

Application of Stereolithography Apparatus to the Investment Casting of Prototype Parts

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ABSTRACT

Concerning investment casting, “decreased cost,” “reduced lead time” and “quick response to design changes,” are often required in the early stages of a project. Thus, stereolithography apparatus (SLA), a typical rapid prototyping technique, has been applied to the master pattern of investment casting prototype parts for our gas turbine engine. Accompanying this new application were problems peculiar to SLA, for example, adhesion of carbonized resin to the surface of the ceramic mold and SLA layer marks. The adhesion problem has been overcome by optimization of the burning conditions and the problem with the layer marks has been overcome with an improved surface finishing method. As a result, prototype parts, which satisfied the design dimension and configuration requirements, could be produced. At the same time, the cost and lead-time were reduced to 1/15 and 1/8, respectively, of those for the conventional method.

1. Introduction

Investment casting of prototype parts for gas turbine engines has traditionally been carried out using the lost wax method. This method requires a metal die to produce wax models through injection molding as a master pattern. This master pattern is used for making a ceramic shell mold to cast the required part. However, this method assumes the part will ultimately be mass produced, and both a significant amount of time and expense are required to produce the metal die. In addition, once the metal die has been produced, it is difficult to quickly respond to design changes.

Thus, there is a call to achieve lower costs, shorter lead-times and quicker response to design changes when producing prototype parts. Various methods have recently been studied in order to attain these three requirements without making a metal die. These methods include a prototype part production method utilizing a so-called “machinable wax,” in which a wax model is machined from a block of wax; and, a method in which prototype part production is carried out by forming the master pattern with a stereolithography apparatus (SLA), in which an

ultraviolet-curable resin is cured with a laser⁽¹⁾.

Although a metal die is not produced with the method using machinable wax, time is required to create the machining program. In addition, measures need to be taken to handle the sag of wax during the machining of thin-walled portions. This makes it extremely difficult for some contours to be produced. However, once a proper model is made, parts can be cast by the conventional lost wax process.

Stereolithography enables a model represented by three-dimensional CAD data to be formed, regardless of the complexity of the shape. However, there are still problems that remain to be solved such as layer marks on the model surface and the post-molding process being different from that used in the lost wax process^{(2) - (4)}.

We have thus far attempted casting using a method that uses conventional wax models and a method that uses machinable wax. Moreover, in order to satisfy the three prototyping requirements mentioned above, prototyping of the functional parts of a gas turbine engine was carried out by applying SLA models as the master pattern. This process along with the problems that occurred and their solutions are reported here.

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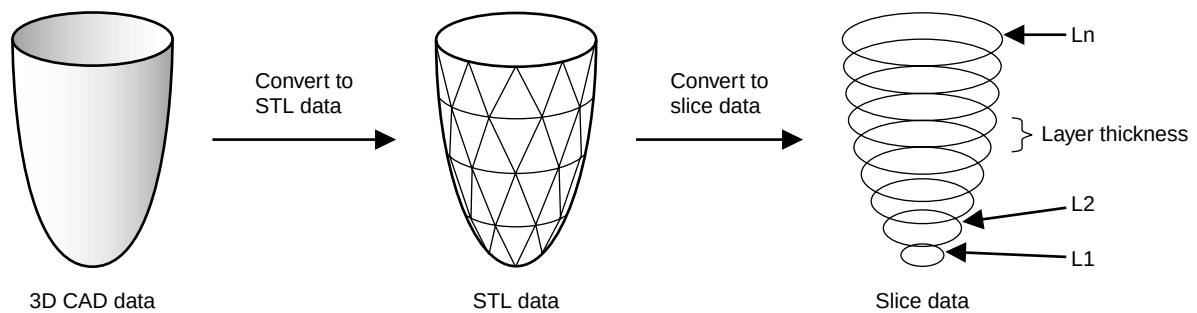


Fig. 1 Data conversion process

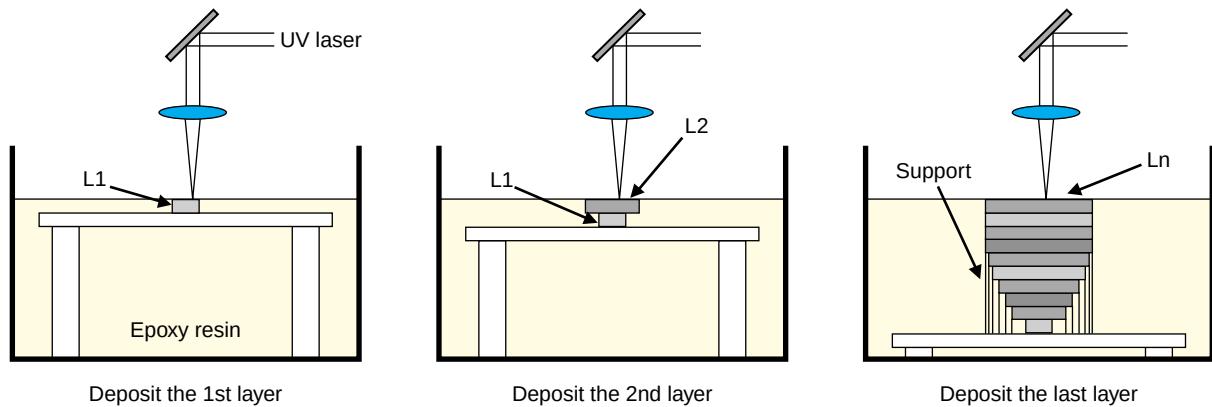


Fig. 2 SLA model deposition

2. The Stereolithography Apparatus (SLA) Forming Method

Rapid prototyping technology, which enables three-dimensional models to be formed directly from three-dimensional CAD data, has evolved rapidly in recent years⁽⁵⁾. Stereolithography apparatus (SLA) is one form of this rapid prototyping technology. SLA enables a model to be produced by irradiating a photocurable resin with an ultraviolet laser to cure the resin. An outline of the SLA forming method is shown in Figs. 1 and 2.

Three-dimensional CAD data is first converted to the stereo lithographic (STL) format, and additionally converted to slice data at the chosen deposition pitch. A table is next placed in a photocurable resin tank. The table is then submerged in a liquid epoxy resin to a depth equal to the deposition pitch, and an ultraviolet laser is used to irradiate the area within the slice data envelope to form the first layer (L1). After forming this first layer, the table is lowered by an amount equal to the deposition pitch, and the second layer (L2) is formed in a similar manner. This process is repeated until the final layer (Ln) is formed to create a three-dimensional model from the deposited layers. Supports are simultaneously formed between the table and any overhanging portions of the model. These supports are removed after the model is completely formed.

SLA models can be formed as solid or hollow models. Solid models have all of the resin cured inside the model and are mainly used for confirming the design and conducting wind tunnel experiments. Hollow models are formed with a thin skin to create a shell of about 0.4 – 1 mm in thickness that is supported by an internal honeycomb structure. When a solid model is used as the master pattern for investment casting, cracking of the ceramic shell mold can occur due to thermal expansion of

the resin when the model is burned away. Consequently, hollow models are used for ordinary investment casting. A typical hollow model is shown in Fig. 3.



Fig. 3 Hollow model (SLA)

3. Prototyping of a Turbine Nozzle

Fig. 4 shows a turbine nozzle for a gas turbine engine produced by applying SLA to form the master pattern. The investment casting process is described below.

3.1 Component Process

Fig. 5 shows the SLA model of the turbine nozzle which would have been made entirely from wax in the past. SLA can be used to form only for the part itself, with wax being used to form the gating system, consisting of the sprues, runners and gates, used in directing molten metal to the actual part. In this example, the gating system was made with the part by SLA in order to reduce the man-hours required for making and assembling the gating system. The model deposition pitch was set at 0.1 mm, so the curved surfaces of the formed model consist of steps

with a pitch of 0.1 mm. This stepped profile is smoothed to a continuous curved surface by sanding or a similar polishing process. Although described later in detail, if this finishing procedure is inadequate, layer marks are transferred directly to the surface of the cast part resulting in surface defects.

A sprue cup is attached to the finished model and a shaft for molding the ceramic shell mold is positioned to give the complete master pattern of the component, as shown in Fig. 6.

3.2 Molding the Ceramic Shell Mold

The ceramic shell mold is molded around the master pattern. The pattern of the component is immersed in a liquid ceramic slurry to wet the model surface which is next sprinkled with ceramic powder (refractory material) to coat the surface. The model is then allowed to dry. This process is repeated about 10 times with a drying time of 3 – 4 hours between each coating. Ceramic powder with a fine particle size is used for the first layer of the refractory coating to ensure that fine surface details of the master pattern are faithfully reproduced on the surface of the casting.

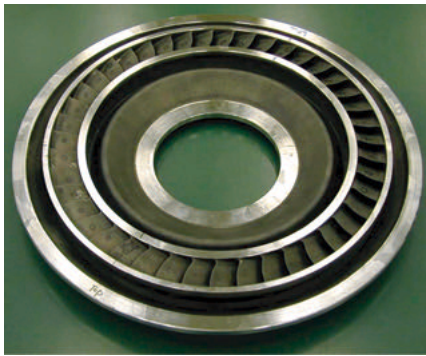


Fig. 4 Turbine nozzle

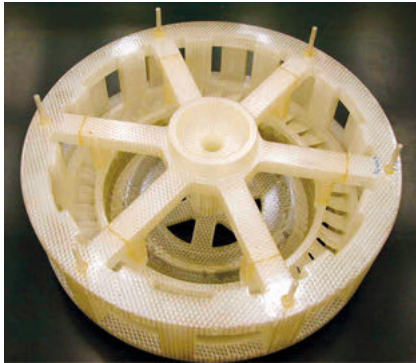


Fig. 5 SLA model of turbine nozzle

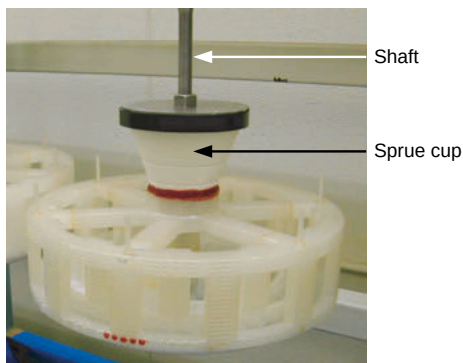


Fig. 6 Turbine nozzle components

Subsequent layers through the backup layer use refractory material of progressively increasing particle size to ensure adequate strength of the ceramic shell mold. The final green ceramic shell mold has a wall thickness of about 8 – 10 mm.

3.3 Model Burnoff and Ceramic Shell Mold Sintering

The SLA model remains inside the green ceramic shell mold up to this point. In the next process, this ceramic shell mold is placed in a kiln, and the temperature inside the kiln is incrementally raised to the firing temperature of the epoxy resin (approximately 400°C) to burn off the material of the SLA model. The temperature is further raised to approximately 1000°C and then maintained for several hours to sinter the ceramic shell mold. Fig. 7 shows the finished ceramic shell mold.

If the resin has not been sufficiently burned off, a carbonized deposit remains inside the ceramic shell mold adhering to its internal surface. If the resulting profile of this deposit is transferred directly to the surface of the casting, it causes a surface defect known as “orange peel.” The specific measures for the orange peel defect are described later.

3.4 Casting

The material used for casting was a Ni-based superalloy. A vacuum melting furnace was used for casting this superalloy to ensure that the mechanical properties of the material were satisfactorily obtained and to reduce misruns into portions having a complex shape. The ceramic shell mold is heated in the vacuum melting furnace to approximately 1000°C and, after being held at this temperature for about 1 hour, the molten material, with a temperature of approximately 1500°C, is poured into the mold and the mold is then allowed to cool. Fig. 8 shows the as-cast state of the turbine nozzle after the ceramic shell mold is taken apart and cleaned.

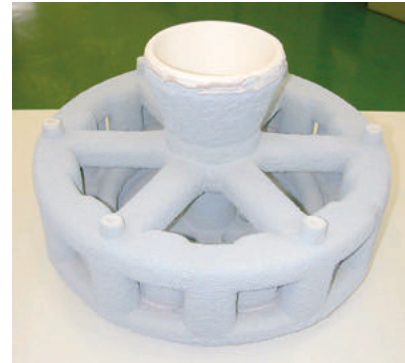


Fig. 7 Ceramic shell mold of a turbine nozzle



Fig. 8 As-cast turbine nozzle with gating system

3.5 Removing the Gating System and Machining

The gating system is removed from the resulting casting and, after undergoing a solution heat treatment and aging treatment, the casting is machined. A dimensional inspection confirmed that the finished dimensions of the cast component satisfied the dimensional tolerance for investment-casting standards as stipulated by JIS.

4. Problems and Solutions

4.1 Orange Peel Defect

The phenomenon by which carbonized resin adhering to the internal surface of the ceramic shell mold after burning off the SLA model is directly transferred to the casting surface is referred to as the “orange peel” defect. Fig. 9 shows the residual carbide adhering to the internal surface of the ceramic shell mold, while Fig. 10 shows the resulting orange peel defect on the surface of a casting.

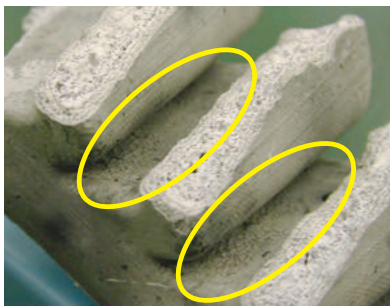


Fig. 9 Carbide adhesion (Mold)



Fig. 10 Orange peel (casting)

Orange peel is characterized by the formation of an infinite number of hairline cracks in close proximity to the surface of the casting, and results in a significant decrease in the mechanical strength of the component. A fluorescent dye penetrant inspection, which is one of the non-destructive inspections performed on cast parts, reveals the presence of such defects over the entire surface.

In order to solve this problem, the fan-shaped test piece shown in Fig. 11 was made by SLA and, after molding the ceramic shell mold, a combustion test was performed by



Fig. 11 Test piece

three different methods. (The ceramic shell mold shown in Fig. 11 was molded to the second layer.)

- (1) Conventional method: The ceramic shell mold was placed directly into a kiln.
- (2) Air blowing method: Hot air was blown through an opening into the ceramic shell mold.
- (3) Air blowing and air venting method: Air was blown through an opening into the ceramic shell mold and then vented through a hole created in the opposite side.

The heating conditions for the kiln were the same for all three methods.

The conventional method resulted in residual carbide adhering to the inside of the ceramic shell mold (Fig. 12). Hot air blown into the mold offered some improvement, although carbide was observed to be adhering to some areas inside of the mold since there was no air flow inside without venting (Fig. 13). When hot air was blown in and then vented, however, no adhesion of carbide whatsoever was apparent on the inside of the ceramic shell mold (Fig. 14).

For prototyping of turbine nozzles, hot air was supplied by placing a stainless steel tube inside the ceramic shell mold during model burnoff. By simultaneously discharging this air through a vent in the outer periphery of the ceramic shell mold, the resin was burned off completely, thereby inhibiting the orange peel defect.

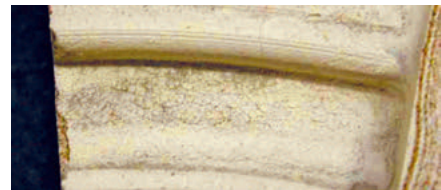


Fig. 12 Carbide adhesion (Usual burning condition)



Fig. 13 Carbide adhesion (Air blowing)



Fig. 14 No adhesion (Air blowing and air vent)

4.2 Layer Marks and Support Marks

An SLA model is layered, so curved surfaces are formed in a series of steps, the height of each step being equal to the layer thickness. Normally, as shown in Fig. 15, slice data are offset outside the model profile. Consequently, after layering, it is necessary to remove the stepped surface to achieve the required surface profile of the model. In addition, supports may have been incorporated, depending on the shape, and those supports must also be removed.

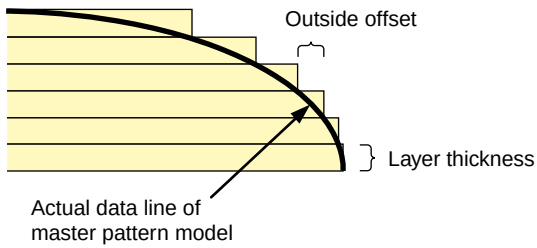


Fig. 15 Offset of slice data

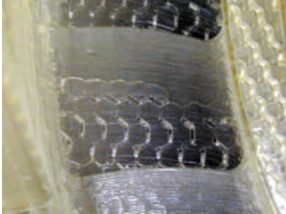


Fig. 16 Layer mark (SLA)



Fig. 17 Remains of support (SLA)

However, as shown in Figs. 16 and 17, since the SLA model is translucent, it is difficult to accurately determine the required finished profile by visual means alone.

When finished by simple visual observation, the layer marks and support marks shown in Fig. 18 and the presence of removed support debris shown in Fig. 19 were apparent on the surface of the casting, clearly indicating that the finished state of the model was inadequate.



Fig. 18 Layer mark and remains of support (casting)



Fig. 19 Remnants of removed support (casting)

Although it is necessary to carefully finish the model to avoid these problems, it is difficult to determine the surface condition since the model is translucent. This problem was solved by applying a primer to the model surface to allow its surface condition to be visually confirmed. Figs. 20 and 21 show the primer-coated surface of the SLA model in the same finished state as that shown in Figs. 16 and 17. The color appeared closer to that of a casting, and the finished state of the surface was more easily apparent.

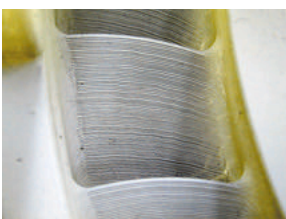


Fig. 20 Primer coated surface of SLA model (Layer mark)



Fig. 21 Primer coated surface of SLA model (Remains of support)

A model finished after being coated with primer is shown in Fig. 22. The finished state obtained without the primer coating shown in Fig. 16 had a surface roughness of $R_z = 70$ to 100 . On the other hand, the finished state obtained by coating with the primer shown in Fig. 22 demonstrated an improved surface roughness of $R_z = 10$ to 15 .



Fig. 22 Finished surface of SLA model (Primer coated)

4.3 Wavy Lines on the Layered Surfaces

The SLA model is formed by converting three-dimensional CAD data into an STL format, generating slice data according to the defined layer thickness, and forming the model based on that data. Consequently, laser scanning is determined by the envelope defined by the slice data, resulting in the final shape of the model. A surface is represented in the STL format by the pitch of a series of interlinked triangles as shown in Fig. 23. Since the laser scans the sides of those triangles, rather than a smooth curve, a wavy line is generated as shown in Fig. 24. Fig. 25 shows these wavy lines reproduced on the casting surface, and Fig. 26 shows the laser scanning lines from the data. Even if the steps between layers of the model are removed by polishing in this state, the wavy lines remain and the skin thickness of the surface layer becomes inconsistent.

In order to correct this, the process called “Z smoothing” was performed on the STL data to obtain a smooth curve from the slice data as shown in Figs. 27 and 28. No wavy lines were apparent when the model was formed from data subjected to Z smoothing.

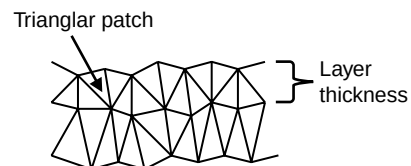


Fig. 23 Image of STL data model

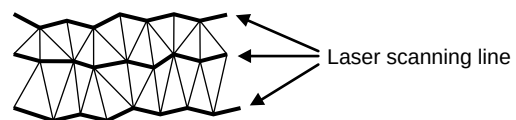


Fig. 24 Image of laser scanning line

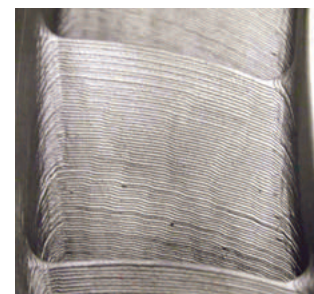


Fig. 25 Wavy lines on blade surface (casting)

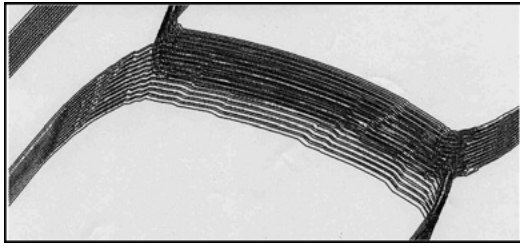


Fig. 26 Laser scanning line on data without Z smoothing

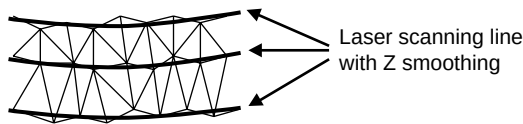


Fig. 27 Image of laser scanning line with Z smoothing

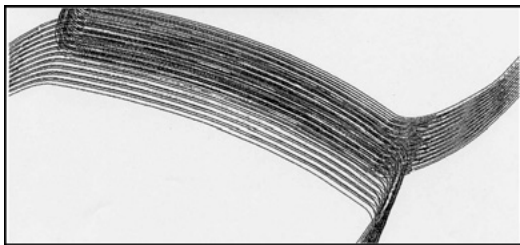


Fig. 28 Laser scanning line on data with Z smoothing

5. Comparison of Cost, Lead Time and Response to Design Changes

A comparison of cost, lead-time and response to design changes was made for the conventional lost wax method, the machinable wax method, and the SLA method. The comparison was based on the prototype turbine nozzle described in this paper. The comparison results are shown in Table 1. The cost indicated is for production of one model and is based on a value of 100% for the lost wax method; the lead time refers to the time required to complete the master pattern from three-dimensional CAD data.

The SLA method enabled the cost to be reduced to about 1/15 and lead time to about 1/8 compared with the conventional lost wax method. In addition, design changes could be accommodated more easily with the SLA method than with the conventional methods.

Table 1 Comparison of cost, lead-time, design change response

	Metal mold	Machinable wax	SLA
Cost (%)	100	13	7
Lead time (month)	4.0	1.5	0.5
Response to design revision	Difficult	Difficult	Easy

6. Summary

A turbine nozzle prototype was produced by applying stereolithography (SLA) to form the master pattern. Problems unique to the SLA method were revealed such as the adhesion of the resin, which remained after burning out the SLA model, to the inside of the ceramic shell mold, and the presence of layer marks on the surface of the SLA model. The problem of residual resin was solved by ensuring complete combustion of the resin by blowing hot air through the ceramic shell mold during burn out and discharging this hot air through a vent in the periphery of the mold. In addition, the problem of the layer marks was solved by coating the model surface with a primer to give better visualization of the surface to thereby enable finishing to a greater surface smoothness.

These actions enabled a turbine nozzle to be produced that satisfied the dimensional tolerance standards for investment casting as stipulated by JIS. At the same time, the master pattern production cost was reduced to about 1/15, and the lead-time decreased to about 1/8 of the figures for the conventional lost wax process.

We intend to proceed further with the application of stereolithography to cast parts, with the gating system, having different shapes from the turbine nozzle studied thus far.

Acknowledgments

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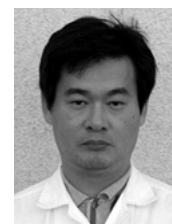
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