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INTEGRATION OF RAPID PROTOTYPING INTO PRODUCT DEVELOPMENT *

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1. ABSTRACT

Sandia National Laboratories is a vertically multi-disciplined research and development laboratory with a long history of designing and developing sophisticated electro-mechanical products in the national interest. Integrating new technologies into the prototyping phase of our development cycle is necessary to reduce the cycle time from initial design to finished product. The introduction of rapid prototyping machines into the marketplace promises to revolutionize the process of producing prototype parts with relative speed and production-like quality. Issues of accuracy, feature definition, and surface finish continue to drive research and development of these processes. Sandia uses Stereolithography (SL) and Selective Laser Sintering (SLS) capabilities to support internal product development efforts. The primary use of SL and SLS is to produce patterns for investment casting in support of a Sandia managed program called FASTCAST that integrates computational technologies and experimental data into the investment casting process. These processes are also used in the design iteration process to produce proof-of-concept models, hands-on models for design reviews, fit-check models, visual aids for manufacturing, and functional parts in assemblies. This presentation will provide an overview of the SL and SLS processes and an update of our experience and success in integrating these technologies into the product development cycle. Also presented will be several examples of prototype parts manufactured using SL and SLS with a focus on application, accuracy, surface finish, and feature definition.

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2. BACKGROUND

Since the 1940's, Sandia has manufactured prototype component parts using state-of-the-art manufacturing methods. The state of the art has progressed from the use of manual machine tools to template-guided machine tools to computer-aided CNC machining centers and wire-feed electrical-discharge machines. Sandia uses the investment casting process to fabricate geometrically complex metal parts that are not suitable for other methods of manufacture. In 1989, a new concept called FASTCAST for rapidly manufacturing production-like prototype metal castings was initiated at Sandia. In support of this effort, a method for rapidly producing wax patterns was needed. Using CNC multi-axis machining centers, wax patterns for investment castings were machined from solid billets of wax. This method was effective in reducing lead times and patterns were dimensionally accurate, but the cost of the patterns was excessive. Subsequently, the acquisition of rapid prototyping processes has had a significant and timely impact on manufacturing prototype parts, particularly regarding the production of investment casting patterns.

3. PRODUCT DEVELOPMENT

Product development begins with a conceptual design based on customer requirements. The design is developed using a computer work station and CAD modeling software to create a three-dimensional solid model. Using solid modeling in the design process has many advantages. The designer can perform engineering analysis, can fit-check mating parts, see a three-dimensional representation of the design, change the design as necessary, document changes immediately, and retain the design information indefinitely.

After a design is established, the designer may choose to have a prototype part built. If the design is final, manufacturing may begin using traditional methods such as machining or casting. If the design is not final, the design iteration process begins and a replica of the CAD model is built quickly using a rapid prototyping machine. The CAD model data is translated to a standard machine readable format called a STL file. The part is then fabricated using a Stereolithography Apparatus 250 (SLA-250)[2], Figure 1, or a Sinterstation 2000™ Selective Laser Sintering (SLS)[3] machine, Figure 2. The SL process produces acrylic or epoxy models (see paragraph, The Stereolithography Process). The SLS process produces polycarbonate, nylon, or wax models (see paragraph, The Selective Laser Sintering Process). The SL or SLS models can be used for proof-of-concept, design review, fit-check, visual aid for other methods of manufacturing, or as patterns for producing investment casting

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[2] The SLA-250 Stereolithography machine is manufactured by 3D Systems, Inc., 26081 Avenue Hall, Valencia, California 91355

[3] The Sinterstation 2000™ Selective Laser Sintering machine is manufactured by DTM Corporation, 1611 Headway Circle, Building 2, Austin Texas 78754

molds. The advantages of using these processes for fabricating prototypes are: 1) ease of fabricating complex geometrically shaped parts, 2) increased design flexibility, 3) reduced lead times and fabrication costs, and 4) more efficient design iteration.

When the design iteration process is complete and a production-like prototype is ready to be fabricated, it is necessary to determine the proper method of manufacture. Typically, the proper method of manufacture for the prototype is the same as for the production part. If traditional machining methods are used, the CAD model data is translated into a manufacturing data file and tool paths are generated. At Sandia, if the method of manufacture is investment casting, the part enters the FASTCAST process. The designer transfers the CAD data over a computer network to a FASTCAST engineer, who modifies the part's solid model geometry for investment casting. The modified CAD data is transferred to the Sinterstation 2000™, or the SLA-250 where a pattern for investment casting is built. If the casting pattern is built using the Sinterstation 2000™, the pattern material is wax or polycarbonate. Wax is the traditional pattern material for investment casting; however, polycarbonate patterns build faster, are more robust, are dimensionally stable, and parts require no support structure during the build process. If the SLA-250 is used, the pattern is built with epoxy resin and Quickcast build style. Quickcast is a software package that permits a lattice-like structure, rather than a solid structure, to be built for investment casting patterns, thus easing the pattern burn-out phase of mold preparation.

Once a pattern is fabricated (by SL or SLS) and post processed, it is sent to the investment casting area where gates and vents are assembled to the pattern to guide the flow of metal into the mold. The entire pattern assembly is then dipped into a binder material and covered with ceramic powder and allowed to dry. This step is repeated several times until the resulting ceramic shell is the required thickness. Next, the shell is placed in a furnace or steam autoclave and the pattern is melted from the shell, leaving a mold cavity the shape of the pattern. After firing, the completed ceramic mold is taken to Sandia's Liquid Metal Processing Laboratory for pouring of the specified metal.

There are many advantages to using SLS and SL processes to fabricate patterns for investment casting. The traditional method of fabricating wax patterns requires the acquisition of an injection mold. This can require several months of lead time and cost thousands of dollars. If the part design changes, the mold becomes obsolete. Using SLS or SL, we are able to fabricate a pattern within five days after receiving an STL file. The designer can now request more complex geometrical shapes, optimize the part design to meet customer requirements, and change the design if necessary. Complex parts can be cast to near-net shapes and be finish machined. Prototypes can be manufactured and tested by the same methods as production parts.

4. STEREOLITHOGRAPHY

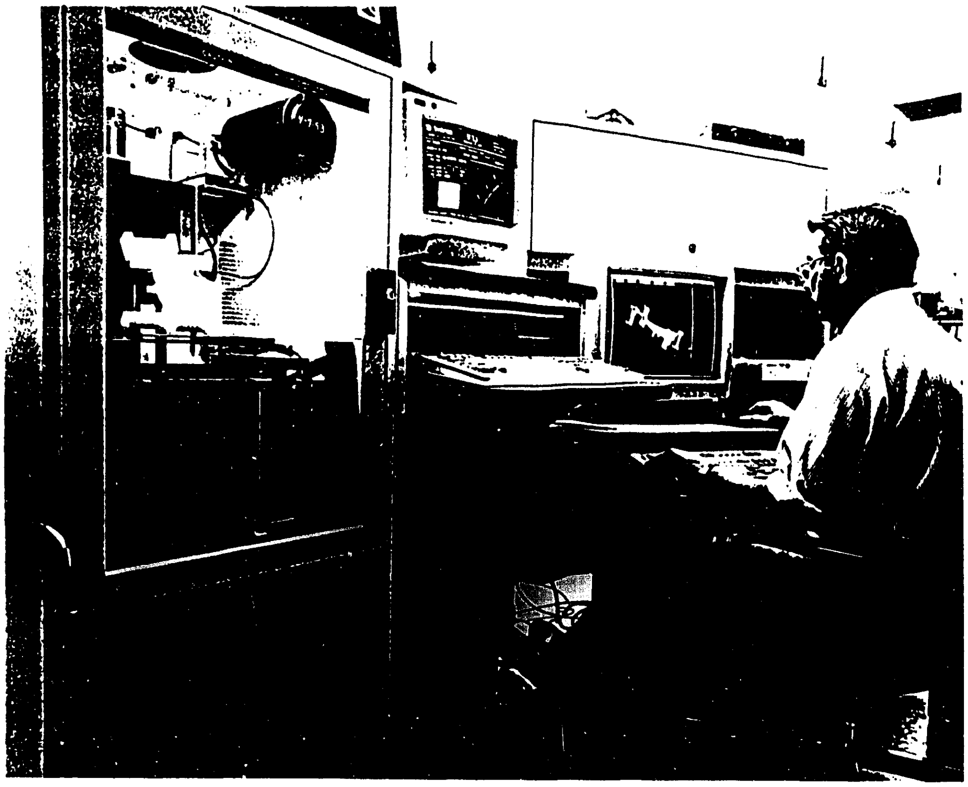

Figure 1 Gerald McCarty completes a build on the SLA-250. To the left is a completed part in the processing chamber and to the right is the CAD solid model on a SGI workstation.

4.1 THE STEREOLITHOGRAPHY PROCESS

Stereolithography is a method of producing complex plastic parts and epoxy investment casting patterns from computer generated data. The sequential sets of operations in the Stereolithography process are discussed below.

CAD Design - The design model is created on a solid modeling CAD/CAM/CAE system. The work reported here was developed using feature-based solid model software called Pro Engineer operating on a Silicon Graphics Incorporated (SGI) workstation.

CAD Interface - The design model and support data are converted to a standard machine readable format. The output from this process is a Stereolithography (STL) file.

Orientation and Support - The model is properly oriented in CAD space and a support structure is designed. The support structure is attached to the model to secure the part in place during the subsequent building process.

Slice - The STL files are sliced into cross sections from .004 inch to .020 inch in thickness. The output is called a Slice (SLI) file.

Build - The machine platform on which the part will be built is lowered into the vat of photocurable liquid resin. The resin leveling system is activated and a precise thickness of resin, specified by the slice file, coats the platform. The laser then draws the first cross section of the support structure, which adheres to the platform. This step is repeated until the laser begins to draw layers of the part geometry. When creating each cross section of the part, the interior and exterior boundaries are solidified by the laser first; then the area between the boundaries is solidified. The elevator dips below the surface, coating the first solidified layer of the part with resin. The recoater arm then sweeps across the surface removing the excess resin and leaving a precise thickness of resin. The second layer is drawn by the laser and becomes firmly attached to the first layer. The process is repeated until the build is completed.

Post Processing - The platform is raised out of the vat and as much liquid resin as possible is drained back into the vat. The part and platform are removed from the processing chamber and the excess resin is removed with solvent. The part is removed from the platform and the support structure is carefully removed from the part by using a variety of hand tools. The clean part is placed in the Post Curing Apparatus (PCA) and exposed to ultraviolet light for approximately thirty minutes for final curing. The part is finished by machining, sanding, polishing, painting, plating, or dyeing.

4.2 STEREOLITHOGRAPHY PROCESS VARIABLES

As with any manufacturing process, there are many variables associated with fabricating a part. Part design, machine accuracy, resin material, information accuracy, operator knowledge, and operator experience are the major influences in achieving part accuracy.

The operator must select the correct machine build parameters in order to build a part. A few examples of build parameters are cure depth, layer thickness, hatch spacing, skin fill spacing, leveling time, and shrink factor. Most of the parameters are resin specific, and resin suppliers recommend parameter settings as a base-line starting point. Fine-tuning these settings is necessary for building the most accurate part. As software and hardware advances are implemented and calibration procedures are established, process parameters become better defined.

The type of resin chosen is determined by the application and structural characteristics required of the finished part. Strength, toughness, surface finish, and appearance are some of the properties to consider when selecting a resin.

Part orientation during the build process is critical because feature definition and accuracy are better in the x-y (horizontal) plane than in the z (vertical) plane.

5. SELECTIVE LASER SINTERING

Figure 2 Brian Pardo is brushing away loose powder from a completed build on the Sinterstation 2000^{TM} SLS machine.

5.1 THE SELECTIVE LASER SINTERING PROCESS

Selective laser sintering is a method of producing polycarbonate or nylon prototypes and wax patterns for prototyping investment cast parts. Listed below is a brief description of each step in the SLS process.

CAD Design - The design model is created on a solid modeling CAD/CAM/CAE system.

CAD Interface - The design model and support data are converted to a machine readable format. The data output from this process is an STL file.

Orientation and Anchor - The operator determines the part orientation and an anchor structure is designed and attached to the part to secure it in place during the build process. No anchor structure is required for polycarbonate or nylon builds.

Slice - The STL files are sliced into cross sections concurrently with the build process.

Build - A thin layer of heat-fusible powder is spread across the part piston (build platform), creating a powder bed. A laser scans a cross section of the part geometry, fusing this layer to the previous layer. The part piston then moves down one layer thickness and the process is repeated until the part is complete.

Post Processing - Post processing consists of manually brushing away the loose unfused powder from around the part. The part is removed from the part piston and taken to the rough break-out station. Utilizing small hand tools, the anchor structures and the rest of the loose powder is removed. The part is then placed in a glass bead machine for final removal of loose powder. The part is finished by machining, sanding, polishing, or painting.

5.2 SELECTIVE LASER SINTERING PROCESS VARIABLES

As a Beta test site of a pre-production machine, much of our effort was focused on working with the manufacturer and other Beta sites to develop parameter settings to produce dimensionally accurate parts with good surface finishes. Since receiving the Sinterstation 2000™ Beta machine in March 1992, we have experienced a very steep learning curve. The process is complex, and it is necessary to understand the dynamics of the process relationships. In an effort to understand these relationships and to establish base-line build parameter settings, we have built the same part numerous times, changing parameter settings on each part until we have achieved the best part and characterized the process. To build a dimensionally accurate part with good surface finish, the thermal environment of the system must be precisely controlled. The best parameter settings for part accuracy are not necessarily the best settings for surface finish or part density. Operator adjustable parameters that affect these part characteristics are chamber temperature, part bed temperature, scan speed, scan spacing, and add powder delay. Understanding the process control parameters and the effects they have on any given geometry is the key to building accurate parts.

In September 1993, we replaced the Sinterstation 2000 Beta machine with the Sinterstation 2000 production machine. The production machine has many process improvements over the Beta machine and should produce higher quality parts.

6. ACCURACY

In an effort to establish the expected accuracy of parts fabricated using the SL and SLS processes, measurements were taken from a benchmark part. The benchmark accuracy part was a bicycle crank arm, Figure 3, fabricated as part of a Technology Transfer program to support a small manufacturer of bicycle components. The geometric shape of the crank arm is representative of a part of average complexity. A polymer model of the crank arm was fabricated on the SLA-250 to verify the design and to serve as a fit-check part to verify dimensional accuracy. After the design was verified, several wax patterns were fabricated using the Sinterstation 2000 SLS Beta machine. The wax patterns were delivered to the component manufacturer who had them cast in titanium.

The measurement results of the SL acrylic models, Table 1, and the SLS wax patterns, Table 2, are from parts after normal post-processing (techniques used to remove support and other excess material after part completion). The parts were measured for dimensional accuracy using a Zeiss UPMC 550 coordinate measuring machine. On each part, twenty-one features were measured for diameter and linear coordinate locations. Thirty radius points and thirty-eight vertical (Z axis) measurements were taken. Tables 1 and 2 show the mean deviation from nominal and the standard deviation.

6.1 CRANK ARM BENCHMARK PART

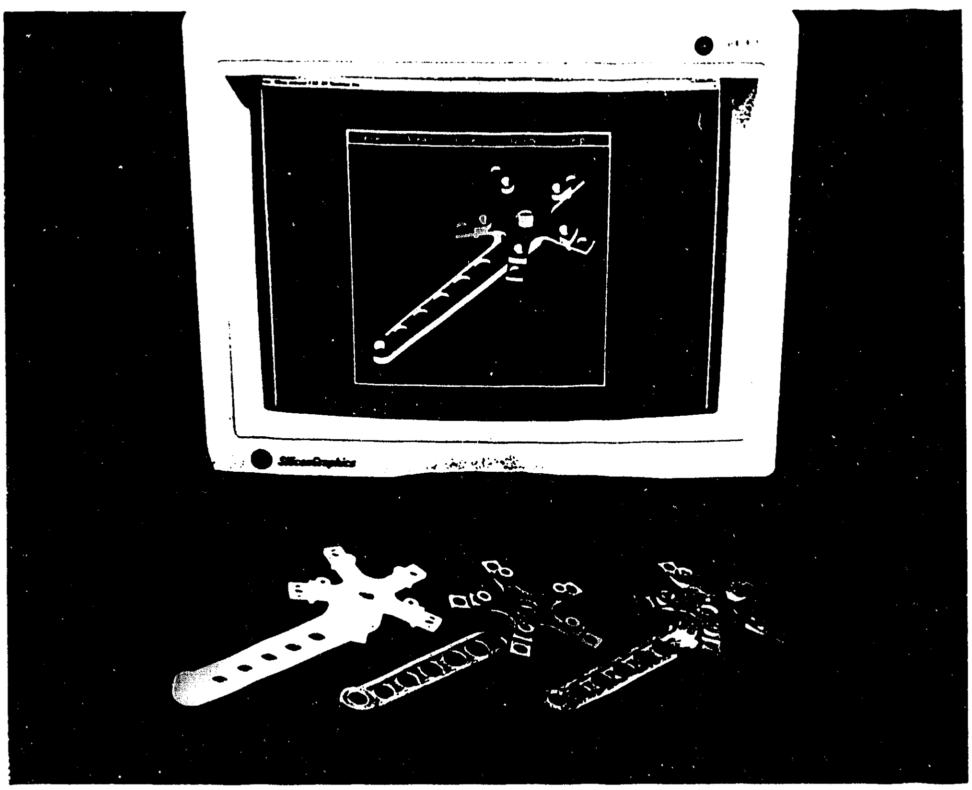

Figure 3 (Top) Three-dimensional CAD Solid Model, (Bottom Left to Right) Acrylic Fit-Check Model fabricated on Stereolithography SLA-250, Wax Pattern fabricated on Sinterstation 2000™ Beta SLS Machine, and Titanium Cast Part.

Table 1
SLA acrylic models average deviation from nominal (inches)

	Mean			
	Diameter	Linear	Radius	Z-Build
Part A (acrylic)	.0018	.0050	.0022	.0203
Part B (acrylic)	.0020	.0037	.0027	.0216
Part C (acrylic)	.0021	.0029	.0029	.0136
Part E (epoxy)	.0037	.0034	.0054	.0028
Part F (epoxy)	.0026	.0028	.0054	.0079

	Standard Deviation			
	Diameter	Linear	Radius	Z-Build
Part A	.0030	.0030	.0030	.0200
Part B	.0017	.0034	.0023	.0178
Part C	.0019	.0029	.0017	.0109
Part E	.0017	.0028	.0015	.0015
Part F	.0012	.0017	.0017	.0042

Table 2
SLS wax patterns average deviation from nominal (inches)

	Mean			
	Diameter	Linear	Radius	Z-Build
Part A (wax)	.0035	.0050	.0119	.0148
Part B (wax)	.0039	.0061	.0117	.0143
Part C (wax)	.0052	.0077	.0120	.0165
Part D (wax)	.0041	.0039	.0116	.0116
Part F (wax)	.0041	.0039	.0083	.0131

	Standard Deviation			
	Diameter	Linear	Radius	Z-Build
Part A	.0030	.0050	.0064	.0083
Part B	.0045	.0061	.0075	.0113
Part C	.0035	.0057	.0073	.0178
Part D	.0044	.0037	.0049	.0067
Part F	.0036	.0032	.0051	.0075

7. CONCLUSION

Rapid prototyping processes have a significant impact on the product development cycle. As these processes evolve and become more accurate, as new materials and applications are developed and found, and as more design engineers begin to use solid modeling as a design tool, the processes will have an even greater impact. At Sandia, the Stereolithography and Selective Laser Sintering processes have effectively reduced the turn-around time and cost of producing complex prototype parts. Consequently, designers have more flexibility in meeting cost, schedule, and performance requirements. Designs are completed without creating engineering drawings; and, ultimately, the entire design iteration process from concept to final product is electronically documented for easy retention (see Figure 4).

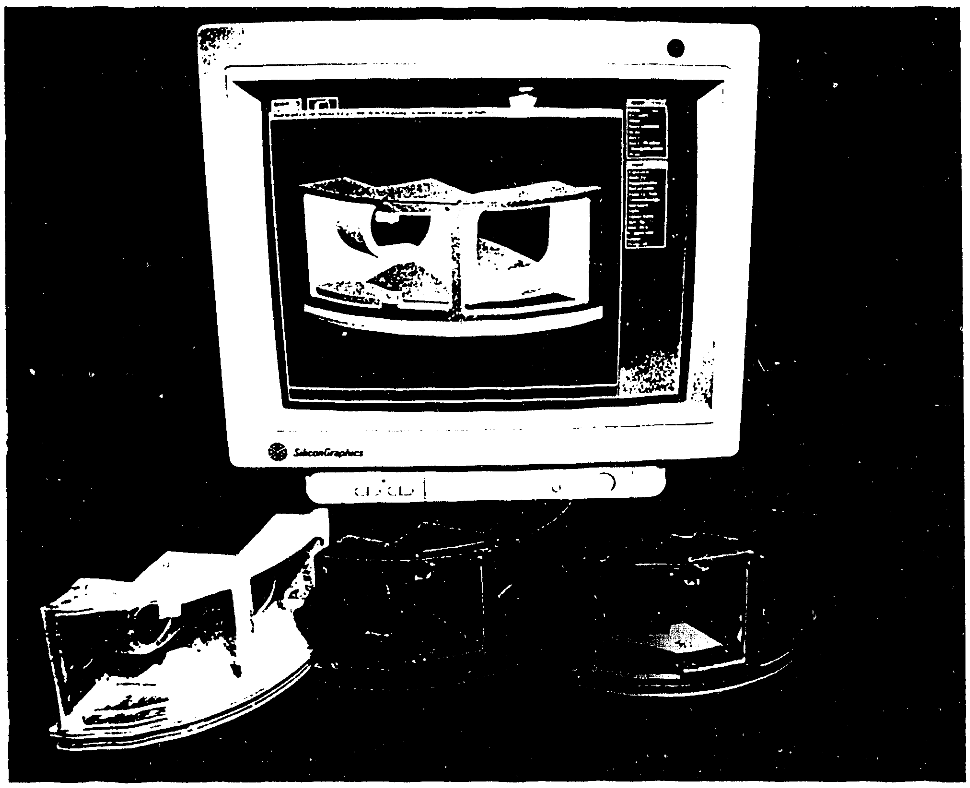

Figure 4 (Top) Three-dimensional CAD Solid Model, (Bottom Left to Right) Acrylic Fit-Check Model, Wax Pattern, 13-8PH Stainless Steel Casting

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