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Rapid Prototyping Using FDM: A Fast, Precise, Safe Technology

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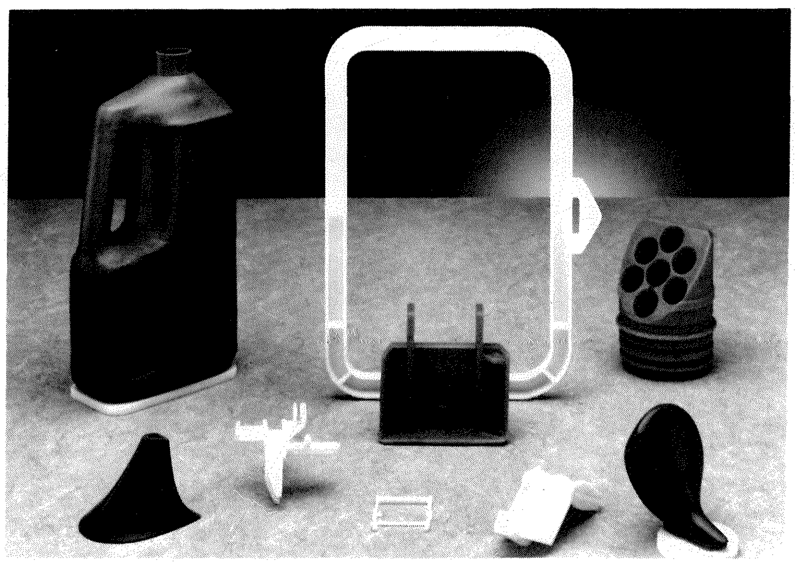
Introduction

This paper outlines the use of FDM to speed product design and to streamline the manufacturing process.

Time compression, the ability to quickly reduce the time it takes to get new products to market, has increased the pressure on all phases of the manufacturing process. Manufacturers must find and implement time saving systems without sacrificing quality.



An assortment of concept models created on the 3D MODELER showing a variety of geometries, complexities, sizes and materials.

Fused Deposition Modeling (FDM) provides a synergistic solution for design and manufacturing engineering: visualization models and part concept designs become accurate physical models leading to final working parts right within the normal engineering office environment.

This clean running, single step operation uses non-toxic, thermoplastic wire-like filaments eliminating liquid photopolymers, powders or lasers from the process.

The current technological quest has been to create a true desktop system suitable for use in an office environment. The FDM process has moved the state of the art beyond lasers, beyond systems that require messy materials and beyond large, cumbersome units to allow for true 3D desktop prototyping.

FDM quickly and safely produces non-toxic physical prototypes from 3D CAD data reducing the time to market, reducing product development costs and allowing verification of production tooling.

Background

In 1988 Scott Crump invented the FDM process (patent pending), an automatic, non-laser based technology using non-toxic materials for rapid part creation. The process builds on early professional experiences with thermofusion control mechanisms and low temperature thermoplastics.

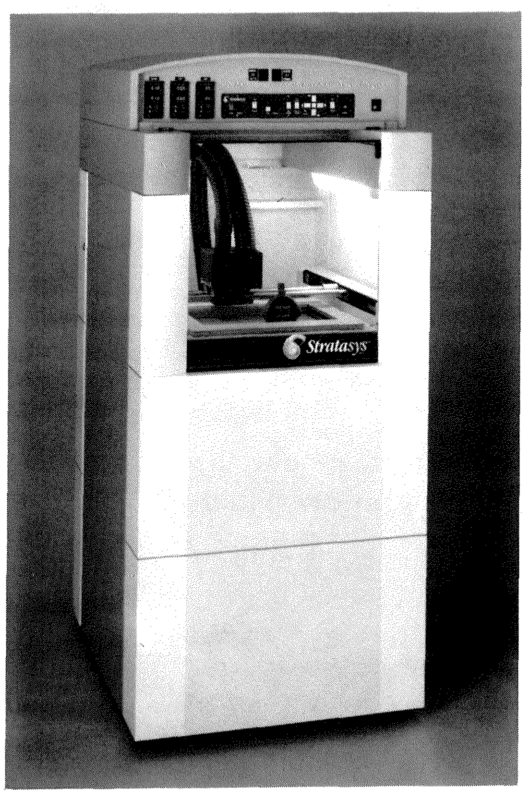
FDM is a unique technology to empower design and manufacturing engineers to be able to quickly produce precise, multi-material models in an engineering environment, right at the CAD workstation.

The Need for Rapid Prototyping

Stratasys, Inc. is a privately held company with partial funding provided by Battery Ventures in Boston. Stratasys, Inc. began shipping 3D MODELERS in the second quarter of 1991.

In today's business environment, manufacturers need every competitive advantage to get a quality product to market as quickly as possible. The ability to rapidly produce 3D models of the images created on CAD workstations has become an additional tool to positively impact both quality and speed (Marks, 1990).

The Stratasys 3D MODELER uses the innovative patented Fused Deposition Modeling (FDM) method to generate three dimensional prototypes and wax patterns from 3D CAD software data.

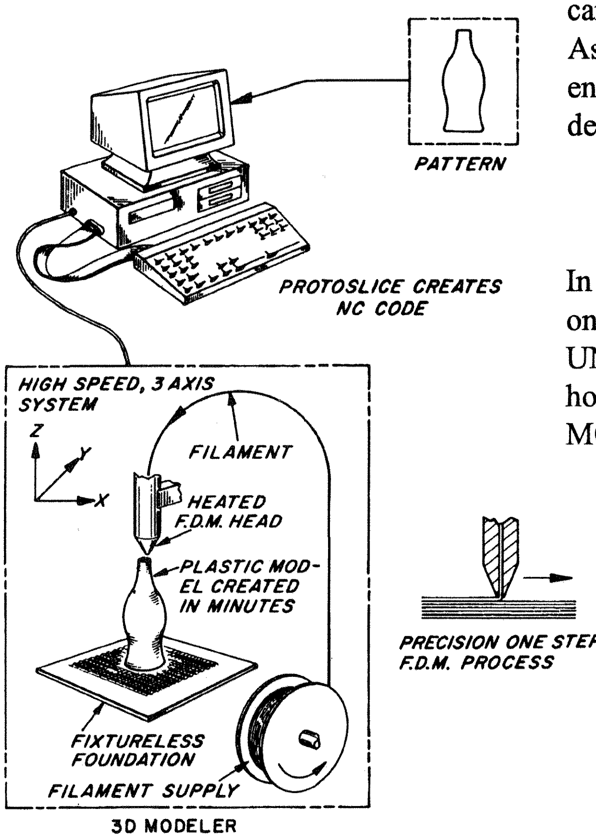


By allowing design and manufacturing engineers to quickly, accurately and efficiently create prototypes, the design process will improve. When an accurate physical model is generated in less than an hour, the designer can economically create multiple iterations prior to final design.

Rapid prototyping gives shape, form and feel to the image on the computer screen by producing 3D models of complex, sculptured-surfaced parts within minutes or a few hours. Rapid prototyping will increase experimentation and allow improvements to be quickly incorporated (Wohlers, 1990).

3D MODELER

The FDM process uses the Stratasys 3D MODELER® in conjunction with a CAD workstation. Stratasys' 3D MODELER is a single step, self-contained modeling system that offers the user several advantages. Speed is an important benefit of this technology; typical models



The Fused Deposition Modeling (FDM) process produces safe, accurate 3D models in minutes.

can be produced in minutes rather than hours or days. As no post curing is required, the FDM technique enables the designer to create multiple versions of a part design within a short time frame.

Elements of the FDM Process

In this process a conceptual geometric model is created on the CAD workstation. It is then imported into a UNIX-based workstation where it is sliced into horizontal layers that are down-loaded to the 3D MODELER.

Liquid thermoplastic material is extruded and then deposited into ultra thin layers from the lightweight FDM head one layer at a time. This builds the model upward off a fixtureless base. The plastic or wax material then solidifies in 1/10 of a second as it is directed into place with an X-Y controlled extrusion head orifice that creates a precision laminate.

A spool of .050 inch diameter modeling filament feeds the FDM head and can be changed to a different material in 1 minute.

Maintaining the liquid modeling material just above the solidification point is fundamental to the FDM process. The thermoplastic melt temperature is controlled to 1 degree Fahrenheit above solidification. The material then solidifies as it is directed into place with an X-Y controlled extruding head nozzle that creates a precision laminate.

Successive laminations, within the 0.001 to 0.030 inch thickness range and a wall thickness of .009 to .250 inch range, adhere to one another through thermal fusion to form the model. Our overall tolerance is ± .005 inches in the X,Y,Z axis over a 12 inch cubed working envelope.

Safety Benefits

The Stratasys 3D MODELER is a stand-alone modeling system that is located next to the CAD workstation. It stands 6 feet tall with a 3' by 2.5' footprint. The system requires no exhaust hood or special facilities, providing a natural extension to the engineering workstation and easily fitting into an office environment.

The process operates at moderate temperatures in the range of 180 to 220 degrees Fahrenheit, making it safe for office use. By comparison, the temperature is similar to that of a hot cup of coffee. There is no worry of possible exposure to toxic chemicals, lasers, or liquid polymer baths. The Stratasys process uses no powders and there is no messy cleanup. Concern over disposal of hazardous materials is eliminated.

Materials

The Stratasys technology allows a variety of modeling materials and colors, with new materials continually under development. All are inert, non-toxic materials developed from the range of commercially available thermoplastics and waxes. The ability to use different materials allows the user to match the material to the end use application of the prototype, whether that is a pattern for tooling or as a concept model.

Currently, there are three materials: a machinable wax, a tough plastic polymer and an investment casting wax. These thermoplastics and waxes soften and liquefy when heat is applied.

The Stratasys investment casting wax is an industry standard investment casting material. This wax rapidly dewaxes from the shell using normal investment casting procedures and provides superior surface finishes. Because this is a standard investment casting wax, it can become part of the foundry's normal recycling process.

The machinable wax is primarily used for conceptual modeling and spray metal molding. For instance, the accuracy of the model allows its use in the spray metal process for injection mold prototyping. Both the investment casting wax and the machinable wax can streamline the manufacturing process by allowing the user to go directly to soft tooling using the model as the pattern for investment casting or spray metal injection molding.

The plastic filament is a tough material producing sturdy models suitable for concept models or fit, form and some function applications.

In the three years the FDM technology was in development several obstacles were overcome. A major breakthrough was the decision to settle on a filament system of material media as opposed to a "hopper" system. The spool based filament system has proven to be a significant strength of the 3D MODELER.

The spools give the user the ability to change material in about one minute by threading the desired material into the prototyping unit. There is virtually no waste and no vat to clean.

The materials to produce a part are cost effective, usually under twenty dollars. For example the material for one golf club head costs approximately $9.00 and one spool of material can produce roughly 20 club heads.

The FDM process is not limited by the UV polymers required by many other rapid prototyping systems and new materials are continuously under development.

Supports

The FDM process does not need elaborate supports to produce a part as do some other systems. The 3D MODELER has the ability to create a support in mid-air rather than building the support up from the base in some applications. The system is also capable of extruding plastic into free space depending on the part geometry. When supports are not used, the FDM head forms a precision horizontal support in mid-air as it solidifies.

TABLE OF SUPPORTED IGES ENTITIES	
Geometric	
100	Circular Arc
102	Composite Curve
104	Conic Arc
106	Copious Data
108	Plane
110	Line
112	Parametric Spline Curve
114	Parametric Spline Surface
116	Point
118	Ruled Surface
120	Surface of Revolution
122	Tabulated Cylinder
124	Transformation Matrix
126	Rational B-Spline Curve
128	Rational B-Spline Surface
140	Offset Surface (limited support)
141	Boundary Surface
142	Curve on a Parametric Surface (limited support)
143	Bounded Surface
144	Trimmed Surface
Annotation Entities	
106	Crosshatching (limited support)
202	Angular Dimension
206	Diameter Dimension
210	General Label
212	General Note (limited support)
214	Leader Arrow
216	Linear Dimension
218	Ordinate Dimension
220	Point Dimension
222	Radius Dimension
228	General Symbol
Structure Entities	
308	Subfigure Definition
314	Color Definition (limited support)
402	Associate Instance
404	Drawing (limited support)
406	Property
408	Singular Subfigure Instance
410	View (limited support)
412	Rectangular Array Subfigure Instance
414	Circular Array Subfigure Instance

Open Systems

The 3D MODELER imports geometry through standard RS232 serial ports. Either wireframe, surface or solid CAD data from all standard CAD software packages can be imported through IGES running on UNIX workstations.

There are four methods of driving the modeler:

1. *Through IGES*

   A file brought into the CAD software program in an IGES format can be edited, scaled, oriented and even surfaced if the input does not already have surfaces (see table above for supported IGES entities). Supports, if needed, can be added graphically. The 3D MODELER can also import digitized data via IGES. The digitized data can be generated by probe, laser scan, sonic scan, Computed Tomography (CT) scan or Magnetic Resonance Imagining (MRI). This input data can be used as the slices or to define surfaces.

2. *Directly from CAD/CAM software that outputs CNC code*

   A user who already has a CAD/CAM capability that outputs CNC code can use that code to drive the modeler.

3. *Through Stratasys' ProtoSlice software*

   The Stratasys system uses a special packaging of CAD/CAM software and, in fact, delivers a full CAD package as part of its total turnkey system, allowing the user to completely design and build a part from scratch. The capabilities include a full NURBS-based surface modeler for complex or simple shape creation.

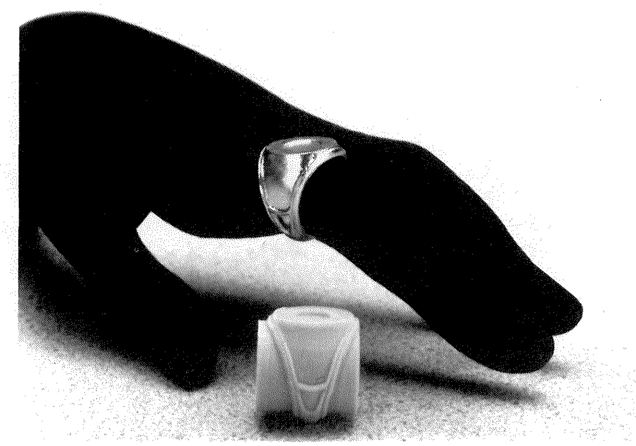
4. *Through .STL format*

   It is possible to import an ASCII or binary .STL file and post out NC code to drive the modeler.

Applications

Applications cross a wide spectrum of industries. Any industry that manufactures a tangible product and can benefit from reducing design and manufacturing errors, increasing manufacturing speed or compressing the time to manufacturing has a potential for this technology.

Companies using rapid prototyping are finding the benefits of the technology go beyond the ability to produce more models faster. Once the model has been completed and approved, the prototype may be used in the next step in the manufacturing process.



Ring produced by the Stratasys 3D MODELER in investment casting wax and actual ring investment cast directly from the wax. Model creation time: 35 minutes. Resolution: .002 inches.

Both injection molding and investment casting can use the Stratasys prototype as a direct input master to the manufacturing process.

Investment Casting

Manufacturing complex metal components requires a multi-step investment casting process. As the name implies, the Stratasys investment casting wax is excellent for lost wax investment castings.

The time consuming step of producing a wax replica of the part to be manufactured can be eliminated. The desired part created in Stratasys' investment casting wax can be dipped or invested directly into the ceramic slurry. The wax quickly dewaxes from the ceramic shell.

A report published in INCAST states this about the Stratasys investment casting wax, "For investment casters, these models are an ideal pattern material. They are gated, dewaxed and fired in shell or solid molds exactly as normal wax patterns are processed." (March, 1991)

Investment Casting Examples

The investment casting process is used by a manufacturer of products for the orthopedic surgeon. These products include reconstructive parts such as hip and knee replacement implants as well as shoulder, ankle and other less frequently replaced joints.

In cases where there has been disease or infection, a small implant can be created to attach to the bone (a resurfacing). Pictured above is a resurfacing of a section where the thigh bone connects to the knee.

Typically the parts are machined from solid blocks of titanium. The need for high quality is apparent when considering the part will be a component of someone's leg or knee for life. From a financial aspect the need for quality is

Airfoil part produced in Stratasys machinable wax. Model creation time: 5 hours, 45 minutes. Resolution .010 inches.

apparent when considering the expense of the titanium. Precision, quality parts with complex surfaces are an ideal match for the FDM process.

The ability to rapidly produce models allows evaluation by the consulting orthopedic physicians, along with the team members from marketing, design, engineering and manufacturing.

Once a design has been analyzed and consensus is reached the company benefits from the advantages of Stratasys' investment casting wax. By saving steps in the manufacturing process, the company can speed its products into this competitive market.

The jewelry industry is another example where investment casting is used extensively. Although it lacks the emotional impact of a life-changing knee implant, other parallels exist. Certainly the high cost of raw material makes the use of a prototype in a less expensive material desirable.

Injection Molding

The accuracy of the Stratasys model allows the use of the model in the spray metal process for injection molding. The filament materials used by Stratasys have high durability and stability required for a master for spray metal molding.

Using a 3D model produced in the Stratasys machinable wax, allows manufacturers to go directly to the spray metal molding process. Customers create spray metal tooling by spraying the metal onto the model in thin coats.

This technique has been applied across industries from the simple casting of urethane in the shoe industry to injection molding of glass filled resins. These glass filled resins are used for high strength, heat resistant, wear resistant parts such as photo equipment, small power tools and appliances.

Saving steps in the manufacturing process translates into time savings for manufacturers using investment casting or injection molding techniques. These savings allow manufacturers to speed products to market.

Fit, Form and Function Applications

A common frustration in assembled products occurs when interior components are built that will not fit together or do not fit the housing. The ability to rapidly produce prototypes reduces this source of manufacturing error or decreases the time it takes to hand produce prototypes of all components.

The aerospace industry is just one example where fit, form and function are a concern.

Conceptual Modeling

The prototype or model itself can be a marketing tool for the manufacturer. To be able to hand a client a prototype of the proposed part at the final presentation or to include a prototype with the proposal package has strong emotional appeal in the sales process.

Conceptual modeling also enables engineers to quickly produce multiple iterations of a sample part to streamline the design process.

Concept models are important in the shoe industry. One major shoe manufacturer creates hundreds of new shoe heel designs each year. Each heel style is normally produced in one size based on the designer's drawing. After this initial prototype design is verified, models are created for sizes 3 through 12, with the heel dimensions graded for the size.

The ability to quickly and accurately produce the concept model allows this manufacturer to improve quality and productivity in the manufacturing process.

Summary

FDM provides a combination of attractive features to provide true desktop 3D modeling. It is a non-laser based system providing a cost effective, accurate and environmentally safe way to produce 3D models and prototypes.

Reducing time to market by accommodating engineering changes quickly and improving product quality demands state-of-the-art prototyping tools.

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