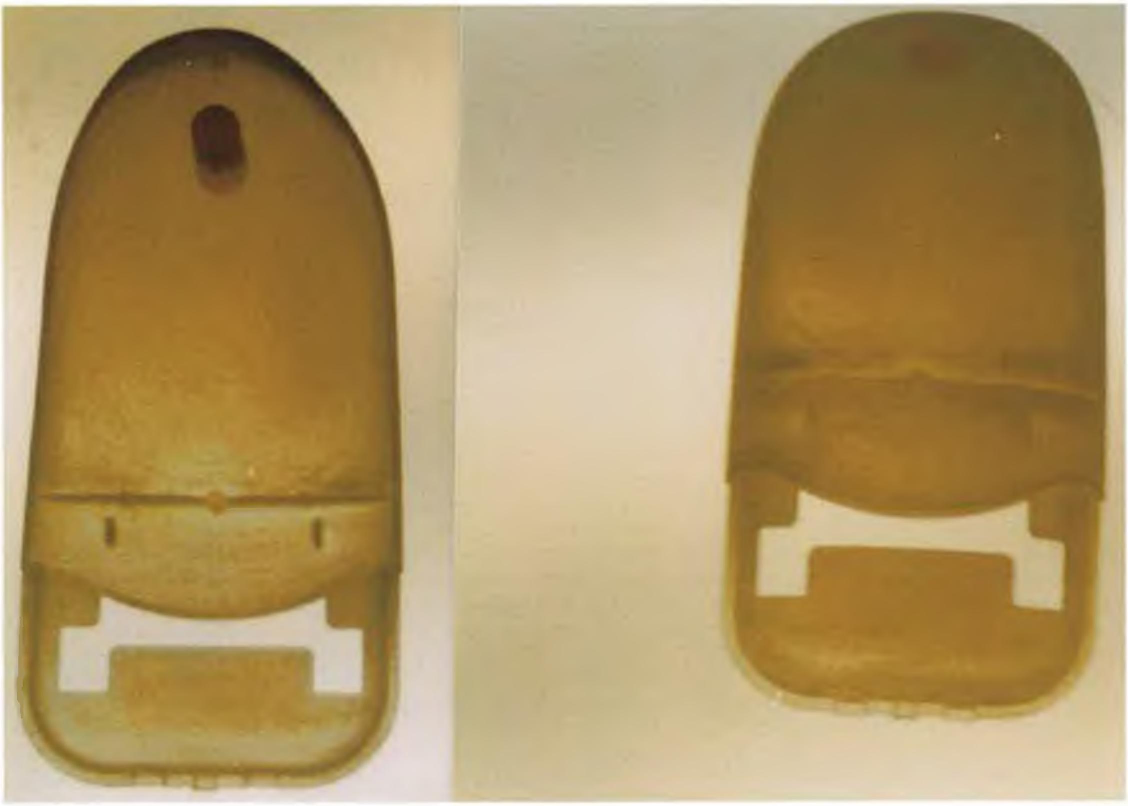
Centre Plate Located with Lower Half of Assembly

SLA Blower Assembly with Centre Plate

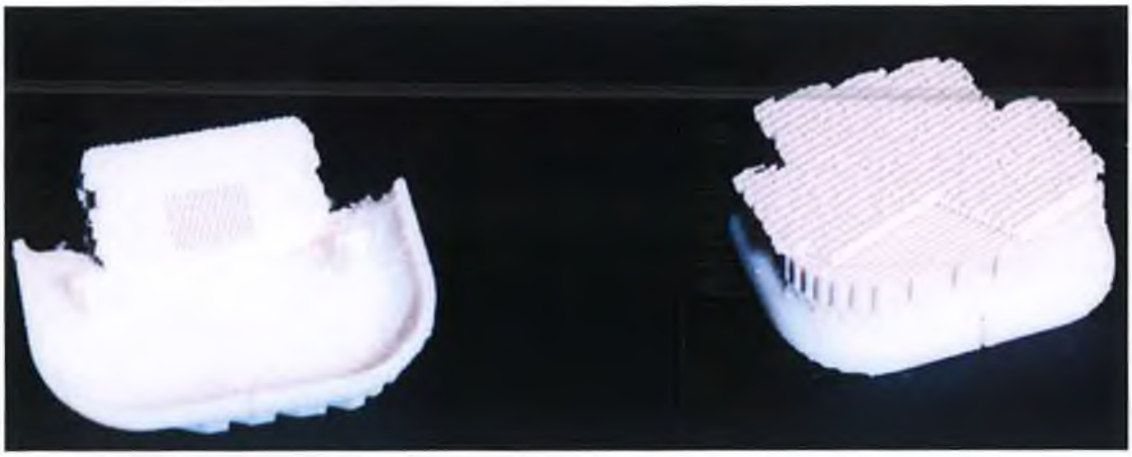
FDM Computer Mouse Bottom Prototype with supports

SLA Computer Mouse Bottom Cover Prototype

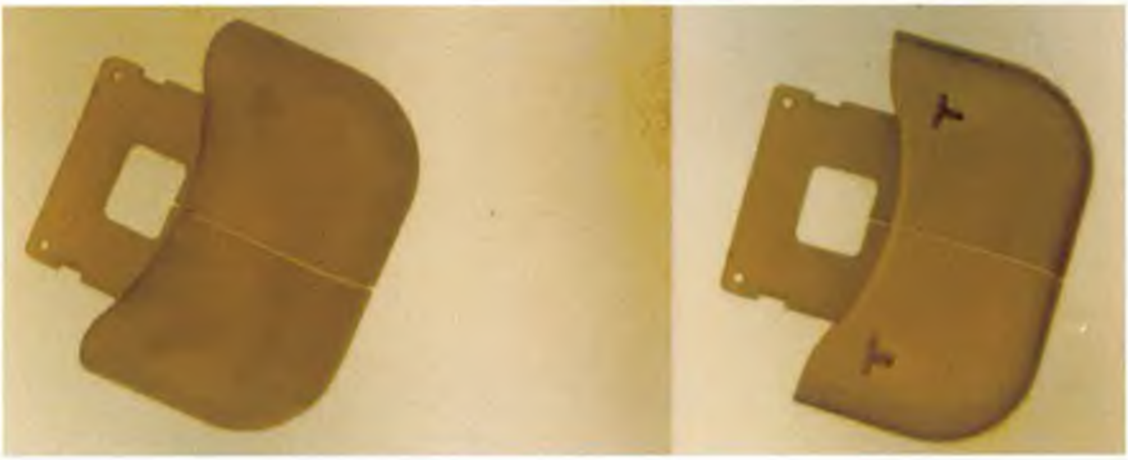
FDM Computer Mouse Top with Build Supports



SLA Computer Mouse Top Cover



FDM Prototype of Computer Mouse Button with Supports



SLA Prototype of Computer Mouse Button

Material Properties

CYCOLAC High Heat Resin Grades

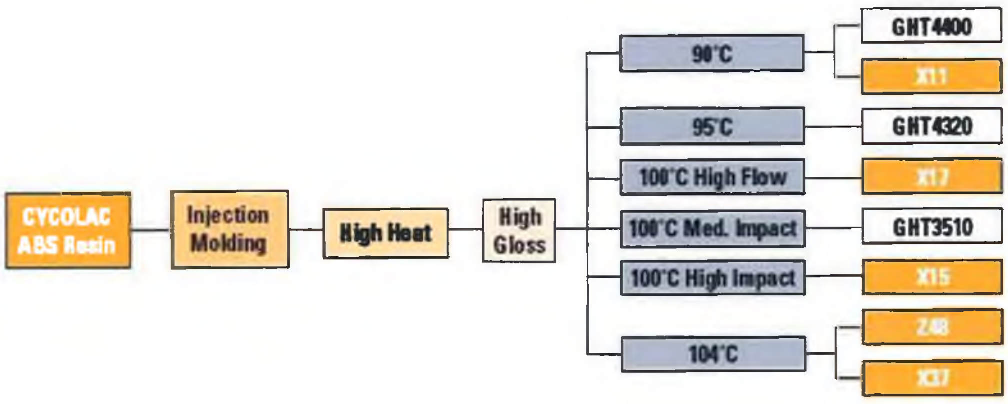
X11
- automotive applications
- high heat
- high impact
- UL 94HB rating*

X15
- automotive applications
- high heat
- very good impact
- improved processability
- UL 94 HB rating*

X17
- very high heat
- good moldability
- high modulus
- UL 94 HB rating*

X37
- highest heat
- medium impact
- UL 94 HB rating*

Z48
- automotive applications
- highest heat
- good moldability / dimensional stability



*These ratings are not intended to reflect hazards presented by any material under actual fire conditions.

CYCOLAC ABS Resin

Typical Property Values - CYCOLAC High Heat Resin Grades

PROPERTY	ENGLISH UNITS (SI UNITS)	TEST METHOD	CYCOLAC X11 resin	CYCOLAC X15 resin	CYCOLAC X17 resin	CYCOLAC X37 resin	CYCOLAC Z48 resin
MECHANICAL							
Tensile Strength, yield, Type 1, 0.125" (3.2mm)	psi(MPa)	ASTM D 638	6,000(41)	6,600(45)	7,200(50)	7,000(48)	6,800(47)
Tensile Modulus, Type 1, 0.125" (3.2mm)	psi(MPa)	ASTM D 638	300,000(2,070)	320,000(2,205)	350,000(2,410)	350,000(2,410)	330,000(2,275)
Flexural Strength, yield, Type 1, 0.125" (3.2mm)	psi(MPa)	ASTM D 790	10,000(69)	11,300(78)	12,500(86)	12,000(83)	12,000(83)
Flexural Modulus, 0.125" (3.2mm)	psi(MPa)	ASTM D 790	310,000(2,135)	340,000(2,345)	380,000(2,620)	350,000(2,410)	350,000(2,410)
Compressive Strength	psi(MPa)	ASTM D 695	7,200(50)	—	9,400(65)	8,600(59)	8,600(59)
Compressive Modulus	psi(MPa)	ASTM D 695	300,000(2,070)	—	380,000(2,620)	340,000(2,345)	340,000(2,345)
Hardness, Rockwell R	—	ASTM D 785	105	108	113	109	110
IMPACT							
Izod Impact, notched, 73°F (23°C)	ft-lb/in(J/m)	ASTM D 256	6.0(320)	5.0(267)	3.0(160)	4.0(214)	4.0(214)
Izod Impact, notched, -22°F (-30°C)	ft-lb/in(J/m)	ASTM D 256	2.0(107)	—	1.1(59)	—	—
Izod Impact, notched, -40°F (-40°C)	ft-lb/in(J/m)	ASTM D 256	1.6(85)	1.6(85)	0.7(37)	1.0(53)	1.0(53)
Gardner Impact, 73°F (23°C)	ft-lbs(J)	ASTM D 3029	—	—	—	10.0(14)	9.0(12)
THERMAL							
HDT, 66 psi (0.45 MPa), 0.125" (3.2 mm) unannealed	°F(°C)	ASTM D 648	208(98)	225(107)	226(108)	—	230(110)
HDT, 264 psi (1.82 MPa), 0.125" (3.2 mm) unannealed	°F(°C)	ASTM D 648	185(85)	202(94)	204(96)	—	210(99)
HDT, 264 psi (1.82 MPa), 0.250" (6.4 mm) unannealed	°F(°C)	ASTM D 648	194(90)	212(100)	214(101)	219(104)	219(104)
HDT, 66 psi (0.45 MPa), 0.250" (6.4 mm) unannealed	°F(°C)	ASTM D 648	—	230(110)	—	—	237(114)
CTE, flow, -40 to 100°F (-40 to 40°C)	in/in °F(mm/mm °C)	ASTM E 831	5.1 E-5(9.2 E-5)	—	3.7 E-5(6.6 E-5)	4.4 E-5(7.9 E-5)	4.4 E-5(7.9 E-5)
Relative Thermal Index, Elec Prop	°C	UL 746B	60	60	60	60	—
Relative Thermal Index, Mech Prop with impact	°C	UL 746B	60	60	60	60	—
Relative Thermal Index, Mech Prop without impact	°C	UL 746B	60	60	60	60	—
PHYSICAL							
Specific Gravity, solid	—	ASTM D 792	1.04	1.05	1.05	1.05	1.05
Mold Shrinkage, flow, 0.125" (3.2 mm)	in/in E-3	ASTM D 955	5-8	5-8	5-8	5-8	5-8
Melt Flow Rate, nom'l 230°C/3.8 kgf (I)	g/10 min	ASTM D 1238	1.5	1.0	1.5	1.0	1.0
Melt Viscosity, 260°C, 1000 sec-1	poise	ASTM D 3835	2290	2290	2290	—	2590
ELECTRICAL							
Dielectric Strength	V/mil(kV/mm)	ASTM D 149	—	—	—	932(36.8)	—
FLAME CHARACTERISTICS*							
UL 94 HB Flame Class Rating	in(mm)	UL 94	0.058(1.47)	0.058(1.47)	0.058(1.47)	0.064(1.62)	—

*These ratings are not intended to reflect hazards presented by any material under actual fire conditions.