SOLID MODELING AND STEREOLITHOGRAPHY AS A SOLID FREEFORM FABRICATION TECHNIQUE AT TEXAS INSTRUMENTS INCORPORATED

By Owen Baumgardner and Paul Blake
Texas Instruments Incorporated

I. INTRODUCTION

Over the past 25 years, the CAE/CAD/CAM industry has developed technological advances that have provided industrial users the ability to increase productivity and decrease the cycle time necessary for product development. These technologies include basic wireframe and surface design, specialized-application software packages, finite element analysis, numerical control, solid modeling, and rapid prototyping.

Each of these technologies plays a significant role in industry today. The Defense Systems & Electronics Group of Texas Instruments currently uses these technologies in the mechanical design engineering process. This paper discusses the two specific technologies of solid modeling and rapid prototyping (specifically stereolithography), including their advantages, benefits, and practical applications within the Texas Instruments Defense Systems & Electronics Group. This paper also discusses the use of stereolithography (SLA) rapid-prototype parts within the solid-mold investment-casting process.

II. SOLID MODELING

Solid modeling is an advanced design capability that offers the mechanical design engineer numerous advantages over traditional wireframe design methods. Visual and analytic capabilities are improved and required inputs for rapid prototyping are provided.

As its name implies, solid modeling represents an object as a solid part. These parts are typically represented as shaded images on the computer screen (Figures 1 and 2). On the other hand, wireframe design systems represent edges as lines and faces as surfaces. As the complexity of a wireframe design increases, the ability to visualize and understand the design decreases. Figure 3 demonstrates the visual ambiguity that wireframe designs create; solid modeling alleviates this ambiguity. Solid modeling also is able to generate cross sections or cutaway views with minimal effort (Figure 4). These capabilities allow the design engineer to visualize and understand what the part looks like and how it functions within an assembly by clearly displaying the critical relationship of part layouts, interferences, and clearances.

The numerical and material information intrinsic to a solid model offers two unique capabilities. First, the solid model permits the engineer to derive mass property data (weight, center of gravity, moments of inertia, surface areas, etc.) of parts and assemblies (Figure 5). This eliminates the need for hand calculations to estimate the data from drawings or sketches. Second, the mechanical integrity of the design may be investigated using various analysis methods to determine structural, thermal, kinematic, and aerodynamic properties. These capabilities allow the engineer to design, analyze, and redesign on the CAE computer, using the same solid model. Automating the design process helps reduce the need for, but does not eliminate, the costly iterations of fabrication and physical testing of the hardware.

Finally, solid-model data bases serve as direct input to rapid-prototyping systems. (It should be noted that surfaced-part data bases may also be used as inputs.) The input is in the form of a tessellation, or "tile" file, that is generated from the solid model or surface data base. The tessellation file is a triangular extraction of the surfaces of the solid model (Figure 6).

The build process is directed by a computer-controlled optical scanning system. It moves a laser beam in the X and Y direction while drawing an image of the part on the photopolymer surface. The photopolymer solidifies wherever the laser beam strikes it. After the laser is finished drawing, a vertical elevator, moving along the Z axis, lowers the newly formed layer into the vat of liquid resin. A recoating blade is used to establish the next layer's thickness. Successive layers are built one on top of another to form a completed "green" part. Part build time varies as the part size and complexity varies. Typically, part build time ranges from 1 to 2 hours for small and simple parts, to upwards of 60 hours for large complex parts.

The green part is cleaned by stripping excess resin with alcohol, then hardened by exposure to ultraviolet light in a postcuring apparatus. After curing, the supports are removed from the part and, if necessary, a light sanding is applied to improve the overall appearance. Required part cleanup time also varies from 1/2 hour to 2 hours per part.

Part size is limited by the volume of the vat (10 × 10 × 10 inches). The vat contains 7.8 gallons of liquid photopolymer resin. The laser is a helium-cadmium-powered device that generates a beam 0.010 inch in diameter with a wavelength of 325 nanometers at a maximum power of 28 milliwatts. The optical scanning system is controlled by a DOS-based 386 computer, while the "slicing" takes place on a UNIX-based 386 computer.

IV. BENEFITS OF SOLID MODELING AND RAPID PROTOTYPING

Use of solid modeling and the SLA rapid-prototyping process have resulted in numerous benefits for the entire design engineering community at Texas Instruments. These benefits include increased visualization capability, decreases in cost and cycle time associated with fabrication of prototype parts, and increased ability to calculate mass properties and detect design flaws before hardware fabrication.

The first benefit of these two technologies, and perhaps the most obvious one, is the enhanced visualization capability. Engineers, designers, technicians, and managers now discuss designs by looking at three-dimensional shaded images and full-scale plastic prototype parts, not two-dimensional drawings. The SLA prototype parts and assemblies are also used for fit-check verification (where tolerances permit), assembly methods and tooling planning, cable routing and weight reduction studies, customer communication models, and vendor quoting tools.

Another benefit derived from the use of rapid prototyping is the decrease of cycle time required to produce prototype parts. The current SLA prototype turnaround cycle, defined as the time difference between data-base receipt to part fabrication completion, is between 2 and 10 days, depending on engineering requirements. This is a dramatic decrease over conventional machining methods, which typically take months. Therefore, the engineering team may visually, dimensionally, and functionally inspect and review the critical and high-risk parts and assemblies earlier in the design phase of the overall design cycle. This benefit also results in the increased ability of the design engineer to explore, accept or reject, and integrate new design ideas into the existing design. Another cycle-time benefit is the increased time available to explore the potential use of the less expensive casting process for part fabrication over traditionally more expensive machine processes.

Texas Instruments has experienced typical cycle-time reductions of 2 weeks for simple parts and 20 weeks for complex machined or cast parts in the fabrication of prototype parts. Also, customer concept communication models have been fabricated for half the cost and in half the time of conventional methods. Specific examples of cycle-time and cost reductions are found in Figures 7 through 10.

The third benefit of solid modeling and SLA rapid prototyping is the cost reduction and avoidance associated with eliminating design flaws early in the design cycle. The product development and fabrication cycle is constantly at the mercy of continuous requirements and design changes. These continuous

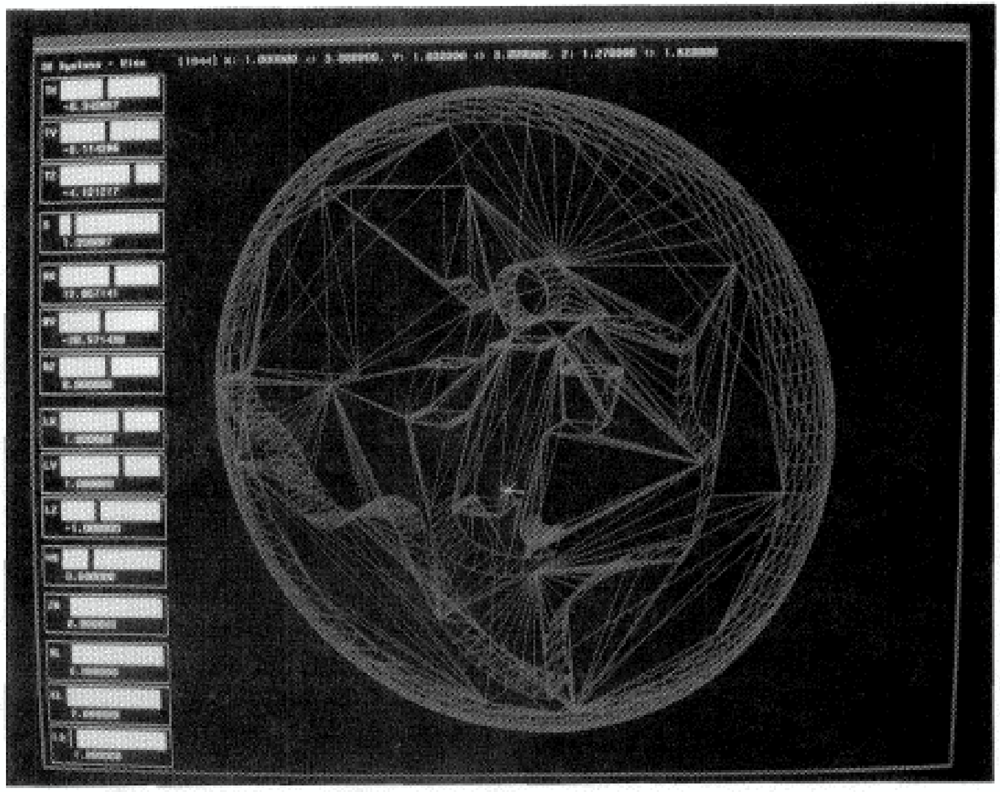


Figure 6. Tesselation Tile File

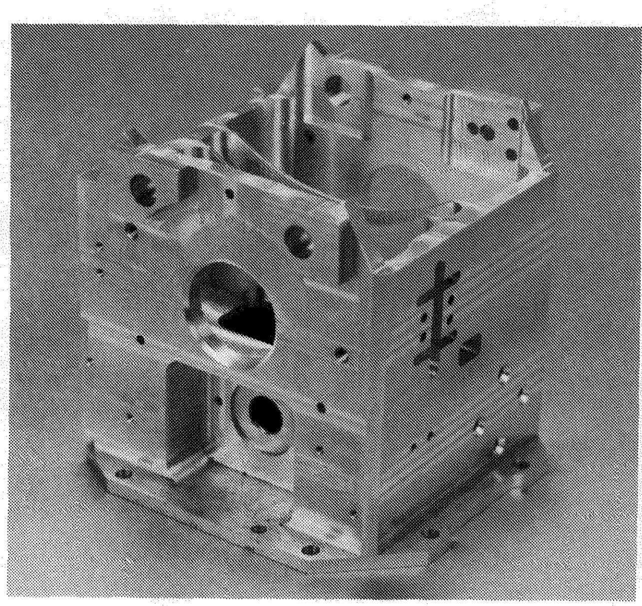
changes, coupled with the inability to easily verify overall part layout configurations, contribute to part assembly problems, such as interferences and misaligned hole patterns. Often, these problems were not found until piece parts were fabricated and assembled. Costs rose as parts were scrapped or modified and the amount of required touch labor increased to assemble and disassemble the piece parts. Engineering change notices had to be incorporated into the design, significantly adding to the overall cost.

Solid modeling permits engineers to visually inspect the designed piece parts and assemblies for mating hole patterns and part clearances. As the design is completed and verified, the engineer may use the SLA rapid-prototyping process to build a three-dimensional model as a final review before committing the design to fabrication. These capabilities serve as cost-avoidance steps that help meet proper fabrication and assembly requirements.

The fourth benefit, specifically attributed to solid modeling, is an increased ability to calculate mechanical properties of the parts and assemblies throughout the design process. For example, weight is a critical design requirement. Solid-modeling mass-property calculations assist the engineer by calculating part and assembly weights. This information allows the engineer to optimize the design for weight requirements before part fabrication. Weight calculations using solid modeling have typically been within ± 1 percent of the actual part weight.

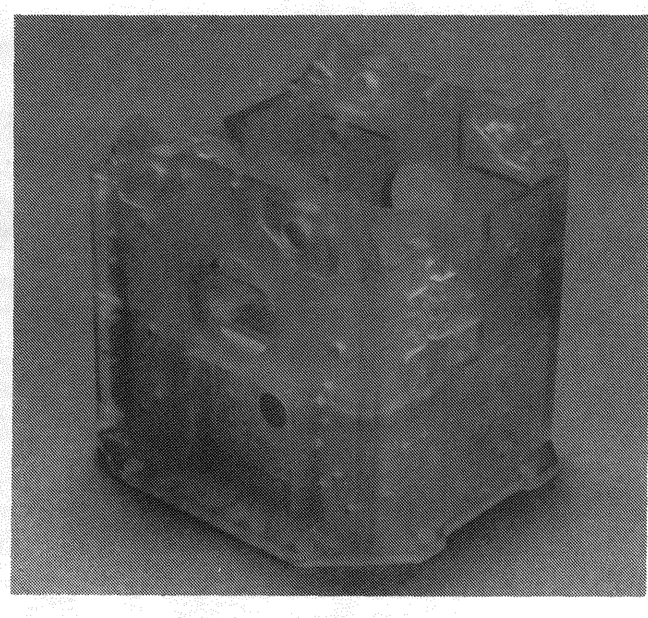
V. STEREOLITHOGRAPHY AND INVESTMENT CASTING

A significant and immediate impact on the cost and cycle time associated with the investment casting process has been achieved by incorporating the SLA part into the process. The ability to use the SLA-modeled part as a wax substitute is the key to supplying castings for low-production runs without the high cost of foundry pattern tooling. In addition, providing machine shops with a near net-shaped part reduces the number of required machining steps to produce a completed part.



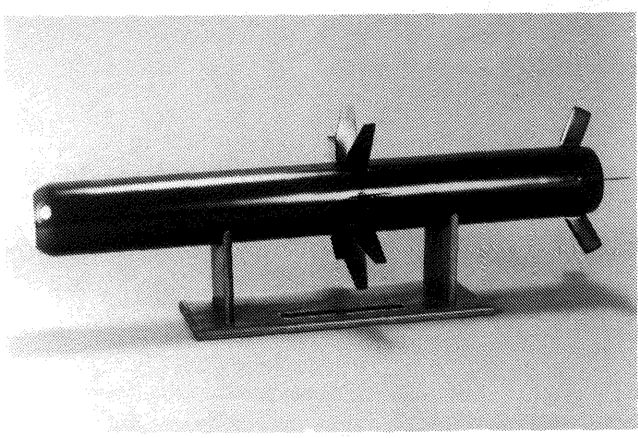
MATERIAL: 6061–T6
TIME REQUIRED: 104 HOURS*
CYCLE TIME: 4 MONTHS

Figure 7. Picture of Machined Part (Motor Housing)



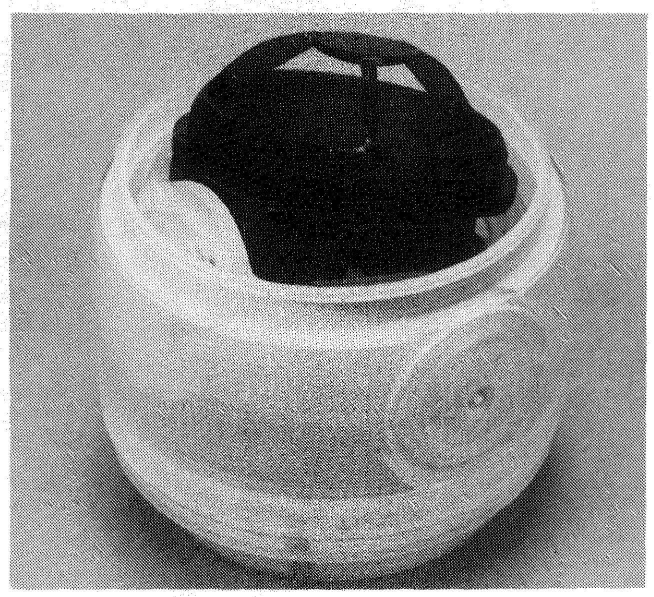
TIME REQUIRED: 8 HOURS*
CYCLE TIME: 3 DAYS

Figure 8. Picture of SLA Model (Motor Housing)



OUTSIDE QUOTE: $10,000 AND 2 MONTHS CYCLE TIME
TIME REQUIRED: 75 HOURS*
CYCLE TIME: 1 MONTH

Figure 9. Picture of SLA Model (Missile)



TIME REQUIRED: 54 HOURS*
CYCLE TIME: 8 WEEKS
LESSONS LEARNED:

1. PRIMARY MIRROR HAD INTERFERENCE WITH GIMBAL IN AZIMUTH SWEEP.
2. SECONDARY MIRROR WAS STRENGTHENED IN ITS ATTACHMENT LEGS.

Figure 10. Picture of SLA Sweep Volume Model (Seeker Assembly)

*TIME REQUIRED IS FOR SLA RAPID-PROTOTYPE TOUCH LABOR ONLY, NOT MACHINE RUN TIME.

There are two types of investment casting processes: solid mold and shell. They differ only in the method used to form the ceramic mold. Both processes require a pattern, gating to a central sprue, ceramic mold (either solid or shell), removal of the pattern by melting, pouring metal into the cavity left by the melted pattern, removal of the mold material from the cast cluster, and cutting of the castings from the sprue.

Currently, the only successful procedure to use the SLA part as a wax pattern substitute for investment casting is the solid-mold process. The SLA part expands more than the traditional wax pattern as it is heated to be melted from the mold. This increased expansion causes the SLA part pattern to crack the weaker mold in the shell process, but not the metal-reinforced mold in the solid-mold process.

The ceramic solid mold is created by placing the SLA part, with the gate and runner system attached, into an open-ended metal flask. Investment slurry is poured into the flask, completely surrounding the SLA part with its gate and sprue system. Before the binder in the slurry solidifies, the flask is placed under a vacuum to remove all entrapped air. When the investment is set, the SLA part pattern is melted out of the mold and the process is completed by following the same procedures used for any normal investment casting.

There are four classes and grades for castings: Classes 1, 2, 3, and 4 and Grades A, B, C, and D. The class is established by the engineer according to design requirements for functionality, safety, reliability, and mechanical properties. The grade is also established by the engineer; it is used as the accept/reject criterion for radiographic inspections. Materials available for the investment casting process include all ferrous and nonferrous alloys.

Texas Instruments has been successful in pouring these nonferrous alloys to date: A356–T6, 356–T6, A357–T6, 357–T6, A201–T7, and an MMC of A357–T6 with 20-percent silicon carbide. Typically, the castings have been Class 3 and Grade C with a cycle time of 4 weeks. This is a 4-month decrease in time required to fabricate a casting. The class and grade of the SLA castings meet the engineering requirements of Texas Instruments. See Figure 11 for examples of parts cast using this process.

VI. GUIDELINES AND PRACTICAL LIMITATIONS

Five practical guidelines can be applied to assist in the implementation of solid modeling and SLA rapid prototyping in the industrial environment. First, there is no substitute for good engineering. CAE/CAD/CAM, computers, and rapid prototyping assist engineers in performing their tasks. These design tools cannot replace engineering judgment, discipline, design creativity, and practical design applications. Solid modeling and SLA rapid prototyping are not panaceas, but are excellent tools to assist engineers in accomplishing their tasks.

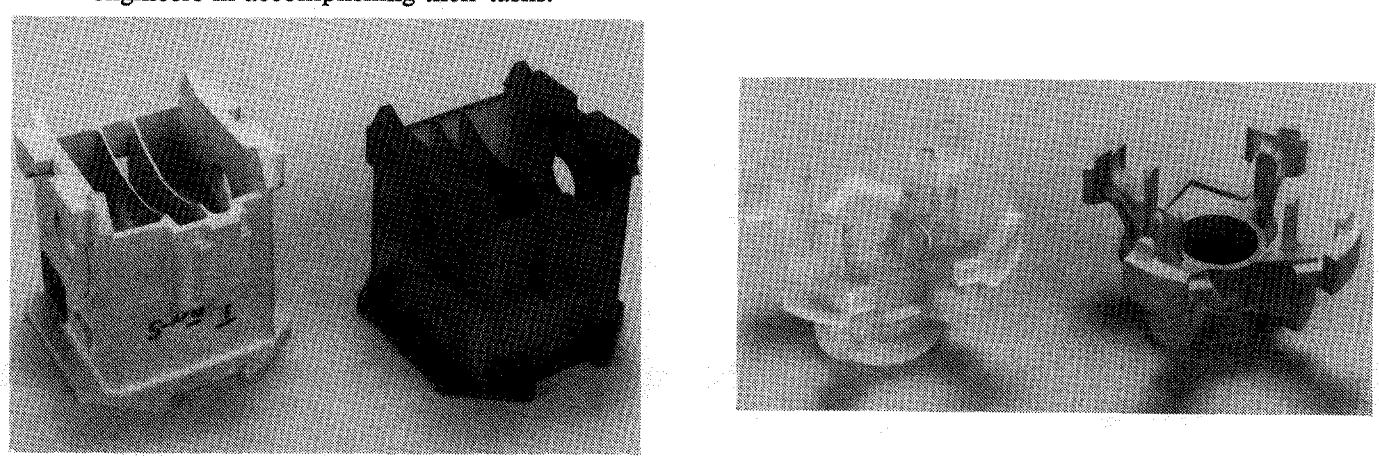


Figure 11. Stereolithography Parts With Casting

Second, as with all CAE/CAD tools, there is a learning curve associated with solid modeling. To receive maximum benefit, sufficient time should be allowed for the user to become acquainted with the capabilities and intricacies of the software.

Third, designing with a solid-modeling system is the most effective way to take advantage of rapid prototyping. If designs are maintained in wireframe mode and an SLA rapid prototype part is desired, the parts must be remodeled or converted into an acceptable data-base format. This adds to the cost and cycle time required to produce a rapid-prototype part.

Fourth, the solid-mold casting process will eventually be supplanted by the current traditional shell-mold investment casting process. As the chemical, casting, and rapid-prototyping industries are successful in developing an acceptable rapid-prototype part for the shell-mold investment process, the requirements of the solid-mold process will diminish.

Finally, the SLA rapid prototyping process does have limitations which need to be balanced against the part requirements. These limitations include: surface finish, tolerance, wall thickness, and feature configurations.

- Surface finish—The general finish is acceptable for engineering evaluation requirements. However, for a display model, surface-finish flaws are noticeable at 5 to 6 feet, but may be corrected by using a fiberglass filler, sanding, and painting.
- Tolerance—Typical part dimensions can be held to ± 5 mils per inch. Tighter tolerances can be controlled with experimentation. NOTE: Part accuracy is controlled by part configuration.
- Wall thickness—As a general rule, 50 mils is the minimum wall thickness that can be repetitively produced. Thinner sections may suffer distortion during the postcuring cycle.
- Feature configuration—Part position and orientation should be aligned with the important engineering design features for the best possible surface finish and accuracy. The layering, or staircase, effect dictates that all critical part features be built in the X and Y plane of the SLA machine, not in the Z plane.

VII. CONCLUSION

Solid modeling and rapid prototyping offer the mechanical design engineer a more cost-effective means of designing and building prototype parts than do traditional methods. Texas Instruments has experienced productivity increases as these processes have been used in the design and fabrication areas of the product-development life cycle. Both solid modeling and rapid prototyping will play important roles in the future as companies strive to decrease design costs and cycle times.