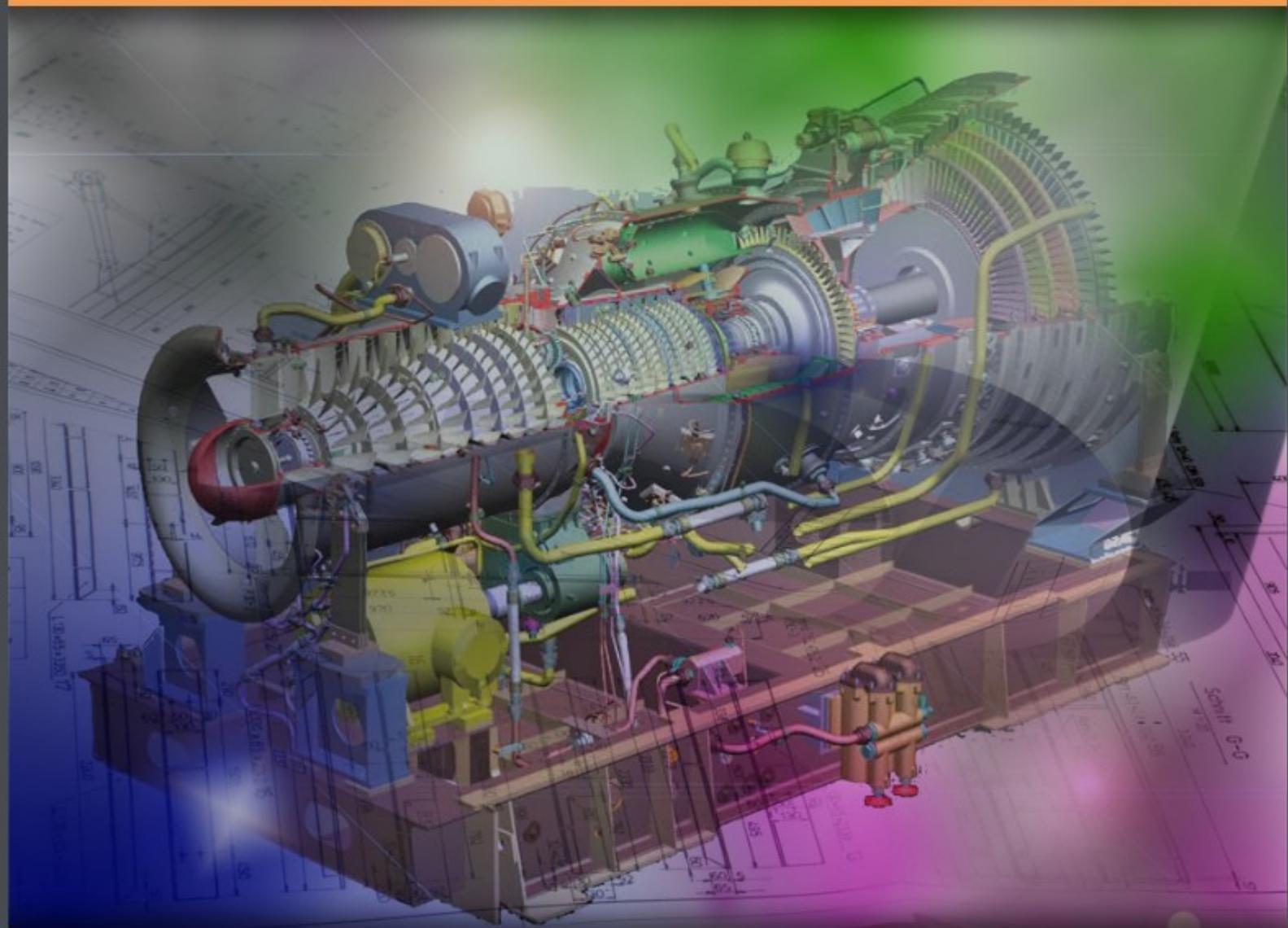


CAD-CAM & Rapid prototyping Application Evaluation

Miltiadis A. Boboulos



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Miltiadis A. Boboulos, Ph.D

CAD-CAM & Rapid Prototyping Application Evaluation

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ISBN 978-87-7681-676-6

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Overview

CAD-CAM systems are probably the most significant development in the field of new technology related to engineering, design and drafting in all technical spheres. These systems find application in all branches of modern design – from machine engineering and microelectronics to architecture and construction building and others. In current publication the author describes in detail via review, analysis and processing case study data the state of art in the selection, application and implementation of such systems.

The past decade has additionally witnessed the emergence of new manufacturing technologies that build parts on a layer-by-layer basis. Using these technologies, manufacturing time for parts of virtually any complexity is measured in hours instead of days, weeks, or months. In other words, it is rapid. A host of related technologies that are used to fabricate physical objects directly from Computer-Aided Design data sources are reviewed in the last chapter. These methods are generally similar to each other in that they add and bond materials in layerwise-fashion to form objects.

1. Computer Programs In Manufacturing

1.1 Parametric Technologies

Pro/ENGINEER[®] is the best CAD/CAM/CAE system for the last 19 years in a worldwide scale. Parametric Technologies have achieved these results for less than 23 years. There is one single reason for this incredible break-through - the company offers revolutionary novel characteristics for the time. The parametric and associative nature of the application along with design operations, which in their character are close to the processes, involved in machine building turn the Pro/ENGINEER into a world leader [1].

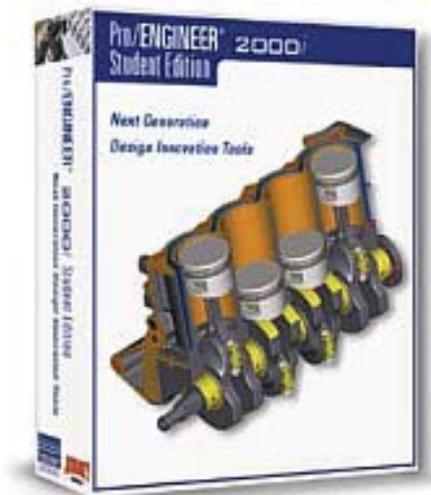


Fig. 1.1.

Dr Samuel P.Gaisberg found the company in 1985. He used to work as a chief engineer-programmer in the competitive companies Computervision and Applicon. He left Computervision in 1984 after his project was rejected. When Parametric Technology Corporation was found in 1985 he succeeded in finding a field for implementing his ideas one of which was the parametric model of designed parts and assemblies, which allowed for a revolutionary change in the approach to automated mechanical design.

The Pro-ENGINEER[®] leads the chart in this sphere with annual sales revenue of \$600.1 million, which is around a 19% share of total sales of CAD/CAM/CAE systems and an annual growth of 52%. Around 3350 people are employed in the company.

The system has been constantly enlarged and new modules and functions added to it through the years. In 2002, a new revision of Pro/ENGINEER called Wildfire was released that dramatically changed the software's graphical user interface. The version Wildfire 4.0 was offered in the market in 2008, which included over 75 modules and the Pro/ENGINEER[®] Wildfire 5.0 version was being offered in 2009. Attention is drawn mainly on the interface of the system, operation with multi-component products, data interchange with other CAD/CAM systems and team operation in

Internet environment. The new model Behavioral Modeler allows for the creation of geometrical models maintaining certain behaviour when varying its dimensions.

The basic module Pro/Foundation provides Windows interface and automatic dimensioning of 2D sketches. The Pro/ENGINEER® Wildfire 5.0 comprises a large class modeler Pro/DESKTOP, which produces and consumes models created by other modules in the family. This provides automation of all industrial design activities involved, detail geometry design, preparations for manufacture, analysis using the method of finite elements and last but not least, overall control of complicated projects for products comprising over 10 000 components and assemblies. All modules operate on a general 3D model of the product all dimensions of the product being parametric.

Pro ENGINEER® provides the unique capability of competitive design achievable through simultaneous operation in all product development and production preparation stages. All revisions made in each design stage are automatically introduced in the other stages. This allows for the detail design to begin before the operation for industrial design has completed. Eventual corrections in the latter would be also introduced into the finished NC programs and drawings without any additional design engineer interference. This operation technique allows the users of Pre/ENGINEER® to be always a foot ahead of competitors as they design faster, make their revisions in the progress of work at each stage without any difficulties, produce less prototypes and their products have an appearance of maximum optimization, which saves materials and improves reliability [1].



Fig. 1.2.

There are over 130000 installed Pro/ENGINEER® workstations in over 20 000 companies worldwide by today's day. There are hundreds of workstations linked in networks in many of them. Some of the largest users of the system are Volvo, BMW, Ferrari SpA, Volkswagen, Motorola, Polaroid, Texas Instruments, Canon, NEC, Silicon Graphics, SUN, PC with Windows. The minimum hardware required is Pentium 75, 64MB RAM, 500 MB available hard disc space, S3 compatible video controller. For professional applications powerful machines with Z buffer and

Open GL built-in the graphics card are preferred with a fast disc, at least 17" monitor and the more memory available the better with a maximum fast processor.

The impressive thing about Parametric Technologies is that a new version of Pro/ENGINEER[®] is released every year and this usually includes 2 – 5 new modules and around 400-500 additions requested by customers and this is offered for all supported hardware platforms and operation systems [1].

1.1.1 Production Modules In Pro/ENGINEER

- **Pro/CASTING** provides means for fast creation of moulding equipment and its components allowing the design engineer of the moulds to easily determine the geometry of the casting, the cavities and cores of moulds, to manufacture the finished castings and improve design to facilitate production.
- **Pro/MFG-MILL** creates NC programs for milling and drilling operations on 2.5 to 5 axis machines [2].
- **Pro/MFG-TURN** creates NC programs for turning operations along 4 axes providing control for double-carriage lathe centers [2].
- **Pro/MFG WEDM** creates NC programs for spark erosion along 2 to 4 axes [2].
- **Pro/MOLDDSIGN** facilitates the design of moulds and tools for processing plastics. It also performs analysis of the process of filling of the mould. Easily defines complicated parting surfaces [2].

1.2 Autodesk

1.2.1 Autocad Inventor Professional Suite

Autodesk's manufacturing solutions are used in various manufacturing segments, including industrial machinery, electro-mechanical, tool and die, industrial equipment, automotive components, and consumer products. Products include AutoCAD Inventor Suite, AutoCAD Inventor Professional Suite, AutoCAD Mechanical, Autodesk Vault, Alias Product and Moldflow.

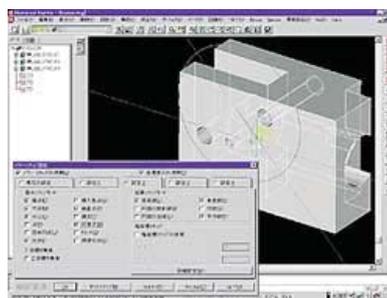


Fig. 1.3.

Available at the disposal of the design engineer are all capabilities listed above in the description of the AutoCAD Inventor Professional Suite but also included in this product is the 3D element library. Algorithms for engineering calculations of strength and deformations under static load using the finite element analysis (FEA) method allows the designer to analyse the construction in

the design stage [2]. Powerful commands for dimensioning and editing of the drawing and model improve efficiency of AutoCAD Inventor users and reduce time by over 30%.

With a customer base of over 123 000 users AutoCAD Inventor is the product with the fastest growing market share in the industry. A significant part for this is played by the Autodesk partners in the MAI program who offer Inventor integrated applications for strength calculations based on MKE, kinematics and dynamic analysis of mechanisms. In addition CAM applications for 2.5D to 5-axes controls for metal processing machines, mould design, sheet metal components, tolerance analysis and dimensional build-up [2] are also offered.



Fig. 1.4.

With the capabilities, production efficiency and ease of operation it provides the new version of AutoCAD Inventor Suite is a solution, which gives the users the freedom to create [2].

1.3 Ansys

ANSYS is among the leaders in this type of systems. The program is based on the finite element theory and is developed in a package adopted in various sectors of industry. ANSYS could be modified and added to. For example, some specialized modules developed by the Spanish company Ingiciber SA and the Swedish company Anker-Zemer AB extend the capabilities of the standard package with means of providing solutions in the area of mechanics of building constructions and hydrodynamics in a limit-element arrangement [2]. ANSYS, Inc. has acquired a number of companies since 2000, including ICEM CFD Engineering, CADOE, CFX, Century Dynamics, Harvard Thermal, Fluent, Inc. and Ansoft.

The pre-processor of ANSYS allows the user to create geometric models and import ready-made ones. When importing models the product performs retranslation of data in the ANSYS format and the geometric models could afterwards be modified. The system provides means for building surface and solid-body geometry and making changes in it. ANSYS solves problems from the area of thermo-physics, hydrodynamics and the electromagnetic theory and makes parallel calculations for side loads and optimization procedures [3].

The program provides specialized final elements allowing not only shifting and rotation within the assemblies but also degree of freedom in temperature, stress, etc. The usage of these elements gives the customer possibilities to perform consistent analysis.

The program for non-linear calculations LS-DYNA of the company LSTC is included in ANSYS as a completely integrated module providing specialized algorithms and support for a number of materials. The customer could use ANSYS and LS-DYNA to model the material processing techniques to analyse emergency situation (like, for example car crashes), final deformations, and interaction between a large numbers of bodies [3]. Solutions could be provided to problems involved in the behaviour of pre-tensioned constructions (like, for example a body getting into a motor turbine and seismic analysis of equipment) and problems for investigating constructions subjected to strong deformations (for example, elastic springing of a thin stamped sheet) [4].

LS-DYNA of LSTC is a multi-functional program using the explicit finite element method and intended for analysis of dynamic deviations in three-dimensional non-elastic structures. Completely automated solution and the multiple final result checking functions allow successful application of the system in most complicated problems involving strikes and moulding [3]. The program provides over 25 algorithms for contact interaction and methods for solving problems in the area of:

non-linear dynamics, quasi-statics, acoustics, thermo-physics, etc. These analytical instruments provide modelling of a wide range of real problems [3];

estimates of striking resistance (for example, crash tests) for cars, planes, trains, etc [3].

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analysis of the dynamic strength of car parts, body, wheels, etc. when moving on an uneven surface [4]; occupant safety analysis.

The product provides means for analysis of metal forming, glass forming, and plastic moulding, rolling, pressing, stamping, etc., hydro-forming (including such involving large deformations), multi-stage processes, problems of streamlining, explosive loads of products, rivet and bolt connections, modeling of earthquakes [4].

ANSYS DesignSpace is a CAE product based on ANSYS and associated with leading CAD products and specifically intended for the design stage preceding the analysis stage. The designers and engineers involved in the analysis of a certain product are working together using the DesignSpace Expert automatically keeping a record of their work with DesignSpace Report [5]. The combination between the power of analysis of ANSYS and the CAD integration with DesignSpace creates a real environment for jointly development.

1.4 Ibm - Catia

CATIA is a highest-class system for automation of engineering labour. It is one of the undisputable leaders in the world of modern CAD/CAM/CAE systems.

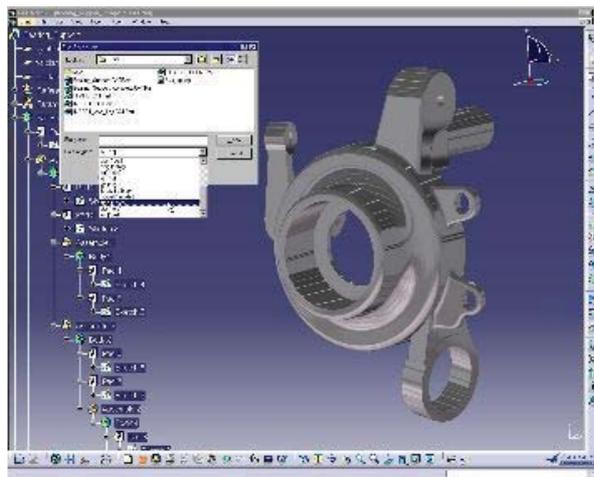


Fig. 1.5.

CATIA was created by Dassault Systems and is being distributed by IBM and works on IBM graphic stations. It is one of the best-known and adopted worldwide systems taking a leading place in the CAD/CAM/CAE market for over 25 years. Meanwhile, it is one of the fastest developing systems. Its open and flexible architecture allows at least two new versions to be produced each year providing new functionalities and improvements [4]. The number of products in the system has grown up from 58 to 108 for three years and most of them, as well as the system as a whole have undergone multiple renovations for this period.

In 1998, an entirely rewritten version of CATIA, CATIA V5 was released, with support for UNIX, Windows NT and Windows XP since 2001. In 2008, Dassault announced and released CATIA

V6.[4] While the server can run on Microsoft Windows, Linux or AIX, client support for any operating system other than Microsoft Windows is dropped [4].

CATIA represents a unique integrated solution for creating and developing engineering products and their optimization in the conditions of team design. This high-tech solution is presently being used in over 9 thousand companies in the world. Many of the largest world manufacturers as well as companies with one or two employees draw competitive advantages from it and attain perfection of design [4].

It improves the entire product line of the system aiming at increasing customer competitiveness in the design, optimization, production and planning of resources [4]. Small and medium scale companies are offered a new and convenient to use module for assembling products based on the abstraction for graphic representation based on the hierarchy tree.

Customers, who consider the shape of the design of significant importance, like for example consumer goods or cars are offered a new product for efficient and high-quality data exchange between CATIA and ALIAS. This increases efficiency when designing shapes allowing easy agreement between the designer and engineer's activities [4].



Fig. 1.6.

The product Generative Shape Modeling dramatically accelerates the process of detail design. The companies where the usage of highly efficient solid-body modelling is critical are able to take advantage of the serious improvements in efficiency compared to earlier CATIA. The drawing generation process has also been accelerated. These improvements are of primal importance for the design of motors, reducers and all types of machine mechanism where large models are usually involved [4].

The CATIA new version is a move forward to a new quality level of automation of technological operations. The Surface Machining Programmer product is a complete and easy to use selection of means for generating 3D programs for 3-axes milling machines. The Multi-Axis Machining Programmer product uses leading NCCS technologies and is addressed to the need of complicated machining in plane building techniques. As a whole, CATIA improves flexibility when selecting between two types of functionalities: fully interactive geometrically based ones and semi-automated process-oriented ones [5].

This version significantly improves the analysis and optimization functions. The product Generative Part Optimization is intended to provide sensitive analysis and optimization of products with the aim of ensuring the best quality design in the fastest possible way and with minimum effort involved. The design engineer is offered intuitive analysis of shell structures, which adds to the existing functions for three-dimensional stress analysis. The two-dimensional arrangement of finite elements is significantly improved and enriched with methods allowing integration of streamlining tests in the design process.

Accelerating the design process for metal ships the CATIA Shipbuilding application has been completely revised to a site oriented product. It uses the unique intelligence of CATIA AEC architecture [5]. The product Product Manager Integration provides unique functions for integration between CAD/CAM/CAE/PDM and company business management systems.

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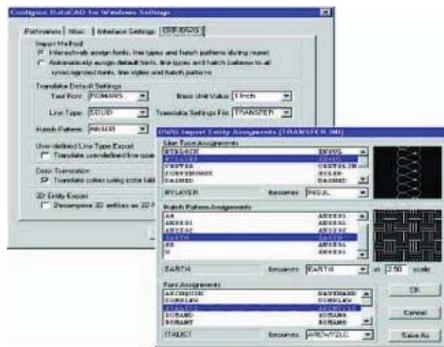
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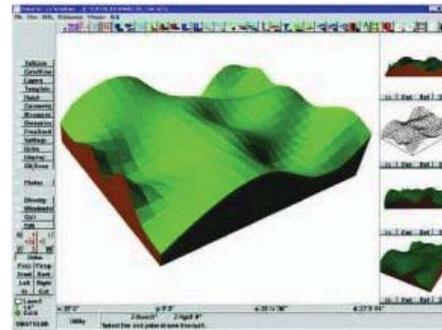
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1.5 Datacad



New DWG/DXF Translator

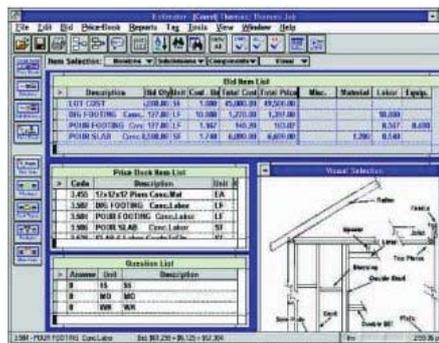
Fig. 1.7.



Digital Terrain Modeler

Fig. 1.8.

DataCAD’s new version (13 - June 2010) includes [6] an all new AutoCAD compatible DXF/DWG translator. A digital Terrain Modeler (DTM), an estimator for Windows, an expanded 3D object libraries, improved display performance and WinHelp based online documentation [9]. The software is of primarily architectural and construction usage rather than manufacturing. Transferring files back and forth between DataCAD and AutoCAD is a breeze with DataCAD's new translator. The DWG translator allows CAD users to benefit from the ease of use of drafting with DataCAD and easily exchange data with engineers and others who use AutoCAD. The new translator will convert custom linetypes in DataCAD to AutoCAD format, so your drawings will display in AutoCAD as they do in DataCAD [10].



New Estimator for Windows

Fig. 1.9.

Improved display list performance provides faster refresh time, object snapping, entity selection, and panning and zooming, improving the program's performance by a factor of up to ten times the speed of DataCAD [11]. The Display List is engineered such that the closer you zoom into the drawing, the faster it performs. This is particularly important for drafting, where the user frequently zooms in on the drawing to perform edits and then changes views. Unlike an isolated feature, display list benefits all DataCAD users immediately and throughout the drawing process with increased program speed [12].

The Digital Terrain Modeler (DTM) allows you to quickly and easily model site plans from survey data or contour lines [13]. Making it easier to draft a realistic landscape, allowing for greater flexibility and creativity in producing realistic models and landscapes and addresses the site-related aspects of building design [13]. The DTM is, most importantly, easy to use. Simply create contours, points, or lines at varying Z-heights, and the terrain modeler will calculate a polygon surface through these points.

There are 1,500 new three-dimensional symbols, including three-dimensional cars and trucks; parking lot, roadway, and walkway lights; park benches; metal, plastic, and wood objects and furnishings; as well as everything for the modern cityscape [14]. In addition, DataCAD includes three-dimensional kitchen and bathroom cabinetry, plumbing fixtures and appliances give you more options for creating detailed 3D models [14].

DataCAD Estimator for Windows, is also included on the DataCAD. Estimator offers instant totaling, "what if" capabilities, an extensive help system, tutorials, markups and an unlimited bid items [15]. The estimator integrates with DataCAD and supports Quicken and Quickbooks formats.

The WinHelp based online documentation is a user-friendly help system [15]. The dual-pane help window means you no longer need to go back and forth between navigating through the help system and displaying topics, and the Contents tab remains synchronized with the selected topic so you can better understand relationships between topics [16]. Printed documentation has also been improved; a completely revised and expanded reference manual is included with every upgrade. The manual is structured to reflect the way a CAD user works and includes a tutorial, whose exercises are synchronized with corresponding reference material [17].

The Productivity Pack includes new 2D and 3D icon toolbars that rapidly access DataCAD most frequently used functions. So that we can quickly and easily annotate the drawing at the correct scale with the new notation, dimension and text toolbars. Additional toolbars address 3D modeling, hatching and common 2D drafting functions [17].

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2. Computer Programs In Design

2.1 Unigraphics Solutions

Solid Edge V1 was released in 1995, in October 1997 the Sheet Metal environment was introduced with V3.5. UGS switched from the ACIS modeling kernel to Parasolid in 1998 with V5. Solid Edge with Synchronous Technology was launched in 2008. Solid Edge with Synchronous Technology 2 was launched in 2009.

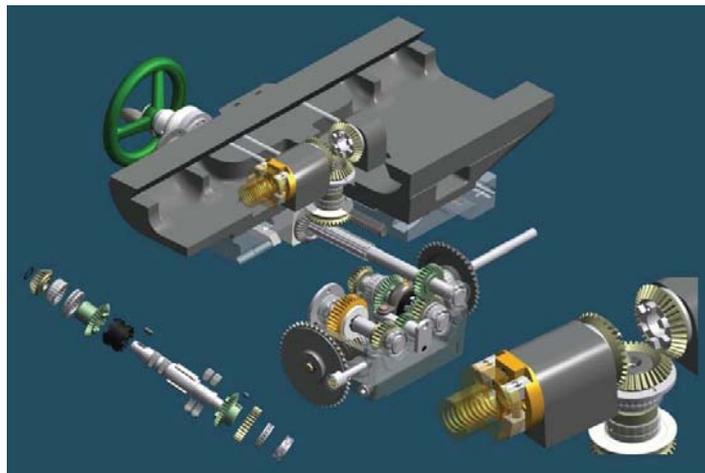


Fig. 2.1

The new product version offers extended capabilities and new application oriented means for automated design of complicated machine parts made of plastic and aluminium, moulding and sheet metal products. The new capabilities in version 20 are accelerated by the STREAM technology of users interface offering the thousands of existing users the most efficient Windows based CAD system [1]. The new pipeline design module Xpress Route is leading the innovations in the new version.

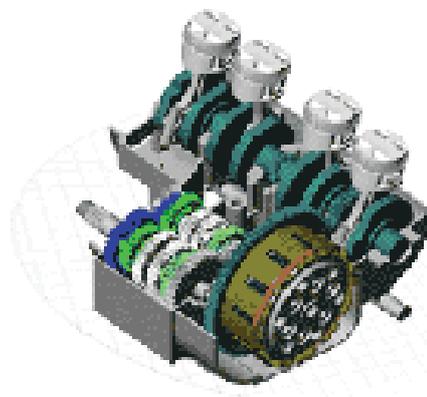


Fig 2.2

This new module is used to design systems that transport fuel, oil, and air, cooling liquids, hydraulic fluids or electricity from one point in an assembled machine configuration to another. The pipes are being modelled in the context of the particular assembly and are completely associated with the parts and components they are connected to [1]. A new method of building thin cavities in restriction areas of the model, as well as new primitives to facilitate the designing of moulding tools were added in Solid Edge 20, as desired by the customers. The design engineers of plastic components could take advantage of the new function of “smoothing” angles and rounds as well as the new capabilities for previewing the results of the mould indexing operation. Several new functions were also added for designing sheet metal products where Solid Edge is a traditional leader [1].

For example, the users could now very quickly unfold metal sheets in seats intended to increase material strength characteristics.

Initially announced in 1996 Solid Edge continues to stand in its leading position in the CAD machine building industry adding up hundreds of improvements for the short time since the latest version 6 [2].

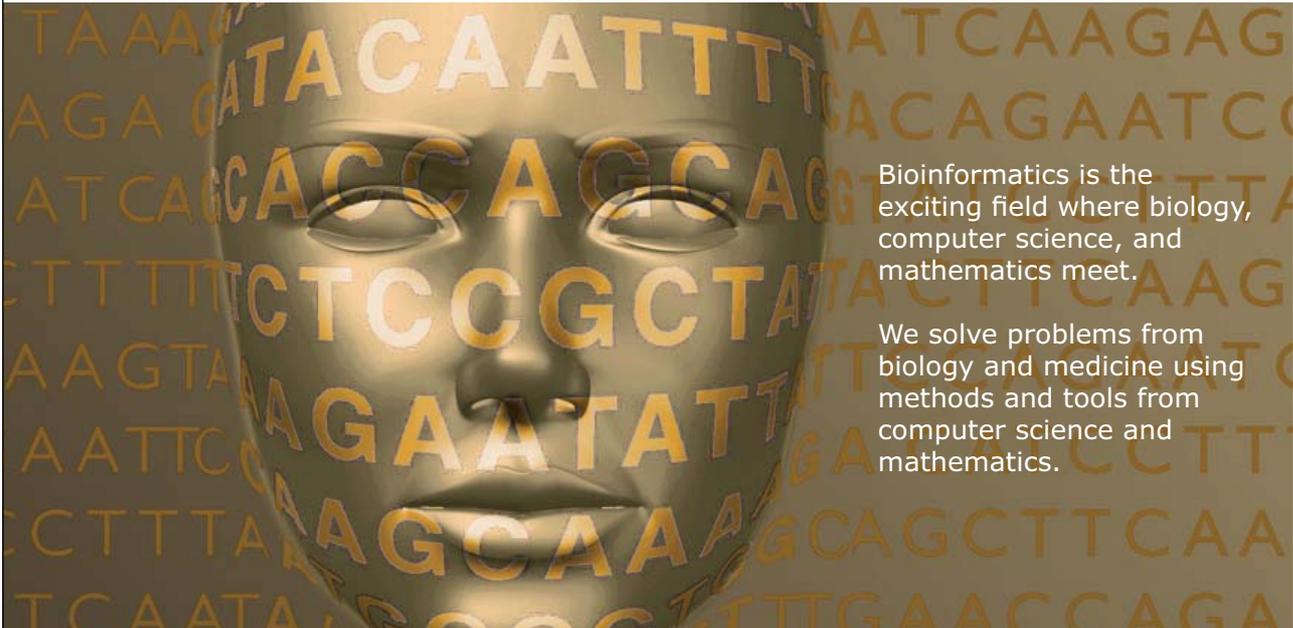
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- **Feature recogniser** – This feature reads and automatically recognizes the primitives and operations in the description of each Parasolid file in the process of loading the file.
- **Assemblies modelling** - Improved creation of repeating primitive sequences, improved measurement means, conical and tangential contact conditions for assembly purposes.
- **Detail modelling** - Copies the position of a detail relative to another available detail, new key curves – 3D spline, coordinate system, etc.
- **Drawing** – An automated feature generates a map of all openings and assigns dimensions and design surfaces in the drawing views.
- **Translators** – Open/Save As IGES or STEP and additional DXF extensions.
- **Revision manager** – A built-in PDM system operating independently from the basic CAD license.
- **STREAM** - A proprietary technology built into the Solid Edge, which speeds up user operation anticipating his intentions as the work progresses using interface logic and a decision management concept.

Solid Edge was written as 100% Windows application. It is 100% file level compatible with UNIGRAPHICS (another CAD/CAM/CAE + PDM software from Unigraphics Solutions) [2]. Solid Edge v.20 comprises the following functions and specialised modules:

- **Solid Modelling** – extended 3D solid-body modelling with Parasolid nucleus
- **Plastics Plus** - plastic and aluminium components and moulding
- **Sheet Metal** – sheet metal operation
- **Assembly Modelling** – assembly of machines, mechanisms and constructions
- **Virtual Studio** – photo realistic visualization and engineering animation
- **Drafting** – drawing and documentation
- **Revisions manager** – PDM system for versions control and parallel design in working groups
- Programming using a built-in Visual Basic
- Parametric libraries of standard elements
- Calculation and optimisation problems for machine designs
- **Interfaces** - MicroStation DGN, AutoCAD DWG/DXF, IGES, STEP, PARASOLID, UG Part, STL.
- **Solid Edge ORIGIN 3D** – a program for new and existing 2D AutoCAD users for transition towards 3D Solid modeling and drawing with 3D Solid modeling.

2.2 Autodesk

2.2.1 Autocad Mechanical /Power Pack

AutoCAD Mechanical is a 2D mechanical software design tool built on the AutoCAD platform. It allows drafting and designing mechanical pieces, and comes with a library of standard objects meant to increase productivity [3].

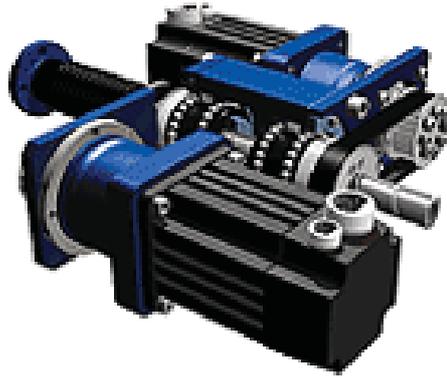


Fig. 2.3

AutoCAD® Mechanical design and drafting software is an AutoCAD® software for manufacturing, purpose-built to accelerate the mechanical design process. Part of the Autodesk solution for Digital Prototyping, it includes all the functionality of AutoCAD, one of the world's leading 2D CAD design software, plus comprehensive libraries of standards-based parts and tools for automating common mechanical CAD tasks [3]. AutoCAD Mechanical design software helps save hours of design time. Added to this platform are strong machine design means providing faster and easier creation, editing, detailed view and management of machine projects and drawings [3].

An exceptionally convenient and intuitive user interface facilitates operation and practically leads to using specialized software functions. Some of the most useful and attractive capabilities are:

AutoCAD Mechanical with Power commands – a single command provides editing and copying, modifying detail and openings specifications and execution of commands for making other items.

- An automated layer control positions items in suitable layers
- Automated output and alignment of items in drawings of assembled units and generation of specifications
- Dimensioning, tolerances, roughness symbols, shape and size deviations according to a user selected design
- Management of two-dimensional assemblies
- AutoDetailing creates detail drawings based on the assembly drawing
- Extended Xref Manager and Block Editor

AutoCAD Mechanical Power Pack library containing over 500 000 standard machine elements, standard technological elements, over 20 000 standard openings, coupling elements, shafts generator, engineering shaft calculations, bearings, selection of materials, etc [3].

2.2.2 Inventor Professional

This is the best-sold Windows based 3D CAD system. This is due to the fact that two-dimensional and three-dimensional design, analysis and preparation for manufacture are performed in a single surrounding, faster and cheaper compared to most other systems available [4].

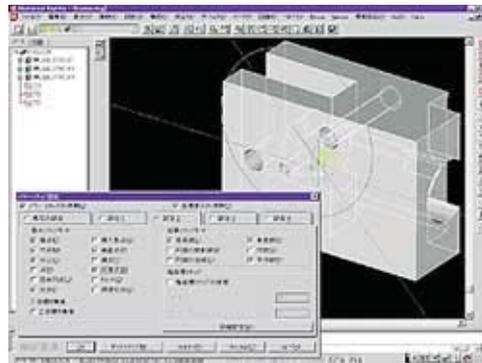


Fig. 2.4

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The new version offers a number of improvements and new capabilities:

InPlace Reference Editing [4] provides in-place editing in the assembly file of specified details defined in external files. This, along with the Design Center (a multiple file design surrounding), which provides simultaneous opening of several files and using and exchanging data between them, facilitates product design activities for products comprising a large number of details and assemblies.

Inventor Professional operates using a nucleus for Solid Modeling ACIS 5.0. The new version offers higher flexibility and stability when building the geometry with “blend”, “termination”, “loft”, “shell” and “surfacing”. The capability to define 2D splines in the side views gives the user freedom in outlining the sections, which along with the included generalized 3D sweep route provides unlimited flexibility in defining solid models [4].

The strong surface modeling functions involved are mainly directed at **users from the tooling production sphere.** It is possible to tack together and merge a large number of surfaces and the result of this merger could be a solid body or a new type of surface [4].

The new dynamic profile evaluation facilitates profile editing by means of real time grips and gives the user visual idea of the alterations.

There are also a great number of **improvements in drawing** and these include the algorithm for calculating hidden lines, multiple drawing sheets, cutting and insertion between separate sheets, and twisted cross-sectioning [4].

Mechanical Desktop also offers a **wide choice of means to develop specialized application programs** – ObjectARX, C++, VisualLISP, VBA, ActiveX.

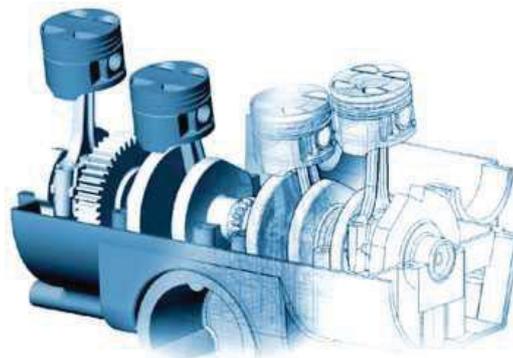
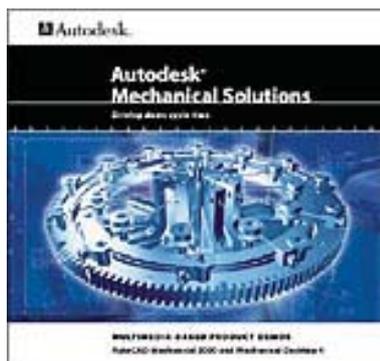


Fig. 2.5

2.3 Cadtek Systems

2.3.1 Ccreate ME10

ME10 is the professional 2D design, drafting and documentation software tailored to the needs of mechanical and electro-mechanical engineers. As a team-based design solution, ME10 contains numerous technologies specially developed for workgroup cocreation such as powerful assembly design, revision checking, associative data structures and a superior integration into the workflow and data management software WorkManager. Furthermore, ME10's [6]. Advisor Technologies make the difference between drafting and professional design. The Design Advisor and Dimension Advisor provide intelligent system consultancy during geometry creation and modification as well as automatic dimensioning.

Workgroup Co-creation in the Engineering Environment

Powerful Assembly Design - ME10 features a "parts concept" that simplifies the design and modification of assemblies through a hierarchical parts structure. With "shared parts," several instances of a part may occur on the same drawing [6]. It's also possible to define multiple drawing scales to handle assemblies with exceptionally large and small parts. A parts structure editor helps maintain control even in the most complex assembly structures. All design activities are simplified, such as defining sub-assemblies, creating instances, re-naming and changing ownership [5].

File Browser with Preview Window - When engineering teams work together on large assemblies, the importance of finding the correct parts quickly increases. Project leaders, in particular, will appreciate the capability of ME10 to preview parts before loading them. The preview window of the File Browser simplifies the process of merging parts to form large assemblies [6]. The File Browser also shows the file history of previously loaded parts, and makes it easy to access them by simply double-clicking on the file history list.

Revision Checker - ME10 provides a Revision Checker, which helps synchronise engineering work. The Revision Checker automatically highlights design changes, and notes differences between design revisions. Revision checking is also supported by WorkManager so that drawings which matched a database query can be transferred to ME10 to show differences [6].

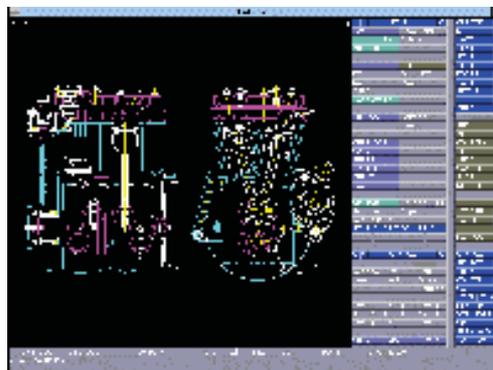


Fig. 2.6

Design Modifications - With ME10, engineers have powerful modification commands that allow them to copy, rotate, mirror, scale and stretch all elements. Advanced trim and extend capabilities provide a quick, effective means to refine drawings and close contours [5]. Dimension-driven modifications allow quick design changes by simply changing the driving dimensions. To make design modifications an easy task ME10 provides advanced component selection commands that give engineers various ways to select drawing elements, like with a polygon area, Boolean operators or with element attributes [7].

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Full Associativity - ME10 features a concept called "Intelligent Data Structures," which form a foundation for providing full associativity by ME10.

Complete Data Management Capabilities - WorkManager, the data management module deeply integrated into ME10, allows users to manage 2D drawings and ME10 parts [7].



Fig. 2.7

Parts Library - Fully integrated with ME10, the Parts Library offers the best and most convenient method for efficient standard parts processing. The use of standard parts in the CAD environment contributes to shorter cycle times from design to production, reductions in part variety and part diversity, greater planning stability and more transparency in commercial applications [7].

Engineering Symbols - Engineering Symbols is the powerful tool integrated into ME10 for the easy creation of ISO and DIN tolerance and welding and surface symbols within mechanical drawings. The Engineering Symbols product allows users to design drawing symbols according to ISO symbols.

Design Advisor

Copilot - ME10's Copilot capability offers intelligent, context-sensitive guidance to aid engineers during the creation of geometry. Key information is displayed on-line to help reduce errors and increase productivity [8]. Displayed information includes: geometry relationships such as parallels and tangents; important geometry elements such as centre points and vertices; and geometry proportions that are being created such as radius or diameter.

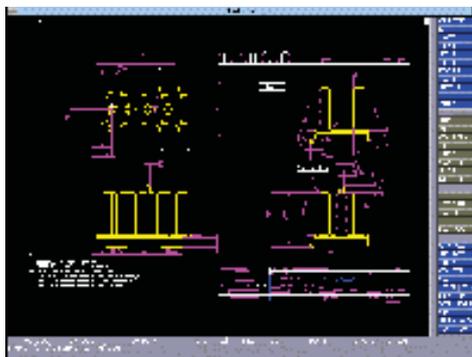


Fig. 2.8

Construction Lines - Construction lines are widely used on drawing boards, and are well known to designers. ME10 leverages this knowledge by providing a comprehensive set of construction commands that emulate a pencil sketch [9]. Construction lines can be composed of any type of linear or circular elements. The creation of complex shapes can be simplified by overdrawing construction lines.

Design Intent Capture - During geometry creation, ME10 generates design rules automatically and, as a result, captures the design intent. This way, sketches evolve into detailed drawings, which can be modified and refined simply by altering dimensions [10].

Dimension Advisor - More Built-in Intelligence

Automatic dimensioning - Groups of dimensions can automatically be created and placed with one keystroke. ME10 recognises potential interference's of dimensions with other objects and automatically creates appropriate islands in the dimension pattern.

Pre-configured dimension styles - ME10 provides pre-set dimension styles for compliance with international drafting standards (ISO, DIN, JIS, ANSI).

Dimension style database - Beyond pre-set standard dimension styles, ME10 makes it easy to define and store user-specific dimension styles that are in compliance with company specifications. A dimension preview window assists during style definition and symbols can conveniently be defined with a font/symbol editor [11].

Feature-based dimensioning - Frequently used geometric features, e.g. screw, can be stored together with dimension patterns. Once stored, ME10 recognises topological matches of design geometry with stored features. Dimension patterns can then be applied with one mouse pick [11].

Advanced Design Technologies

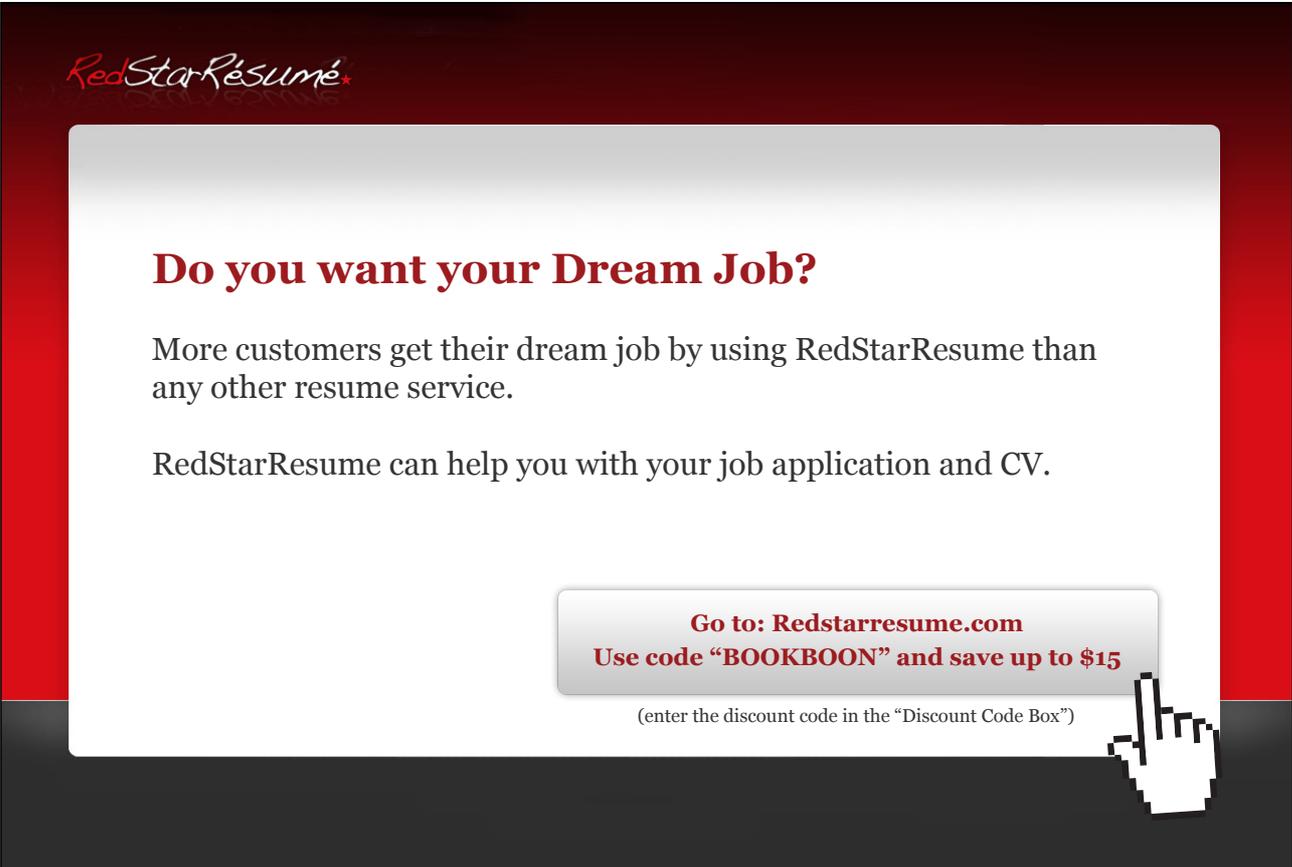
Parametrics - Parametric design capabilities provide a powerful, interactive way to adapt existing drawings and create families of parts. With these capabilities, it's possible to accomplish the most complex design modifications by simply changing the driving dimensions. ME10 allows users to parameterise drawings and specify design rules whenever it makes the most sense in the design process. Users can parameterise all or any part of a design, while ME10 handles under and over constraint designs [12].

Customisation through Macro Language - ME10 features a comprehensive BASIC-oriented macro language which provides a high degree of customisation and ease-of-use. This language also allows structured programming, with on-line editing and debugging aids to meet highly specific and often complex needs [12]. The power of the macro language can be seen in ME10's user interface which is based on this macro language. It is very easy to implement user preferences that allow a look and feel optimised to the needs of every user.

User Interface - ME10's user interface not only distinguishes itself for being easy to use but also fast. A flat structure of menu layers (main- and sub-menus) features self-explanatory commands,

prompts and on-line help. Menus can be easily picked and arranged on-screen. The menu buttons are easy to understand for engineers because the text contains typical terminology for mechanical engineers. This drastically reduces learning time [13].

Growth into Solid Modelling with SolidDesigner - The fact that ME10 and SolidDesigner share the same design concepts guarantees the co-existence of both 2D and 3D design. Take for example the parts structure concept. Every engineer used to working with large assemblies in ME10, and using the corresponding parts editor, can apply the same ideas when working with SolidDesigner. Additionally, SolidDesigner's integrated module - called SolidDesigner Annotation - guarantees an easy to use and fully associative drawing generation which easily integrates into an existing ME10 design environment as both systems support the same drawing format (native MI) [13].



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2.4 Solidworks

2.4.1 Solidworks 2010

SolidWorks is a 3D mechanical CAD (computer-aided design) program that runs on Microsoft Windows and was developed by Dassault Systèmes SolidWorks Corp., a subsidiary of Dassault Systèmes, S. A. (Vélizy, France) [8]. This product reflects the latest achievements in the world of engineering design, exclusively easy to understand and use and available for every machine-building company. These are the first and major characteristics of SolidWorks 2010 - SP4.0. The latest version of the product is the latest achievement in succession, which affirms it as a standard among the three-dimensional design systems operating under Windows [14].

A tool for reflecting engineering ideas

SolidWorks 2010 accelerates the process of reflecting and conveying engineering ideas. It allows alterations of dimensions, relations and geometry of engineering components to be made at any time and allows the user to return and rearrange the history of their creation. All data are 100% editable. All connections between details, assembled units and drawings are constantly current [14].

SolidWorks 2010 allows fast and efficient operation adequately using all typical means of Windows menus like indicating, selecting, copying, holding and shifting objects. It is easy to organize and develop complicated projects using the so-called FeatureManager, which reflects the history of creation of engineering components. The work of the user has been additionally facilitated by Internet access provided by the so-called FeaturePalette, a constantly updated library of standard details and engineering components [15]. The product Solidworks Viewer allows a wide group of engineers and managers to view and supervise the development of the projects.

The latest version of SolidWorks has means built-in to ease transitions between two-dimensional and three-dimensional design, which include an AutoCAD command emulator. This emulator allows AutoCAD users to apply their acquired habits and skills to create drafts and drawings in SolidWorks [15].

Efficiency and ease in creating drawings

Solidworks 2010 offers means for efficient generation of technical documentation at minimum effort. Drawings are generated automatically from three-dimensional models and include all drafting elements – views, cross-sections, dimensions and notes. The drawings generated are completely associated with respective three-dimensional models-details and assembled units, so each change in the drawing is reflected in the model and vice versa. Adopted are the standards ISO, ANSI, DIN, JIS, BS and GOST [15].

The latest version provides simpler detail means especially when making detail views and cross-sections. Various layers could be maintained. The conditions for more complete implementation of company standards and proprietary symbols, texts and formatting frames have greatly been improved [16]. Some capabilities have been added to provide copying views from different sheets, making tabulated drawings as well as adjustment of various gauges for material specifications.

Impressive capabilities for designing assembled units



Fig. 2.9

SolidWorks 2010 allows building of assembled units by means of direct addressing to details already created and creating new details in an existing assembly unit based on the built up geometry. SolidWorks 2010 offers impressive efficiency and convenience when using both methods also known as bottom-to-top and top-to-bottom design [16]. Interconnections – alignment, concentricity, parallelism, distance, tangential have been adopted between the elements of an assembly unit. This makes the assembly unit a kinematical mechanism, which can be moved to test the kinematical links and interrelation of separate mechanism components. SolidWorks 2010 has a built-in Collision Detection, which establishes any available inter-collision between separate parts of the mechanism in real time [16]. When this is activated and the user actuates the mechanism the colliding elements are illuminated in red light and when the respective operation is activated the movement is immediately interrupted.

Independent components in the assembly unit in SolidWorks 2010 could be reorganized, grouped together and rearranged in an exceptionally flexible manner using the well-known FeatureManager. The design of assembly units could be accelerated by means of the so-called SmartMates – an intelligent means or pre-determining the possibilities for linking geometrical elements when moving them [17]. Processing and visualization of large assembly units is considerably facilitated by the possibility for partial loading of participating details and sub-units into the so-called Lightweight mode. An especially important role has been given to the freedom of the user to operate with various alternatives called configurations both for the entire assembly unit and for all its separate sub-units [17].

Improved detail design means

SolidWorks 2010 provides the user with more than what could be expected for a three-dimensional design system. He can easily create with it three-dimensional objects without using the Extrude and Revolve operations, build cavities, make rounds and create bodies and surfaces using the Loft and Sweep operations. A significant improvement is the so-called dynamic editing of geometric objects where a certain body reacts to the alterations in real time from the very process of editing side views over which this body is to be built



Fig. 2.10

[18]. The so-called 3D Sketcher appears in the latest version, which allows users to design three-dimensional curves making simultaneous sketches in several planes. The visualization of objects has also been improved by introducing additional means to control illuminating lights. The means generating uneven surfaces typically used for press and injection moulding equipment have also been improved [18].

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3. Cadcam System Selection, Evaluation & Management

In this chapter a report for a CAD/CAM selection, evaluation and management (implementation) of the system is described. This is a “case study” method of research with focus for an in-depth investigation on the use of CAD/CAM systems. Engineers act as consultants in a small company involved in the introducing CAD-CAM systems.

What does it mean to introduce a CAD-CAM system? It involves complex activities covering all stages; from identifying customer needs giving consideration to its individual capabilities, to the selection stage and instalment of the optimum software meeting customer needs [1].

3.1 Pros & Cons Of Introducing A Cadcam System

The current task has been to consult the introduction of a suitable CAD/CAM system in Pumpco – a manufacturer of pumping equipment for various industrial applications. The main objective of the company is to implement the CAD/CAM system to optimise the design process and provide integration with production. Following discussions with the managerial board and the undertaken study, we were able to identify the factors influencing the selection of a suitable CAD/CAM system for Pumpco:

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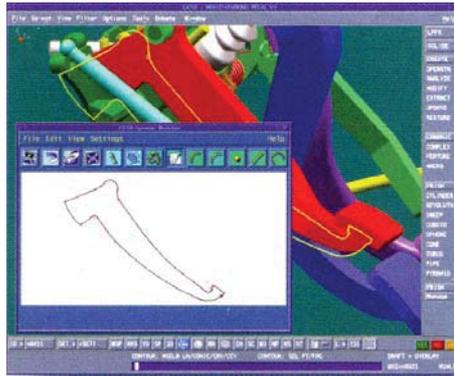


Fig. 3.1

- Pumps are being designed within the company itself. A number of the components are company manufactured as well.
- Most pumps are specifically designed and manufactured to suit particular customer needs.
- Each individual pump is sold with its own assembly drawing and parts list.

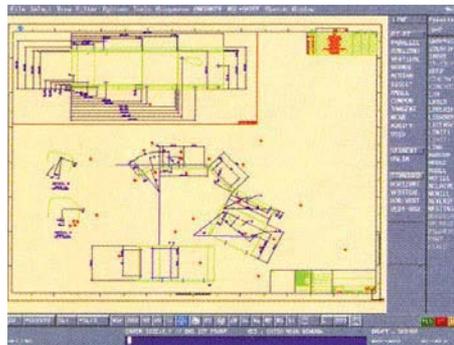


Fig. 3.2

As specialists, we are aware of the benefits of implementing CAD/CAM, nonetheless the hardest part was to convince the Pumpco managerial board, in order to achieve the optimum result. Hence, a presentation was made where we included all arguments in favour of introducing CAD/CAM. Also, and decided to explain possible drawbacks which could cause difficulties.

Firstly, we emphasised the **benefits associated with the 2D drawing process**:

- The average statistics indicates that a draftsman will produce drawings three times **faster** using CAD systems compared to when using a conventional drawing board [1];



Fig. 3.3

- **High drawing accuracy.** Every point in a CAD drawing has its precise position;
- **Perfectly made drawings.** CAD's graphics system and computer printing ensure excellent lines and text;
- **Assembling of drawings.** Every completed drawing or part of a drawing can be computer memorised for further use.

We also emphasised the benefits offered by CAD systems for **3D modelling**:

- **Fast calculations and analysis** ensured by modern computer equipment and software packages;
- **Superior form of design.** Powerful computer modelling techniques, such as finite element analysis, have freed the designer from the shackles of restrictive conventional formulae and allowed more inventive shapes to be developed. These shapes may be quickly modified and optimised for cost savings to an extent which would have previously been too time-consuming.
- **Less development required.** CAD simulation and analysis techniques can drastically cut the time and money spent on prototype testing and development - often the costliest stage in the design process.
- **Integration of design with other disciplines.** The vastly superior communications available under an integrated computer network enables CAD to work far more closely with other engineering departments than was possible under the old type of design organisation.
- Access to CAD technology means that **the marketing personnel can be included in the concurrent engineering process.** When designs are finalised and prototypes developed, marketing can use these to generate illustrations for packaging [1].

Another advantage to be explained was the CAD-CAM interrelation. It needed some clarification: CAD/CAM is an integration of CAD and CAM techniques into one complete process. This means, for example, that a component can be drawn on a VDU screen and the graphics data then transferred via coded electrical signals along a cable link to a manufacturing system, where the component would be automatically produced on a CNC machine.

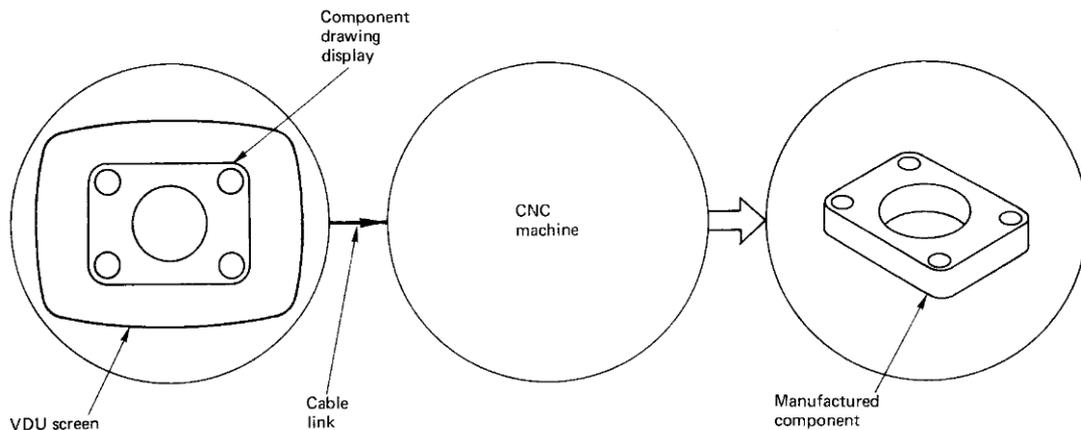
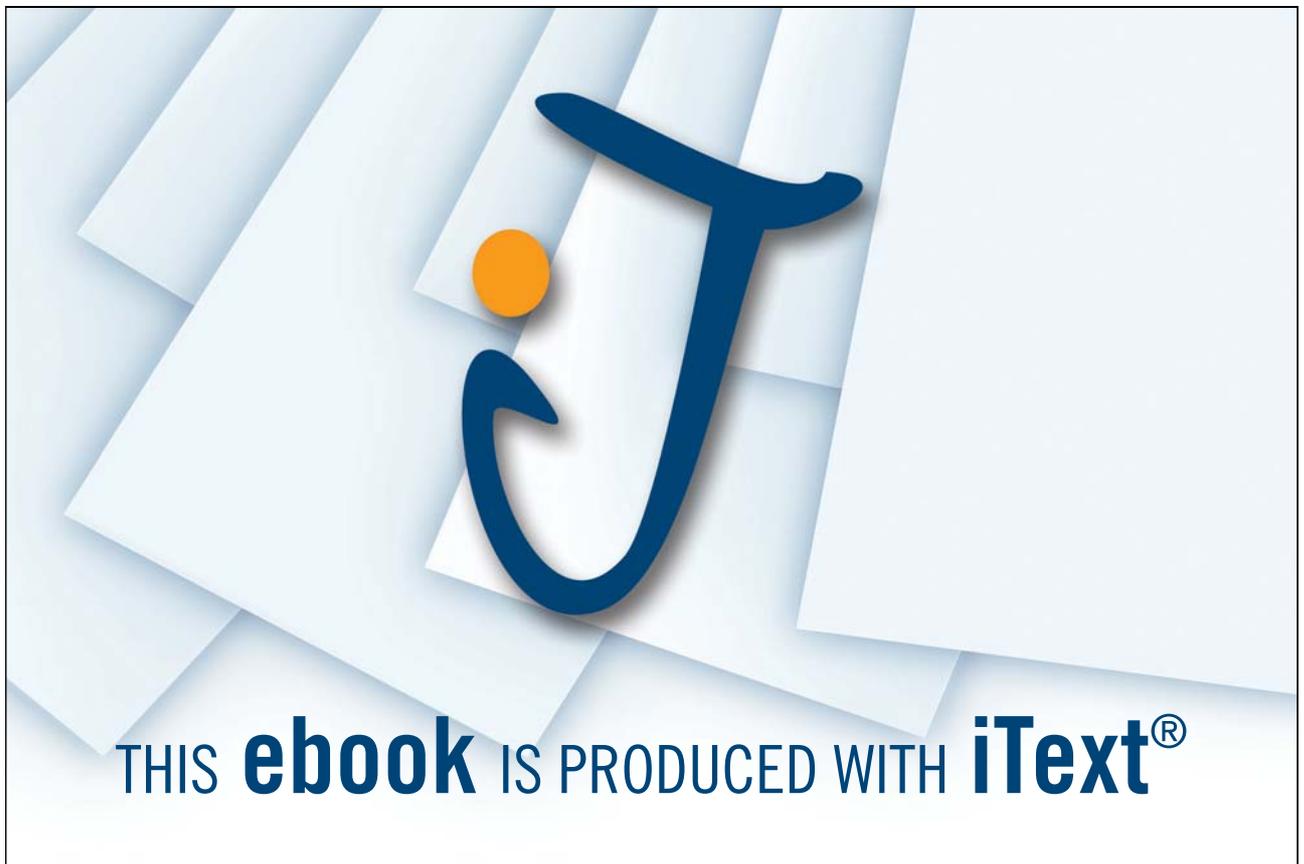


Fig. 3.4.

We emphasised the benefit of expecting results from using CAM in the company considering the fact that the available CNC's could be used for the time being:

- Higher production rates with lower workforces;
- Less likelihood of human error and the consequences of human unreliability;
- Greater versatility of manufactured form;
- Cost savings due to increased manufacturing efficiency (e.g. less material wastage) and increased efficiency of storage and assembly [2];
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Finally, we pointed out the positive **financial aspect** of introducing the CAD/CAM system: Superior Product, Cheaper Product, Shorter Delivery Times, Quicker Sales Quotations, Faster Drawing and Production Rates, Lower Production Costs, Lower Labour Costs, and Lower Development Costs.

We also had to distinguish factors that were likely to cause **certain difficulties**:

- High Purchase Cost of the System.
- Defective information integration policy.
- Effect on manufacturing flexibility. What would happen with the custom-designed products?
- Redundancy. This is obviously the principal fear of any employee involved with the change to new technologies.
- The amount of time required for implementation. Problems may arise because of different level of technology integration, personnel may be unfamiliar with utilisation.
- Effect on labour relations. Passing of Old Skills. Some employees may feel resentment that particular skills in which they may have excelled, such as the ability to produce hand-printing, or turn fine surfaces are irrelevant to CAD/CAM [2].

Introducing a CAD/CAM system is a complex activity that should involve the support of all company managers and specialists. Therefore, we proceeded with selecting the suitable systems.

3.2 Method Of Proceeding

The method for proceeding has been based on the results analysis from the study and the following activities [2] were carried out based on: 1) defining production interests, 2) formulating specific requirements for CAD/CAM suppliers, 3) preliminary comparative market analysis, 4) testing eventual suppliers and 5) follow-up synthesis of possible solutions. To accomplish this line of action, we have had extensive discussions with managers, design engineers and production and marketing specialists in Pumpco. We have identified two basic stages of study and fixed some of their areas of coincidence:

1. **Company study** [3], aimed at identifying both company needs and company capabilities. Having compared these two, the optimum requirements for the supplied software can be identified. The study concentrated on several basic aspects: the technical and production aspect, the time aspect, the staff and qualifications aspect and the financial and economic aspect.
2. **Market study** [4], for a software specialised in the CAD/CAM field.

3.2.1 Pumpco's Production Interests

The main purpose of introducing the CAD/CAM system is to optimise the design process and integrate it with the manufacturing processes [3]. One pre-condition for the successful application of this system is to identify the activities to be involved in these processes and the expected

improvements. Pumpco is a manufacturer of a wide range of pumping equipment used in various industrial applications. Pumps comprise the following components:

- Body parts (body, flanges, turbines)
- Company manufactured component parts using design drawings made in the design engineering department of the company
- Standard company manufactured products
- Standard bought-out components
- Electrical elements

Pumps are usually sold out with company-made assembly drawings and specification sheets. My summarised conclusions for the processes accompanying the production of basic components are as follows:

Component parts: These are manufactured to design drawings prepared in the company's own design department. Some of these parts are sub-contracted with other manufacturing companies. It is also possible to use CNC machines in the company or other manufacturers to make these parts. Only current drawings are used for the manufacturing process [6]. A major objective to the design of these parts is to achieve unification of design characteristics.

Standard parts and components: These are made-out or bought-in parts. Recent standardisation documentation should be available in the company to use as reference when preparing assembly drawings and part drawings. It would be preferable to use a CAD system with a large library set of such standard component parts. This should regularly be updated using the Internet [7].

Electrical parts: Used to provide power supply for pump motors.

Assembly drawings: These are prepared for each individual pump and are usually accompanied by parts list. Possibility should be provided here for final product cost calculations.

3.2.2 Formulation Of Specific Cadcam Requirements

We were able to formulate specific requirements for the CAD/CAM system, within diverse areas:

- Technical and manufacturing requirements:
 - Integrated calculations of machine elements and standard element database.
 - Integration of the design department and the economic department of the company;
 - 3D design capability and automatic production of 2D drawings based on the 3D model, assembling and linkage between all listed above in both directions;
 - Automated exploded views; automated generation of specification lists;
 - Calculations and dimensioning of turbines and turbine components, including for pump design and analysis purposes, calculation of fluid dynamics directly in a CAD/CAM modelling environment;
 - Direct exchange of data and drawings via the Internet;

- Availability of libraries of standard elements; compliance with various international standards - ISO, DIN, ANSI etc.;
 - Possibilities for direct CNC machine operation using the appropriate programming automatically based on the produced 3D model.
 - Guarantee period and follow-up service and maintenance
 - The system must provide for further upgrading and adding new modules.
- Time aspect requirements:
 - Minimum training time and minimum time to achieve maximum efficiency of use of the CAD/CAM system.
 - Time of software going out of date and depreciation time of the hardware configuration.
 - Minimum time for creating engineering drawings based on the 3D model;
 - Staff and qualification requirements:
 - Easy to use software;

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- Initial training provided by the supplier of the CAD/CAM system and follow-up training in the course of actual operation in production conditions;
- Initial training must also include a beginners' computer course to cover a wider range of specialists.
- Financial requirements:
 - Low software cost
 - Comparable prices of the software product and the hardware configuration (which includes computers and peripheral equipment)
 - Possibility to pay in several regular instalments.
 - Minimum installation cost.

3.2.3 Cadcam Market Study

Based on the identified requirements, a preliminary comparative analysis of the capabilities and characteristics of the specialised software has been made. Two of the CAD/CAM systems met Pumpco's needs to a large extent:

- Solid edge v.20
- Autocad inventor professional

Based on personal experience, we have presented a concise analysis of each product in the company's managerial directors:

3.2.3.1 Autocad Inventor Professional

This is a powerful and flexible professional system for 3D modelling based on Auto CAD 2008 platform. Inventor professional is a suitable solution for parametric and surface modelling of solids allowing flexible and intuitive design work in both 2D and 3D environment, also offering possibilities for strength analysis and engineering calculations [8].

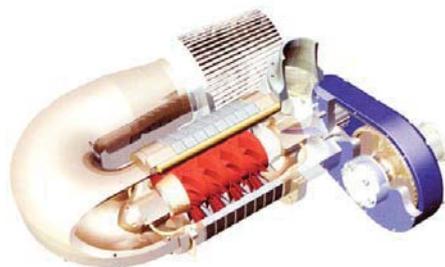


Fig. 3.5

autodesk*

The Power Pack module is completely integrated into the AutoCAD Inventor Professional Suite to ensure even higher productivity offering libraries containing over 1.2 million standard 2D and 3D components, holes, bearings, springs, etc. along with intelligent arrangement and positioning of components and some engineering calculations, i.e. everything that would facilitate engineering design activities in Pumpco.

The software features improved possibilities for solid modelling. Efficiency is greatly increased and designer's ideas are assisted by intelligent tools and commands [9]. AutoCAD Inventor offers fast and convenient means of creating various geometric shapes. Many of these components are subject to subsequent design work by pump production.

Several improvements in AutoCAD Inventor can result in an immediate increase in the efficiency of producing various models and drawings and this is definitely going to raise the interest of Pumpco specialists:

- Flexible creation of assembled models.
- Improved production of engineering drawings.

Integrating AutoCAD Inventor's complete functionality into latest Internet technology will offer Pumpco customers better opportunities of using created designs and convenient information exchange with colleagues. The benefits of the new functions are expressed in several basic directions:



- Online exchange of data and information;
- Updating Autodesk based software;
- Team work using the Real-time design feature: it is possible for other people to watch design work in real time conditions [10].

3.2.3.2 SOLID EDGE V.20 – UNIGRAPHICS SOLUTIONS -SIEMENS

Solid Edge finds wide application in a number of industrial fields and engineering activities [11]. Some typical applications include:

- Design of machine components, spare parts for machines and non-conventional equipment, design of complicated machines and mechanisms involving a large number of components, with integrated 2D/3D solid modelling, modelling of assemblies with kinematical analysis, sheet material, documentation including specification sheets and cost analysis of products;
- Hydraulic and pneumatic equipment, hydraulic motors, cylinders and drive units, compressors, refrigeration units and machines involving hydro-, pneumo-, and electrical installations and connections;

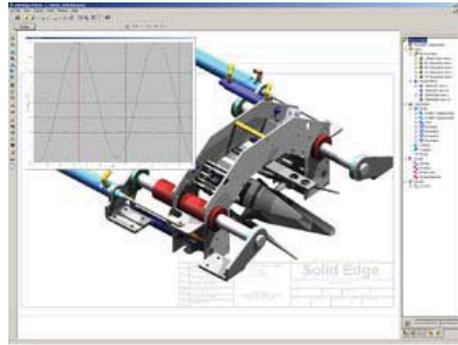


Fig. 3.6

Included in the package are the following options, which will definitely be of interest to the specialist in Pumpco:

- A user interface predicts designers intentions;
- Intelligent sensors track critical dimensions and ratios in assemblies. Rapid modelling of large multiple component assemblies;
- Integrated system for design documentation and data control;
- Integration of design departments and economic departments within the company;
- Integrated calculations of machine elements and a database of standard elements. Direct control of structures using engineering tables;
- Modelling of formatted pipes and pipework. Solutions to hydro-pneumo-driving mechanism tasks in the context of specific assemblies;

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Additionally, SolidEdge offers a wide range of fully integrated applications and 3D libraries of standard elements developed by other CAD software manufacturers. There are over 150 different additional software products, specialised applications and libraries. An example of such an optional product which could be helpful for Pumpco specialists is *CETI software* used for dimensioning turbines and turbo-components, including for design purposes; analyses of pumps, compressors, pneumatic compressors, fans, turbines and expanders [12]. These two systems are among the best in CAD/CAM applications, having unquestionably their drawbacks also.

3.3 Procedure For The Final Selection

As consultants, we prepared and performed a benchmark test to identify the CAD/CAM system that we were going to offer to the management of the company and that would give me the confidence of achieving the desired result.

The requirements placed before the CAD/CAM systems have been considered as of dissimilar significance to the company [13]. There are some of them, which are a particular necessity, and the work quality is dependent on them (fixed requirements) and others, which support and facilitate activities and software usage. In order to analyse how various CAD/CAM systems meet these requirements we will adopt a specific score method of assessment – **benchmark test** (Table 3.1) [14]. Various requirements will be assessed to a maximum score number relevant to their overall significance. This will be accomplished by means of allocating up to 50 scores to highest priority requirements (those, which are most significant to the company), while requirements of lower significance to the company will be assessed to a lower maximum number of scores, 30, 20 and 10. Thus, after finally adding up the scores, the CAD/CAM that does not meet the basic company requirements will be rejected.

The classification of requirements according to their significance is based on considerations and priorities accumulated in the course of the analysis of preliminary study results.

Table 3.1

No	Requirement	Max No. of points	SOLID EDGE v.20	AUTOCAD INVENTOR PROFESSIONAL
1.	Significant time savings in design work	50	48	46
2.	Simple-to-use	50	40	45
3.	3D Modelling	50	47	45
4.	2D CAD	50	40	50
5.	Assembly	50	46	45
6.	2D and 3D feedback connection	50	46	50
7.	Price	50	40	45

8.	System compatibility with the operation system selected by the company	50	50	50
9.	Simplified conventional drafting via built-in intelligence	40	35	33
10.	Available standard element libraries and databases	40	32	35

No	Requirement	Max No. of points	SOLID EDGE v.20	AUTOCAD INVENTOR PROFESSIONAL
11.	Capabilities to operate in networks	40	40	40
12.	System service and maintenance offered	40	40	40
13.	Automatic blending, trimming and filleting of intersecting surfaces	40	38	36
14.	IGES interface for communicating with other CAD systems	40	36	38
15.	Intuitive workflow	30	30	30
16.	Supporting and automated conversion between international drawing standards	30	30	30
17.	3D-CNC Programming from drawings, models or IGES data	30	26	27
18.	Minimum hardware configuration	20	15	18
19.	Realistic product visualisation with dynamic rotation of images	20	18	16
20.	Electric design automation	20	20	20
21.	Calculation of volume and area	20	20	20
22.	Availability of self-tuition programme	10	10	10
23.	Engineering analysis	10	10	10
24.	Virtual elimination of laborious construction geometry	10	9	8
25.	Design calculations and dimensioning of turbines and turbo-components,	10	8	6

including for pump design and analyses purposes

26.	On - line data and information exchange with colleagues	10	9	10
27.	Possibilities to update software	10	10	10
Final score		870	793	813

The applied technique is based on the comparative analysis method. The final score resulting from adding up all scores in the vertical direction determines the capabilities of a CAD/CAM system to meet our particular requirements. The general conclusion from the above comparison between the two software packages is that **SOLID EDGE v.20** has a number of advantages in modelling compared to **AutoCAD Inventor Professional Suite**, which is preferable for preparing AutoCAD based drawings and provides better chances for Internet communications. The CAD/CAM system to get the highest score is **AutoCAD Inventor Professional Suite** and this was our choice for Pumpco.

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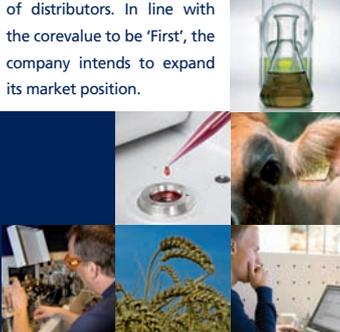
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3.4 Master Implementation Plan

Given the difficulty of managing technological changes, the engineers had to come up with an operation implementation strategy, for the company to start utilising the system in an effective way [15]. Hence, an implementation plan for a successful system operation has been drawn to consider the following:

1. Allocating sufficient resources.

Purchasing of computers and accompanying peripheral devices. Network establishment. Commissioning and Installation of the CAD/CAM system by the supplier [15].

2. Setting up workstations.

Setting up 5 workstations in Pumpco's design department – two for R&D activities and 3 for preparing drawings for customers. One of the computers will be used as a server where the new electronic archival storage of the company will be located and the rest will be used for the workstations [16].

3. Training of the design office. Restructuring of jobs. Worker Displacement.

Beginners' computer training will be provided for all employees and one engineer and three draftsmen will undergo specialised training to use AutoCAD Inventor Professional Suite. Forty percent of the hand drawings will be stored in the course of the specialised training exercise. Trained specialists will then train their associates;

An engineer will be responsible for the R&D unit (and the server) and the other will deal with customers. The two older draftsmen will stay in the office until their retirement is due. Other draftsmen could also stay to work for the company for the time being as the process of moving from hand-drafting to computer processing will have to be smooth and will take some time. All of them will be given opportunity to work on the computer stations observing a specific time schedule [17].

Five months later an analysis of the progress of draftsmen could be made to select those who will continue to work for the design department and the rest will have to be offered alternative jobs.

1. CAD/CAM control over planning of Productional capacity, materials needed, processes and CNC programming.

Preparation of the CNC machines. General equipment inspection; purchase of additional equipment. CAD part programming will be entered and edited directly to the CNC's machine units to produce the first parts. Further practical training will be done on interrelation between CAD/CAM and the CNC's to achieve a computer driven processing [18].

2. CAD/CAM control over production planning, order entry, production economics.

High flexibility of Production Planning: The new flexible technology will be used in the planning of production processes. Many product models will be produced to appeal to markets

that demand product variety. Small batches of many product models will be produced and production processes will be economical to operate under these conditions [19].

Fast delivery of customer orders: With small batch sizes, operations that can be quickly changed to other products, and fast production rates, customer orders will be produced and shipped quickly utilising the order entry module [19].

Changed Production economics: With the introduction of CAD/CAM technology, the majority of costs will be estimated. Fixed, variable and predominant costs will be transferred into the system's DATA BASE module to be regularly checked up during the course of the first two months. Overhead costs in equipment, tooling, maintenance and billing will be accessible to the Company's Purchasing, Design and Accounting offices [20].

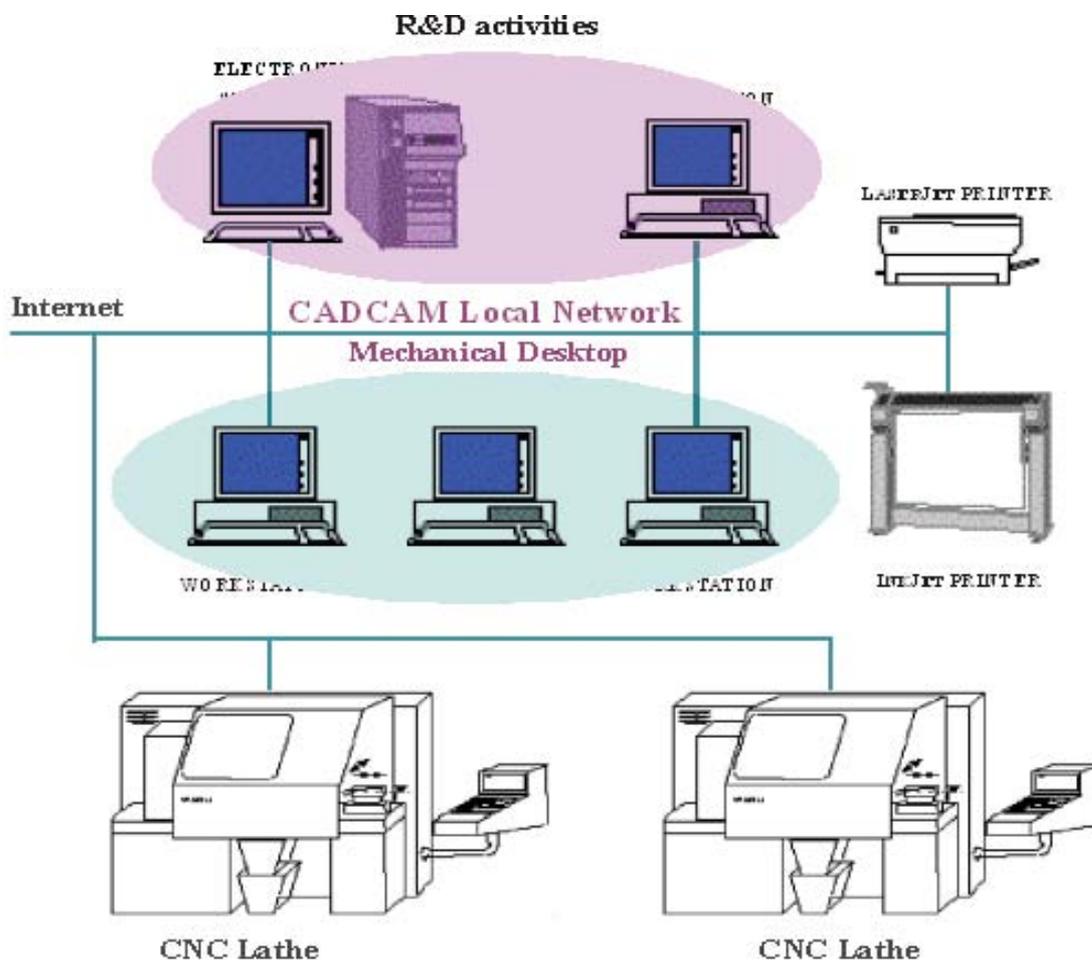


Fig. 3.7

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4. Cam Application Evaluation: A Model Processing Case Study

The chapter presents the processing of a solid model part (mastsktfrg.prt) through the manufacturing module of ProEngineer and the same part exported as an igs file (mastskt.igs) through EZ-CAM, a stand alone CAM application. The following basic tasks have to be accomplished for the purposes of the present development:

- Developing a manufacturing process plan for a fully featured part suitable for CNC manufacture on a three axis machining centre.
- Produce a full set of machining sequences for the manufacture of a part.
- Use CAD/CAM software (both systems - Pro/engineer and EZ-MILL) to simulate the manufacturing of the part and to estimate the machining time.
- Comparing and contrasting two CAM software applications based on own experiences gained from using the software

The following software applications were adopted to carry out the specified task:

- Pro/ENGINEER Firewall
- EZ-CAM, module EZ-MILL

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A solid model part was pre-defined using the available files: - mastsktfrg.prt (Pro/ENGINEER file format) and mastskt.igs (the same model part but exported in an igs format to allow it to be imported and processed in a EZ-MILL). The model part was build up as a solid part using the Part module of Pro/ENGINEER Firewall and using the igs file - mastskt.igs as a basis. The Tooling Catalogue (Sandvik Die & Mould Catalogue) [1] was used in the cutting tool definition part of the task where cutting tool characteristics and cutting conditions were defined.

The following sequence was observed for the methodological proceedings involved in the accomplishment of the task:

- Technological analysis of the design solid model and preliminary definition of required NC Sequences in accordance with the analysis results;
- Definition of appropriate cutting tools and calculating cutting conditions;
- Using Pro/ENGINEER to simulate the manufacturing process of the part on the three axis machining centre;
- Using EZ-MILL to simulate the manufacturing process of the part on the three axis machining centre;
- Discussion relating to usability and available features of each software, including machinability data related to the manufacturing processes;
- Identifying and analysing innovative approaches to optimise the manufacturing Process plan (scheme).

4.1 Technological Analysis Of The Model

The solid model in Fig. 4.1 represents a component part of the following overall size 230mm×150mm×60mm. We assume the part is made of steel of Brinell hardness of HB = 170. It is made up of a bottom parallelepiped shape (1), a top protrusion (2), a cylindrical pocket of OD Ø90mm and 30mm deep (3), a rectangular pocket with edges chamfered to 5mm radii and 20mm deep (4), a set of 4 holes of Ø20mm OD (5), a set of 7 holes of Ø12mm OD (6), pockets shaped to read “JBa” positioned along the sides and 2mm deep (7).

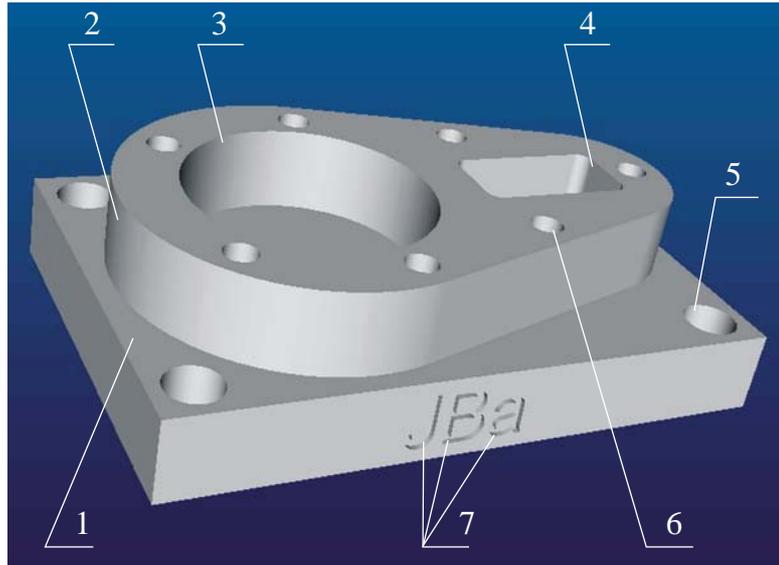


Fig. 4.1

Therefore, if we assume the workpiece to be a block of material with the size of 230mm×150mm×60mm, the following operational sequence will be required and sufficient to produce the design model piece:

- **Milling** the top protrusion (2 - Fig. 4.1). A cutter of $\text{Ø}63\text{mm}$ OD can be used for the purpose, which will allow a single profile to be cut into various depths to remove the excessive material.
- **Milling** the cylindrical pocket (3 - Fig. 4.1). A smaller diameter, 25mm cutting tool is better used here due to high shear forces resulting from larger diameter cutters.
- **Milling** the rectangular pocket (4 - Fig. 4.1). Since its chamfer radii is $R = 5\text{mm}$, the cutting tool to be used shall be a smaller radius milling machine, for example $R = 4\text{mm}$ (or $\text{Ø}8\text{mm}$).
- **Drilling** the set of 4 holes of $\text{Ø}20\text{mm}$ OD (5 - Fig. 4.1).
- **Drilling** the set of 7 holes of $\text{Ø}12\text{mm}$ OD (6 - Fig. 4.1).
- **Milling** the 2mm deep text pockets positioned alongside (7 - Fig. 4.1). The width of the groove in the narrow section of the letter “a” allows for using a cutter of a diameter of no more than 1.2mm. This operation shall be carried out using the same machine but with a different positioning of the part, the Z axis of the machine being perpendicular to plane of the “JBa” writing.

4.2 Specifying The Cutting Tools And Calculating Cutting Data

Based on the operational sequence thus defined using the catalogue provided by Sandvik we can now select the appropriate cutting tools and calculate suitable cutting conditions:

4.2.1 For The First Operational Sequence– Milling Of The Top Protrusion:

Coromill® 390 - A Ø63mm OD cutter

Ordering code: R390-063Q22-11M

Number of teeth: $z = 6$

Operating length of the tool: $l_1 = 40$ mm

max $a_p = 10$ mm

max rpm = 20700

Inserts code: R390-11T308M-PM (from Page 38) wit coromant grade 1025

Recommended feed: $f_z = 0.15$ mm/z for insert geometry PM and coromant grade =1025

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Calculating cutting data

Assuming the processed material is steel of Brinell hardness $HB = 170$, specific cutting force $k_c = 1700\text{N/mm}^2$, basic grades 1025 and $fz = 0,15$ mm/tooth cutting speed:

$$V_c = 295 \text{ m/min}$$

$$\text{Spindle speed: } n = \frac{1000 \times V_c}{\pi \times d} = \frac{1000 \times 295}{3.14 \times 46} = 1494 \text{ rpm}$$

Select a spindle speed: $n = 1400$ rpm

Calculate table feed: $V_f = n \times fz \times z = 1400 \times 0,15 \times 6 = 1260$ mm/min

4.2.2 For The Second Operational Sequence – Milling Of The Cylindrical Pocket:

Coromill® 390 – A Ø25mm OD cutter

Ordering code: R390-025A-11M

Number of teeth: $z = 3$

Operational length of the tool: $l_1 = 40$ mm

max $a_p = 10$ mm

max rpm = 36500

Inserts code: R390-11T308M-PM (from Page 38) wit coromant grade 1025

Recommended feed: $fz = 0.15$ mm/z for insert geometry PM and coromant grade =1025

Calculate cutting data

Assuming the processed material is steel of Brinell hardness $HB = 170$, specific cutting force $k_c = 1700\text{N/mm}^2$, basic grades 1025 and $fz = 0,15$ mm/tooth cutting speed:

$$V_c = 295 \text{ m/min}$$

$$\text{Spindle speed: } n = \frac{1000 \times V_c}{\pi \times d} = \frac{1000 \times 295}{3.14 \times 42} = 3757 \text{ rpm}$$

Select spindle speed: $n = 3700$ rpm

Calculate table feed: $V_f = n \times fz \times z = 3700 \times 0.15 \times 3 = 1665$ mm/min

4.2.3 For The Third Operational Sequence – Milling Of The Rectangular Pocket:

Solid carbide endmill - a Ø8mm OD cutter

Ordering code: R216.22-08030CAC08L

Number of teeth: $z = 2$

Operational length of the tool: $l_3 = 29$ mm

Grade 1010

max $a_p = 8$ mm

Calculate cutting data

For $D_c = 8\text{mm} \Rightarrow$ feed/tooth is: $f_z = 0.06 \div 0.11 \text{ mm/z}$

Select $f_z = 0.06$

Cutting speed is: $V_c = 200 \div 400 \text{ m/min}$

Select $V_c = 200 \text{ m/min}$

Spindle speed: $n = \frac{1000 \times 200}{3.14 \times 8} = 7961 \text{ rpm}$

Select $n = 7000 \text{ rpm}$

Calculate table feed: $V_f = n \times f_z \times z = 0,06 \times 7000 \times 2 = 840 \text{ mm/min}$

Axial step depth selected from page 62: $a_p = 0.8\text{mm}$

Radial step depth (page 62): $a_e = 2\text{mm}$

4.2.4 For The Fourth Operational Sequence – Drilling The Set Of 4 Holes With Diameter 20mm:

Carbide drill - $\varnothing 20\text{mm OD}$

Ordering code: R415.5-2000-30-8C0

Operating length of the tool: $l_6 = 79 \text{ mm}$

Coromant grades 1040

Calculate cutting data

For drilling steel of Brinell hardness $HB = 170$, coromant grades 1040 and drill diameter

$D_c = 20\text{mm} \Rightarrow$ cutting speed V_c and feed f_n are:

$V_c = 60 - 100 \text{ m/min} \Rightarrow$ Select $V_c = 80 \text{ m/min}$

$f_n = 0.18 \div 0.30 \text{ mm/r} \Rightarrow$ Select $f_n = 0.20 \text{ mm/r}$

Spindle speed: $n = \frac{1000 \times 80}{3.14 \times 20} = 1273\text{rpm}$

Select: $n = 1200\text{rpm}$

Feed on Z-axis: $V_f = f_z \times n = 0.12 \times 1200 = 240\text{mm/min}$;

4.2.5 For The Fifth Operational Sequence – Drilling The Set Of 7 Holes With Diameter 12mm:

Carbide drill - $\varnothing 12\text{mm OD}$

Ordering code: R415.5-1200-30-8C0

Operational length of the tool: $l_6 = 55\text{mm}$

Coromant grades 1040

Calculate cutting data

For drilling in steel with Brinell hardness $HB = 170$, coromant grades 1040 and drill diameter $D_c = 20\text{mm} \Rightarrow$ cutting speed V_c and feed f_n are:

$V_c = 60 - 100\text{m/min} \Rightarrow$ Select $V_c = 80\text{m/min}$

$$fn = 0.15 \div 0.25\text{mm/r} \Rightarrow \text{Select } fn = 0.20\text{mm/r}$$

$$\text{Spindle speed: } n = \frac{1000 \times 80}{3.14 \times 12} = 2123 \text{ rpm}$$

$$\text{Select: } n = 2100\text{rpm}$$

$$\text{Feed on Z-axis: } V_f = f_z \times n = 0.20 \times 2100 = 420\text{mm/min};$$

4.2.6 For The Sixth Operational Sequence – Milling The Text Pocket “Jba”:

Since the minimum size of cutting tools specified in the Sandvik catalogue is 2mm, we select the required tool, a carbide endmill with diameter $\varnothing 1.2\text{mm}$, specified in the catalogue of Mitsubishi Carbide [12].

Ordering code: EM-0012C227354

Number of teeth: $z = 2$

Operational length of the tool: $l_1 = 7 \text{ mm}$

max $a_p = 0.3\text{mm}$

Recommended feed: $f_z = 0.03 \text{ mm/z}$

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Calculate cutting data

For a steel processing material of Brinell hardness $HB = 170$ and $fz = 0,03$ mm/tooth cutting speed:

$$V_c = 35 \text{ m/min}$$

$$\text{Spindle speed: } n = \frac{1000 \times 35}{3.14 \times 1.2} = 9288 \text{ rpm, select } n = 9000 \text{ rpm}$$

Select spindle speed: $n = 9000$ rpm

Calculate table feed: $V_f = n \times fz \times z = 0.03 \times 9000 \times 2 = 540$ mm/min.

4.3 Pro/Engineer Part Manufacture Simulation

As soon as Pro/ENGINEER is started, it is recommended that **Set Working Directory** is selected from the **FILE** drop down menu and the directory is indicated where the current session of the program is going to save its working files. The mastsktfrg.prt. file is also saved in this directory.

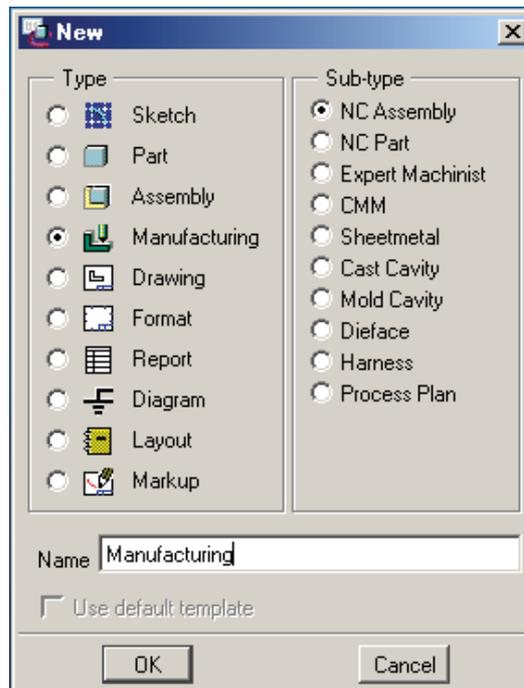


Fig. 4.2

4.3.1 Creating A New File

To create a new file for the machining data select **File** and from the drop down menu select **New**. In the new window that appears click on **Manufacturing** and **NC Assembly** (Fig. 4.2) specifying a *Name* for the newly created **file** in the appropriate field, in our case, *Manufacturing*. Click **OK** to close the New window and open the main window of the Manufacturing module. Now **Menu Manager** is currently displayed in the upper right corner of the screen.

Manufacturing.asm is an assembly file (the Assembly of the Ref.Model and Workpiece), and in order for it to be complete, both its constituent components have to be defined:

- Ref Model.prt (Design Model) = The model to be machined –the *mastsktfrg.prt* file in our case.
- Workpiece (Stock) = A model representing the material from which the Ref Model will be machined.

The blank file thus created is ready to store all the manufacturing information and the first data to be inserted into the file is the model to be machined. This is accomplished by the Command from **Menu Manager**

Mfg Model ⇒

Assemble ⇒

Ref Model The Open menu opens here allowing us to specify *mastsktfrg.prt* from the contents of the set directory and accept this selection.

Done/Return

The model is displayed as in Figure 4.3.

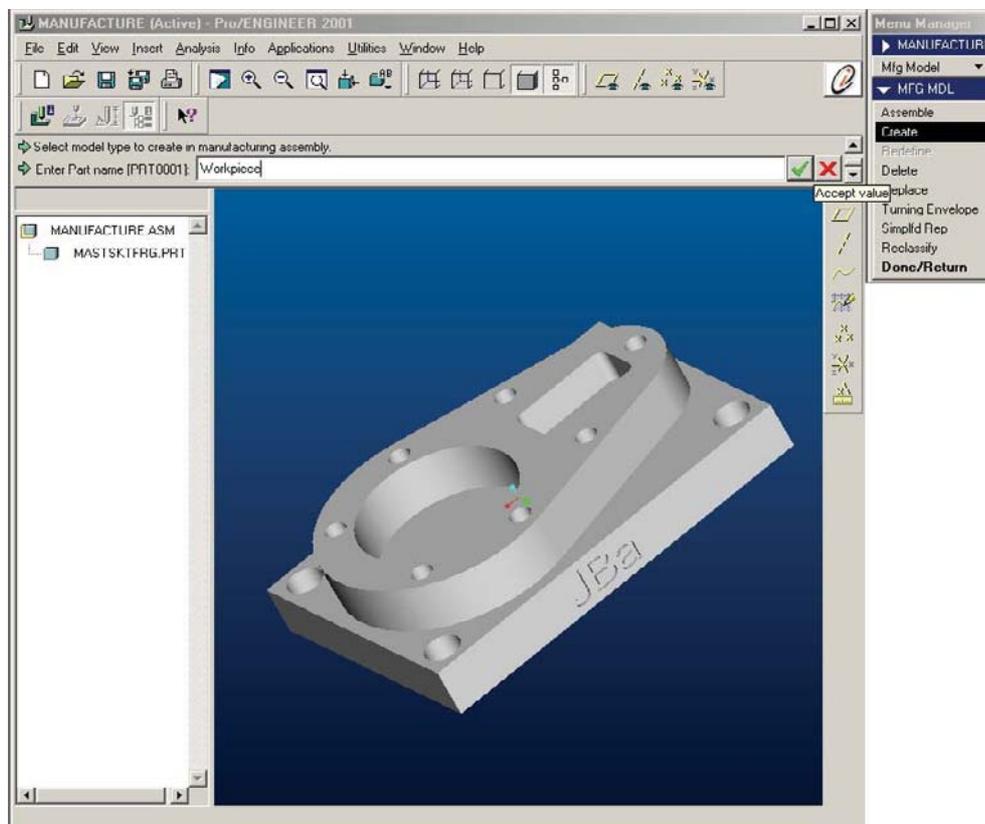


Fig. 4.3

The second piece of data to be inserted into the assembly file is the **Workpiece**.
From the **Menu Manager** select:

Mfg Model ⇒
Create ⇒
Workpiece



Enter the name of the **Workpiece** file in the field - *Workpiece* (Figure 4.3) and accept entered data.

Solid ⇒
Protrusion ⇒
Extrude ⇒
Solid ⇒
Done ⇒
Oneside

Done Then use the cursor to click on the underside of the model and use **Flip** to change the direction of the arrow to point up. Select **Okay**, and **Top** – now appear the top flat planes of the design model and Pro/ENGINEER automatically goes in sketch operation mode (Fig. 4.4)

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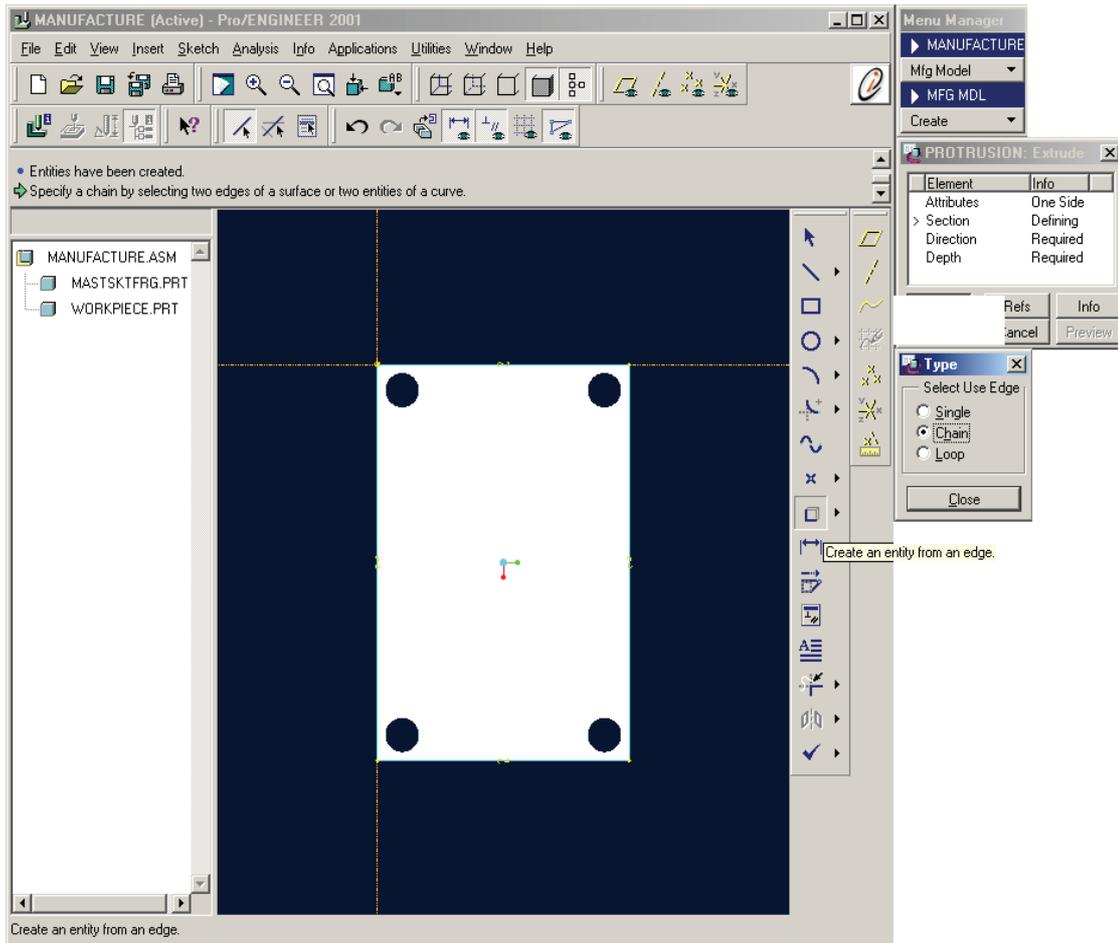


Fig. 4.4

From the Sketcher Toolbar on the left press the “**Create an entity from an edge**” button and select all the outer edges of the base protrusion (rectangle). Confirm using the bottom-most button on the Sketcher Toolbar - “**Continue with the current section**” and Pro/ENGINEER automatically exits sketch mode. When the profile is selected, define the extruded depth specifying it from the Menu Manager:

Blind and confirm by selecting
Done

In the prompt bar that appears, enter the value for depth 60mm using the keyboard and confirm using the “**Accept value**” button.

OK then
Done/Return.

The external profile/surfaces of the workpiece is then displayed in green (Figure 4.5) .

Thus, these two components have been inserted into the assembly file machine_ex1.asm. Now we can start with the machining process.

4.3.2 Defining A Co-Ordinate System For The Machine Tool

For sequences 1 thru 5 we will need a co-ordinate system the zero point of which will be used to set the zero position of the machine and the Z axis is coincident with the tool axis. To do this select **Datum** and then **Co-ordinate System** from the drop down menu **Insert**. Then, select from the **Menu Manager**:

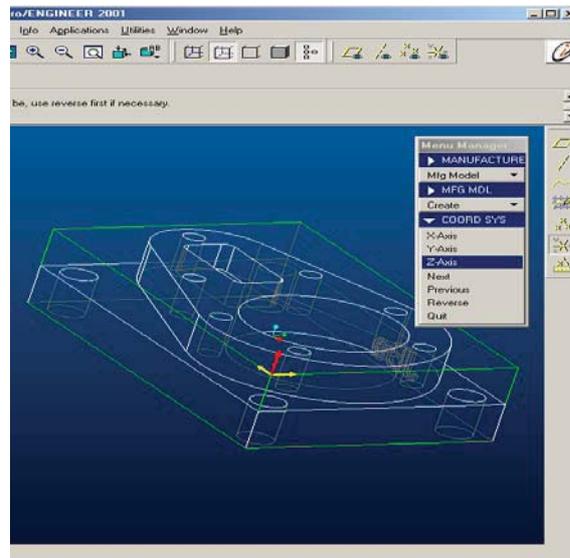


Fig. 4.5

3 Planes

Done and select 3 planes the crossing point of which will give the starting point of the new Co-ordinate System (Figure 4.6). The sub-menu commands – **X-axis**, **Y-axis**, **Z-axis**, **Next**, **Previous**, **Reverse** are used to set the required directions of axes and the new co-ordinate system is identified as ACS0.

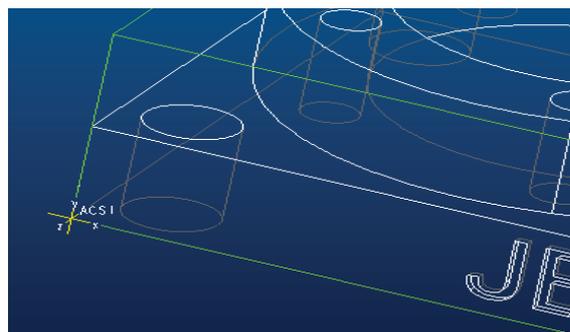


Fig. 4.6

As we mentioned earlier, a different co-ordinate system must be used for the workpiece in the last operational sequence 6. Therefore, another co-ordinate system – ACS1 is introduced as described above (Figure 4.7).

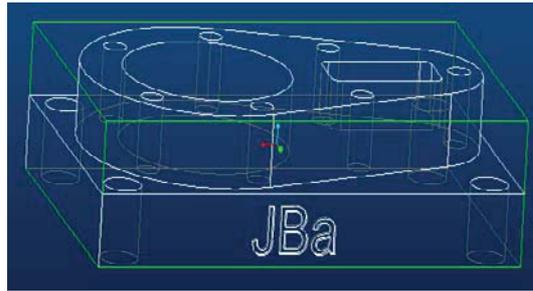


Fig. 4.7

4.3.3 Operation Setup

Before the machining sequences can be generated the type of machine and machine setup have to be defined for the sequence. All machining is done on a single 3-axis milling machine. However, the first 5 sequences are machined using the ACS0 co-ordinate system, and the last sequence – using the ACS1 co-ordinate system. Actually, the machining of the workpiece is performed on a single milling machine but using two different workpiece jigs. The machining operation is defined by a series of commands from the **Menu Manager**:

MACHINING ⇒ **OPERATION** and the fields in the **Operation Setup** window are then filled-in (Figure 4.8) as follows:

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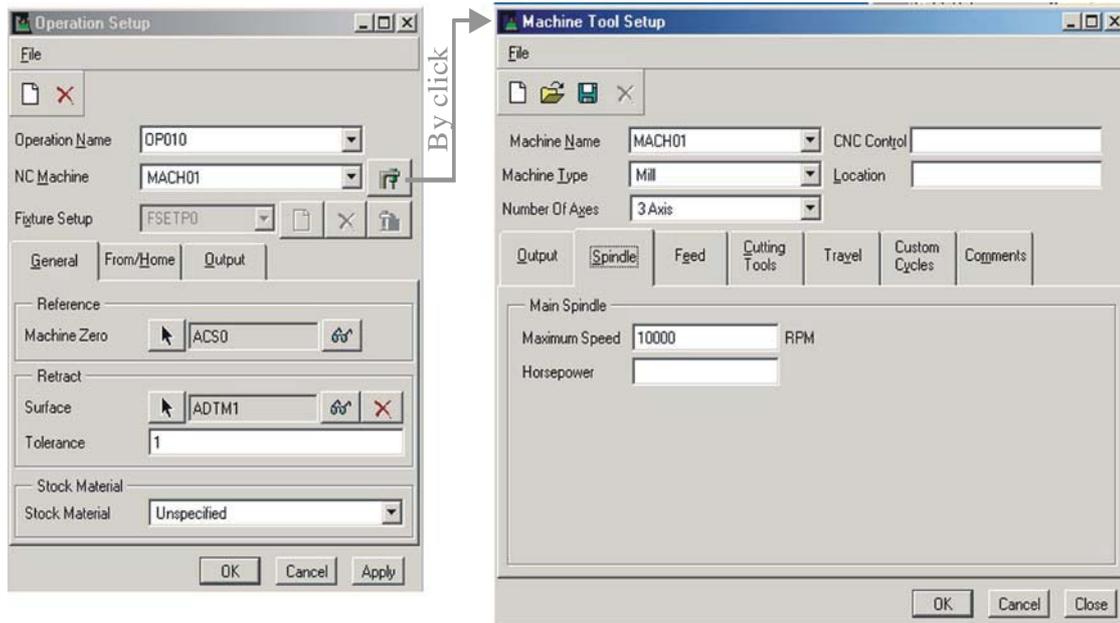


Fig. 4.8

Operation Name: OP010

NC Machine: click on the icon on the right to open the **Machine Tool Setup** window, which is in turn filled-in (Figure 4.8):

Machine Name: MACH01

Machine Type: Mill

Number of Axis: 3Axis

Spindle ⇒ Main Spindle ⇒ Maximum Speed: 10000 rpm

Cutting Tools ⇒ Tool Change Time = 5 sec

OK and once the **Machine Tool Setup** window is closed, MACH01 automatically sets in the **NC Machine** field.

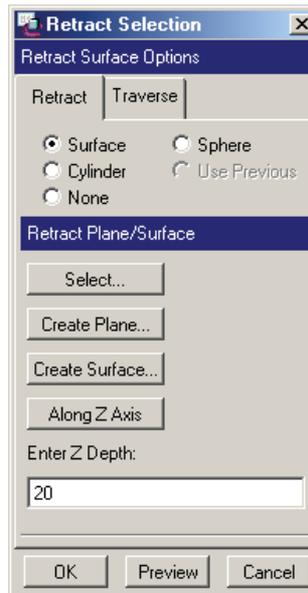


Fig. 4.9

To set the **Machine Zero**, click on the arrow and then click on the name of the co-ordinate system ACS0 in the drawing and it is automatically entered in the dialogue box opposite to the **Machine Zero**.

- **Retract** is used to define a plane a set distance away, which the machine tool will start from and retreat to. The Z-axis has been defined to point vertically away from the top of the Workpiece. This axis can be selected to specify the retract plane. To specify the **Retract Surface**, click on the arrow and in the **Retract Selection** menu that appears indicate as follows:
 - **Along Z Axis** ⇒ and enter a value of 20mm. Then **OK** for **Retract Selection** and
 - **OK** for **Operation Setup**
 - **Done/Return**

4.3.4 Creating The Machining Sequences

4.3.4.1 Milling

NC Sequence is title given to the elements that make up one cut. These elements include the type of tool, the surfaces or features to be machined, the speed (rpm) and feed rate at which the tool is to operate, and the cutter path.

The first cut is a profile cut to machine the top external surface of the model (surface 2 from Figure 4.10). From the Menu Manager select:

Machining ⇒

NC Sequence ⇒

Machining ⇒

Profile ⇒

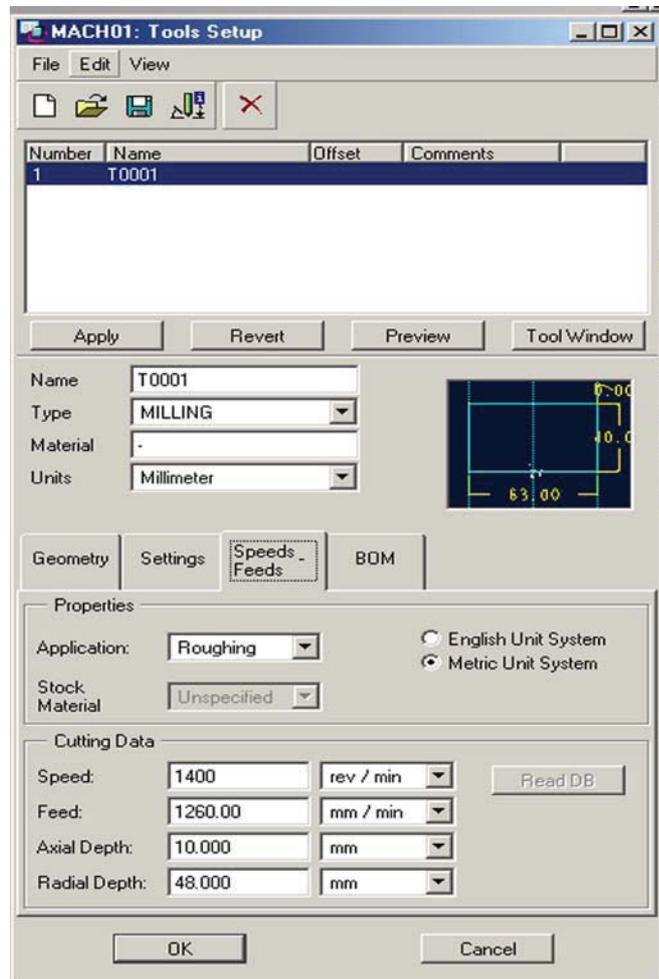


Fig. 4.10

From the SEQ SETUP dialogue box below the following terms must be ticked (see Figure 4.10): Name, Comments, Tool, Parameters, Surfaces. Co-ordinate system and Retract have already been specified in the **Operation Setup** above.

Done

A series of questions appear to help define the above terms and generate the NC Sequence:

Name: *MILLING*

Accept

Comments: *Milling the upper profile of the model*

OK

Tools Setup dialogue box (Figure 4.11) is filled in as follows:



Fig. 4.11

Name: T0001
Type: MILLING
Cutter Diameter: 63
Length: 40

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Number of Teeth: 6

From **Settings** ⇒ **Tool Number:** 1

From **Speeds-Feeds** ⇒:

Speed: 1400 rev/min

Feed: 1260 mm/min

Axial Depth: 10 mm

Radial Depth: 48 mm

Having filled-in all the values, the tool can be added to the list of tools using the **Apply** button.

Values are taken from preliminary calculations as made in para 2 above.

Axial Depth is the maximum step of the tool along the Z-axis. For Radial Depth it is theoretically recommended to be kept at 0.8 of the tool diameter as a maximum.

OK – confirm and close the **Tools Setup** dialogue box with all settings entered so far.

Then proceed with the settings for cutting conditions using the commands of the **Menu Manager**:

MFG Parameters ⇒

Set (Figure 4.12)

CUT_FEED: 1260

STEP_DEPTH: 8

SPINDLE_SPEED: 1400

COOLANT_OPTION: ON

CLEAR_DIST: 3

Done from **Menu Manager** confirms inserted cutting data and closes the **Param Tree** Menu.

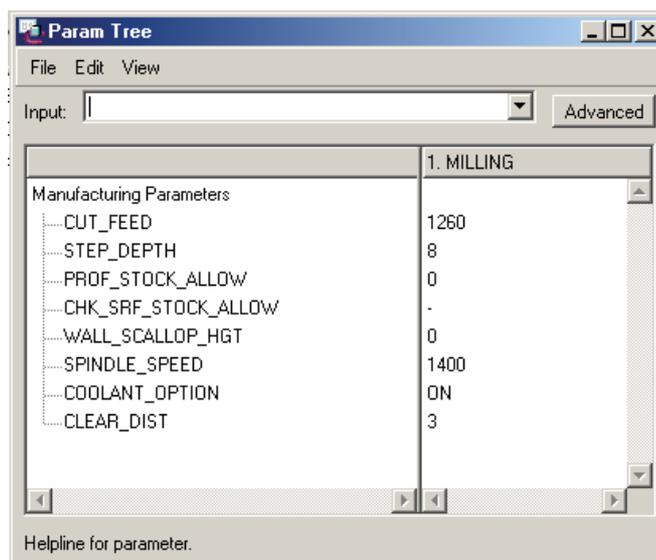


Fig. 4.12

Now comes the definition of machined surfaces and Pro/ENGINEER automatically shows the **SURF PICK** from the **Menu Manager**:

Model

Done

Query Sel and then select one by one the external surfaces of the top protrusion (Figure 4.13)

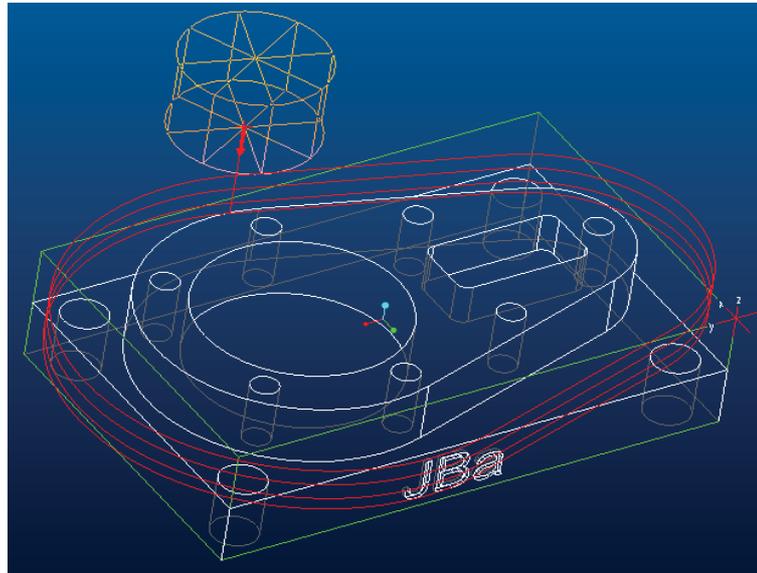


Fig. 4.13

Done Sel ⇒

Done ⇒

Done Return

To view the cutter path/NC sequence:

Play Path ⇒

Screen Play ⇒

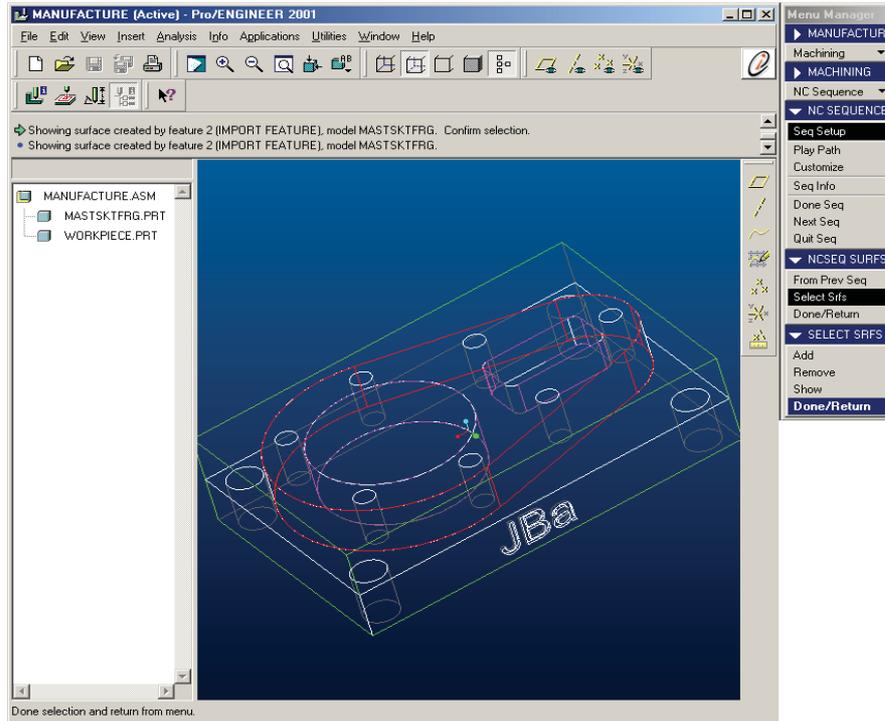


Fig. 4.14

Done. The computer is generating here the machine simulation. Screen play depicts the track of the cutter axis, and playback speed is adjustable. Here we can see the generated cutter path, points of penetration and withdrawal of the tool and directions of movement.

Destination MMU



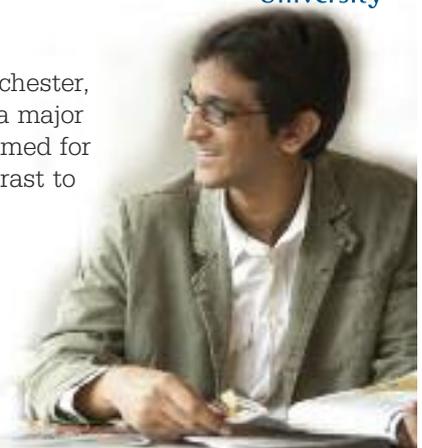
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To view the simulation in colour we can also perform a NC check (to do this it has to be enabled – and all required libraries are made available) and it needs to be set for each session.

NC Check ⇒

Display and the computer generates the simulation

Run to view.

The estimated time for the NC Sequence Milling and any other information can be taken from the report generated with the command

Seq Info ⇒

NC Sequence ⇒

Done Sel

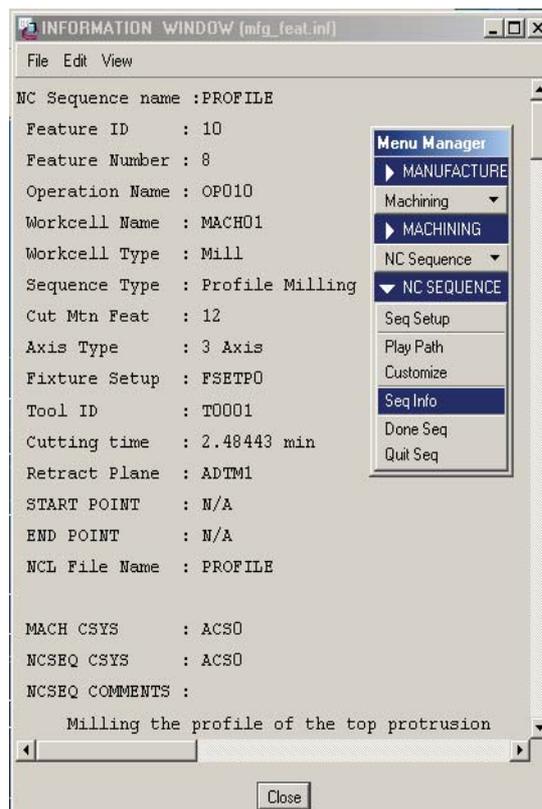


Fig. 4.15

It can be seen from this report that the cutting time for NC Sequence *Milling* is: $t = 2.48443$ min (Figure 4.15).

Pro/ENGINEER saves these reports in the Current Working Directory.

The command **Done Seq** finalises the current sequence setup and allows to continue with the next sequence.

4.3.4.2 Milling The Cylindrical Pocket

Now a NC Sequence can be created to machine the cylindrical pocket in the design model. We must clarify here that Pro/ENGINEER provides for setting up a direct NC Sequence of a Pocketing type, but this only relates to Pockets already existing into the workpiece, which only require some additional machining.

In other words, in the Pocketing operation sequence, the tool is first machining the side surfaces performing several transitions and only finally machines the bottom of the workpiece but when the material in the middle of the machined workpiece is too dense, the tool will not have sufficient side cutting edge to remove this material (as seen from Figure 4.16). Therefore, it is far better here to use the volume-type NC Sequence since the cutter path there corresponds to the cutter path in the Pocketing NC Sequence in EZ-MILL. This will also facilitate the subsequent comparative analysis between the two applications.

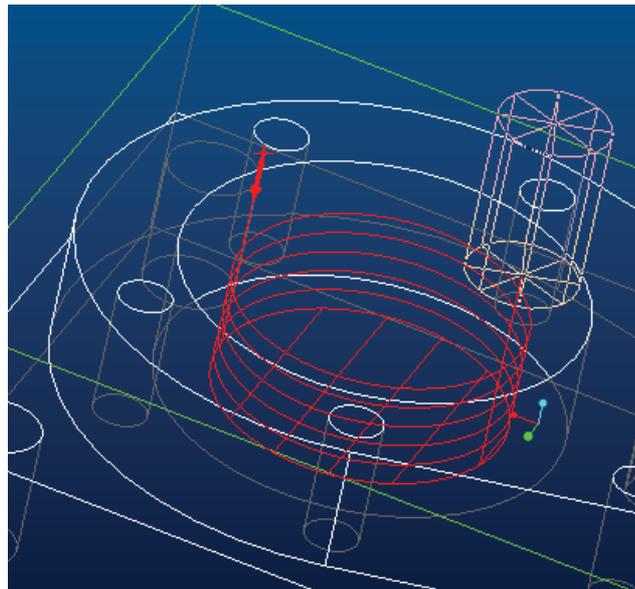


Fig. 4.16

Machining ⇒
NC Sequence ⇒
New Sequence ⇒
Machining ⇒
Volume ⇒
Done

From Sequence Setup highlight and fill in the following fields:

Name: *VOLUME1*

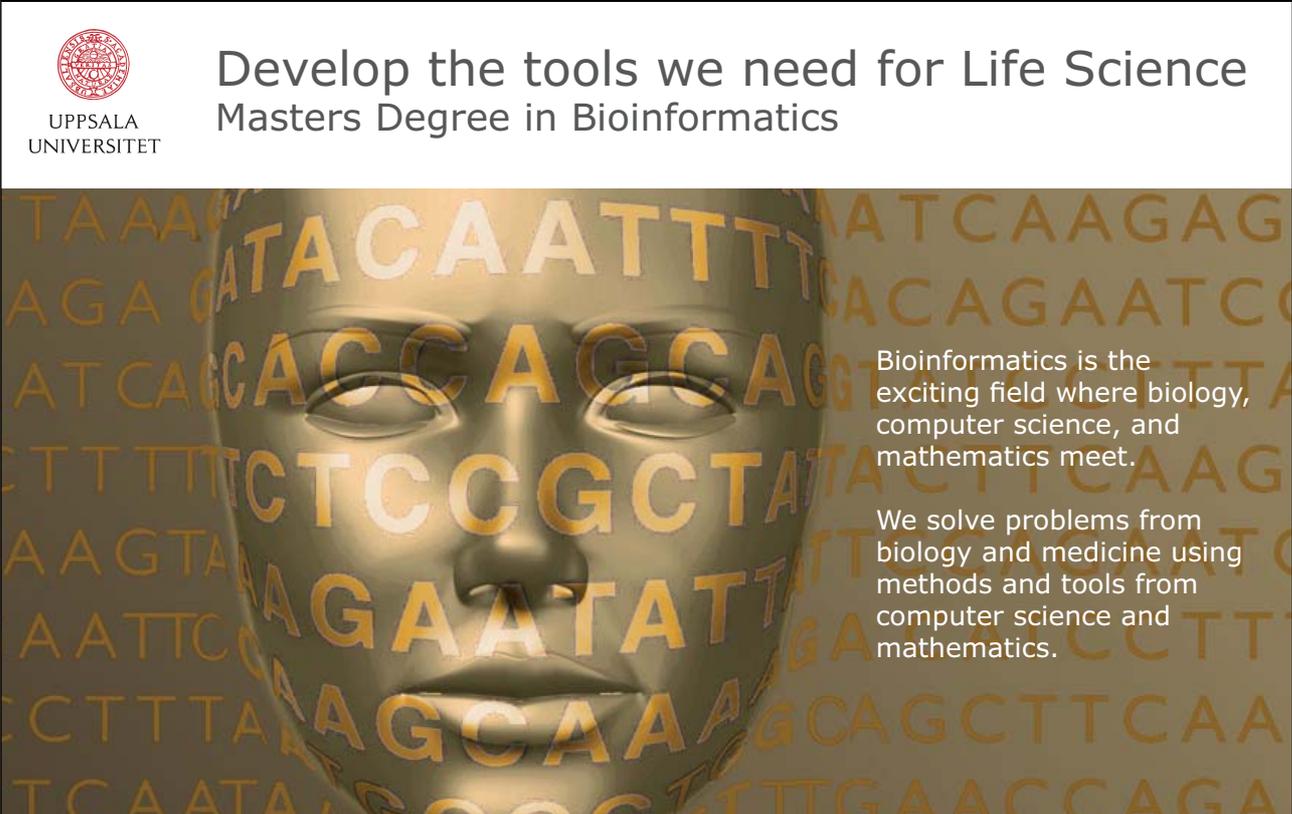
Accept**Comments:** *Milling the top cylindrical pocket***OK****Tools Setup** dialogue box is filled in as follows:**Name:** T0002**Type:** MILLING**Cutter Diameter:** 25**Length:** 40**Number of Teeth:** 3From **Settings** ⇒ **Tool Number:** 2From **Speeds-Feeds** ⇒:**Speed:** 3700 rev/min**Feed:** 1665 mm/min**Axial Depth:** 10 mm**Radial Depth:** 20 mm

Having filled in all the settings, add the new tool to the list of tools using the **Apply** button.

Values are taken from preliminary calculations made in para 2 above.

The Radial Depth in the Volume NC Sequence is inherently limited by the Pro/ENGINEER application to a maximum of 0.5 of the diameter of the tool.

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OK – confirm and close the **Tools Setup** dialogue box with all the settings thus entered.

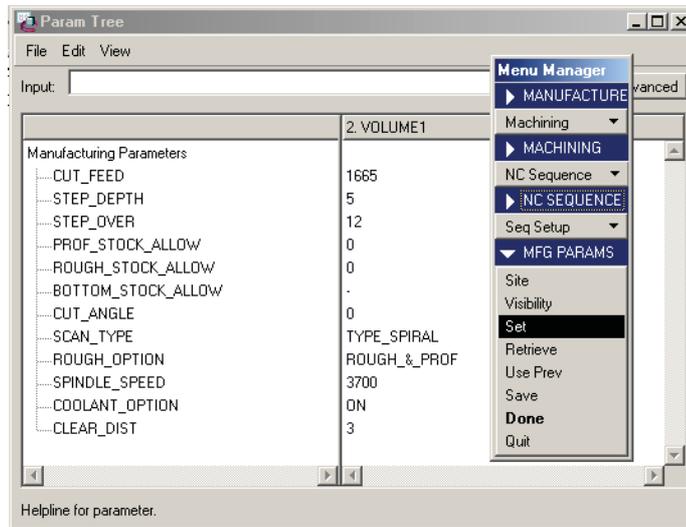


Fig. 4.17

The cutting conditions settings are then entered using the **Menu Manager** commands:

MFG Parameters ⇒

Set (Figure 4.17)

CUT_FEED: 1665

STEP_DEPTH: 5

STEP_OVER: 12

SCAN_TYPE: TYPE_SPIRAL

ROUGH_OPTION: ROUGH_&_PROF

SPINDLE_SPEED: 3700

COOLANT_OPTION: ON

CLEAR_DIST: 3

Done

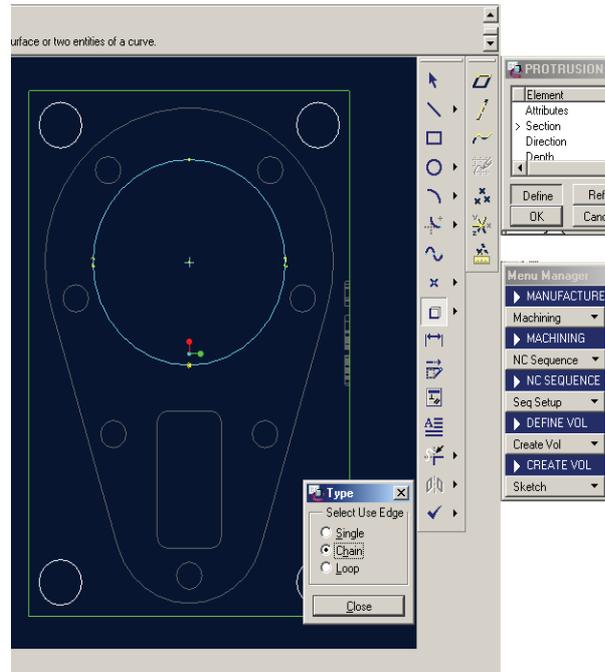


Fig. 4.18

DEFINE VOL ⇒

Create Vol ⇒ specify volume name: Volume1 and press Accept.

Sketch ⇒

Extrude ⇒

Solid ⇒

Done

One Side ⇒

Done

Query Select ⇒

Flip ⇒

Okay

From here we can highlight the circumference of the bottom of the cylindrical pocket in the sketch mode, confirm it, select

Blind ⇒

Done and specify the value of 30mm, which is the limit for the height of the volume thus created (i.e. a volume is being created to correspond to the cylindrical shape of the pocket being machined).

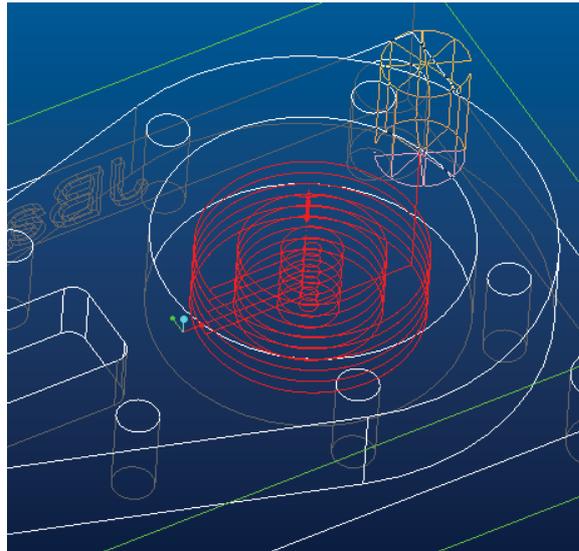


Fig. 4.19

OK

Done/Return

To view the cutter path/NC sequence:

Play Path ⇒

Screen Play ⇒

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Done. The computer now generates the machine simulation and the cutter path (Figure 4.19).

Seq Info ⇒

NC Sequence ⇒

Done Sel

Cutting time for NC Sequence *Volume1* is: $t = 2.44602$ min.

Done Seq finalises the current sequence setup.

4.3.4.3 Milling The Rectangular Pocket

This sequence setup is performed in a similar way to the previous sequence using the Volume type NC Sequence. The steps here are the same:

Machining⇒

NC Sequence ⇒

New Sequence ⇒

Machining ⇒

Volume ⇒

Done

From Sequence Setup, highlight and fill in the fields as follows:

Name: *VOLUME2*

Accept

Comments: Milling the top rectangular pocket

OK

Tools Setup dialogue box is filled in as follows:

Name: T0003

Type: MILLING

Cutter Diameter: 8

Length: 29

Number of Teeth: 2

From **Settings** ⇒ **Tool Number:** 3

From **Speeds-Feeds** ⇒:

Speed: 7000 rev/min

Feed: 840 mm/min

Axial Depth: 0.8 mm

Radial Depth: 2 mm

Once the settings are entered the new tool is added to the list of tools using the **Apply** button.

OK – confirms the settings thus entered and closes the **Tools Setup** dialogue box.

Setting up the cutting conditions using the **Menu Manager** commands:

MFG Parameters ⇒

Set

CUT_FEED: 840
STEP_DEPTH: 0.8
STEP_OVER: 2
SCAN_TYPE: TYPE_SPIRAL
ROUGH_OPTION: ROUGH_&_PROF
SPINDLE_SPEED: 7000
COOLANT_OPTION: ON
CLEAR_DIST: 3
Done

Then we apply the above procedure to create the volume required for drilling Volume2, the height of the created volume set at 20mm.

OK
Done/Return

To view the tool path/NC sequence (Figure 4.20):

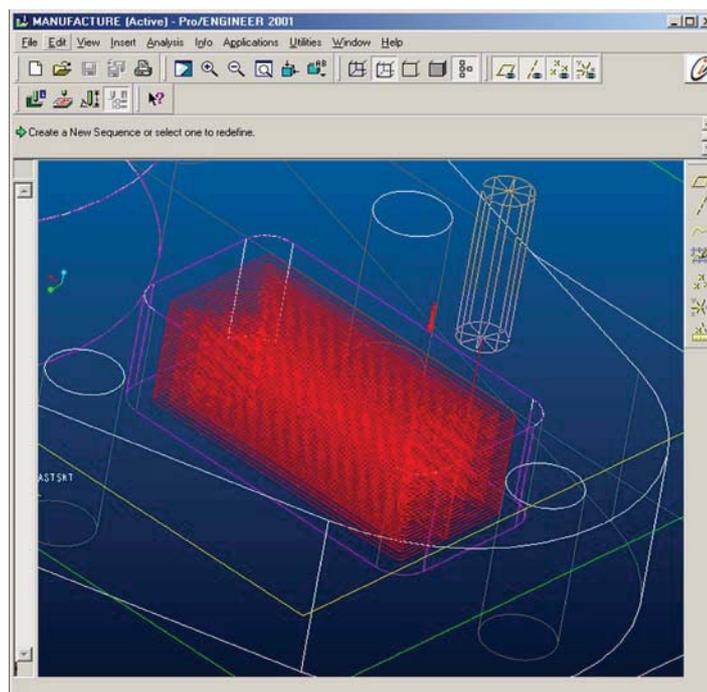


Fig. 4.20

Play Path ⇒
Screen Play ⇒
Done.

Cutting time for NC Sequence *Volume2* is: $t = 24.2657$ min.
Done Seq finalises the setup for the current sequence.

4.3.4.4 Drilling The Holes With Diameter 20mm

Before we create this operational sequence we specify the axes of model openings. This is performed from the **Insert** drop down menu (Figure 4.21) selecting:

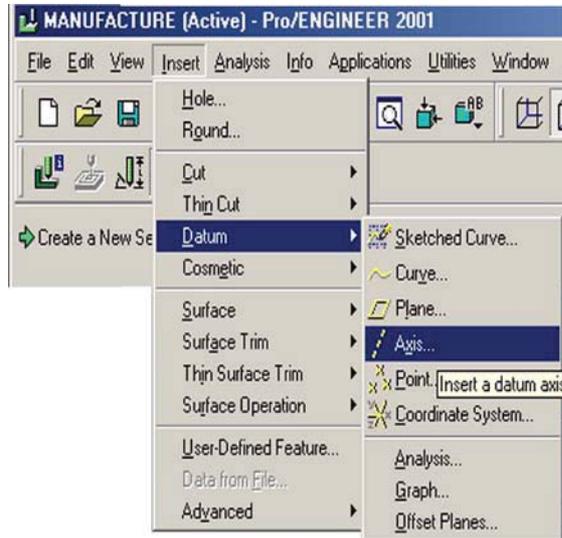


Fig. 4.21

Datum⇒

Axis ⇒

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Then from the **Menu Manager**:

Thry Cyl

Query Sel

Consecutively tick and confirm the cylindrical surfaces of holes, which also provides visualisation of their axes. We can then proceed with Drilling1 NC Sequence:

Machining⇒

NC Sequence ⇒

New Sequence ⇒

Machining ⇒

Holemaking ⇒

Done ⇒

Drill ⇒

Standard ⇒

Done. From the SEQ SETUP dialogue box below tick the following terms: Name, Comments, Tool, Parameters, Holes.

Done

Consecutively define the above terms to generate the NC Sequence:

Name: *Drilling20*

Accept

Comments: *Drilling the 4 holes with diameter 20mm*

OK

Tools Setup dialogue box is filled in as follows:

Name: T0004

Type: DRILLING

Cutter Diameter: 20

Length: 79

From **Settings** ⇒ **Tool Number:** 4

From **Speeds-Feeds** ⇒:

Speed: 1200 rev/min

Feed: 350 mm/min

Axial Depth: 60 mm

The new tool is added to the list of tools using the **Apply** button.

The cutting conditions are then specified using the **Menu Manager** commands:

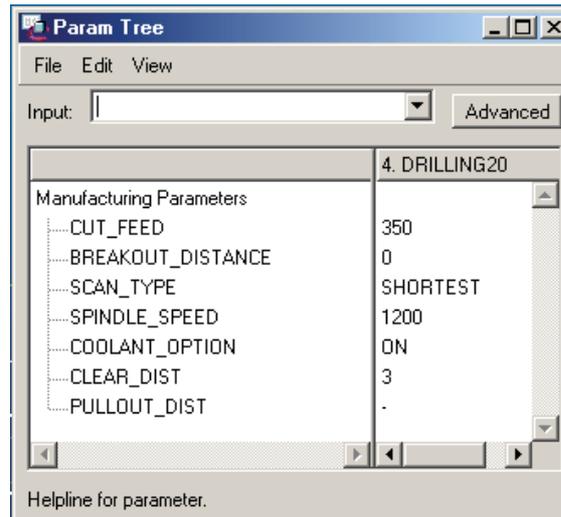


Fig. 4.22

MFG Parameters ⇒

Set (Figure 4.22)

CUT_FEED: 350

SCAN_TYPE: SHORTEST

SPINDLE_SPEED: 1200

COOLANT_OPTION: ON

CLEAR_DIST: 3

Done from **Menu Manager** confirms the inserted cutting data and closes the **Param Tree** Menu.

Now comes the time to define the holes to be drilled. By looking at the dialogue box there are a number of ways of defining the position of the holes in the design model to be machined.

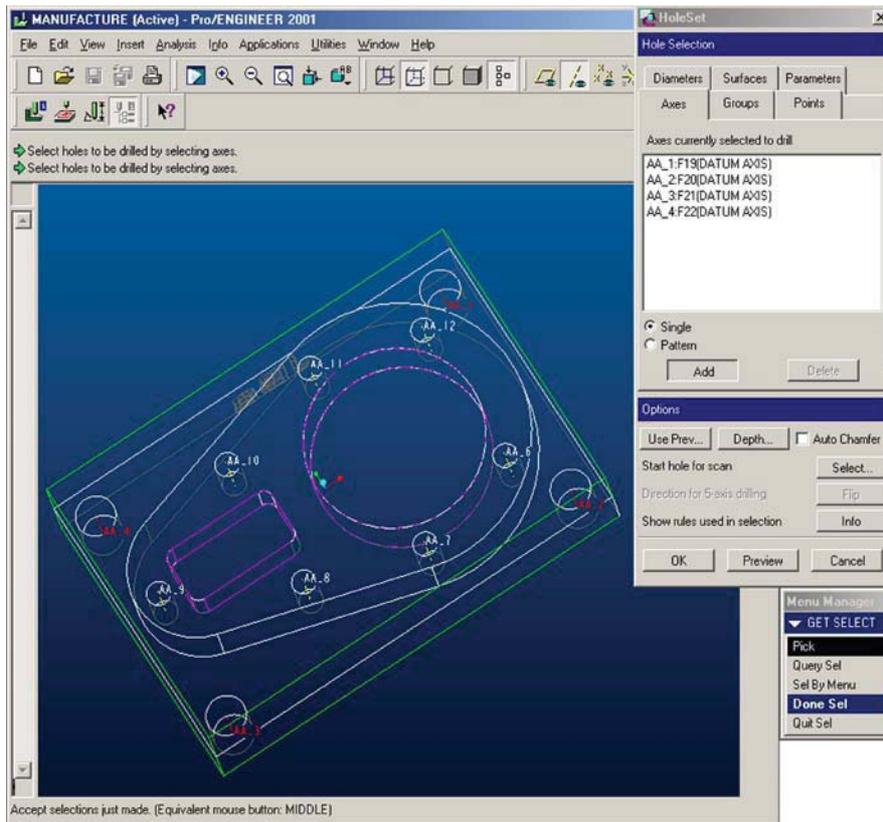


Fig. 4.23

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From the **Hole Selection** dialogue box, use the button Add to consecutively click on the axes of appropriate holes and accept. Selected axes are coloured in red and their designations appear in the field of the dialogue box (see Figure 4.23). A new dialogue box appears after **Depth** is depressed – the **Hole Depth Criteria** dialogue box, which is used to select

AUTO

OK. Then select **OK** from the **Hole Selection** dialogue box to close this box. From the **Menu Manager Done/Return**

To view the tool path/NC sequence (Figure 4.24):

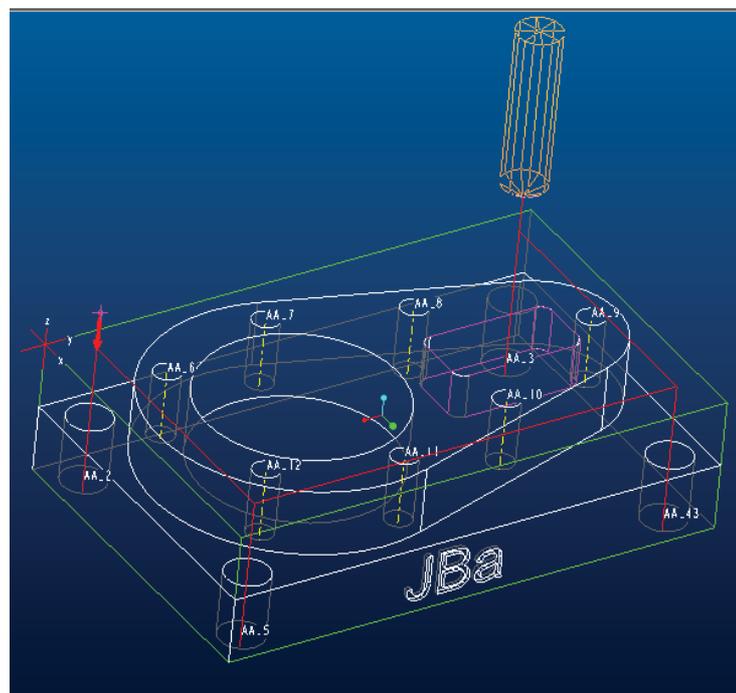


Fig. 4.24

Play Path ⇒
Screen Play ⇒
Done.

Cutting time for NC Sequence *Drilling20* is: $t = 2.9347$ min.

Done Seq finalises the setup for the current sequence.

4.3.4.5 Drilling The Holes With Diameter 12mm

Creating this operational sequence is similar to the previously described procedure with the only difference being in the provided data and hole axes.

Machining ⇒

NC Sequence ⇒

New Sequence ⇒

Machining ⇒

Holemaking ⇒

Done ⇒

Drill ⇒

Standard ⇒

Done. From the SEQ SETUP dialogue box below tick the following terms: Name, Comments, Tool, Parameters, Holes.

Done

The above terms are defined consecutively to generate the NC Sequence:

Name: *Drilling12*

Accept

Comments: *Drilling the 7 holes with diameter 12mm*

OK

Tools Setup dialogue box is filled in as follows:

Name: T0005

Type: DRILLING

Cutter Diameter: 12

Length: 55

From **Settings** ⇒ **Tool Number:** 5

From **Speeds-Feeds** ⇒:

Speed: 2100 rev/min

Feed: 420 mm/min

Axial Depth: 30 mm

The new tool is added to the list of tools using the **Apply** button.

The cutting conditions are then specified using the **Menu Manager** commands:

MFG Parameters ⇒

Set (Figure 4.22)

CUT_FEED: 420

SCAN_TYPE: SHORTEST

SPINDLE_SPEED: 2100

COOLANT_OPTION: ON

CLEAR_DIST: 3

Done from **Menu Manager** confirms the inserted cutting data and closes **Param Tree** Menu.

The 7 holes to be drilled of 12mm Dia are then defined following the procedure described above. The only difference is in specifying the depth of holes since these are blind holes. Therefore, we select **Blind** pressing the **Depth** button in the dialogue box - **Hole Depth Criteria** (see Figure 4.25)

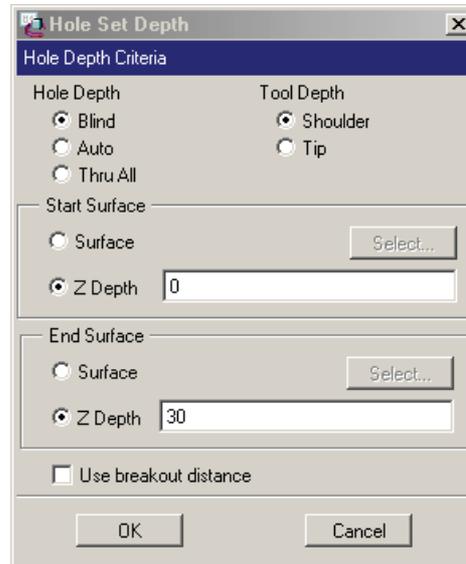


Fig. 4.25

Tick **Z Depth** in the **Start Surface** and specify the value 0 in the appropriate field.

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Then tick **Z Depth** in **End Surface** and enter the value 30mm in the field.

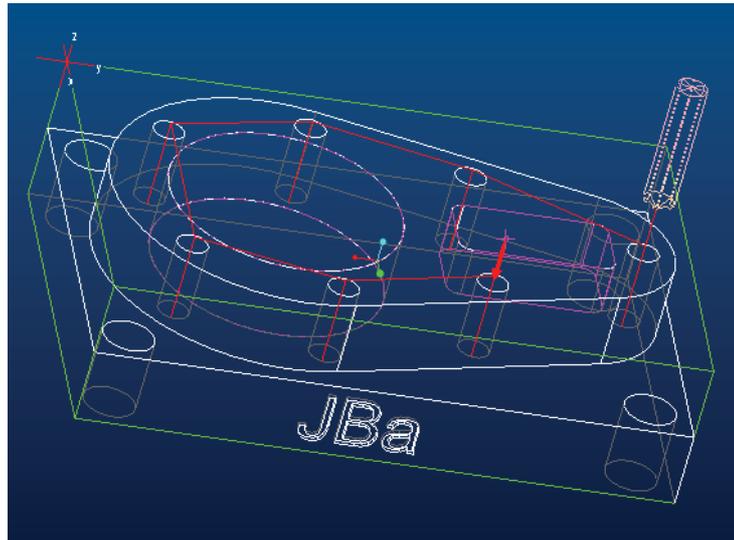


Fig. 4.26

OK. Then select **OK** from the **Hole Selection** dialogue box to close. From the **Menu Manager** **Done/Return**

To view the tool path/NC sequence (Figure 4.26):

Play Path ⇒

Screen Play ⇒

Done.

Cutting time for NC Sequence *Drilling12* is: $t = 2.2233\text{min}$.

Done Seq

Thus we finalise the setup procedures for all operational sequences performed in the first workpiece positioning arrangement employing specification of Machine Zero using the ACS0 co-ordinate system.

4.3.4.6 Milling The Text Pockets

As we already mentioned, to mill the letters “JBa” we need a different co-ordinate system ACS1 (see Figure 4.7) to perform the machining operation. In other words, the operation will be carried out on the same 3-axis milling machine (MACH01) we already defined but using another positioning of the machined workpiece, the text surface arranged perpendicular to the Z-axis of the tool.

In the **Operation Setup** dialogue box insert a new operation name - OP020 and the machine specification is the same (MACH01). We only need to position the **Machine Zero** relative to the ACS1 co-ordinate system by means of clicking on the arrow and then clicking on the ACS1 designation for the co-ordinate system in the drawing. The specified setting for the **Machine Zero** is automatically inserted in the corresponding dialogue box. We also define here a new **Retract** -

new plane a set distance away, which the machine tool will start and retreat to. To position the **Retract Surface** click on the arrow and in the **Retract Selection** menu specify as follows:

Along Z Axis ⇒ and insert a value of 12mm. Then **OK** for **Retract Selection** and **OK** for **Operation Setup**
Done/Return

We can use for this NC Sequence the pocketing function of Pro/ENGINEER, since the width (s) of milled letters is commensurate with $2 \times D_c$, where D_c is the diameter of the tool.

Machining ⇒

NC Sequence ⇒

New Sequence ⇒

Machining ⇒

Pocketing ⇒

Done From the SEQ SETUP dialogue box below tick the following terms: Name, Comments, Tool, Parameters, Surfaces.

Done

Name: *Pocketing*

Accept

Comments: *Milling the text pocket "JBA"*

OK

Tools Setup dialogue box is filled in as follows:

Name: T0006

Type: MILLING

Cutter Diameter: 1.2

Length: 7

Number of Teeth: 2

From **Settings** ⇒ **Tool Number:** 6

From **Speeds-Feeds** ⇒:

Speed: 9000 rev/min

Feed: 540 mm/min

Axial Depth: 0.2 mm

Radial Depth: 0.6 mm

Once the settings are specified, the new tool is added to the list of tools using the **Apply** button.

The values for the settings are taken from preliminary calculations made in para 2 above.

OK – confirms and closes the **Tools Setup** dialogue box with the settings thus specified.

The cutting conditions are then specified using the **Menu Manager** commands:

MFG Parameters ⇒

Set

CUT_FEED: 540
 STEP_DEPTH: 0.2
 STEP_OVER: 0.4
 SCAN_TYPE: TYPE_3
 SPINDLE_SPEED: 9000
 COOLANT_OPTION: ON
 CLEAR_DIST: 3

Done from **Menu Manager** accepts the inserted cutting data and closes the **Param Tree Menu**. Now comes the time to define the machined surfaces and Pro/ENGINEER automatically displays **SURF PICK** from the **Menu Manager**:

Model

Done

Pick Many – this is a very useful for this particular case option of Pro/ENGINEER, allowing a multi selection of all letters simultaneously by means of including them in a window selection.

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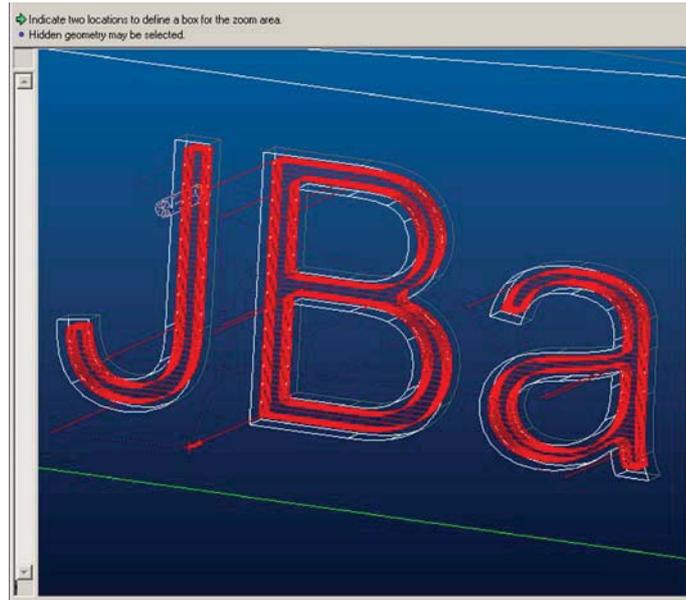


Fig. 4.27

Done Sel ⇒
Done ⇒
Done Return

To view the tool path/NC sequence (Figure 4.27):

Play Path ⇒
Screen Play ⇒
Done.

To view the simulation:

NC check ⇒
Screen Display
Run to view.

Cutting time for NC Sequence *Pocketing* is: $t = 11.0915\text{min.}$

Done Seq

The files is saved from **File** ⇒ **Save**. A suggested name appears in the field (MANUFACTURING.MFG) ⇒ **Accept**

Total cutting time for the part, as well as further information on many other manufacturing parameters can be displayed in the form of a report from the **Info** drop down menu

Info Manufacturing...⇒

and ticking **Manufacturing Model** in the appearing **Manufacturing Info** dialogue box. The report is generated either on the display or optionally, as a file.

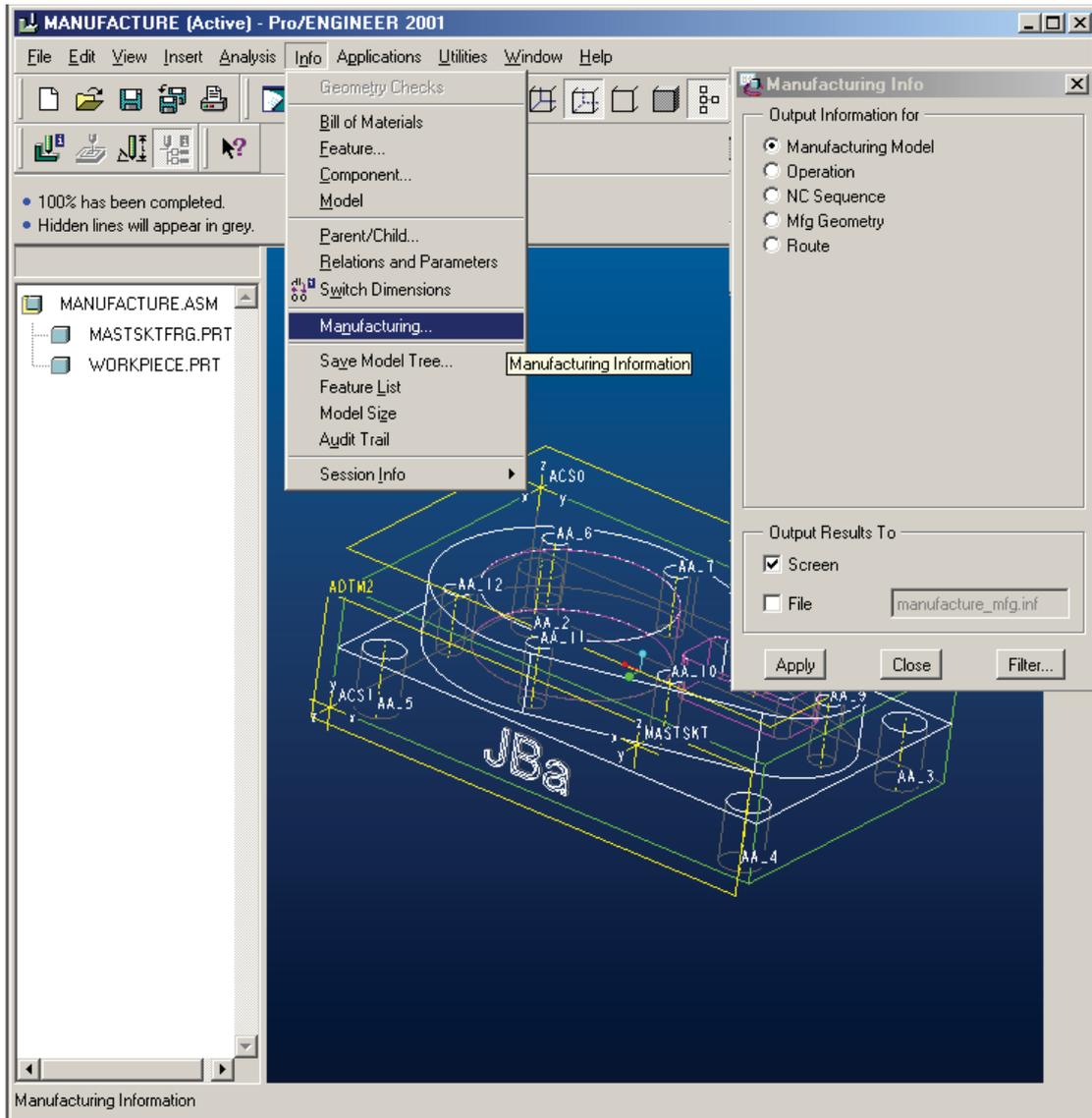


Fig. 4.28

4.3.4.7 Total Machining Time

Total machining time by Pro/ENGINEER manufacturing simulation for the machined part:

$$T = 45.4457\text{min}$$

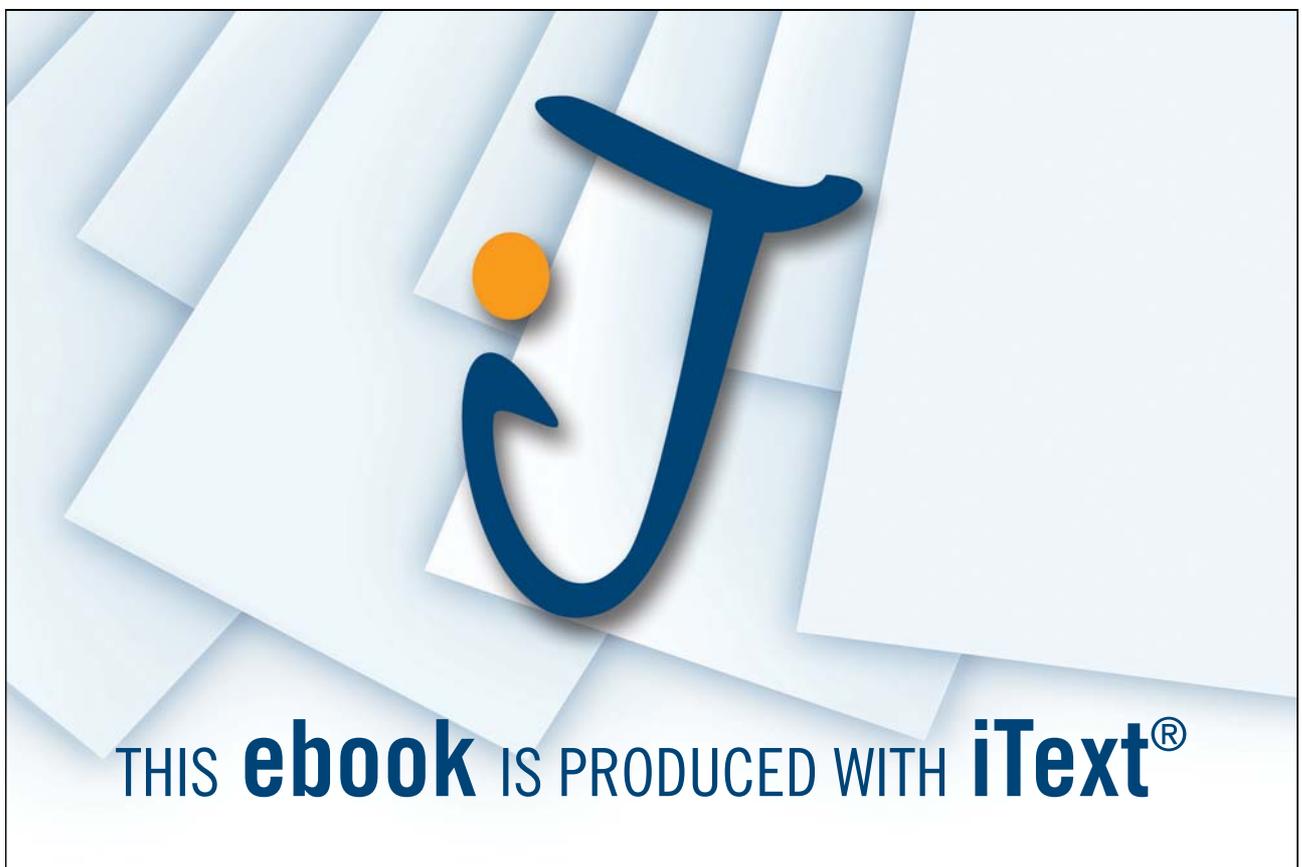
Thus, the concept of the machining the design model mastsktfrg.prt is complete.

4.4 Ez-Mill Simulation Of The Manufacturing Of The Part

As we mentioned earlier, the same part, exported in advance as an iges file (masksk.igs), will be machined using EZ-MILL in the same technological sequence and applying the same pre-calculated cutting data allowing us subsequently to draw up a comparative analysis.

To do this, we have to load the masksk.igs file from the **File** drop down menu using the **Open** command (Figure 4.29).

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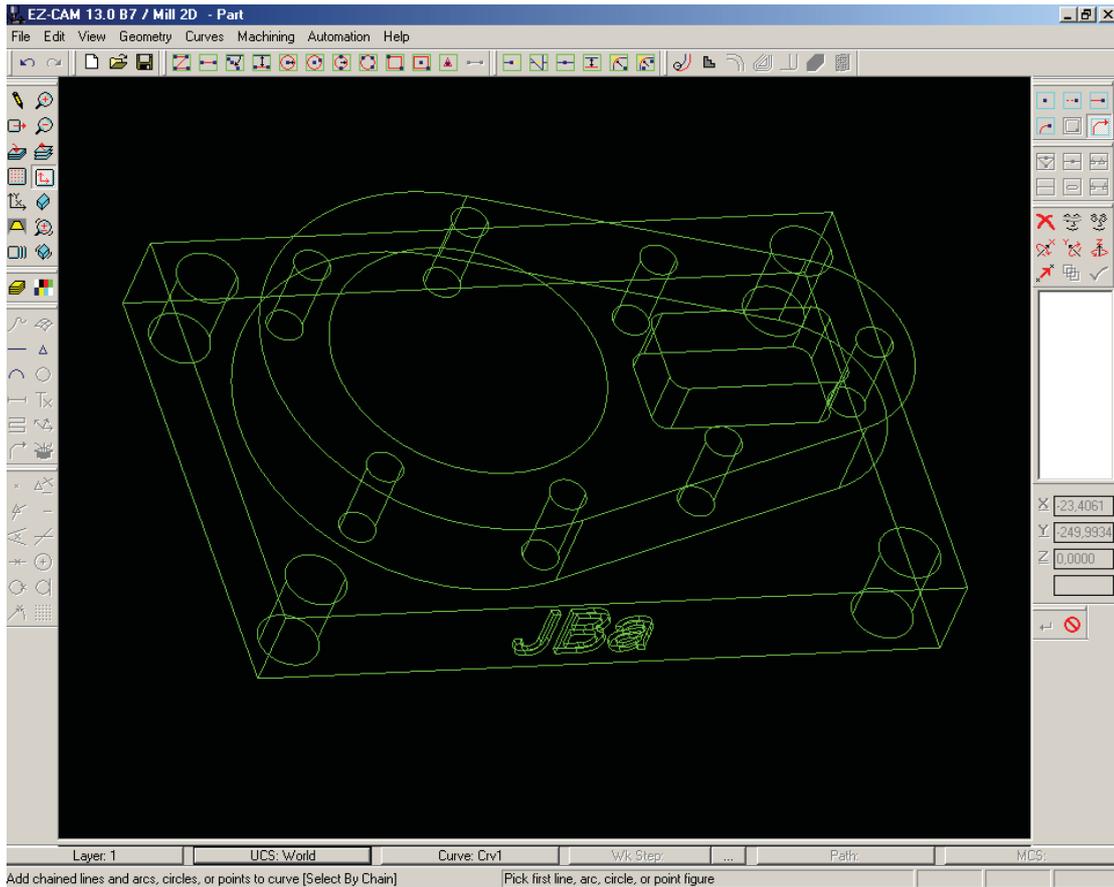


Fig. 4.29

4.4.1 Defining A Co-Ordinate System For The Machine Tool

It is exceptionally important for EZ-MILL to have an accurate definition of a co-ordinate system. In this particular case, two new co-ordinate systems have to be created similar to Pro/Engineer: one for the first 5 operations, UCS1 and another one for milling the wording, USC2.

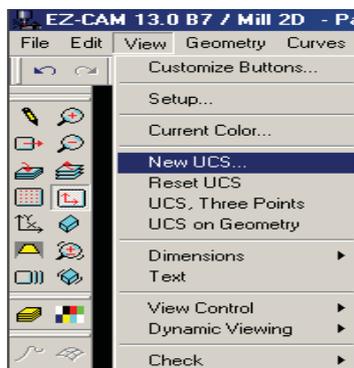


Fig. 4.30

Select **New UCS...** from the drop down menu **View** (Figure 4.30) and specify the designation: **UCS1** in the appearing **UCS ID** dialogue box; accept with **OK**.

A co-ordinate system is displayed, which has to be accurately positioned relative to the X-, Y-axes. To do this:

First specify (in the fields on the right of the display) the co-ordinates for the new “0” and confirm with **ENTER** from the keyboard;

then specify the co-ordinates of a point on the desired X-axis and confirm the selection with **ENTER**;

specify the co-ordinates of a point on the desired Y-axis and confirm the selection with **ENTER**.

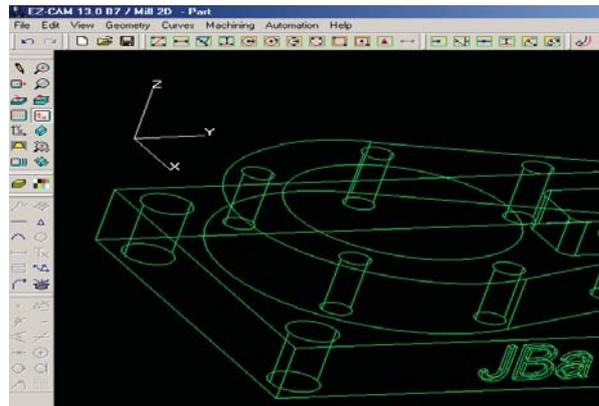


Fig. 4.31

The new co-ordinate system UCS1 is positioned as the current co-ordinate system (Figure 4.31). In a similar way, define the USC2 co-ordinate system to be used for milling the text on the workpiece (Figure 4.44).

4.4.2 Creating The Machine Work Steps

4.4.2.1 Milling

From the **Curves** drop down menu select **New...** and specify the name in the appearing **Curve ID** dialogue box: *Crv1*; then confirm the selection using **OK**. This automatically activates the Curve Chain mode (this mode could also be entered using the button in the upper right corner of the display). Position the cursor on the contour to be milled and double-click. The contour is coloured in blue and an indication of the direction of movement of the tool is given (Figure 4.32).

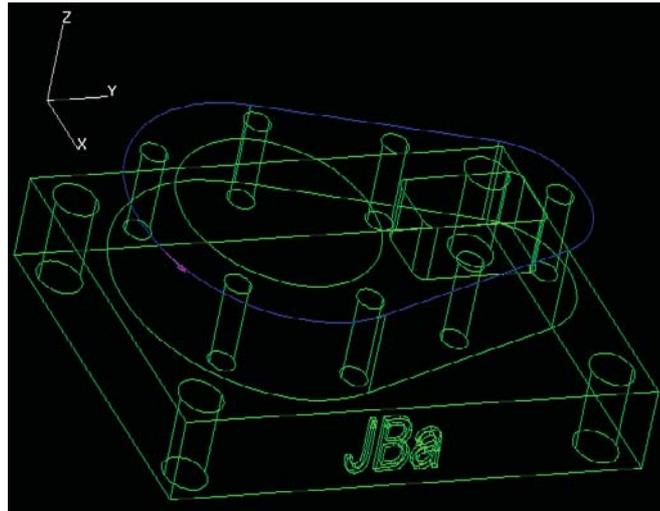


Fig. 4.32

Click on the **Work Step Data** button (located in the horizontal setup bar in the bottom of the display, next to the **Wk Step** button– see Figure 4.29) and the **Work Step Data** dialogue box appears. This is not in active mode until a new work step is defined. From this box we can tick only:

Tool Info ⇒

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New opens the **Work Step ID** dialogue box where we can specify the name *Milling* and use **OK** to activate the **Work Step Data** dialogue box. Enter parameter settings as shown in figure 4.33. Cutting data is the same as calculated in para 2 above.

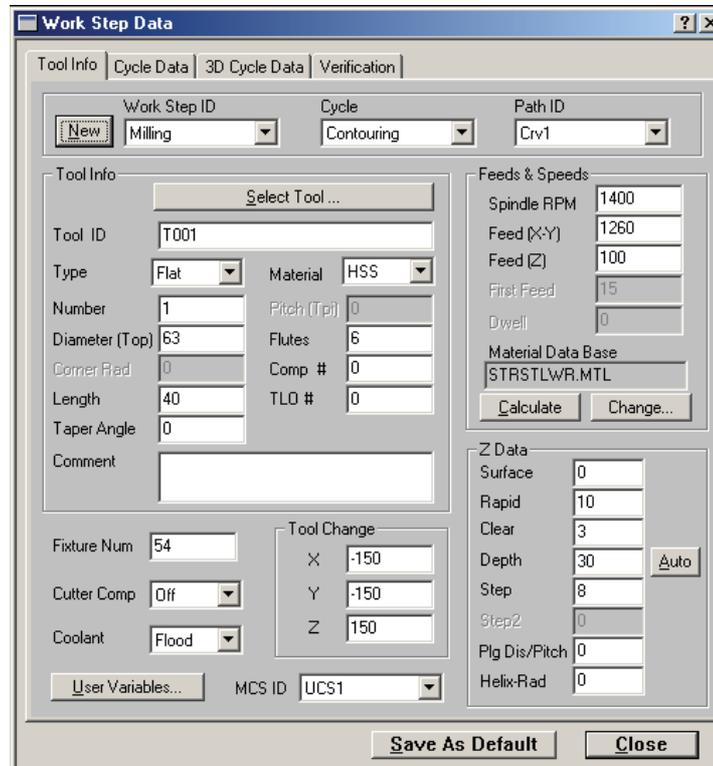


Fig. 4.33

We must say here that we can do the same thing using the **Automation** ⇒ **Contour** drop down menu where the **EZ Contour** dialogue box appears (Figure 4.33). Having filled in the field and clicking on **Advanced**, the abovementioned **Work Step Data** dialogue box opens (Figure 4.32)

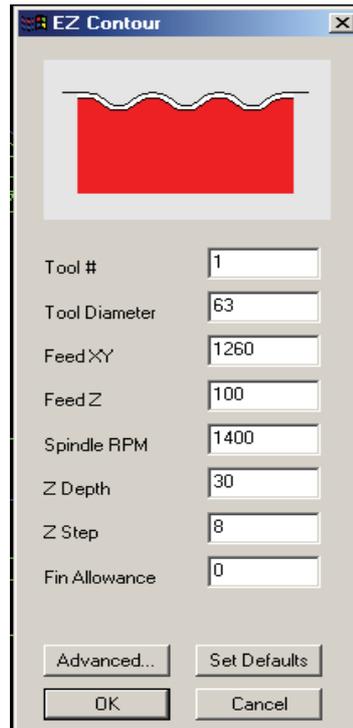


Fig. 4.34

Click on **Close** and the work step is complete.

From the **Verify** button located on the **Verify** toolbar (horizontal, upper in this case - see Figure 4.29) we can view the path of the tool along the contour only for this particular operation as ticked in the Selection list box.

From the **Verify All** button we can view the cutter path and the cutting time for all work steps defined so far (Figure 4.35).

The entire operation can be reviewed as a solid and in colour using the **Preview 3D** button.

The machining time for the first work step *Milling* is:
 $t = 2.74\text{min}$ (Figure 4.35)

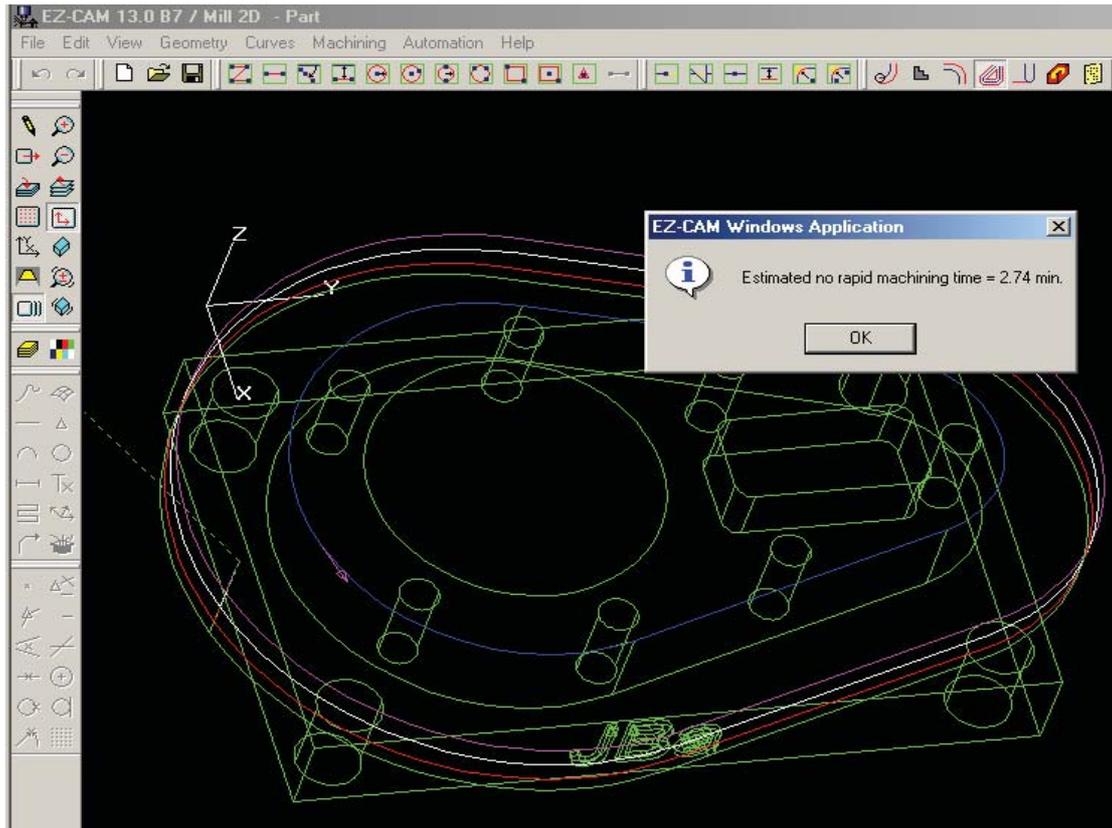


Fig. 4.35

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4.4.2.2 Milling The Cylindrical Pocket

Define a new curve: *Crv2* from drop down menu **Curves** employing the method explained above. Position the cursor on the contour of the upper circumference of the cylindrical pocket to be milled and double-click. It turns blue (Figure 4.36).

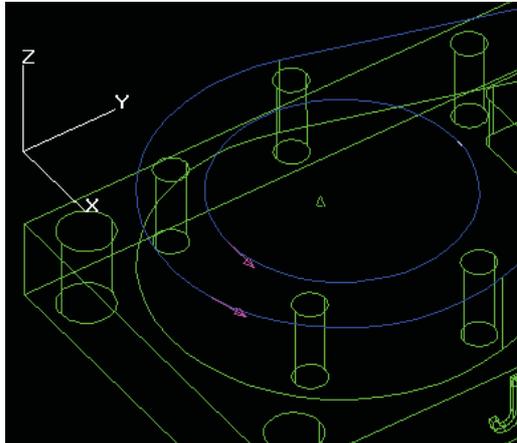


Fig. 4.36

Define a new work step: *Pocket1*

Fill in the **Work Step Data** Dialogue box (Figure 4.37). The **Pocketing Cycle** will be employed in this operation. Set the value 12mm for **Step Over** in the **Cycle Data**.

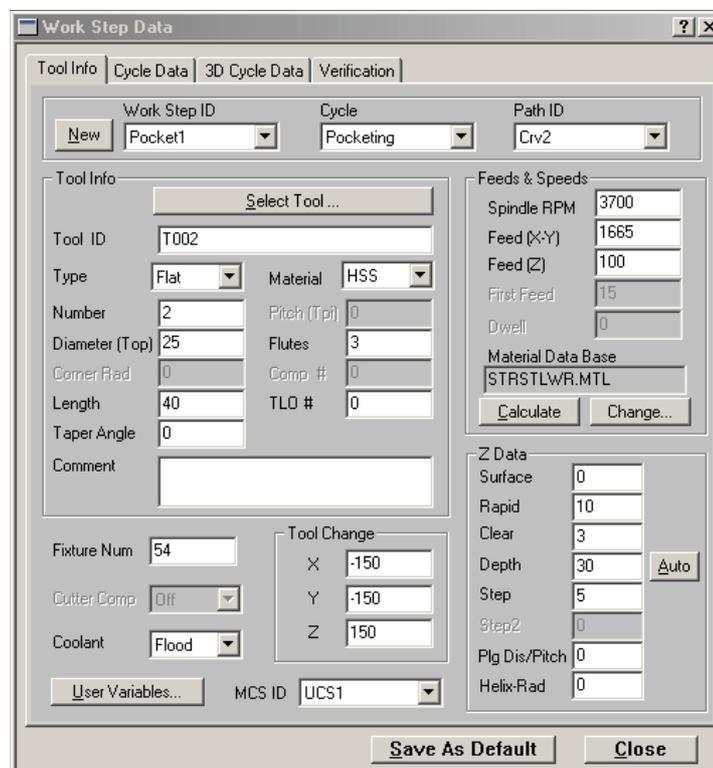


Fig. 4.37

Click on **Close** to complete the work step.

Use the button **Verify** to view and verify the cutter path.

The machining time for second work step *Pocket1* is:

$$t = 1.96\text{min.}$$

4.4.2.3 Milling The Rectangular Pocket

Define a new curve: *Crv3*. Position the cursor on the upper contour of the rectangular pocket to be milled and double-click. The contour is coloured in blue (Figure 4.38).

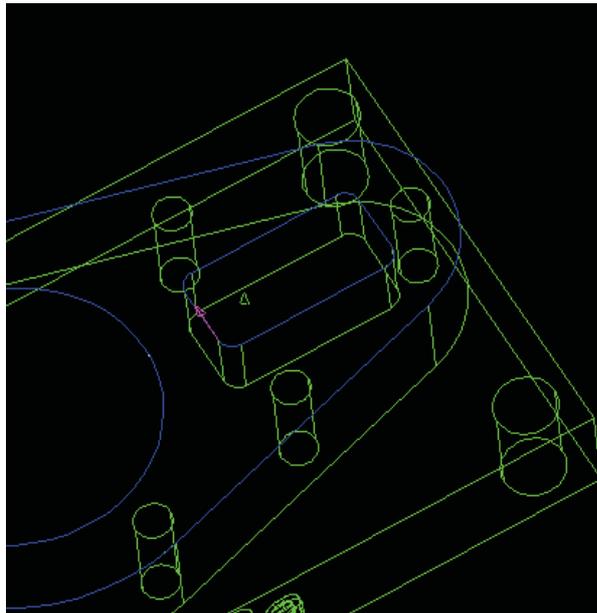


Fig. 4.38

Define a new work step: *Pocket2*

Fill in the **Work Step Data** Dialogue box (Figure 4.39). The **Cycle: Pocketing** will again be used to perform this operation. Specify *Carbide* in the **Tool Info** \Rightarrow **Material** field since this is how the tool was initially specified in para 2 above. Set a value 2mm for **Step Over** in **Cycle Data**.

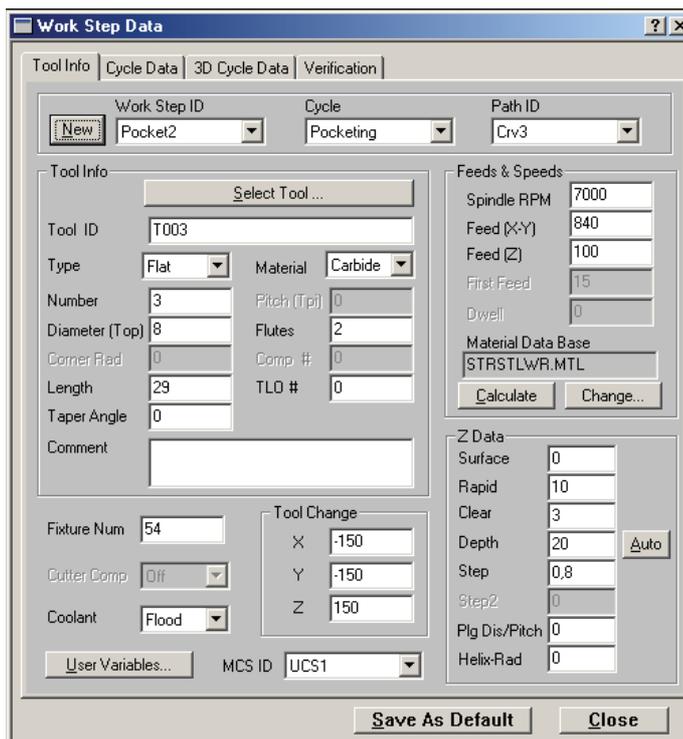


Fig. 4.39

Clicking **Close** completes the work step.

Use the **Verify** button to view and verify the cutter path.

The machining time for the third work step *Pocket2* is: $t = 20.59\text{min}$.

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4.4.2.4 Drilling The Holes With Diameter 20mm

Define a new curve: *Crv4*. Position the cursor on the upper contour of each of the four holes to be drilled and double-click. EZ-MILL automatically builds the sequence in the cutter path itself observing the specified sequence of selection (Figure 4.40).

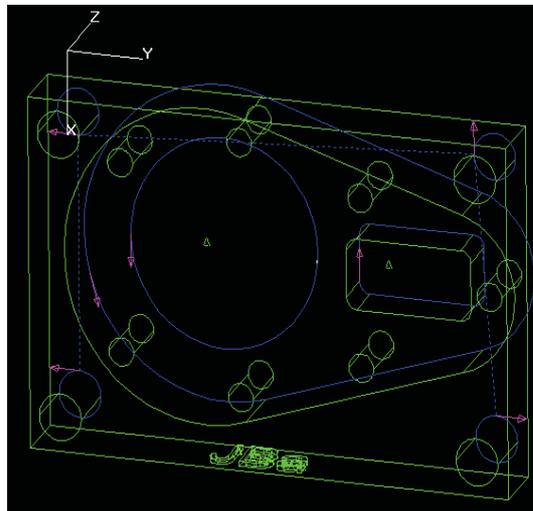
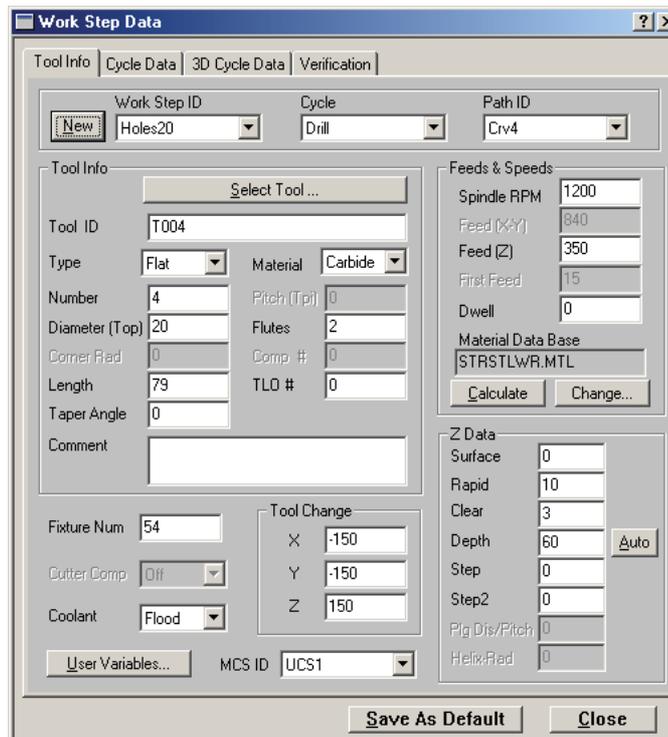


Fig. 4.40

Define the new work step: Holes20.

Fill-in the **Work Step Data** Dialogue box (Figure 4.41). To perform this operation we will use **Cycle: Drill**. Select **Carbide** for **Tool Info** ⇒ **Material**.



Close and the work step is complete.

Use the **Verify** button to view and verify the cutter path.

The machining time for the fourth work step *Holes20* is:

$t = 0.72\text{min}$.

4.4.2.5 Drilling The Holes With Diameter 12mm

Define a new curve: *Crv5*. Position the cursor on the upper contour of each of the seven holes to be drilled and double-click. EZ-MILL automatically builds the sequence in the cutter path itself observing the specified sequence of selection (Figure 4.42).

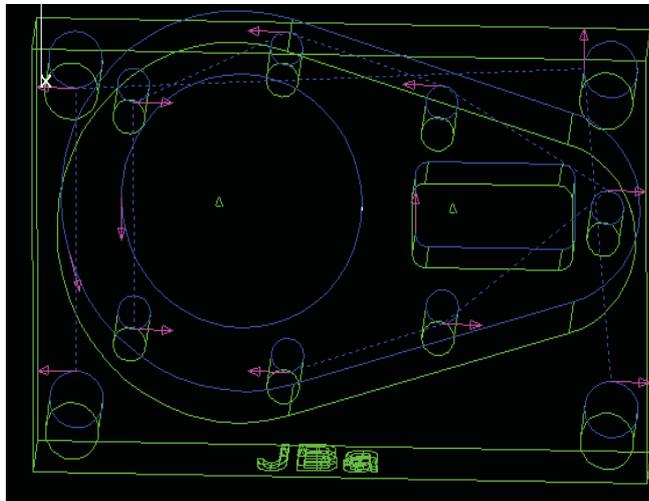


Fig. 4.42

Define a new work step: *Holes12*.

Fill in the **Work Step Data** Dialogue box (Figure 4.43). For this operation, use **Cycle: Drill**. Select *Carbide* for **Tool Info** \Rightarrow **Material**.

Close and the work step is complete.

Use the **Verify** button to view the cutter path

The machining time for the fourth work step *Holes12* is:

$t = 0.55\text{min}$.

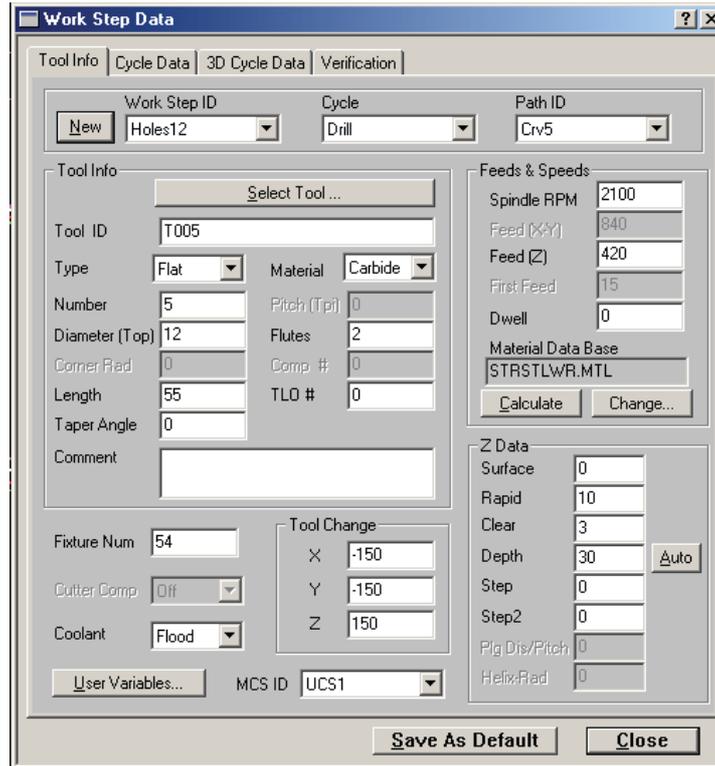


Fig. 4.43

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4.4.2.6 Milling The Text Pockets

As mentioned earlier, we will use a different co-ordinate system for this particular work step and namely the UCS2 co-ordinate system as initially defined. It is very important when defining a new curve to specify the co-ordinate system to be used for the machining operation as the current system (see Figure 4.44: **USC: USC2**). Otherwise, it will be hard to make an accurate selection of complex curves, such as the curves involved in the text, for example. Define a new curve: *Crv6*. Position the cursor on each of the closed loops shaping the upper contour of the letters “JBa” and double-click on each. The contour is then coloured in blue (Figure 4.44).

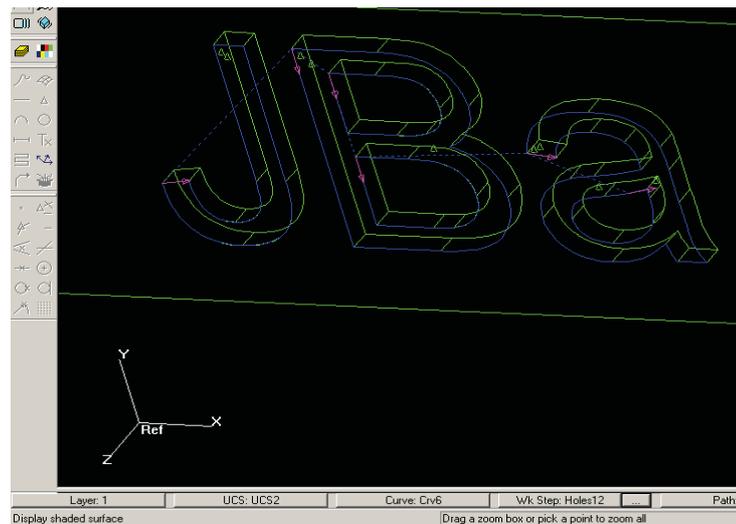


Fig. 4.44

Define a new work step: *Text_Pocket*

Fill in the **Work Step Data** dialogue box (Figure 4.45). To perform this operation we will use **Cycle: Pocketing**. Select *Carbide* for **Tool Info** ⇒ **Material**.

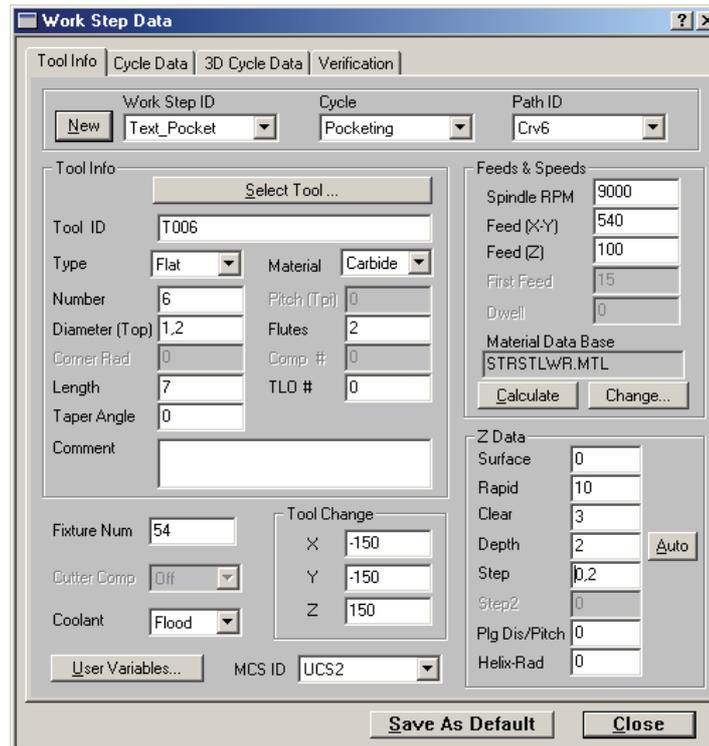


Fig. 4.45

Specify the value 0.4mm for **Step Over** in the **Cycle Data**. Specify UCS2 for **MCS ID** in the appropriate field.

Click **Close** to complete the work step.

Use the **Verify** button to view and verify the cutter path.

The machining time for the sixth work step *Text_Pocket* is:

$t = 11.79\text{min}$.

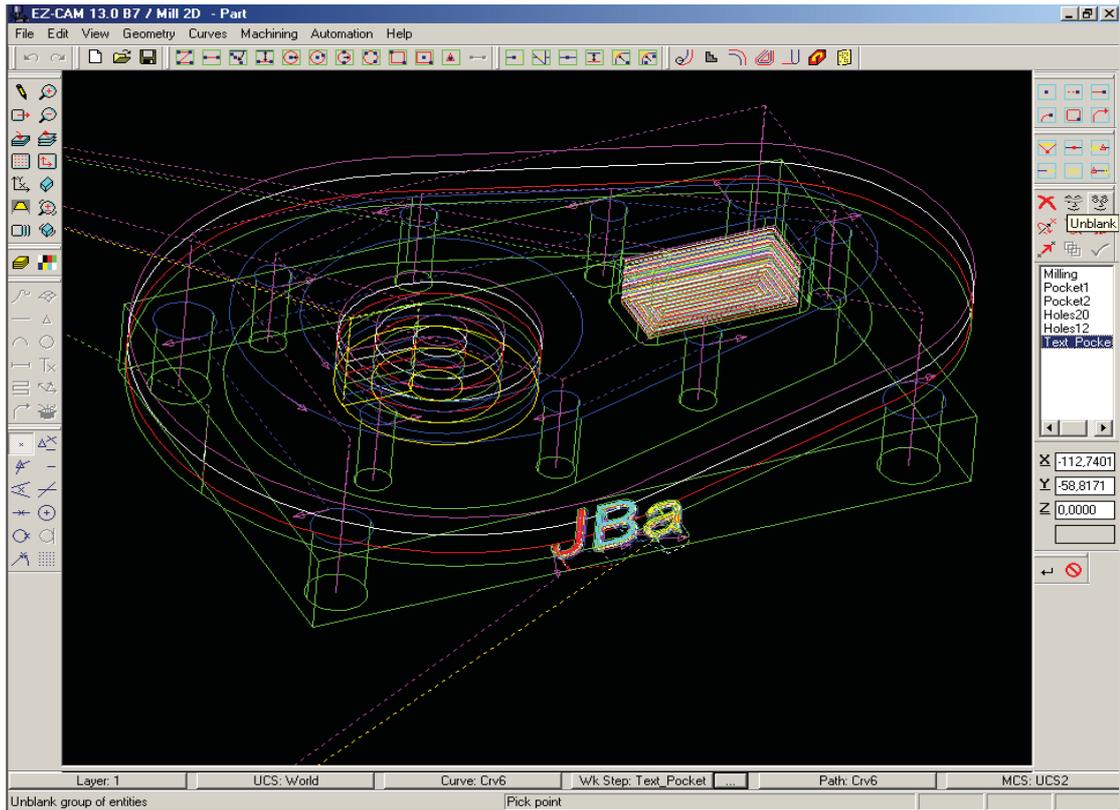


Fig. 4.46

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4.4.2.7 Total Machining Time

Using the **Verify All** button we can view and verify the cutter path for all work steps (Figure 4.46) and also total machining time.

Total machining time by EZ-MILL manufacturing simulation for the machined workpiece is:
 $T = 38.34\text{min}$

The button **Preview 3D** can be used to preview the settings as a solid and in colour. However, all settings for the workpiece required for the simulation process will have to be specified beforehand:

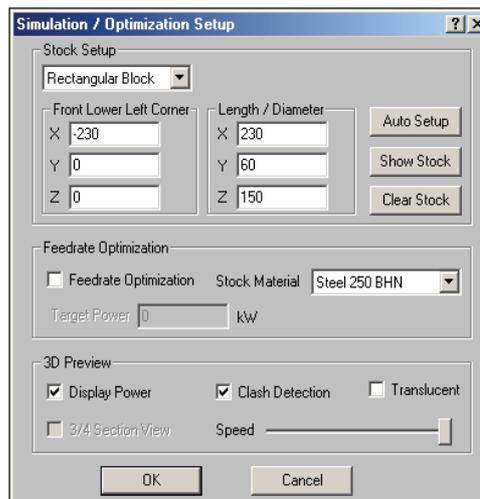


Fig. 4.47

Machining \Rightarrow **Stock & Optimisation Setup...** and the appropriate dialogue box are filled in as shown in figure 4.47. The simulation process follows the sequence of the work steps (Figure 4.48) and the final result is shown in figure 4.49.

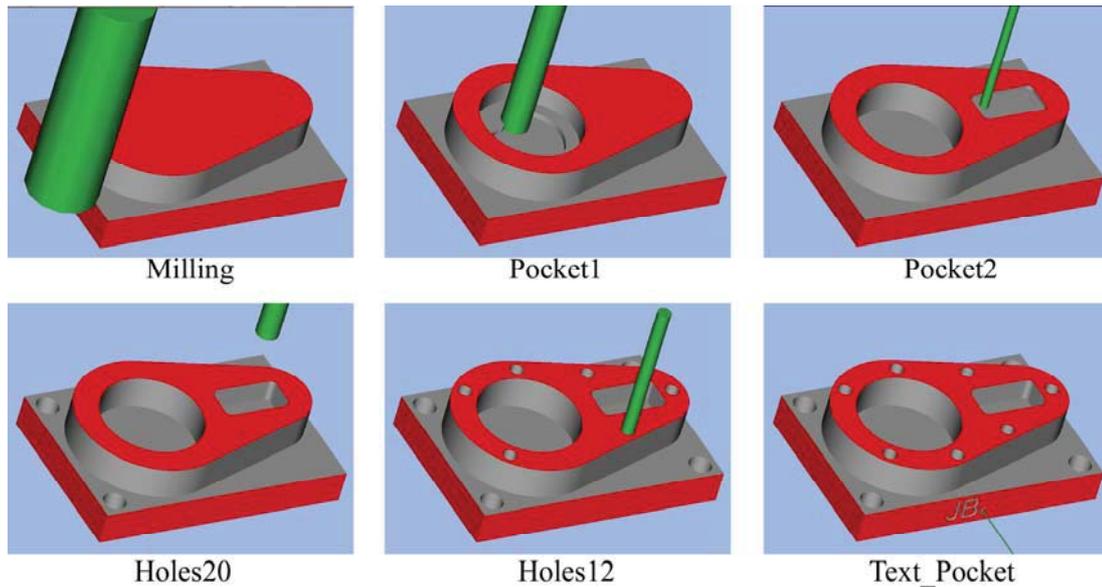


Fig. 4.48

The Save command in the File drop down menu saves the file as a geo- and a 3dp-file separately.

This completes the concept of machining of the design model mastskt.igs.

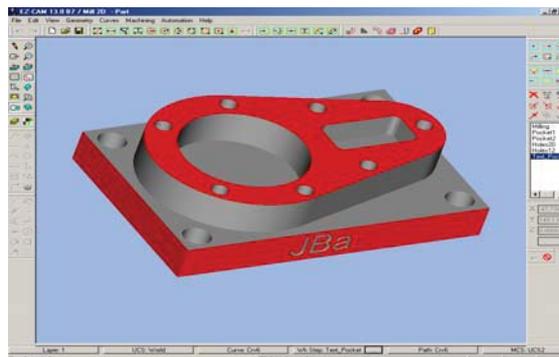


Fig. 4.49

4.5 Usability and Available Features Of Pro/Engineer And Ez-Mill

4.5.1 File Organisation

When making a comparative analysis of the two software applications it is advisable to start with file organisation of operational files involved:

In Pro/ENGINEER a common mfg-file is used where the Ref.Model, Workpiece assembly and the machining process data is stored. In other words, this common manufacture.mfg file is made up of the following files: manufacture.asm, mastsktfrg.prt and workpiece.prt, whereas manufacture.asm is in turn an assembly of the mastsktfrg.prt and workpiece.prt files and this can be created as a separate file before the machining process is generated or within the manufacture.mfg file.

Therefore, to be able to operate using the mfg-file it is necessary to have all 4 files available.

separate file before the machining process is generated or within the manufacture.mfg file. Therefore, to be able to operate using the mfg-file it is necessary to have all 4 files available.

EZ-MILL operates with two files:

- a geo-file comprising the model and the defined co-ordinate systems and curves; and a
- 3dp-file comprising machining process data (work steps, tool parameters, cutter paths and cutting data).

Quantitatively, the file organisation of EZ-MILL is simpler than that for Pro/ENGINEER. However, Pro/ENGINEER has the advantage that once the files have been created it is then sufficient to load only the mfg-file and it automatically loads the rest of the files and establishes the appropriate links. Whereas EZ-MILL requires that both files are opened.

4.5.2 Operational Organisation

The operational organisation of the two software applications is another difference between them, although the basic technological principles of both applications are similar. Pro/ENGINEER is a CAM-software of highest ranking and it requires higher skills and competence to apply. Its organisation is based on consecutively opening menus, submenus and dialogue boxes allowing to choose from multiple alternatives and a variety of tools. Each selection requires individual confirmation, which improves operational reliability, on one hand but slows down operations, on the other.

The EZ-MILL operation is simpler using primarily commands from toolbars and dialogue boxes. A useful feature is the bottom horizontal button bar from which one can monitor, select or edit some basic elements of the manufacturing process, such as: Layer, UCS, Curve, Work Step, Path, MCS. Other available characteristics are readily accessible and editable.

The same outcome results after several transitions within **Menu Manager** in Pro/ENGINEER but we must note here that once you get experienced this is very convenient, too.

4.5.3 Usability And Available Features

Both applications are used to create a workpiece, but with Pro/ENGINEER this is saved in a separate file, while with EZ-MILL the created workpiece is not saved in a separate file. Nevertheless, it is still possible to define a workpiece similar to the procedures involved in Pro/ENGINEER if one starts from the very beginning using the tools available in the **Geometry** toolbar, but as it turned out this is not a compulsory exercise since we made the preliminary assumption that the size of the workpiece will be 230x150x60mm.

Some of the terms applied in the two software applications are different as well but they still refer to the same thing, such as: NC Sequence (Pro/ENGINEER) and Work Step (EZ-MILL) – both are title given to the elements that make up one cut

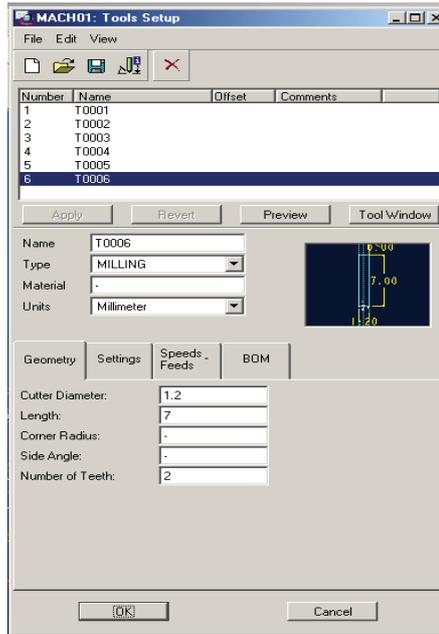


Fig. 4.50

Two alternatives of proceeding with the machining of the part exist in EZ-MILL:

- First is to pre-define all curves to be involved in the machining operations and these are saved as a geo- file, and then proceed with the definition of appropriate tools and cutting data and all ends up saved as a 3dp-file ;

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- Another alternative is to consecutively define each individual work step as a set of curves, toolpath, tool and cutting data. Having defined all work steps the file is then saved first as a geo-file and then also saved as a 3dp-file without any interruption to the current session.

With Pro/ENGINEER the NC Sequences have to be defined consecutively one after the other, but the tools in the **Tools Setup** dialogue box for example, can be defined all at a time (see Figure 4.50).

Both applications are capable of selecting and importing tools from pre-existing libraries. Only that Pro/ENGINEER provides for importing the processing NC machine from an existing ready-made library (such library can be created as a separate gph-file).

Defining the co-ordinate systems with the two applications is rather similar for both of them with the only difference being that Pro/ENGINEER provides a much higher number of alternative means to do this (see Figure 4.51).

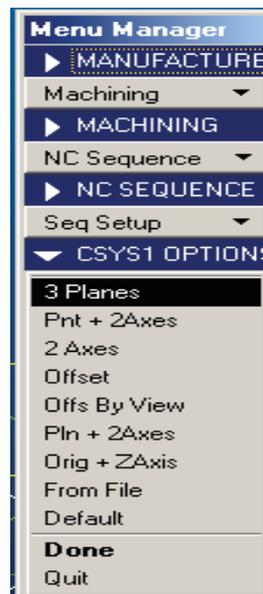


Fig. 4.51

Both applications allow for defining some conventional technological processes, such as contouring, pocketing, drilling, thread cutting, etc. Pro/ENGINEER provides for defining a greater variety and more complicated processes involving a higher number of parameters. For example, when Holemaking is selected a choice of 7 possible alternatives appears. EZ-MILL also provides for defining a sufficient variety of technological processes. But we must note here, that Pro/ENGINEER achieves better insight into the parameters being set and hence, improved definition of the entire machining process.

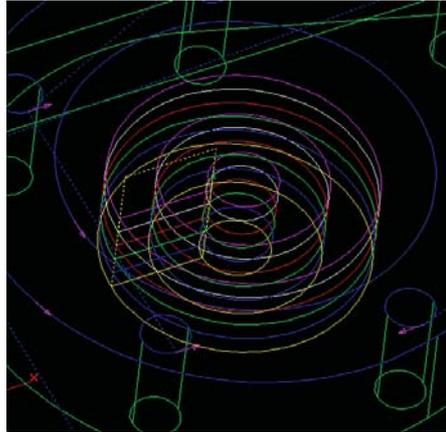


Fig. 4.52

Considering the particular part described in this report we should also mention the differences in the two applications when the pocketing operation is concerned. When this was applied with EZ-MILL and eventually viewed, the cutter path looked as shown in figure 4.52. For the same cylindrical pocket we used NC Sequence Volume in Pro/ENGINEER and the cutter path is the same for the same cutting data (see Figure 4.53). If we had used Pocketing with Pro/ENGINEER the result would have been different (as was already shown in figure 4.16 and explained in para 3.4.2).

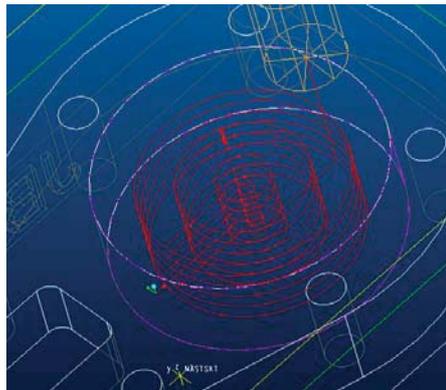


Fig. 4.53

Another significant difference is that while Pro/ENGINEER specifies some parameters on its own based on the defined surfaces, EZ-MILL requires values to be specified regardless of the model. For example, when Pocketing is specified and the bottom plane is selected, Pro/ENGINEER does not require you to specify depth, while EZ-MILL will operate until the set value is reached. In other words, Pro/ENGINEER provides a higher level of intuitively.

Both applications provide viewing capabilities, including three-dimensional views, but again here Pro/ENGINEER gives an advantage in the means of controlling the viewing function – by means of adjusting the speed, using the Pause characteristic, applying the dynamic control capability, etc. Moreover, it provides for playing back the history of the entire manufacturing file – from the **Utilities** drop down menu ⇒ **Model Player**.

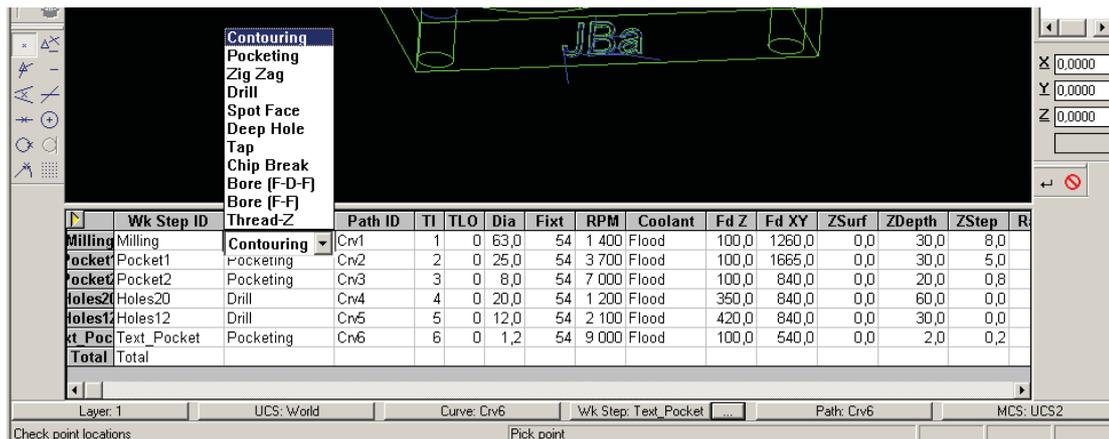


Fig. 4.54

Additionally, both applications provide for calculating the cutting time for each individual operation and also the total cutting time. But the additional information for the machining process generated in the form of various reports by Pro/ENGINEER is highly varied and larger in quantity.

However, EZ-MILL features a very useful informational facility that provides for even editing specified cutting data: from the **Machining** drop down menu ⇒ **Show Spread Sheet**. The table which appears here is editable even for multi-optional parameters (see Figure 4.54). This allows for every work step to be re-defined from here.

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4.6 Innovative Approaches To Optimise The Manufacturing Process Plan

If we analyse the cutting times for every NC sequence of the machining process, defined in the course of the simulation (para 3 thru 4), it is obvious that the operation of the longest duration is the milling of the rectangular pocket. With Pro/ENGINEER the cutting time for this operation is:

$$t = 24.2657\text{min}$$

Moreover, the Volume type of sequence is employed here to remove the excessive material from the pocket. Meanwhile, tool diameter is limited to the rounded corners radii of 5mm. Using this sort of tool with a small diameter and relatively small axial step (max. 0.8mm – refer to Sandvik catalogue, page 62) naturally leads to significant increase in the total machining time for this component part.

What can we do using the capabilities of the CAM application software Pro/ENGINEER to optimise the manufacturing process plan in order to reduce cutting time and hence, reduce the manufacturing cost?

Utilising some clever alternatives and efficient ways provided by the application we can investigate how this reflects on both cutting time and the overall time, facilities and additional capabilities involved in the usage of Pro/ENGINEER:

NC Sequence named Volume2 will be replaced by two new NC Sequences Pocket2_1 and Pocket2_2, and the first sequence will use a $\varnothing 25\text{mm}$ Dia tool, and the second sequence - a $\varnothing 8\text{mm}$ Dia tool. Additionally, the specified sequence type Volume will be replaced by Pocketing.

1. *Pocket2_1*: From Menu Manager

Machining ⇒

NC Sequence ⇒

New Sequence ⇒

Machining ⇒

Pocketing ⇒

Done From the SEQ SETUP dialogue box below tick the following terms: Name, Comments, Tool, Parameters, Surfaces.

Done

Name: *Poketing2_1*

Accept

Comments: *Milling the rectangular pocket with tool 25mm*

OK

Tools Setup – It is important to note here that the tool and its parameters (tool name T0002) have already been specified in the previous NC Sequence. Therefore, we only have to click on **T0002** and it is selected as current (Figure 4.55). Moreover, tool type and parameters are saved in a

t0002.tpm file. This is accomplished by clicking on the “**Save tools parameter to a file**” button. Thus, the customer can build his own library to use for his future convenience.

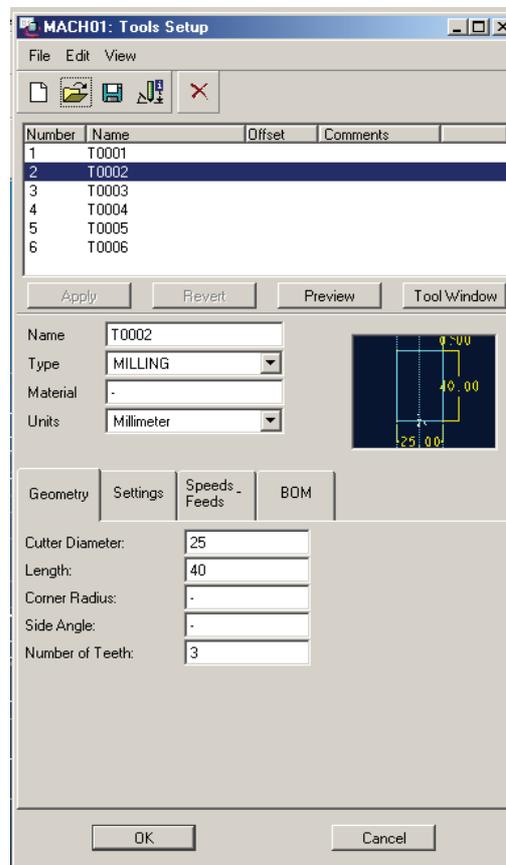


Fig. 4.55

OK – confirms the setting and closes the **Tools Setup** dialogue box

MFG Parameters ⇒

Another important moment – select **Retrieve** instead of **Set** and from the **Open** dialogue box select the pocket2_1.mil file (see Figure 4.56). Settings are loaded automatically and it is not necessary to fill in the appropriate fields again. The mil-file is created in advance and saved in a library while defining one of the previous sequences. Of course, we can always select **Set** and edit all settings. All these provisions make the process very convenient and contribute to the unification of parameters providing opportunities for multiple comparative playbacks.

Mil-file is save by selecting **Save** in the **MFG PARAMS** submenu (see Figure 4.56).

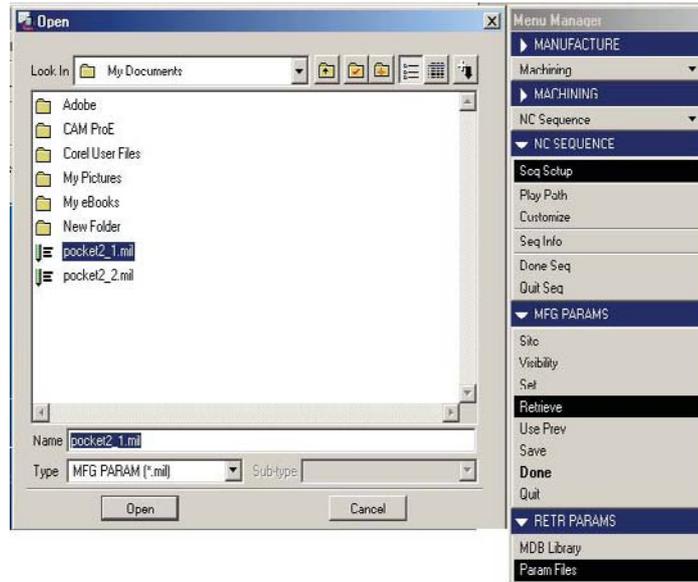


Fig. 4.56

Done and Pro/ENGINEER automatically suggests that we define the surfaces to be processed:

Another important moment here is that instead of **Model** we select:

Mill Volume ⇒
Select Vol

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Opens the **Selection Tools** dialogue box where we click on *Volume2*. It turns red. (see Figure 4.57). There are many alternatives here as we can also proceed with **Pick** and continue as described earlier with **Model** ⇒ **Done** ⇒ **Query Select**

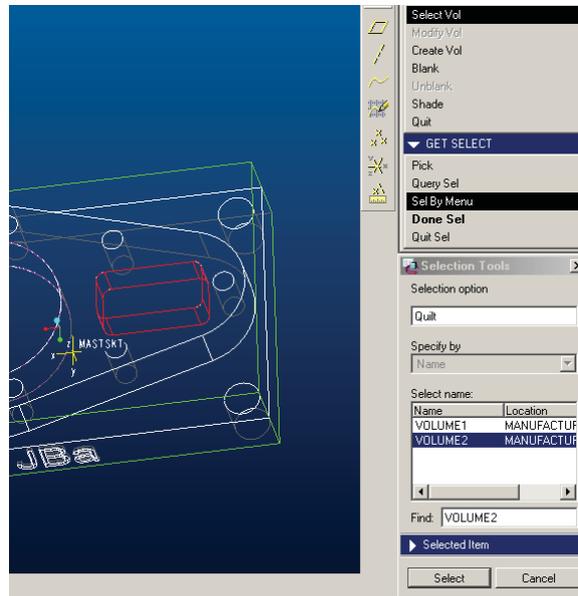


Fig. 4.57

However, the optimum choice is **Select Vol** as *Volume2* has already been defined and saved in para 3.4.3. so it can be used as set. Confirm the setting with **Select**.

Done Sel⇒

Done Return⇒

Play Path⇒

Screen Play

The cutting tool removes material only in a few strokes (see Figure 4.58) and the time it takes is:

$$t = 0.288\text{min.}$$

Some material is still left in the corners because of the relatively big tool radius. This will be later removed by the next tool, a 8mm diameter T0003.

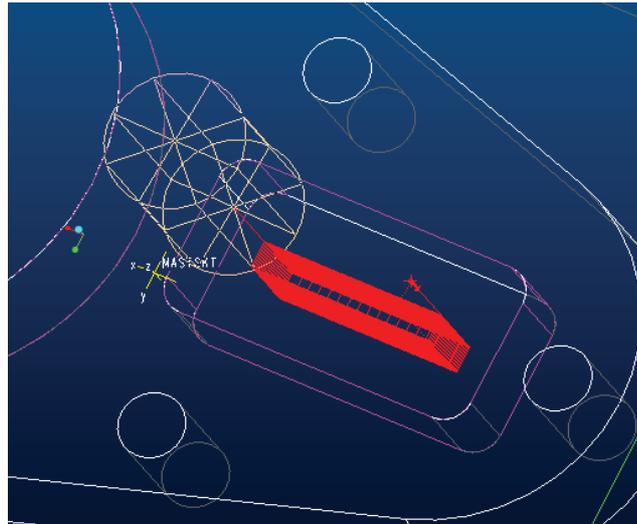


Fig. 4.58

2. *Pocket2_2*:

The procedure is similar to *Pocket2_1* with only a few differences:

Name: *Poketing2_2*

Accept

Comments: *Milling the rectangular pocket with tool 8mm*

OK

Tools Setup – just click **T0003** and it becomes current

OK – confirms and closes the **Tools Setup** dialogue box

MFG Parameters ⇒

Retrieve and from dialogue box **Open** tick the *pocket2_2.mil* file (see Figure 4.56).

Done

Select *Volume2* observing absolutely the same procedure as for *Pocket2_1* (see Figure 4.57).

Done Sel⇒

Done Return⇒

Play Path⇒

Screen Play

The tool removes the rest of the excessive material in an optimum manner (see Figure 4.59) for the time of:

$t = 5.307\text{min}$

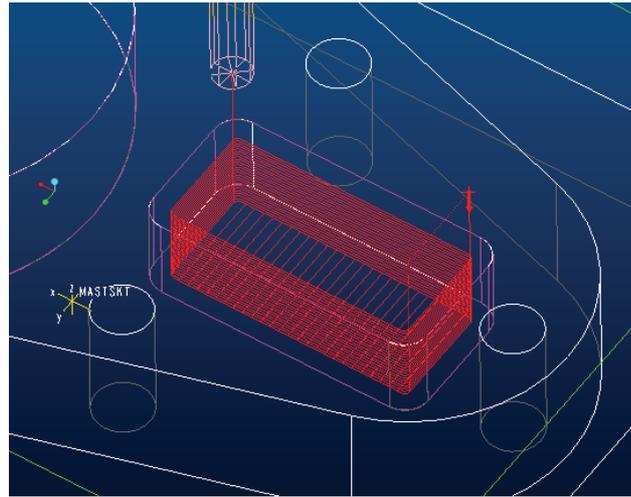


Fig. 4.59

In other words, the total time for machining the rectangular pocket is:

$$t_{p2} = 0.288\text{min} + 5.307\text{min} = 5.595\text{min} \text{ (was } 24.2657\text{min)}$$

This is a triple reduction.

Then the total machining time for all sequences by Pro/ENGINEER simulation is:

$$T = 26.775\text{min} \text{ (was } 45.4457\text{min)}$$

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Moreover, optimisation of the machining tool path is achieved, which will actually form two concentric contours of the two tools (Figures 4.58 and 4.59). The fact that two sequences are performed instead of one has no negative effect as no replacement of tools is involved since sequences 2 and 3 use the same type of tool, T0002.

To be able to achieve absolutely the same cutter path with EZ-MILL, the *Pocket2* work step shall be divided into three separate operations (Figure 4.60) with cycles:

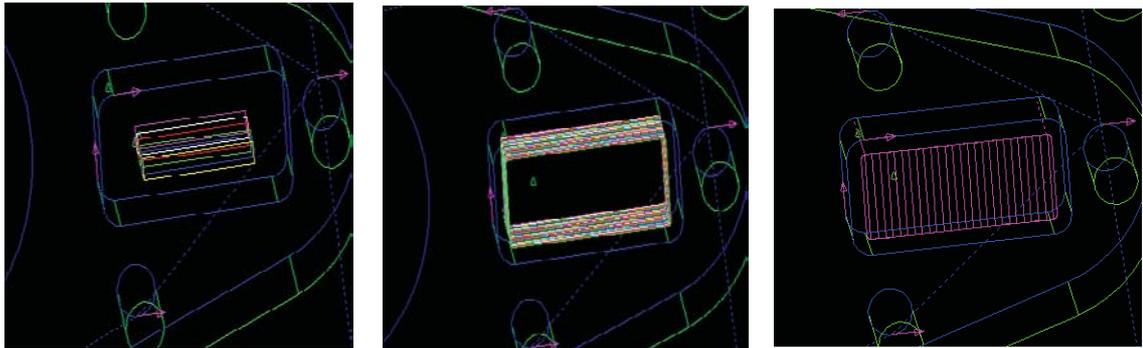


Fig. 4.60

- Pocketing using tool T0002 ($\varnothing 25\text{mm}$); $t = 0.62\text{min}$;
- Contouring using tool T0003 ($\varnothing 8\text{mm}$); $t = 4.56\text{min}$;
- Zig Zag along the bottom using tool T0003 ($\varnothing 8\text{mm}$) $t = 1.12\text{min}$;

In other words, the total time required to machine the rectangular pocket is:

$$t_{p3} = 0.62\text{min} + 4.56\text{min} + 1.12\text{min} = 6.30\text{min} \text{ (was } 20.59\text{min)}$$

The total machining time by EZ-MILL simulation is:

$$T = 24.05\text{min} \text{ (was } 38.34\text{min)}$$

The results are very similar. Minor differences result from some parameters, such as rapid strokes, etc., which are associatively specified by Pro/ENGINEER, unless user specified.

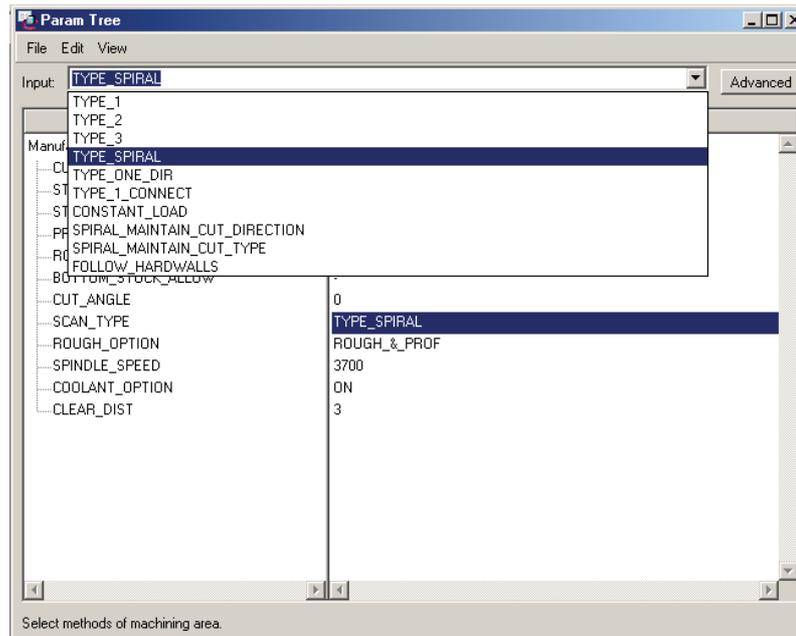


Fig. 4.61

We should mention here the opportunities to select the type of trajectory of the tool for various types of NC sequences (Pro/ENGINEER). This is defined by the submenu **MFG PARAMS** ⇒ **Set** for each sequence. For example, if we consider the second NC sequence (this is a Volume type sequence), the possible selections for a cutter path can be seen in the **Param Tree** dialogue box, the **SCAN_TYPE** field (Figure 4.61). Figure 4.62 shows a playback and views of three of them: **SPIRAL_MAINTAIN_CUT_DIRECTION**, **TYPE_ONE_DIR**, **TYPE_1_CONNECT** (Figure 4.16, para 3.4.2. shows a view of **TYPE_SPIRAL**).

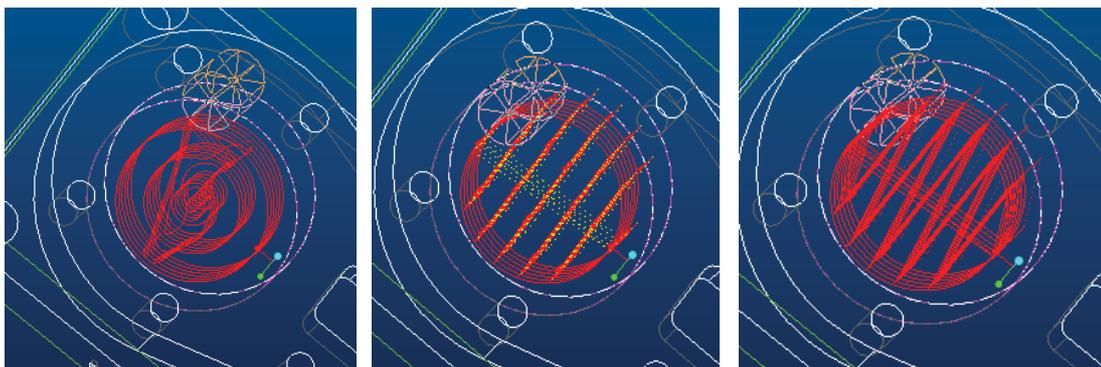


Fig. 4.62

Additionally, if the **Param Tree** dialogue box is switched to **Advanced View** mode, a number of parameters appear comprising the following groups: Names, CUT OPTION, CUT PARAMETERS, FEED, MACHINE, ENTRY/EXIT. Specifying these parameters provides complete definition of the machining process.

As we mentioned earlier, the EZ-MILL application provides a more limited number of alternative specifications and the same can be performed there resulting in the same cutting path. For example, two possibilities exist for this particular cylindrical pocket. From dialogue box **Work Step** data (or from **Machining ⇒ Spreadsheet**) select **Cycle: Zig Zag** or **Pocketing** for work step Pocket1 (Figure 4.63). For the first selection, the machining time is 2.48min, and for the second selection, $t = 1.96\text{min}$.

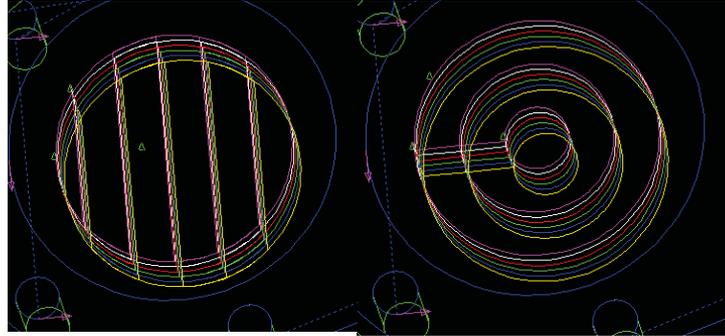


Fig. 4.63

The discussion included in para 6 above was an example of the use of CAM-software innovative approaches to optimise the manufacturing Process plan.

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4.7 Reiterative Approach To Optimise The Machining Sequences And Minimise Machining Time

Optimising machining sequences and minimising machining time and cost can also be achieved by optimising some of the parameters used in defining sequences. An example of a route that can be used to achieve this involves another simulation of the machining process of the model again using Pro/ENGINEER and involving the optimisation described in the previous paragraph, and namely, replacing the Volume2 sequence with two sequences – Pocket2_1 and Pocket2_2:

1. In the first NC Sequence Milling optimisation possibilities are present only in step depth, which can be varied from 8mm to 10mm. This will reduce the number of transitions from 4 to 3. 10mm is the maximum specified step depth for this type of tool.

Machining ⇒

NC Sequence and from **NC SEQ LIST** select **1. Profile** ⇒ **SEQ SETUP** where **Parameters** shall be ticked.

Done ⇒

Set

In the **Param Tree** dialogue box: **CUT PARAM - STEP_DEPTH** is set from 8 to 10. As a result of this modification operation time is now:

$$t = 1.8837\text{min} \quad (\text{was } 2.48443\text{min})$$

2. In the second NC Sequence Volume1 in the **Param Tree** dialogue box: **CUT PARAM - STEP_DEPTH**: 8mm (was 5mm);

$$t = 1.64568\text{min} \quad (\text{was } 2.44602\text{min})$$

3. In the third NC Sequence Pocket2_1 in the **Param Tree** dialogue box: **CUT PARAM - STEP_DEPTH**: 8mm (was 5mm);

$$t = 0.24024\text{min} \quad (\text{was } 0.288\text{min})$$

4. In the fourth NC Sequence Pocket2_2 the tool operates with the maximum parameters recommended in the appropriate specifications and under optimum conditions, so no modifications are required:

$$t = 5.3311\text{min}$$

5. No modifications shall be introduced in the fifth NC Sequence Holes20 – the tool here operates with the parameters recommended in the appropriate specifications and under optimum conditions:

$$t = 2.9347\text{min}$$

6. No modifications are introduced in the NC Sequence Holes12 either:
 $t = 2.22333\text{min}$

7. In the NC Sequence Pocketing in the **Param Tree** dialogue box:

CUT PARAM - STEP_OVER: 0.6mm (was 0.4mm);
CUT OPTION - SCAN_TYPE: TYPE_SPIRAL (was TYPE_3)

$$t = 10.5833\text{min (was 11.0915min)}$$

Then the total machining time for all sequences by Pro/ENGINEER simulation is:

$$T = 24.842\text{min (was 45.4457min)}$$

Similarly, we can use the same procedure when using EZ-MILL. It is even easier and faster to pre-define parameters with this application and especially when the facility **Spread Sheet** is used as mentioned in para 5 (Figure 4.54). The results with machining times will be similar to above.

In principle, we could also vary such parameters as feed and axial step and this will further reduce machining time but on the other hand, will have a negative effect on tool wear, will reduce tool life cycle and increase the risk of tool breaking. This will in turn result in adding cost to manufactured products and eliminate the benefits of reduced machining time.

4.8 Conclusions

The experience gained in this chapter has confirmed the huge benefit brought by CAM applications in developing a design for the manufacturing process. Essential conclusions can be drawn based on the experience working with the two software applications Pro/Engineer and EZ-MILL:

- File organisation of the two CAM software applications is very similar; a file comprising the model and its parameters is usually used and another file (or files) comprising all the data used to define the machining process.
- The organisation of operations is very specific to individual applications but dialogue boxes and menus are primarily used in both.
- A significant issue when working with CAM software applications is the correct definition of required co-ordinate systems;
- High significance is also given to tool definition. Provisions are made for both importing of ready-made libraries and for creating new ones, as well as editing existing ones.

- Based on common technological principles, CAM software applications operate using certain types of processes, the diversity and degree of parametric definition of which are different for different applications.
- Both applications require specification of machined surfaces or contours but they employ different ways of defining them, Pro/Engineer for example, allowing for volumes to be defined as well.
- Very useful are memorising features used to save the parameter sets of definitions (of machines, tools, cutting data, volumes, etc.).
- A powerful tool facilitating the optimisation process is the tool path simulation feature, machining time calculation feature, process verification feature, as well as the editing and pre-definition facility.
- Reports generation and making analyses (especially with Pro/Engineer) are also useful features.

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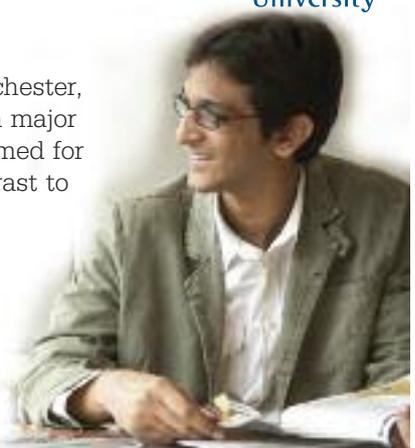
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If we compare these two applications we could say that Pro/Engineer is a CAM-software application of the highest ranking. It offers a wider set of modules, tools and capabilities and one needs to be much more skilled and familiar with it to be able to use it. On the other hand, EZ-MILL is faster and simpler to operate with. It is a simpler CAM software application suitable for smaller series production and for component parts of simple configuration.

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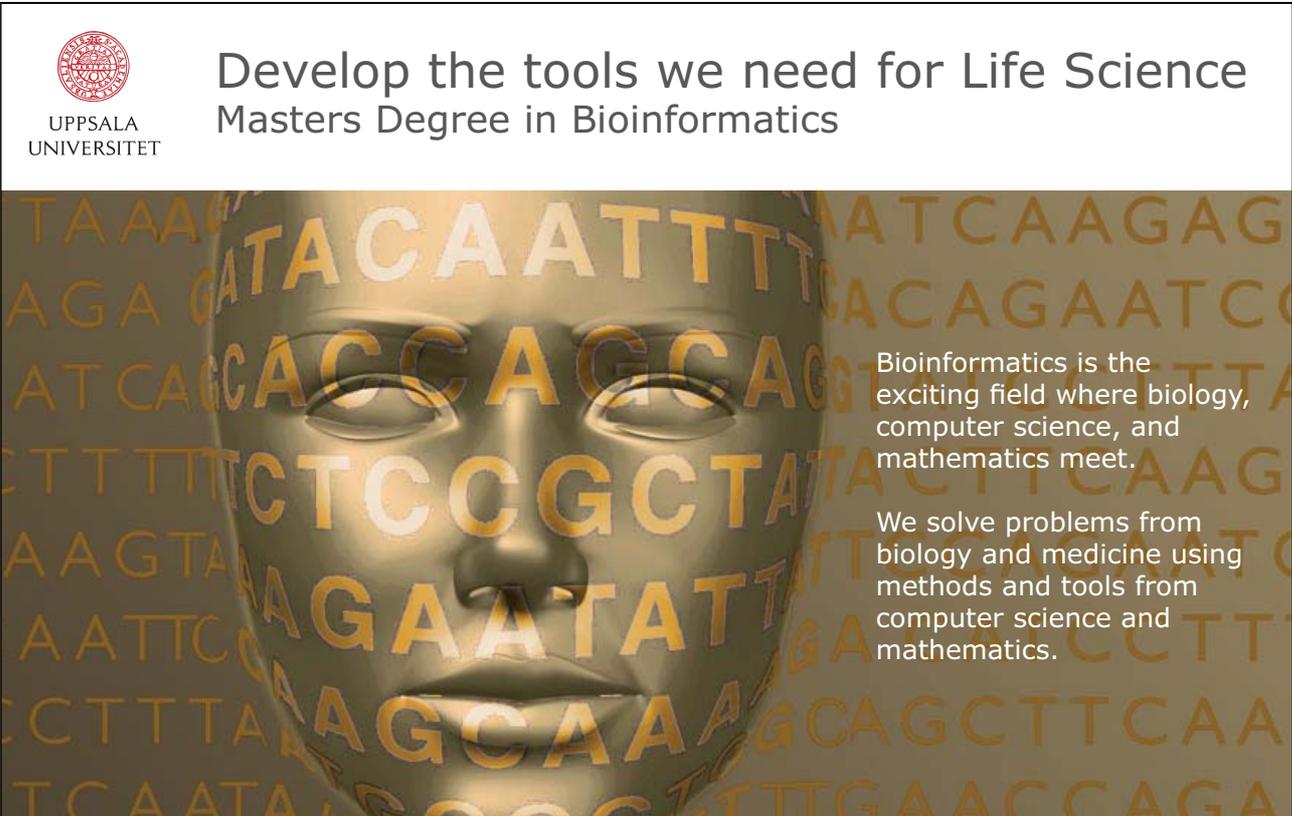
5. Reverse Engineering & Rapid Prototyping

The present chapter describes an assessment of the “state of the art” in respect to rapid prototyping processes. Based on a variety of reference material on latest developments of modern RP techniques, it is also aimed at identifying the reasons why these processes have developed and identifying the key features of the process.

5.1 Brief Rp Flashback

The first commercial process was presented at the AUTOFACT show in Detroit (US) in November 1987, by a company called 3D Systems, Inc. At that time, the process was very inaccurate and the choice of materials was limited. Therefore, the parts obtained were considered prototypes. Like in software engineering, a prototype is something to look at, serves as a basis for discussion but cannot be used for anything “serious”, *i.e.* in a production environment [1].

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Since then, Rapid Prototyping Technologies (RPT) have taken enormous strides. Nowadays, there are over 30 processes, some of which are commercial, while others are under development in research laboratories [1]. The accuracy has improved significantly, and the choice of materials is relatively large, to the extent that the term prototype is becoming misleading; the parts are more and more frequently being used for functional testing or to derive tools for pre-production testing. It is very likely that a new term, or one of the numerous other expressions that are floating around, will replace it in the future.

Rapid prototyping is the name given to a host of related technologies that are used to fabricate physical objects directly from **Computer-Aided Design (CAD)** data sources. These methods are generally similar to each other in that they add and bond materials in layerwise-fashion to form objects [1]. This is directly the opposite of what classical methods such as milling or turning do. Objects are formed in those processes by mechanically removing material.

These "three dimensional printers" allow designers to quickly create tangible prototypes of their designs, rather than just two-dimensional pictures. Such models have numerous uses. They make excellent visual aids for communicating ideas with co-workers or customers. In addition, prototypes can be used for design testing [1]. Designers have always utilised prototypes; RP allows them to be made faster and less expensively.

In addition to prototypes, RP techniques can also be used to make tooling (referred to as *rapid tooling*) and even production-quality parts (*rapid manufacturing*). For small production runs and complicated objects, rapid prototyping is often the best manufacturing process available [2].

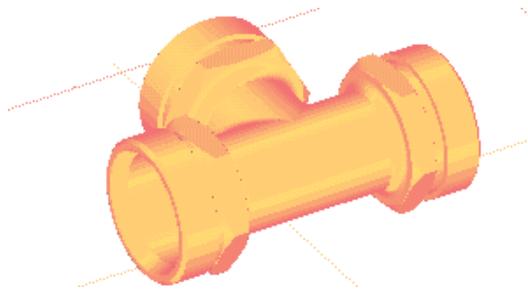


Fig. 5.1: CAD solid object

Rapid prototyping isn't necessarily very rapid and doesn't necessarily have to do with prototypes, either. Speed is relative: The processes can shave weeks to months off a design cycle, but still may require many hours to fabricate a single object. Prototypes for design evaluation are often made using these processes, but the technology also is beginning to address the direct production of final useful parts and assemblies, and injection moulding and other types of tools. Therefore "rapid" is a relative term. Most prototypes require from three to seventy-two hours to build, depending on the size and complexity of the object. This may seem slow, but it is much faster than the weeks or months required to make a prototype by traditional means such as machining. These dramatic time savings allow manufacturers to bring products to market faster and more cheaply [2].

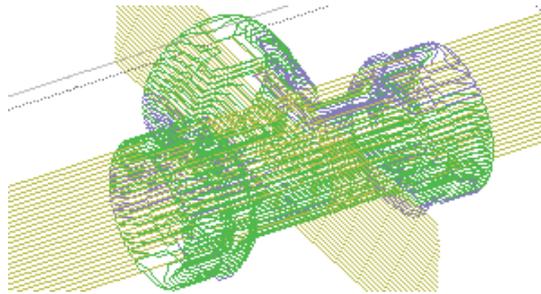


Fig. 5.2: Converted in STL format object

Because RP technologies are being increasingly used in non-prototyping applications, the techniques are often collectively referred to as solid free-form fabrication, computer automated manufacturing, or layered manufacturing. The latter term is particularly descriptive of the manufacturing process used by all commercial techniques. A software package "slices" the CAD model into a number of thin (~ 0.1 mm) layers, which are then built up one atop another [2]. Rapid prototyping is an "additive" process, combining layers of paper, wax, or plastic to create a solid object. In contrast, most machining processes (milling, drilling, grinding, etc.) are "subtractive" processes that remove material from a solid block. RP's additive nature allows it to create objects with complicated internal features that cannot be manufactured by other means [2].

5.2 The Basic Process

Although several rapid prototyping techniques exist, all employ the same basic five-step process. The steps are:

- **CAD Model Creation:** First, the object to be built is modelled using a CAD software package (Fig. 1).
- **Conversion to STL Format:** The various CAD packages use a number of different algorithms to represent solid objects. To establish consistency, the STL (Standard Triangulation Language -Stereolithography, the first RP technique) format has been adopted as the standard of the rapid prototyping industry [3]. The second step, therefore, is to convert the CAD file into STL format (Fig. 2). This format represents a three-dimensional surface as an assembly of planar triangles, like the facets of a cut jewel. The file contains the coordinates of the vertices and the direction of the outward normal of each triangle. Since the STL format is universal, this process is identical for all of the RP build techniques [3].
- **Slice the STL File:** In the third step, a pre-processing program prepares the STL file to be built. Several programs are available, and most allow the user to adjust the size, location and orientation of the model. The pre-processing software slices the STL model into a number of layers from 0.01 mm to 0.7 mm thick, depending on the build technique [3]. The program may also generate an auxiliary structure to support the model during the build. Each PR machine manufacturer supplies their own proprietary pre-processing software.

- **Layer by Layer Construction:** The fourth step is the actual construction of the part. Using one of several techniques RP machines build one layer at a time from polymers, paper, or powdered metal [3].
- **Clean and Finish:** The final step is post-processing. This involves removing the prototype from the machine and detaching any supports. Some photosensitive materials need to be fully cured before use. Prototypes may also require minor cleaning and surface treatment. Sanding, sealing, and/or painting the model will improve its appearance and durability [4].

5.3 Applications Of Rapid Prototyping

Rapid prototyping is widely used in the automotive, aerospace, medical, and consumer products industries. Although the possible applications are virtually limitless, nearly all fall into one of the following categories: prototyping, rapid tooling, or rapid manufacturing.

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Prototyping: As its name suggests, the primary use of rapid prototyping is to quickly make prototypes for communication and testing purposes. Prototypes dramatically improve communication because most people, including engineers, find three-dimensional objects easier to understand than two-dimensional drawings. Such improved understanding leads to substantial cost and timesavings [4].

Prototypes are also useful for testing a design, to see if it performs as desired or needs improvement.

Rapid Tooling: A much-anticipated application of rapid prototyping is rapid tooling, the automatic fabrication of production quality machine tools. Tooling is one of the slowest and most expensive steps in the manufacturing process, because of the extremely high quality required. Rapid tooling can be divided into two categories, indirect and direct [5].

- **Indirect Tooling:** RP parts are used as patterns for making moulds and dies. RP models can be indirectly used in a number of manufacturing processes:
 - *Vacuum Casting, Sand Casting, Investment Casting, Injection moulding.*
- **Direct Tooling:** To directly make hard tooling from CAD data is the one of most important for rapid tooling. Realisation of this objective is still several years away, but some strong strides are being made:
 - **RapidTool:** A DTM process that selectively sinters polymer-coated steel pellets together to produce a metal mould. The mould is then placed in a furnace where the polymer binder is burned off and the part is infiltrated with copper. The resulting mould can produce up to 50,000 injection mouldings [5].
 - **Laser-Engineered Net Shaping (LENS)** is a process that will create metal tools from CAD data.
 - **Direct AIM (ACES Injection Moulding):** A technique from 3D Systems in which stereolithography-produced cores are used with traditional metal moulds for injection moulding of high and low density polyethylene, polystyrene, polypropylene and ABS plastic [6].
 - In another variation, cores are made from thin SLA shells filled with epoxy and aluminium shot.
 - **LOMComposite:** There are ceramic composite materials for Laminated Object Manufacturing. LOMComposite parts would be very strong and durable, and could be used as tooling in a variety of manufacturing processes [6].
 - **Sand Moulding:** At least two RP techniques can construct sand moulds directly from CAD data. DTM sells sand-like material that can be sintered into moulds, while Soligen 3D Printing machines can produce ceramic moulds as well [7].

Rapid Manufacturing: A natural extension of RP is rapid manufacturing (RM), the automated production of saleable products directly from CAD data [6]. Currently only a few final products are produced by RP machines, but the number will increase as metals and other materials become more widely available. RM will never completely replace other manufacturing techniques, especially in large production runs where mass-production is more economical [7].

For short production runs, however, RM is much cheaper, since it does not require tooling. RM is also ideal for producing custom parts tailored to the user's exact specifications.

The other major use of RM is for products that simply cannot be made by subtractive (machining, grinding) or compressive (forging, etc.) processes. This includes objects with complex features, internal voids, and layered structures.

RPT in Industrial Design: When comparing industrial design applications to the manufacturing of toolings, the role of dimensional accuracy is not as significant as the quality of the surface. The stairstepping effect can be reduced in several ways. Firstly, good software tools can help minimise the problem. Secondly, post-treatment can be applied, and in this case, the part is usually polished. Finally, the processes can be improved to virtually eliminate the problem. For instance, the technology developed by Laser 3D can use a layer thickness as low as resulting in parts with no noticeable stairstepping effect to the naked eye. Soligen claims that their process can also eliminate the stairstepping using different principles [8].

RPT in Medical Applications: Applying RPT in the medicine is a new and exciting field. Many applications have become possible due to the convergence of three distinct technologies, namely Medical Imaging, Computer Graphics and CAD, and RPT [8].

Computer-Assisted Tomography (CT) and Magnetic Resonance Imaging (MRI) provide high-resolution images of internal structures of the human body, e.g. bone structures and organs. Once these images have been processed by suitable software tools, it is possible to transfer the result to a RP process and obtain a physical part, called a *medical model* (Figure 5.3).

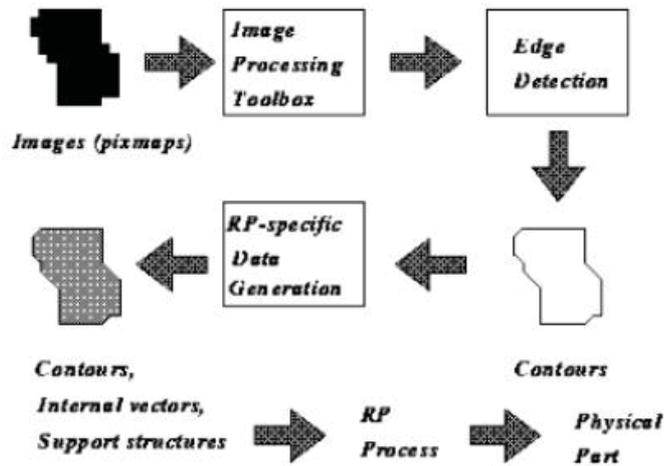


Fig. 5.3: Obtaining medical models from scanned images

Together, these technologies provide doctors and surgeons with new tool-physical models of human internal structures-to better plan and prepare complex surgeries. If the surgeries can be carried out more successfully, less cost associated to post-operative treatment are expected, in addition to reduced risks, reduced patient suffering, and improvements in the quality of the results.

Another recent application has been the manufacturing of a human chromosome [8].

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5.4 Rapid Prototyping Techniques

The new rapid prototyping technologies are additive processes. They can be categorised by material: photopolymer, thermoplastic, and adhesives.

Photopolymer systems start with a liquid resin, which is then solidified by discriminating exposure to a specific wavelength of light. **Thermoplastic systems** begin with a solid material, which is then melted and fuses upon cooling. **The adhesive systems** use a binder to connect the primary construction material [8].

The names of specific processes themselves are also often used as synonyms for the entire field. Among these are stereolithography (SLA for stereolithography apparatus), selective laser sintering (SLS), fused deposition modelling (FDM), laminated object manufacturing (LOM), solid ground curing (SGC), inkjet systems and three dimensional printing (3DP).

Several processes are now most widely distributed in the United States, Europe, and Asia; many more are in the developmental stages.

5.4.1 Stereolithography (SlA)

5.4.1.1 Principle Of Operation

Patented in 1986, stereolithography started the rapid prototyping revolution and is a free form fabrication technology, developed by 3D Systems, Inc. Due to its accuracy and surface finish, it has become the most popular of the rapid prototyping methods.

The technique builds three-dimensional models from liquid photosensitive polymers that solidify when exposed to ultraviolet light. Stereolithography builds plastic parts or objects a layer at a time by tracing a laser beam on the surface of a vat of liquid photopolymer. This class of materials, originally developed for the printing and packaging industries, quickly solidifies wherever the laser beam strikes the surface of the liquid [8].

5.4.1.2 Process Description

The STL file of the proposed component is sliced by software. Each slice is then hatched on to the surface of a photosensitive ultraviolet curable resin with a "swinging" laser. Where the focused beam of the laser strikes the surface the resin is cured. Each slice is typically 0.1mm thick. After each layer is cured the partially built model is lowered in to a vat of resin by one layer thickness. A recoating blade then lays a thin film of uncured resin over the surface of the resin [9].

Overhanging portions of the model are supported by a lattice that is automatically generated and incorporated into each layer by the software. The model is built on a support lattice to prevent direct adhesion to the recoating table, thus allowing the model to be removed relatively easily on completion of the build. On completion of the build the model is carefully removed from the

platform and washed in a solvent to remove the uncured resin from the surface [9]. The model is then placed in a ultraviolet oven to harden any uncured resin. The process is shown in Figure 5.4.

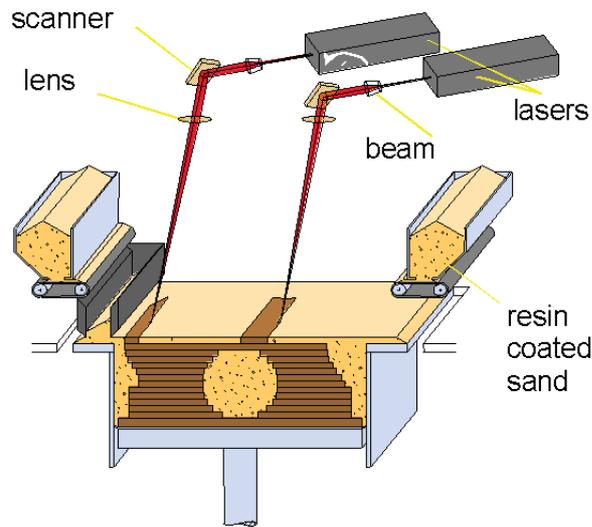


Fig. 5.4: Schematic diagram of the stereolithography process

Because it was the first technique, stereolithography is regarded as a benchmark by which other technologies are judged. Early stereolithography prototypes were fairly brittle and prone to curing-induced warpage and distortion, but recent modifications have largely corrected these problems [9].

5.4.1.3 Advantages

Stereolithography generally is characterised with:

Good dimensional accuracy - The process is able to maintain the dimensional accuracy of the built parts to within $\pm 0.1\text{mm}$.

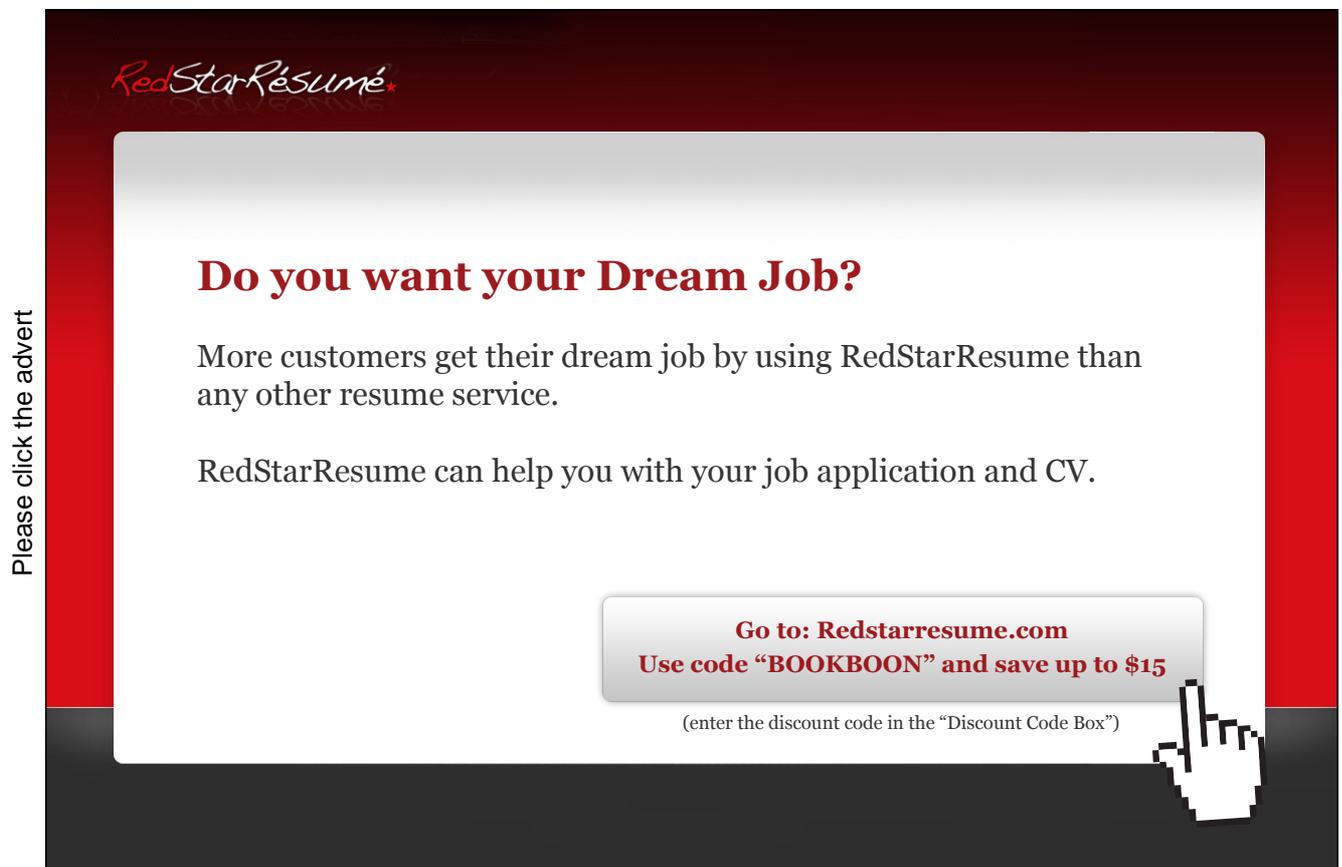
- Good surface finish - Glass-like finishing can be obtained on the top surfaces of the part although stairs can be found on the side walls and curve surfaces between build layers [9].
- Unattended building process - The system is very stable. Once started the process is fully automatic and can be unattended until the process is completed.
- The process is of high resolution and capable to build parts with rather complex details
- 3D Systems Inc. have developed a software called "Quickcast" for building parts with hollow interior which can be used directly as wax pattern for investment casting
- It is the most widely used process in the RP field [9].

5.4.1.4 Disadvantages

Stereolithography also have some disadvantages, as follows:

- Curling and warping - The resin absorb water as time goes by resulting curling and warping especially in the relatively thin areas [10].
- Relatively high cost (US\$200-500K) - However, it is anticipated that the cost will be coming down shortly.
- Narrow range of materials - The material available is only photosensitive resin of which the physical property, in most of the cases, cannot be used for durability and thermal testing.
- Post curing - The parts in most cases have not been fully cured by the laser inside the vat. A post curing process is normally required [10].

High running and maintenance cost - The cost of the resin and the laser gun are very expensive. Furthermore, the optical sensor requires periodical fine-tuning in order to maintain its optimal operating condition, which will be considerable, expensive [10].



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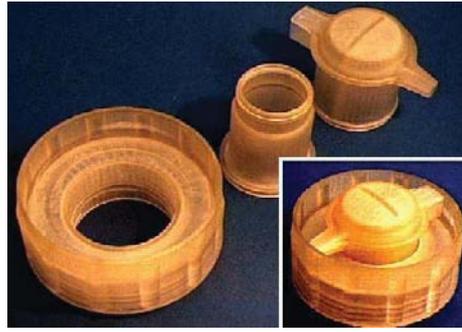


Fig. 5.5: Objects in different prototyping states

5.4.1.5 Application Field

- Prototypes for concept models (Fig. 5.5);
- Form-fit for assembly tests and process planning;

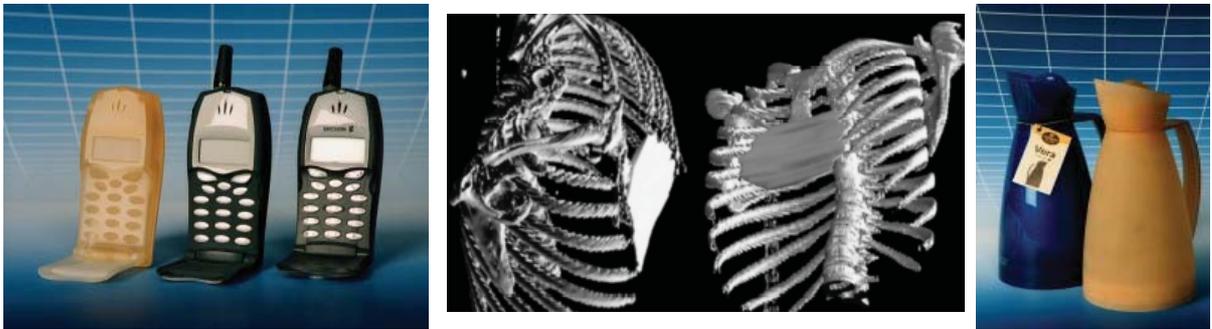


Fig. 5.6: SLA RP Prosthesis

- Models for investment casting, replacement of the wax pattern;
- Patterns for metal spraying, epoxy moulding and other soft tooling;
- A medical application of the stereolithography in surgery to produce equipment; design and manufacturing of orthopaedic implants (Fig. 5.6) [10].

5.4.2 Selective Laser Sintering (SIs)

5.4.2.1 Principle Of Operation

Developed by Carl Deckard for his master's thesis at the University of Texas, selective laser sintering was patented in 1989. CAD files are transferred to the system, where they are sliced and drawn, one cross-section at a time, by applying the laser beam to a thin layer of powder. The laser beam fuses the powder particles to form a solid mass that matches the CAD design. As each layer is drawn, the prototypes take shape within the system.

5.4.2.2 Process Description

The technique, shown in Figure 5.7, uses a laser beam to selectively fuse powdered materials, such as nylon, elastomer, and metal, into a solid object. Parts are built upon a platform which sits just

below the surface in a bin of the heat-fusible powder. A laser traces the pattern of the first layer, sintering it together. The platform is lowered by the height of the next layer and powder is reapplied. This process continues until the part is complete. Excess powder in each layer helps to support the part during the build [10].

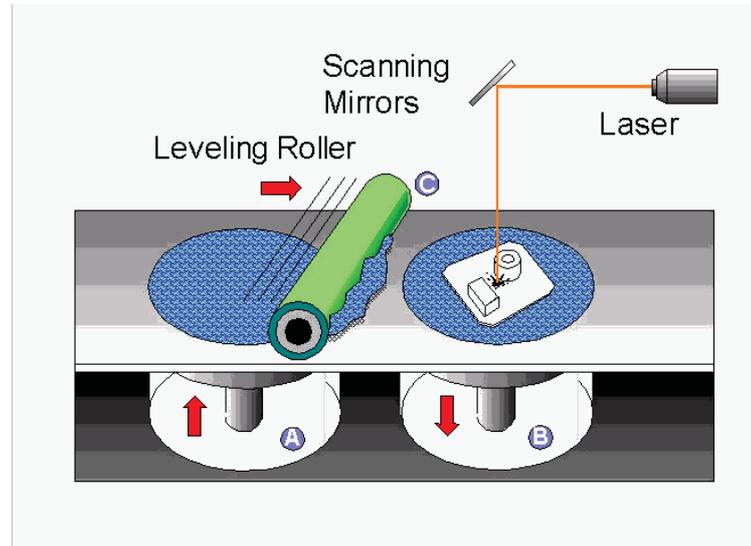


Fig. 5.7: Schematic diagram of selective laser sintering

The finished objects have a matte, powdery surface. Objects made by SLS using nylon powder have a powdery white appearance. The surface is absorbent and marks easily, but otherwise the objects are fairly robust, and can be made with moving parts such as hinges. Models can be sanded down and painted if required, to give a smooth finish. Commercial systems are made by DTM Corporation and EOS GmbH. SLS models can be made in wax, sand or steel powder as well as nylon [10].

Materials most often used in selective laser sintering are polycarbonate and nylon. For polycarbonates, densities of 75-92% of that of the standard injection-moulded material can be obtained; for nylon even better values, 87-93%, have been realised. Another material that is well suited for the process is investment casting wax. This allows the direct construction of wax patterns for foundry use. The SLS process provides the most functional rapid prototype available [10].

5.4.2.3 Advantages

- Capable of producing the toughest part compared with other process
- Large variety of material can be used, including most engineering plastic, wax, metal, ceramic, etc.
- Parts can be produced in short time, normally at a rate of up to 1 inch per hour
- No post curing of parts is required
- During the building process, the part is fully supported by the powder and no additional support is required.
- Parts can be built on top of others [10].

5.4.2.4 Disadvantages

- The powder material requires to heat up to the temperature below the melting point before the building process, which takes about 2 hours. After building the parts, it also takes 5 to 10 hours to cool down before removing the parts from the powder cylinder.
- The smoothness of the surface is restricted to the size of the powder particles and the laser spot resulting that the surface of the part is always porous. Smooth surface can only be obtained by post processing [10].
- The process chamber requires continuous supply of nitrogen to provide a safe environment for the sintering process to be taken place resulting expensive running cost of the process.
- Toxic gases will be generated from the process, which leads to an environmental issue.

5.4.2.5 Application Field

Considering the density results just mentioned, selective laser sintering is particularly suited to build fully functional prototypes in polycarbonates and/or nylons, that closely approximate the mechanical properties found in the final (i.e., injection-moulded) products. Such models can be tested before any capital outlay for the construction of injection moulds becomes necessary [10].

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Fig. 5.8: Processes SLS LaserForm; SLS DuraForm; SLS CastForm PS

5.4.3 Fused Deposition Modeling (Fdm)

5.4.3.1 Principle Of Operation

FDM is the second most widely used rapid prototyping technology, after stereolithography. Fused deposition modelling builds a product up in thin layers of thermoplastic wire-like filaments. There's no need for messy liquid photopolymers, no powders, no lasers.

5.4.3.2 Process Description

In this technique, filaments of heated thermoplastic are extruded from a tip that moves in the x-y plane. Like a baker decorating a cake, the controlled extrusion head deposits very thin beads of material onto the build platform to form the first layer. The platform is maintained at a lower temperature, so that the thermoplastic quickly hardens. After the platform lowers, the extrusion head deposits a second layer upon the first. Supports are built along the way, fastened to the part either with a second, weaker material or with a perforated junction [10].

Several materials are available for the process including ABS and investment casting wax. ABS offers good strength, and more recently polycarbonate and polysulfone materials have been introduced which extend the capabilities of the method further in terms of strength and temperature range. Support structures are fabricated for overhanging geometries and are later removed by breaking them away from the object. A water-soluble support material which can simply be washed away is also available [11].

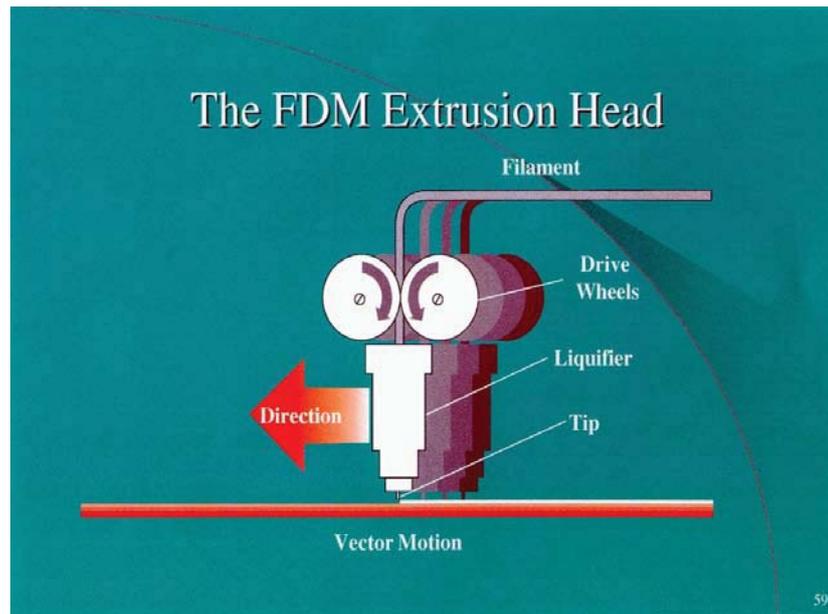


Fig. 5.9: Schematic diagram of fused deposition modelling

The method is office-friendly and quiet. FDM is fairly fast for small parts on the order of a few cubic inches, or those that have tall, thin form-factors. It can be very slow for parts with wide cross sections, however. The finish of parts produced with the method have been greatly improved over the years, but aren't quite on a par with stereolithography. The closest competitor to the FDM process is probably three-dimensional printing [11]. However, FDM offers greater strength and a wider range of materials than at least the implementations of 3DP from Z Corp. which are most closely comparable.

5.4.3.3 Advantages

The advantages of FDM Rapid Prototyping are follows:

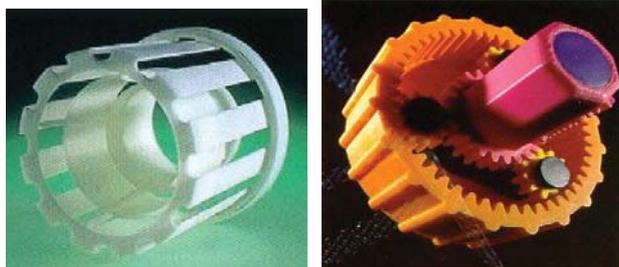
- Quick and cheap generation of models;
- Different colours are possible;
- Easy and convenient date building;
- There is no worry of possible exposure to toxic chemicals, lasers, or a liquid polymer bath [11];
- The system does not waste material during or after producing the model, it does not require clean-up;
- Materials can be changed quickly.

5.4.3.4 Disadvantages

- Restricted accuracy due to the shape of the material used: wire of 1,27 mm diameter.
- Supports may be required
- Part strength is weak perpendicular to build axis.
- Temperature fluctuations during production could lead to delamination [11].

5.4.3.5 Application Field

- Model for operation and functional part testing;
- Design model for assessing a product's final appearance and geometry;
- After assembling the parts, the working of complete products can be evaluated;
- Investment casting and injection moulding.



*Fig. 5.10: Fully functional model built by fused deposition modelling
Complex model built of a number of separate parts each made by fused deposition modelling*

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5.4.4 Laminated Object Manufacturing (Lom)

5.4.4.1 Principle Of Operation

In this technique, developed by Helisys of Torrance, CA, layers of adhesive-coated sheet material are bonded together to form a prototype. The original material consists of paper laminated with heat-activated glue and rolled up on spools.

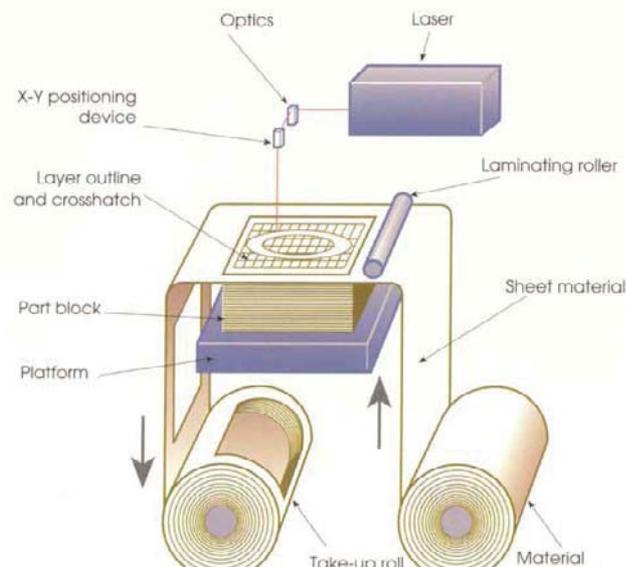


Fig. 5.11: Laminated object manufacturing

5.4.4.2 Process Description

Profiles of object cross sections are cut from paper or other web material using a laser. A focused laser cuts the outline of the first layer into the paper and then cross-hatches the excess area (the negative space in the prototype). The paper is unwound from a feed roll onto the stack and first bonded to the previous layer using a heated (laminating) roller (Figure 5.11), which melts a plastic coating on the bottom side of the paper. The profiles are then traced by an optics system that is mounted to an X-Y stage. After cutting of the layer is complete, excess paper is cut away to separate the layer from the web. Waste paper is wound on a take-up roll [11]. The method is self-supporting for overhangs and undercuts. Areas of cross sections which are to be removed in the final object are heavily cross-hatched with the laser to facilitate removal (Figure 5.12).



Fig. 5.12: Cubes separating from the object's surface

Helisys developed several new sheet materials, including plastic, water-repellent paper, and ceramic and metal powder tapes. The powder tapes produce a "green" part that must be sintered for maximum strength [12]. While there are limitations on materials, work has been done with plastics, composites, ceramics and metals. Some of these materials are available on a limited commercial basis.

5.4.4.3 Advantages

LOM has following advantages:

- The raw materials costs are relatively low;
- The process is much faster than competitive techniques;
- The process produces virtually no internal stress and associated undesirable deformation [12];
- LOM Slice possesses the robust capacity of dealing with imperfect STL files, created with discontinuities, in which the surfaces of STL objects are not closed completely;
- Best suited for building large parts.

5.4.4.4 Disadvantages

- The stability of the objects is limited by the bonding strength of the glued layers;
- As the procedure is not well suited for manufacturing parts with thin walls in the z-direction, the application range is approximately restricted to complex parts [10];
- Hollow parts, like bottles, can not be built.

5.4.4.5 Application Field

- LOM objects are used as precise patterns for secondary tooling processes such as rubber moulding, sand casting and direct investment casting [8];
- LOM objects can be used to make spray metal moulds for prototype injection moulding.
- LOM's geometrical stability, inherent precision and high resolution lends itself to the plaster casting process.
- The durability and rigidity of LOM objects make them suitable for low to medium volume vacuum forming of thin plastic components [8].
- LOM objects can be used also for limited testing and as visual models.

There are also variations, developed by many others companies and research groups, which seek to increase speed and/or material versatility by cutting the edges of thick layers diagonally to avoid stair stepping.



Fig. 5.13: Some LOM's applications

5.4.5 Solid Ground Curing (Sgc)

5.4.5.1 Principle Of Operation

Developed by Cubital (Israel), solid ground curing (SGC) is something of a hybrid between Stereolithography and laser printing. The machine makes an image of the cross-section of the model on a glass plate, using similar methods to those employed in a laser printer [8]. The surface of the liquid photo-polymer is solidified by exposing it to light from a UV lamp (similar to stereolithography), using the glass plate as a mask which allows the light through to expose the liquid surface in selected areas. Unlike SLA, SGC cures an entire layer at a time.

5.4.5.2 Process Description

Figure 5.14 depicts solid ground curing, which is also known as the solider process. First, photosensitive resin is sprayed on the build platform. Next, the machine develops a photomask (like a stencil) of the layer to be built. This photomask is printed on a glass plate above the build platform using an electrostatic process similar to that found in photocopiers. The mask is then exposed to UV light, which only passes through the transparent portions of the mask to selectively harden the shape of the current layer.

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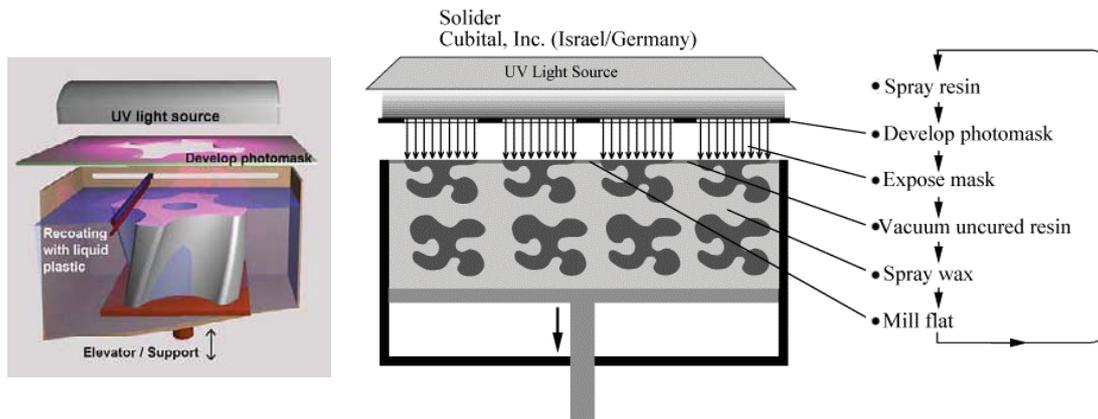


Fig. 5.14: Schematic diagram of solid ground curing

After

the layer is cured, the machine vacuums up the excess liquid resin and sprays wax in its place to support the model during the build. The top surface is milled flat and then the process repeats to build the next layer [8]. When the part is complete, it must be de-waxed by immersing it in a solvent bath. SGC machines are quite big and can produce large models.

5.4.5.3 Advantages

- Multiple parts can be positioned within the entire working envelop resulting high throughput;
- No support structure is required as the wax support the structure in all directions [7];
- Part complexity does not effect speed, however volume does;
- Each layer is fully cured resulting that the dimension is very stable with no shrinkage effect after the process and requires no post-curing process;
- Capable to build even the most complicated parts without much difficulty;
- Build session can be interrupted and erroneous layer can be erased [8].

5.4.5.4 Disadvantages

- The process is rather complicate which required skilled people to look after and unattended operation is not possible;
- The resin consumption is disregard of the size of the cross section of the parts but only depended on the number of layers resulting that it is too expensive for parts with small cross sectional area [9];
- The machine is very large (Fig. 5.15) and machining is noisy;
- Very few materials available;
- High equipment cost (over US\$500,000) made it not easily to be justified.



Fig. 5.15: SGC machine Solider 5600

5.4.5.5 Application Field

Application field of Solid Ground Curing is similar to SLA and can produce parts with even more complicated details:

Form-fit for assembly tests and process planning; prototypes for concept models (Fig. 5.16); models for investment casting, replacement of the wax pattern; soft tooling; and medical application [11].



Fig. 5.16

5.4.6. Ink-Jet Printing

5.4.6.1 Principle Of Operation

This technology is also called Three Dimensional Printing (3DP). Actually, there is a broad range of diverse technologies that fall into the ink-jet printing category, but all rely on squirting a build material in a liquid or melted state, which cools or otherwise hardens to form a solid on impact.

5.4.6.2 Process Description

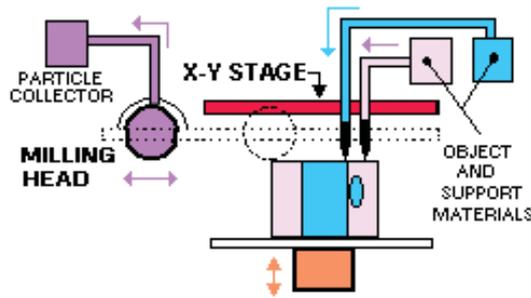


Fig. 5.17: Schematic diagram of Ink-jet printing technology

Solidscape, Inc.'s inkjet method (Thermal Phase Change Inkjets) uses a single jet each for a plastic build material and a wax-like support material, which are held in a melted liquid state in reservoirs (see Figure 5.17). The liquids are fed to individual jetting heads which squirt tiny droplets of the materials as they are moved in X-Y fashion in the required pattern to form a layer of the object [12]. The materials harden by rapidly dropping in temperature as they are deposited. After an entire layer of the object is formed by jetting, a milling head is passed over the layer to make it a uniform thickness. Particles are vacuumed away as the milling head cuts and are captured in a filter. The process is repeated to form the entire object. After the object is completed, the wax support material is either melted or dissolved away [13].

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5.4.6.3 Advantages

The most outstanding characteristic of the Solidscape system is the ability to produce extremely fine resolution and surface finishes, essentially equivalent to CNC machines.

5.4.6.4 Disadvantages

However, the technique is very slow for large objects. While the size of the machine and materials are office-friendly, the use of a milling head creates noise which may be objectionable in an office environment. Materials selection also is very limited [13]. All thermal phase change inkjets have material limitations and make fragile parts.

5.4.6.5 Application Field

The applications range from concept models to precise casting patterns for industry and the arts, particularly jewellery.

5.4.7 Multijet Modelling (Mjm)

5.4.7.1 Principle Of Operation

One example of the technology variations available in these so-called phase change inkjets is provided by 3D Systems. This company produces an inkjet machine, called the ThermoJet Modeler (formerly Actua), based on MultiJet Modelling (MJM) technology, which utilises several hundred nozzles.

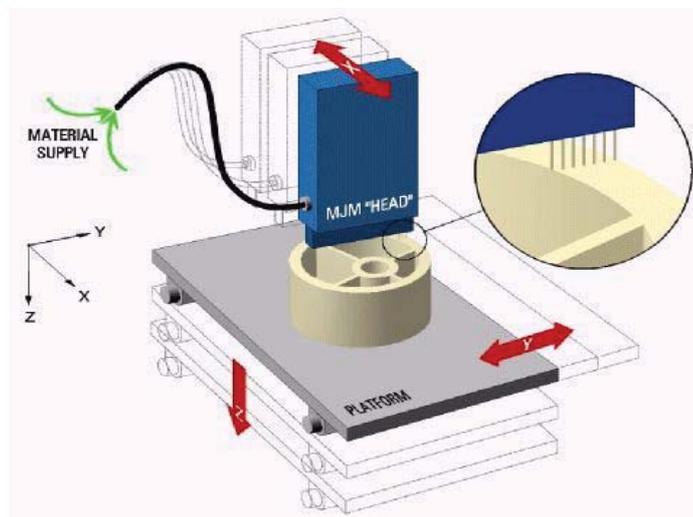


Fig. 5.18: MJM - 3D Systems

5.4.7.2 Process Description

The completed CAD solid model is transferred to a STL file, ready for the build process. Parts are built by an innovative process that uses a MultiJet Modelling (MJM) head to apply a

thermopolymer material in three dimensions. The print head comprises multiple jets that build the model layer by layer. If the part is larger than the MJM head the build platform will reposition within the Y-axis such that the process may continue (Fig. 5.19). MJM head is illustrated in Figure 5.18 [13].

The material deposition process of the 3D printer is very similar to that of the ink jet printer and is illustrated in Figure 5.18.

As the development stage processes near manufacture, costs of change increase accordingly. Changing a functional prototype has the disadvantage of high cost and delay to production. Desktop 3D printing is the best solution to concept modelling where changes can be introduced early within modelling. Introducing a change in the concept phase can be easily absorbed.

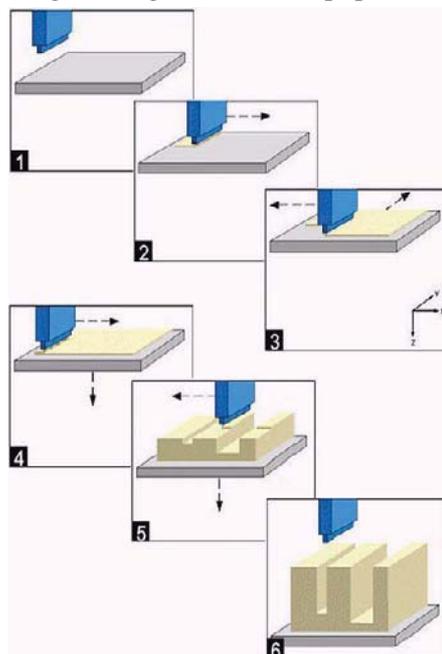


Fig. 5.19

5.4.7.3 Advantages

Three-dimensional printing is often used as a direct manufacturing process as well as for rapid prototyping. Desktop rapid prototyping machines are based on desktop printing technology [14]. They are no larger than a photocopier, run just as cleanly and quietly and have a number of advantages over other rapid prototyping techniques:

- the machines have lower purchasing costs,
- parts are cheaper to construct

Three-dimensional printing offers the advantages of speedy fabrication and low materials cost. In fact, it's probably the fastest of all RP methods. Recently colour output has also become available.

5.4.7.4 Disadvantages

There are limitations on resolution, surface finish, part fragility and available materials. Models constructed using the 3D printer method are weak and can easily be damaged and distorted [14]. In this case these models can be strengthened by infiltrating with wax, and ink can be added to the initially transparent wax to produce parts that have a variety of colours.

Some rapid prints need post-processing, either for design integrity or aesthetic appearance. Typical post-processing involves sanding or painting, making the part more appealing for presentational purposes. Completed models are initially fragile and require dipping into molten wax or an epoxy which introduces durability.

5.4.7.5 Application Field

One application for 3D Printing is to create ceramic moulds for metal casting. Another application is to print metal parts directly [14]. New efforts are directed at making structural ceramic parts and parts for medical application within the human body.



Fig. 5.20: Injection moulding tools made by 3D Printing; Ceramic mould made by 3D Printing and an orthopaedic knee casting poured into a similar mould;. Colour-coded objects, such as this model of a compressor.

5.4.8 Paper Lamination Technology (PLT)

5.4.8.1 Principle Of Operation

This technique is a variation on LOM and was developed by Kira Corporation. Paper Lamination Technology (PLT) uses a knife to cut each layer instead of a laser and applies adhesive to bond layers using the xerographic process. The Paper Lamination Technology (PLT) uses an additive/subtractive process by which layers of paper (for use with copy machine) are bonded together by high heat and pressure and then uses computerised cutter to cut to desired profiles [14]. Similar to the LOM technology, the part does not go through a phase change.

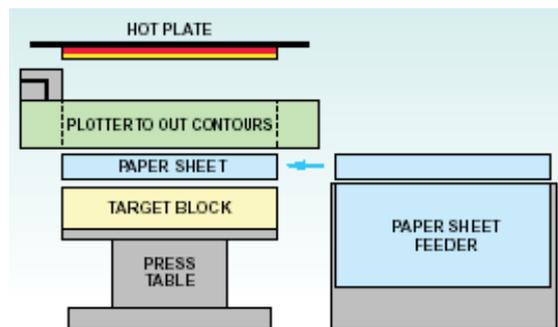


Fig. 5.21: PLT System

5.4.8.2 Process Description

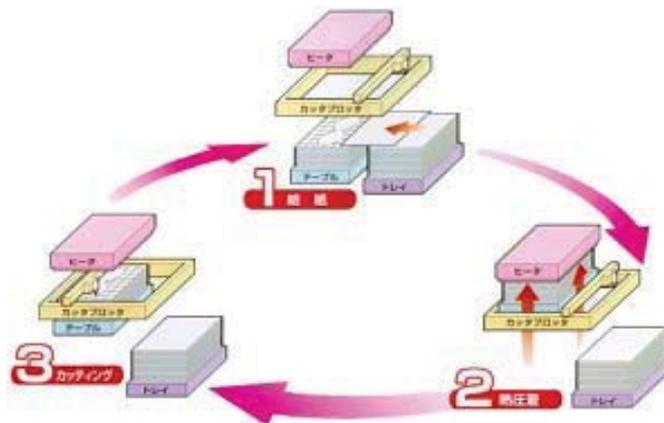


Fig. 5.22: PLT process

Products are made by paper lamination as follows:

- Paper Feed Unit (Figure 5.22-1): A sheet feed mechanism orients the one sheet on the target block.
- Hot Press System (Figure 5.22-2): Using high pressure, the hot press moves the target block with sheet up a hot plate. All the area of the sheet is applied adheres to the target block. The amount of movement up to the hot plate is measured. If deviation in sheet and

resin thickness is identified, automatic compensation is made to insure dimensional integrity of the completed 3D model [14].

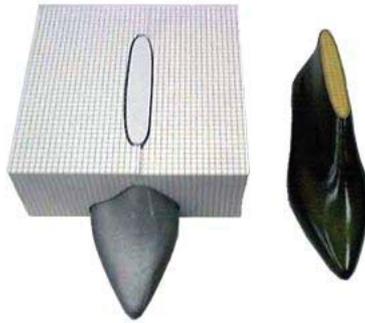


Fig. 5.23

- Cutting Process (Figure 5.22-3): The PC generates plotting data based on section data of the target shape. A mechanical cutter cuts the top layer of the target block along the contour of the section [14].
- Processes are repeated rapidly and accurately. Unnecessary portions are removed (Figure 5.23).

5.4.8.3 Advantages

- High lamination pressure makes the model 25% harder than wood (as substitutes);
- Minimal internal strain and no curing;
- Use commercial paper and toner;
- Low running cost and relatively small size of equipment;
- Requires no special operation techniques [15].

5.4.8.4 Disadvantages

- The models must be sealed and finished with paint or varnish to prevent moisture damage. It can be time consuming to remove extra material for some geometries [15].
- Like method, based on laminated object manufacturing will be limited in what can be accomplished because of the raw material thickness.



Fig. 5.24

5.4.8.5 Application Field

The field of PLT applications is too large (Fig. 5.24): Modelling, Prototypes, Sand Casting, Vacuum Casting Silicon Mould Application, 3D-GIS Models, Industrial Models, Vacuum Casting, Wind Volume Test Models.

5.4.9 Laser Engineered Net Shaping (Lens)

Laser Engineered Net Shaping (LENS) is a technology that is gaining in importance and in early stages of commercialization. A high power laser is used to melt metal powder supplied coaxially to the focus of the laser beam through a deposition head (Figure 5.25). The laser beam typically travels through the centre of the head and is focused to a small spot by one or more lenses. The X-Y table is moved in raster fashion to fabricate each layer of the object. The head is moved up vertically as each layer is completed [15]. Metal powders are delivered and distributed around the circumference of the head either by gravity, or by using a pressurised carrier gas. An inert shroud gas is often used to shield the melt pool from atmospheric oxygen for better control of properties, and to promote layer to layer adhesion by providing better surface wetting [15].

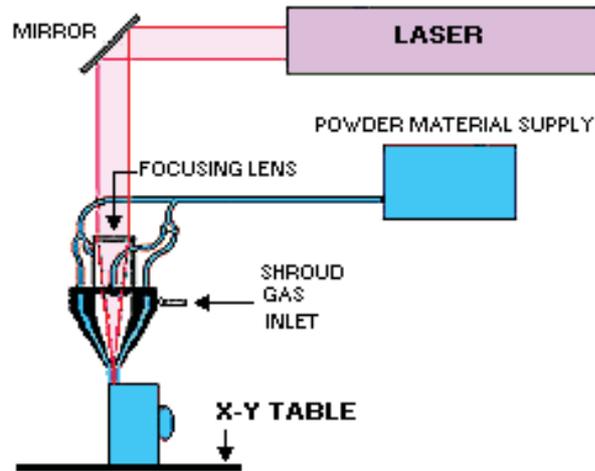


Fig. 5.25: Schematic diagram of Laser Engineered Net Shaping

A variety of materials can be used such as stainless steel, Inconel, copper, aluminium etc. Of particular interest are reactive materials such as titanium. Materials composition can be changed dynamically and continuously, leading to objects with properties that might be mutually exclusive using classical fabrication methods.

The strength of the process lies in the ability to fabricate fully dense metal parts with good metallurgical properties at reasonable speeds. Objects fabricated are near net shape, but generally will require finish machining. They have good grain structure, and have properties similar to, or even better than the intrinsic materials.

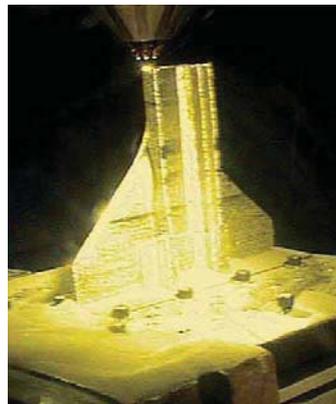


Fig. 5.26: LENS process

LENS has fewer material limitations than SLS and doesn't require secondary firing operations as some of those processes do, however [10].

5.4.10 Photopolymer Phase Change Inkjets

Recently, inkjet technology has been extended to operation with photopolymers resulting in systems that have both fast operation and good accuracy.

Objet Geometries Ltd., an Israeli company, announced the Quadra™ system in early 2000. It's potentially a promising replacement for stereolithography. The process is based on photopolymers, but uses a wide area inkjet head to layerwise deposit both build and support materials. It subsequently completely cures each layer after it is deposited with a UV flood lamp mounted on the printhead [12]. The support material, which is also a photopolymer, is removed by washing it away in a secondary operation. The low price, approximately \$65K, and specifications that are similar to laser-based stereolithography systems costing ten times as much make this an important technology to watch [11].

In July, 2002, 3D Systems introduced a similar photopolymer-based system called the InVision™.

5.4.11 Electroset Technology

rapid prototyping technology. Electroset Synergistic Technologies Corporation holds the international patent rights [13]. Electroset rapid prototyping technology uses electric fields to shape objects. The typical electroset system consists of a personal computer (with graphics system), an electrode printer, and a high-voltage power supply.

This process takes several steps. First, a cross section of the object is generated on the computer. The computer then sends the image to the printer where the electrodes are formed into the shape of the image and attached to a frame (the frame is a sheet of conductive material such as aluminium foil). When all frames are complete, they are sandwiched into a mould, which is connected to a power supply [14]. The mould is immersed into a bath of Electroset fluid and energised. Upon energising, the fluid between the electrodes solidifies. The mould is withdrawn from the bath and excess fluid drains from the object. After trimming off the mould framing, the part is complete. The hardware required for a manually operated system of this type would have a price of about \$5000. Any added automation would drastically raise the price [16].

A unique feature in this technology is the ability to electrically predetermine the material properties of the cured object. Material properties that are programmable include density, compressibility, hardness, and adhesion. The material properties can be programmed during Electrosetting by controlling the maximum applied current independently from the maximum applied voltage [16].

Common Electroset materials used include silicone rubber, polyester, polyurethane, and epoxy.

5.4.12 Photochemical Machining

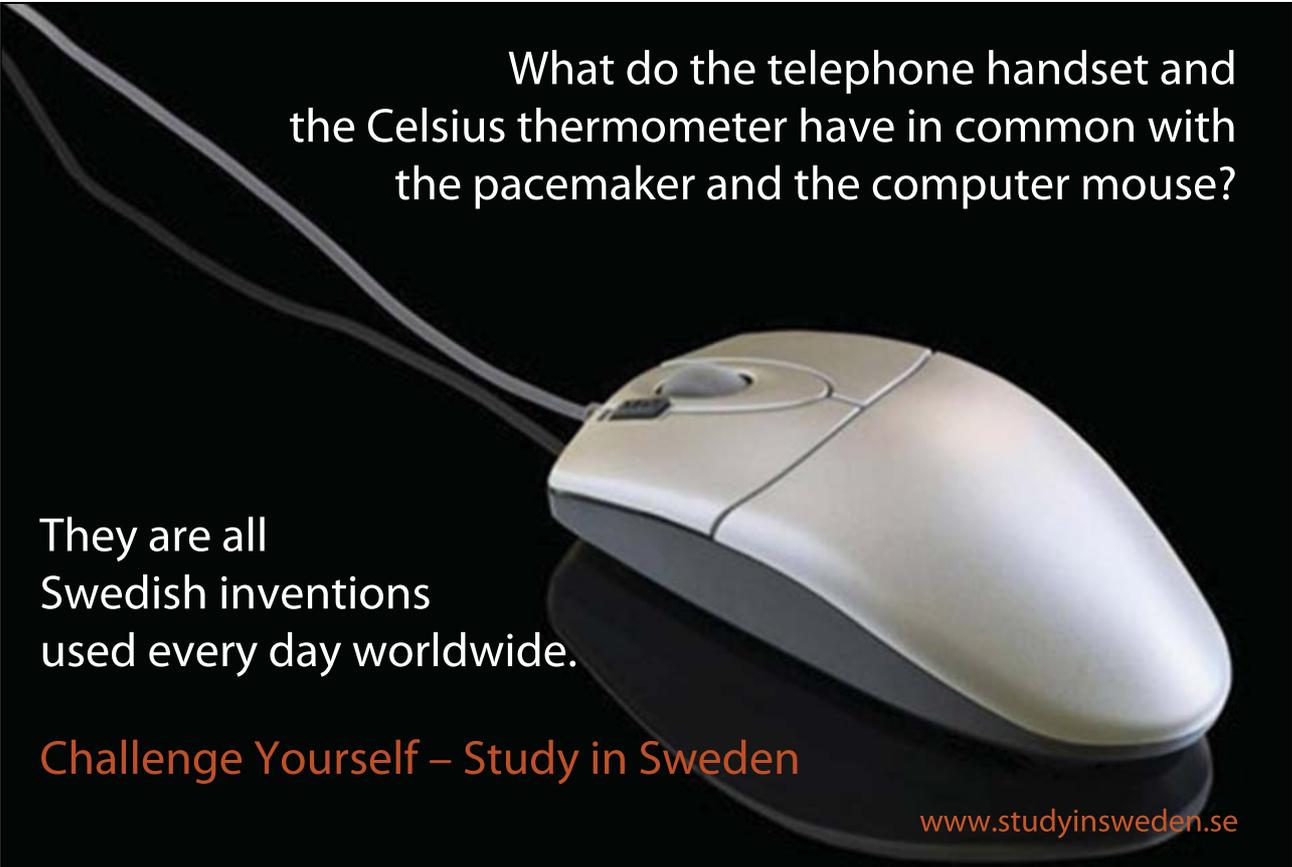
Photochemical Machining, a process similar to SLA but still under development, uses two intersecting laser beams to form a three-dimensional prototype out of a photopolymer block. Research on this process by Battelle (Columbus, OH) and Formigraphics Engine Corporation (Berkeley, CA) dates back to the 1960s with related patents [15].

Because of the use of two lasers, this method could be the most versatile photopolymer-based rapid prototyping process. One beam moves in the x-y plane. The other beam moves in the y-z plane.

Each beam has different wavelengths. The combination of the intersecting beams polymerises the material, rather than a single laser beam solidifying an area on the surface of the material [15]. Forming a part in the z-axis no longer needs to be done in layers. Initialising the laser's movement in any set of X-, Y-, Z-coordinates allows the ability to trace the part in three dimensions rather than two. This capability would reduce prototyping time even more.

Areas in need of research and development are in the lasers and in the photopolymer [15]. The lasers need improvement in the selectivity of the laser sensitises and in quality of the beam. Also, work needs to be done on the speed and efficiency of the beams; it currently takes almost a minute for the beam to cure the polymer. Work also remains to be done in developing a polymer that will not cure by the exposure of a single laser beam [15].

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5.4.13 Design-Controlled Automated Fabrication (Descaf)

The Design-Controlled Automated Fabrication (DESCAF) process builds prototypes a layer at a time by exposing liquid polymer to ultraviolet light through a photomask. An entire layer is solidified simultaneously. The SOMOS Solid Imaging System is similar to SLA but differs in the photopolymer used and the laser system [15]. The material is a white, low shrinkage, proprietary resin with properties similar to silicon rubber. This material is claimed to have high photospeed, low shrinkage and warpage, wide exposure latitude, flexible and homogeneous photoformed parts, and good layer-to-layer adhesion. The SOMOS system employs an argon-ion laser with high-precision scanning in a raster pattern and high-speed beam modulation [15]. The Solid Creation System (SCS) uses similar technology used in Stereolithography, but has the ability to build larger parts. The largest system has a build area of 40x32x20 inches.

5.4.14 Liquid Metal Jet Printing (Lmjp)

The Liquid Metal Jet Printing (LMJP) is a revolutionary process technology in additive solid freeform manufacturing process. It can build mechanical parts and electronic interconnects in an additive manner. Unlike spray forming, LMJP is similar to ink jet printing where every individual molten droplet is controlled and printed to specific location. By changing the orifice size, the system will dispense molten spheres of metal with diameters from 100 to 1000 microns [15].

At the moment research work is focused on development of an aluminium-printing device for rapid prototyping of near net shaped mechanical parts. Previous research work has included metal ball generation and capture, solder masks, and jetting copper for printing circuits [15].

5.4.15 Sparx- Hot Plot

Sparx AB of Molndal, Sweden, has introduced a rapid prototyping system very similar to the Laminated Object Manufacturing technology developed by Helisys. This Swedish system is called "Hot Plot." It is currently the least expensive commercial system but does require a considerable amount of operator assistance [14]. It consists of a flat-bed plotter equipped with a heated cutting electrode and a mounting fixture.

The process begins with the mathematical generation of cross-sectional data from the three-dimensional CAD model. Next, the polystyrene sheet material is manually positioned on the plotter bed. This material has been coated with pressure-sensitive adhesive and backed by removable foil. The electrode cuts the outline of the cross-section [14]. The operator picks up the sheet representing the layer and affixes it on a mounting fixture. The foil backing is peeled off to expose adhesive for the next layer. Excess material is manually removed from the plotter bed to accommodate the next sheet. This process continues until completion of the part.

This sheet material, supplied by Sparx, is currently 0.04 in. thick. It costs two dollars per sheet (\$50 per inch of part). The software interface accommodates AutoCAD, but cannot yet accommodate the .STL file. This system is best suited for visual modelling since the material is very weak and the layers are very thick [14].

5.5 RP Process Evaluation

5.5.1 Accuracy

Stairstepping: Since rapid prototyping builds object in layers, there is inevitably a "stairstepping" effect produced because the layers have a finite thickness. Those methods that produce the thinnest layers have less stairstepping than others, but it's almost always visible. The technology that produces the thinnest layers is based on inkjets [13]. These machines have the advantage that each layer is milled flat after it's deposited and as little as 0.0005 inches of material can be left as a layer thickness. Of course, that makes the building process very slow. Stereolithography can also produce thin layers, although not quite at that level and this feature is mainly used to make small parts in the several millimetres or less range.

Everything else produces more pronounced stairstepping. Obviously methods based on one or another form of laminated object manufacturing (LOM) will be limited in what can be accomplished because of the raw material thickness. Methods based on powders, for example selective laser sintering (SLS) or three dimensional printing (3DP), have the finite size of the powder as a lower limit [13]. Layer thickness will almost always be greater than the minimum particle size. In some experimental methods of LOM, variable layer thickness is used and cutting means may be employed that shapes edges so that less stairstepping is visible.

Absolute accuracy/Precision: Absolute accuracy can be defined as the difference between an intended final dimension and the actual dimension as determined by a physical measurement. In addition to those for linear dimensions, there are accuracy specifications for such features as hole sizes and flatness. In a few fields absolute accuracy isn't very important, but in most areas it's a critical issue [13]. Taking stereolithography as a starting point, as shown in the table, one can get at least a qualitative idea. A good rule is that stereolithography will produce accuracy results of about ± 0.004 inches over a dimension of about six inches. LOM and powder-based methods will generally be somewhat less accurate than that. The inkjet methods are somewhat better. Since the final numbers depend on the geometry of the part, the particular dimension measured, the material used and other factors it's difficult to make a more definitive statement [13].

5.5.2 Finishes

The **finish and appearance** of a part are related to accuracy, but also depend on the method of RP employed. Here again, taking stereolithography as "very good," getting about the same differentiation among the methods produced by accuracy as described above. Technologies based on powders have a sandy or diffuse appearance, sheet-based methods might be considered poorer in finish because the stairstepping is more pronounced.

Resolution refers to the minimum feature size that can be faithfully reproduced and is related to the finish and appearance and accuracy that can be achieved. For most RP systems, resolution is in the "few mils" range [11]. Specially modified systems are available that can reproduce much finer features, but they are limited in the size of the parts they can fabricate. Inkjet based systems from Solidscape and Sanders International are capable of very high resolution.

In any case, it will probably be necessary to sand, paint, fill, polish, infiltrate a secondary material to decrease porosity, or perform other operations on the part before it can be used [11].

5.5.3 Secondary Operations

In many cases, plastic or other soft material-based rapid prototyping parts can be used directly, or after relatively minor finishing operations. Parts made by stereolithography are frequently not completely cured when removed from the machine. Final cure is effected in a box called a post-cure apparatus (PCA) where the part may be bathed in UV light while on a turntable [10].

Parts from processes such as three dimensional printing (3DP) can be very fragile and might not be able to take normal handling or shipping stresses. They are often infiltrated with cyanoacrylate adhesive or wax as a secondary operation to make them more durable.

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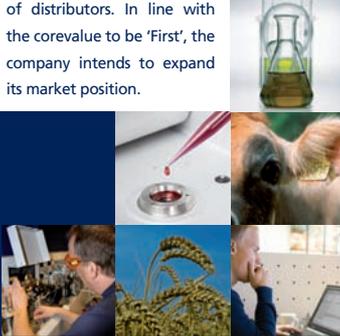
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All rapid prototyping methods, which directly produce metal parts will almost certainly require final machining and other secondary operations before acceptable final finishes and tolerances are achieved, although there may be a few exceptions based on the requirements for a particular part. Before they can be final-machined, metal and ceramic parts made by selective laser sintering (SLS) must usually undergo a thermal baking cycle to lightly consolidate them into a "brown" part, and then they may undergo a final thermal cycle to sinter and infiltrate them with a material to make them fully-dense [10].

Powder-based methods of rapid prototyping are self-supporting for features such as overhangs and undercuts; the excess powder is simply shaken off or vacuumed away. All other methods require a support structure of some kind which is fabricated right along with the part. This must subsequently be removed in a secondary operation which may require considerable effort and time [12].

Stereolithography parts require the supports to be cut off and the areas they were attached to finished, often by hand.

Inkjet based systems either use a hair-like support structure, as in the case of MultiJet Modeling (MJM), or a second support material which is removed with a solvent. The hair-like structures can be brushed away and the remaining down-facing surfaces cleaned up manually [13].

Fused deposition modelling (FDM) may use either a snap-away support structure made from a second material that doesn't stick to the part material, or a water-soluble support structure [14].

Laminated object manufacturing (LOM) may require labour-intensive work to "de-cube" trapped volumes or other portions of the part that need to be removed. It may be necessary to perform this delicate operation with a hammer and chisel (Figure 12). Methods of LOM have been under development for several years that avoid this issue, but there is nothing commercially available yet.

5.5.4 Speed

All RP technologies are fairly slow taking from hours to even days to output a part. Nevertheless, this is still often much faster overall than if the same part were made using subtractive CNC. It is not unusual with some complex parts to save literally weeks of machining time. The use of the term "rapid" is relative and not absolute.

Raster-based RP methods are generally faster than ones that fabricate each layer in a vector fashion, and ones that build in thicker layers are faster than those making thin ones. Thus, three dimensional printing (3DP) as exemplified by Z Corporation's products are the speediest - quicker than stereolithography and far faster than some inkjets or fused deposition modelling (FDM) [14]. Inkjets which use just a couple of nozzles and make high resolution objects are probably the slowest in any side by side race. But that's not the complete story.

Even though one RP method may be considerably slower than another in a side by side fabrication race, that doesn't necessarily mean that it would lose. One also has to take into consideration the ancillary secondary operations that have to be performed [14]. Fused deposition modelling (FDM)

may be slower than stereolithography in making a particular part, but if can simply wash away the support structure it might be possible to be in business a lot sooner.

5.5.5 Cost

RP pioneer 3D Systems sold 1600 SLA machines from 1988 through 1999. These machines cost \$100,000 to \$800,000. Stereolithography process involves high equipment, material, and maintenance costs. Selective Laser Sintering (SLS), the second most popular RP technology have prices range from about \$270,000 to \$325,000. Prices range of fused deposition modelling (FDM) is from \$100,000 to around \$300,000 [13]. 3-D printers are as much as 10 times faster and about one-third as costly - systems cost \$75,000 to \$80,000. A different sort of 3D printer is the Z 402 system from Z Corp., which debuted in 1997 (List price: \$57,000). System prices of RP technologies are shown in table 1.

Table 5.1: Comparison of important commercial rapid prototyping technologies.

Technology >>	Stereo-lithography	Wide Area Inkjet	Selective Laser Sintering	Fused Deposition Modelling	Single Jet Inkjet	Three Dimensional Printing	Laminated Object Manufacturing
Representative Vendor >>	3D Systems			Stratasys	Solidscap	Z Corp.	Cubic Technologies
General Qualitative Features							
Maximum Part Size (inches)	20x20x24	10x8x8	15x13x18	24x20x24	12x6x9	20x24x16	32x22x20
Accuracy	very good	good	good	fair	excellent	fair	fair
Surface Finish	very good	fair	fair	fair	excellent	fair	fair to poor (depending on application)
Speed	average	good	average to fair	poor	poor	excellent	good
Strengths	market leader, large part size, accuracy, wide product line	market leader, office okay,	market leader, accuracy, materials,	office okay, price, materials,	accuracy, finish, office okay,	speed, office okay, price, colour, price	large part size, good for large castings, material cost
Weaknesses	post processing, messy liquids	size and weight, fragile parts, limited materials, part size	size and weight, system price, surface finish	speed	speed, limited materials, part size	limited materials, fragile parts, finish	part stability, smoke finish and accuracy
System Price	\$75-800K	\$50K	\$300K	\$30-300K	\$70K-80K	\$30K-70K	\$120-240K
Material Costs \$/pound							

Plastics	\$75-110	\$100	\$30-60	\$115-185	\$100		\$9
Metal			\$25-30				
Other			\$5 (foundry sand)			starch: \$0.35 / cu in plaster: \$0.60 / cu in + infiltrant	\$5-8 (paper)

5.5.6 Strengths & Limitations

Stereolithography's strengths lie in part quality. The process produces a highly accurate model with excellent surface finish. These factors make SLA suitable for visual presentations and patterns for tooling.

SLA has also been limited by its photopolymer materials, which suffered from brittleness and properties that can change with humidity and ambient temperature. However, newer SLA materials have evolved from acrylic-based to epoxy-based polymers. One of the newest of these is said to emulate PP [15].

An advantage of the SLS process is that it can make parts from thermoplastics—proprietary nylon materials, which can be glass-filled. SLS prototypes now approach the aesthetic quality of stereolithography [12]. SLS has a significant learning curve, similar to SLA. And fine powder residues on parts require extra clean-up effort.

FDM's strength lies in its simplicity. It extrudes a filament of proprietary ABS material through a heated tip. The durable ABS models made with FDM can be sanded, drilled, painted, and tested for fit and function [12]. Also, the FDM machine is suitable for an office environment.

The major advantage of Z Corp.'s Z 402 modeller (3DP) is its speed, which outperforms all other RP methods. It uses low-cost starch- or plaster-based materials and is relatively affordable. Its limitations are in model quality. But the last year has seen improvements in materials, software, and the mechanics of deposition that produce higher accuracy and crisper edges [13].

5.5.7 Materials

Plastics account for the preponderance of materials used in rapid prototyping systems. While in some cases, the plastics have the same name and chemical composition as familiar, home-grown materials such as nylon or ABS, there are substantial differences in what comes out of an RP system compared to the results from machining or injection moulding the same materials [10].

Selective laser sintering (SLS) is the technology which produces plastic parts which most closely emulate those from other processes. However, there is always some porosity of at least a few percent because the parts are sintered from powder layers, and powders always have spaces between the particles. In a similar fashion, fused deposition modelling (FDM) while nominally using materials such as ABS and several other thermoplastics, produces parts with a grain structure because they are vectorially extruded a layer at a time out of a nozzle [10]. In general, the physical properties of parts produced by a rapid prototyping system, such as tensile strength and elongation, will be somewhat poorer than those produced by other methods.

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Stereolithography and other photopolymer-based methods offer plastic parts, too. However, **liquid photopolymers** are not exactly thermoplastics. The chemistry of photopolymers is very rich, however, and these materials are improving at a rapid pace [11]. Photopolymers that imitate polypropylene, ABS, polyethylene and a number of other plastics are available, as well as specialty materials for optical, medical and other applications.

Inkjet systems also output plastic parts. MultiJet Modeling (MJM) offers a soft, thermoplastic material which is essentially a hot melt adhesive. Other inkjets offer polyester or wax-like materials.

It should be noted that while the choice of plastic-like materials is the greatest available in the rapid prototyping field, it still is a very limited one - really just a handful compared to the literally thousands of materials and grades available for other processes. It's a very good thing that numerous secondary processes exist for changing the output from a rapid prototyping machine into some other material. Many of these processes are listed in the tables for tooling applications.

Metals: Commercially available choices are extremely limited for the direct fabrication of metal parts by rapid prototyping. For the most part today, metal parts made by rapid prototyping processes are being used to make injection moulds. RP technology can offer great time and monetary savings, as well as provide functionality, which would be impossible to obtain otherwise [15].

Selective laser sintering (SLS) offers two basic choices, which can be rudely described as soft and hard. The particular materials used are exclusive to each of the two competing SLS brands in the market, EOS GmbH (Germany) and 3D Systems. Soft materials comprise either a copper-polyamide system from 3D, or a bronze alloy system from EOS. The hard materials are a stainless steel from 3D Systems and steel from EOS [15].

Laser engineered net shaping (LENS) and related processes offer the direct fabrication of fully-dense steel parts. Final machining is necessary before parts can be used.

Three dimensional printing (3DP) is also being used to make steel parts. DME's MoldFusion process requires similar thermal cycles to selective laser sintering (SLS) to consolidate and infiltrate the parts to final density. Finish machining is also required.

Ceramics parts can be acquired from a limited number of commercial sources and a few university labs.

Paper has been the material most closely associated with laminated object manufacturing (LOM). Several companies provide systems that fabricate paper parts. One advantage is that the material is very inexpensive, but paper parts are not very stable. Paper parts have the look and feel of wood and are often used as sand casting patterns [16].

Plaster and starch parts are available from three dimensional printing (3DP) machines made by Z Corp. These are also inexpensive material but require some care in handling and must usually be infiltrated to make them durable.

Foundry sand parts can be fabricated using selective laser sintering (SLS) and also by a process from Generis GmbH (Germany) that is similar to three dimensional printing (3DP). This machine is most appropriate for making very large parts [17].

5.6 Conclusions

By building three-dimensional parts in a layer-by-layer additive manner, the RP techniques allow freeform fabrication of parts of complex geometry directly from their CAD models automatically, without having to use special fixtures as in the material removal processes. The rapid prototyping technology has helped product developers to develop their products more rapidly at lower costs in the ever changing and more competitive global market. It was initially used to make physical prototypes of three-dimensional parts as visualisation and communication aids in design as well as for examining the fit of various parts in assembly. It has provided substantial reduction of time-to-market, hence widely called as rapid prototyping in industry. Thanks to intensive research and development in the areas of material, process, software, and equipment, applications to rapid tooling have also been developed by directly or indirectly employing rapid prototyping processes in the tool, die and mould fabrication.

Rapid Prototyping processes have been used extensively, because they:

- Increase effective communication;
- Decrease development time;
- Decrease costly mistakes;
- Minimise sustaining engineering changes;
- Extend product lifetime by adding necessary features and eliminating redundant features early in the design.

Several business objectives can be significantly improved by using rapid prototyping technologies such as marketing new products, manufacturing flexibility; and new product development.

The key to applying the RP technologies for competitive advantage lies in innovative use. This involves using the technologies not only to deliver improvements, but also to enable new things, which previously might have been impossible or uneconomic.

Whilst the pursuits of time and cost reductions are both clearly necessary business objectives, it is evident that by using rapid prototyping in more innovative ways, firms can derive more significant benefits.

Included in these innovative applications are: the development of new analysis and testing procedures; manufacture of production tooling; improving communications across product divisions; and supporting customised manufacturing.

Applications of RP technology have found favour in both large and small firms. Time savings on prototyping parts vary, ranging from 60 to 80 percent reductions when compared to conventional methods for producing prototype components.

Rapid prototyping technologies must be viewed as enablers of new business strategies. Firms should therefore be looking at fundamental issues and addressing how they can apply the technologies to support expansion into new markets, to increase market share, to differentiate from competitors, to modify the basis of competition, and to develop more innovative products.

The main benefits of Rapid Prototyping as a system development tool are the following:

- Makes the product real for (at least some) customers and investors; makes them feel that real progress is being made;
- Enables iteration and change, especially on required design features, early in the design process;

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- Enables detection of errors, leading to better solutions, early in the design process;
- Proves that the system is manufacturable, or even feasible;
- Although users may find it difficult to describe what they want in a system, they usually recognise what they want/don't want when they see it.

The future looks very promising for rapid prototyping. The benefits for most applications far outweigh the disadvantages especially when they are used in the correct situation. The price and size are rapidly falling to the point where they will soon be commonplace in any manufacturing company.

There seems to be a divergence in the applications of rapid prototyping. While many companies are concentrating on the application to produce physical 'models', and hence not fully working components, other machines are tending towards the production of fully working components, with research being put into vastly improving the mechanical properties of PR components. Other firms are heading in the direction of cast and mould making using rapid prototyping processes. The rapid prototyping technology is therefore advancing beyond the production of 'prototype models' for which it was originally used.

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