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Rapid Fabrication of Flat Plate Cavity Phosphor Thermography Test Models for Shuttle Return-to-Flight Aero-Heating

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Abstract

Methods, materials and equipment are documented for fabricating flat plate test models at NASA Langley Research Center for Shuttle return-to-flight aeroheating experiments simulating open and closed cavity interactions in Langley's hypersonic 20-Inch Mach 6 air wind tunnel. Approximately 96 silica ceramic flat plate cavity phosphor thermography test models have been fabricated using these methods. On one model, an additional slot is machined through the back of the plate and into the cavity and vented into an evacuated plenum chamber to simulate a further opening in the cavity. After sintering ceramic to 2150°F, and mounting support hardware, a ceramic-based two-color thermographic phosphor coating is applied for global temperature and heat transfer measurements, with fiducial markings for image registration.

Introduction

The effects of cavity geometry and momentum thickness Reynolds number on cavity flow conditions were experimentally examined in NASA Langley's 20-Inch Mach 6 Air hypersonic wind tunnel (Everhart et al., 2005) using phosphor coated ceramic aeroheating test models. These studies were in support of an agency-wide effort to prepare the Shuttle Orbiter for return to flight. To determine the effects of isolated roughness elements on the boundary layer ahead of cavities, both protuberances above the windward surface of the Shuttle Orbiter, simulating possible expanded repair devices, and cavities below, simulating unrepaired tile damage, were also examined in NASA Langley's hypersonic wind tunnels (Liechty, Berry and Horvath, 2005). In the study of cavities, a critical condition to be determined is whether an opened or closed interaction with the surface boundary layer is present. That is, whether the external flow skips over the cavity, with only relatively low enthalpy flow recirculating within the cavity, or if the external boundary layer spills into or is entrained in the circulating cavity flow, possibly causing much greater damage to the vehicle. Global heat transfer images of flat plate cavity models were obtained using phosphor thermography and used to infer the status of cavity flow conditions in wind tunnel experiments. Cavity flow prediction algorithms from these experiments are being developed for tile damage simulations to prioritize repair efforts in the case of future damage during Shuttle Orbiter missions (Wood et al., 2004).

The purpose of this paper is to document the methods, materials and equipment used in fabricating the ceramic aeroheating test models used in these experimental studies. The fabrication process includes building a pattern using a rapid prototyping stereolithography (SLA) system, using a slip casting process to transform the pattern into a ceramic model, sintering the ceramic model to give it strength, attaching a mounting support, coating with phosphor, and marking fiducials for registering acquired images. A typical schedule for performing all these tasks is shown in figure 1, including the one-time task of fabricating the mounting plate alignment fixture. Other applications and uses of rapid fabrication technology for ceramic, metal and composite test models at Langley are also documented by Buck, 2000.

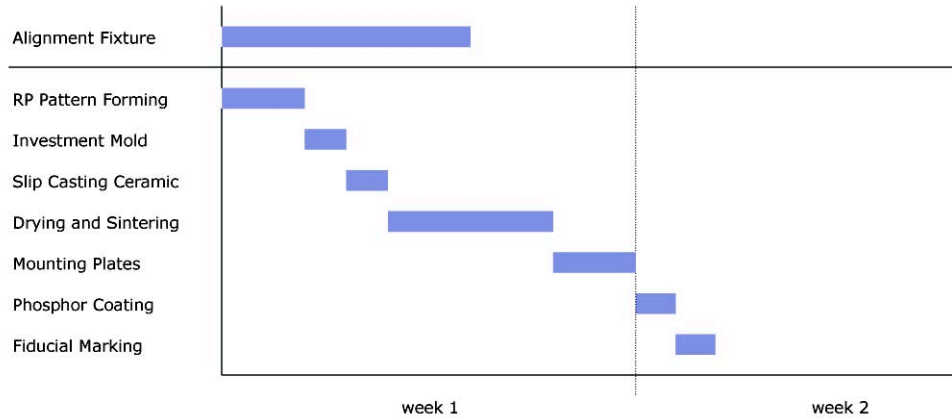


Figure 1. Model fabrication schedule.

Building Rapid Prototype Stereolithography Casting Patterns

There are two rapid prototyping stereolithography (SLA) systems at NASA Langley Research Center, both of which were used in building mold patterns for flat plate cavity test models. The first machine, shown in figure 2 (top), is a larger build (~20 inches cubed build area) model SLA 7000 manufactured by 3D Systems which was used to build the main plate sections, up to 18 inches long by 4 inches wide and $\frac{3}{4}$ inches thick. The second machine (fig. 2, bottom) is a smaller (~10 inches cubed build area), but faster system, model Viper SLA, also manufactured by 3D Systems, which was used to build the smaller insert pieces simultaneously. Both systems use a solid state Nd:YVO4 laser with 354.7 nanometer ultraviolet (UV) output to interact with and build photo reactive resin materials. To the left of the Viper SLA machine in figure 2 is the post-cure apparatus which is also used to irradiate the finished parts in UV (365 nanometer, mercury arc) radiation after removal from the build machines to finish curing and harden the resin. An SLA-resin casting pattern is shown alongside a final slip-cast ceramic test model in figure 3.

The photo reactive resin used in both machines is the Accura SI 10 material, which is also distributed by 3D Systems. This material is known for low linear and differential shrinkage and post build rigidity, even under high humidity conditions.

The parts are first designed in Pro-Engineering CAD solid modeling software and exported in a *.stl formatted file. The *.stl CAD file is then converted to a build file using resident machine software configuring the build orientation, resolution and internal pattern for the build. Patterns are built using a solid internal pattern. The Viper is operated in high-resolution mode at 0.003 inch spot diameter and 0.001 inch incremented build height. The SLA 7000 is operated in standard mode at at 0.010 inch spot diameter and 0.003 inch incremented build height with a build time of 24 to 30 hours and the capability to build as many as 20 plates in one session. The SLA patterns are removed from the machine and cleaned, removing supports and excess resin. Parts are then placed in the post-cure apparatus and UV cured for 90 minutes.



Figure 2. Rapid prototyping stereolithography systems used to build model patterns: top) SLA 7000 and bottom) Post Cure Apparatus and Viper SLA machine.

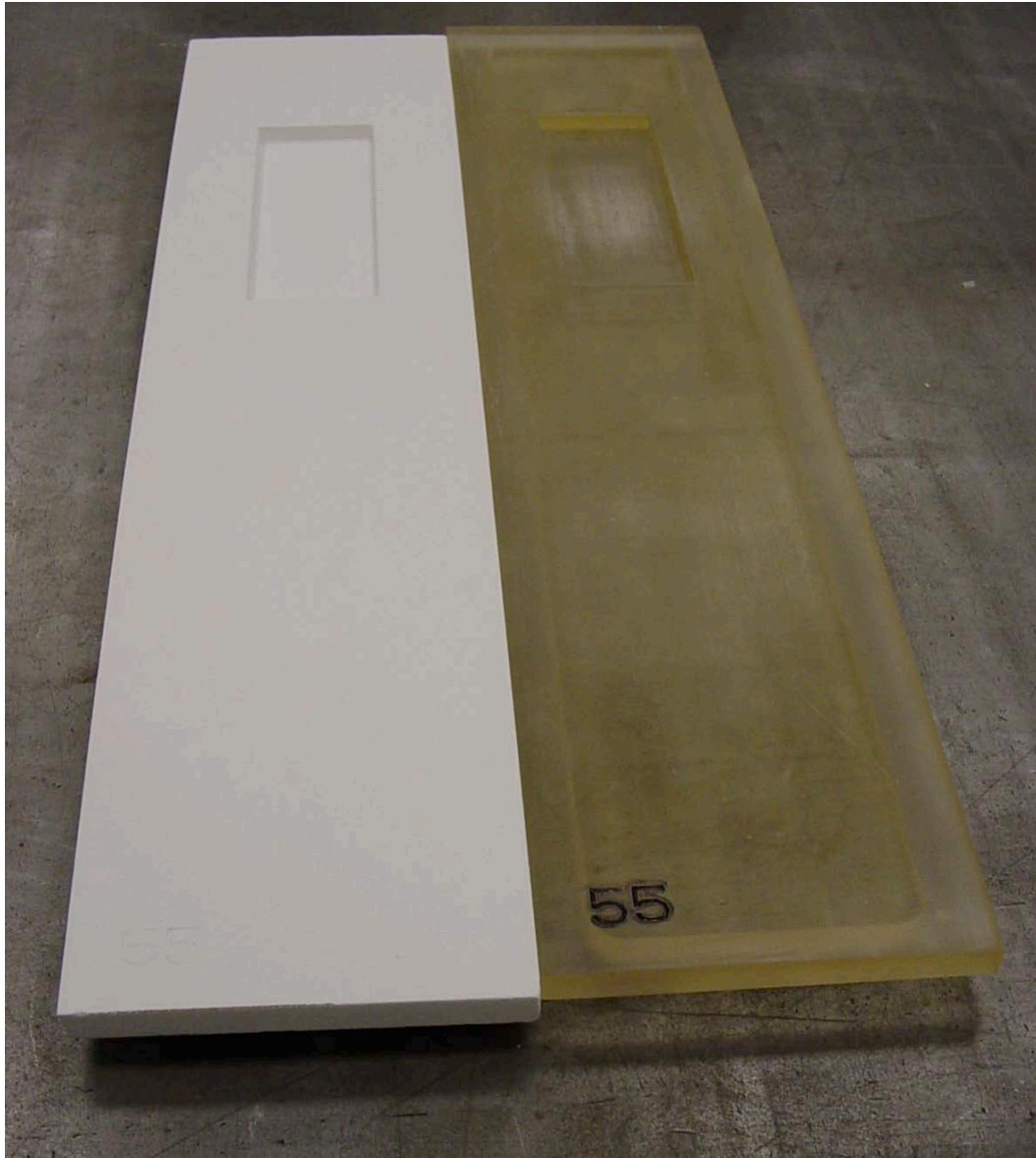


Figure 3. Stereolithography resin casting pattern alongside final slip-cast ceramic test model.

Hydraulic Casting and Curing of Investment Mold

The process used for slip casting requires an investment mold that is porous or liquid permeable, such as plaster of Paris, which is commonly used with aqueous or water based slips. The investment mold draws liquid from the slip, compacting the powder along the mold surface to form a high-density cast shape. An investment mold is formed with a calcium sulphate bonded refractory reinforced castable material, which can be processed quickly using high temperature curing.

A three part investment mold (fig. 4) is constructed, with forms shown in figures 5 and 6. A form is constructed as shown in Figure 5 using an SLA pattern for the backside shape of the test plate, metal dams to form the external walls of the mold, and a foam gate core (white) to form part 1 in figure 4. The foam gate core is used to form the mold opening for pouring in the slip casting material. A flexible silicone mold (fig. 6) is used for fabricating small loose parts, such as part 2 in figure 4. The gate pattern is formed from a typical block of 8 pound modeling foam. This piece is shown in the center of figure 5 (white).

The material used for the investment mold is a hydraulic setting calcium sulphate bonded investment mixture which contains calcined silica, fiberglass, and various specially graded refractories. It is a castable product from Ransolm and Randolph, Inc., that is part of their line of materials conventionally used for non-ferrous metal castings. In particular, the product used is R&R 910, which has been shown to have the optimum mix of reinforcement materials and fine surface texture for silica ceramic slip casting.

A flexible mold form (Figure 6) is used to form part 2 of the investment mold illustrated in figure 4. This flexible mold is first formed from SLA patterns. For this flexible mold, a two-component, tin catalyzed, RTV silicone rubber is used. This is a product manufactured by Plastic Tooling Inc., called GI-1000.

For part one of the three-part investment mold, a layout as shown in figure 5 is assembled using an SLA pattern, metal dams and a foam gate core. The investment mold castable material is mixed with water (>28% by weight to desired consistency) and then poured into the dam. The investment mold castable is allowed to set 1 hour, then the side dams are removed and the mold lifted and inverted. The SLA pattern is removed from the table and placed back in the part one mold. Dams are again placed around the mold and a fitting SLA pattern (also used to form part two mold) is placed in the cavity (reference top surface shown in fig. 3). Parting agent is applied to the surfaces and the investment mold castable material is again poured into the dam to form part 3. Part 2 investment mold is formed using the flexible mold shown in Figure 6, which itself is formed in a similar manner with side dams over SLA patterns. The two-component catalyzed silicone is allowed to set overnight before being used to cast part two investment mold pieces.

A Gruenberg electric oven (shown in fig. 7), with a maximum operating temperature of 650°F, is used to cure the three-part investment mold. The mold is first allowed to air dry for two hours and is then cured in the electric oven overnight at 550°F.

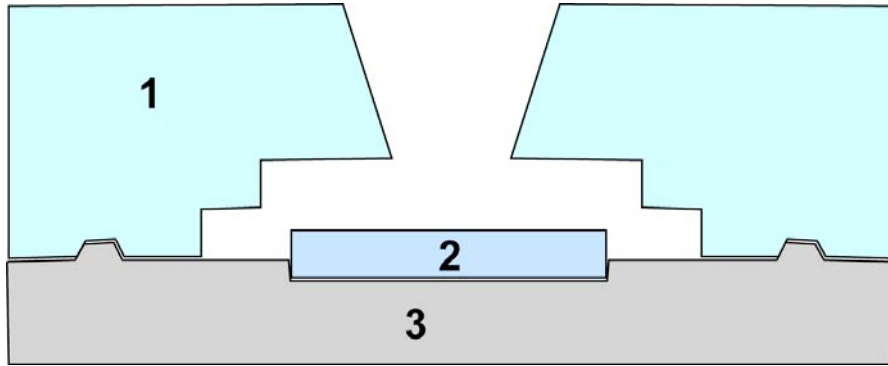


Figure 4. Diagram of three part investment mold used for slip casting ceramic plates.

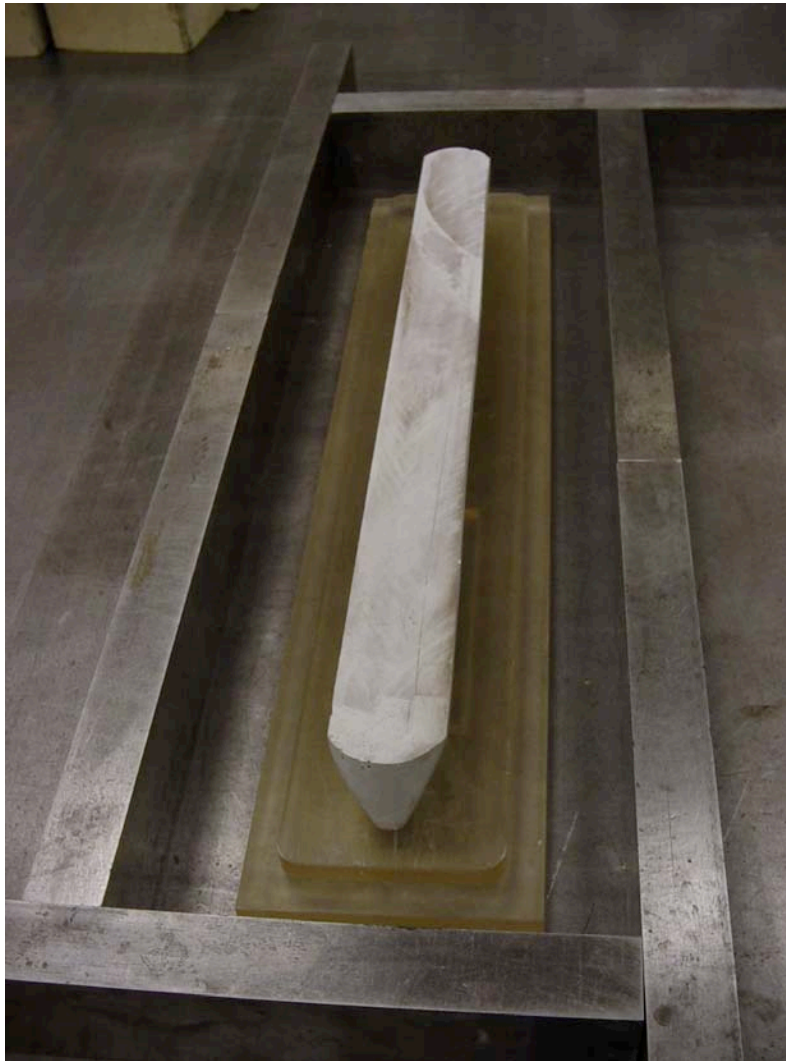


Figure 5. Layout for hydraulic casting of part one of investment mold.

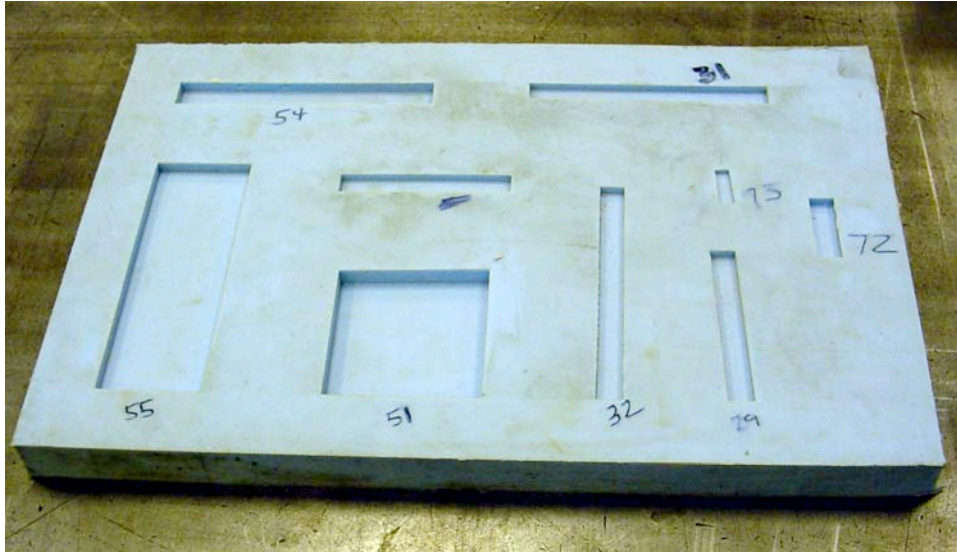


Figure 6. Flexible mold formed from SLA patterns for hydraulic casting multiple second parts for several different investment molds.



Figure 7. Curing oven for overnight firing investment molds to 550°F.

Slip Casting and Mold Removal

A “slip” refers to a crowded suspension of particles in a liquid. The mold draws liquid from the slip compacting the powder along the mold surface to form a high-density cast shape. This cast shape is referred to as being in the “green” state. This state has to have some strength so that the mold can then be removed. Intermediate binders are usually added to the slip to give it this green strength.

Advantages of the slip cast process include high purity materials, void free substrates, smoothness and an accurate reproduction of the mold surface. Accuracy is achieved because of the low shrinkage of the ceramic during drying and sintering. The silica slip used for aeroheating test models is 83% solids and the slip casting process removes most of the remaining liquid to compact the green shape. Silica ceramic also has very low linear shrinkage relative to other ceramic slip castings. From a fully dense casting, with complete sintering, silica has a theoretical minimum linear shrinkage of 0.75%, whereas alumina ceramic has a theoretical minimum linear shrinkage of 3%.

The silica slip is purchased from the Ceradyne corporation. It comes completely formulated in 75 pound drums. The suspended powder is an amorphous fused silica with a median particle size of approximately 10 microns. Before use, the slip is placed on rollers to keep the ceramic powder from settling. The last two batches purchased were batch numbers 052301-24 and 082001-26, and in the past three years 1,725 pounds of slip were used in casting silica ceramic test models at NASA Langley.

After removal from the electric curing oven the shell mold is allowed to cool to room temperature and assembled. Loose debris is removed with blown air. The mold is then filled with the ceramic slip. After 20 to 30 minutes, excess slip is poured out of the mold gate and the mold pieces are removed from the “green” cast ceramic model. The model is then allowed to air dry for 24 hours.

Ceramic Sintering

After removal from the mold, the ceramic model is taken to a high temperature (2150°F for silica) burning out the intermediate binder and bonding, or “sintering,” the powder to itself giving it its final strength.

An electric resistance L&L kiln is used for sintering with a maximum temperature capability of 2350°F (Figure 8). After drying a minimum of 24 hours after shell removal, the green model is placed in a kiln, supported evenly by fine zirconia sand as shown in figure 9. The kiln temperature is ramped at a rate of 12°F per minute to 250°F and held for 4 hours. Next, it is ramped at 5.76°F per minute (5.5 hours) to 2150°F and held for 4 hours. It is then allowed to cool to room temperature before removing the sintered model.

Attachment of Mounting Plate

Aluminum mounting plates are used to attach the ceramic test plates to wind tunnel supports as illustrated in figure 10. Prior to assembly, a plate alignment fixture (fig. 11) is fabricated and used in the model assembly. Both plates and alignment fixture are fabricated from 6061 aluminum. The inside and outside dimensions of the mounting plates are cut using an abrasive water jet. The alignment fixture is cut using a typical end mill machine.

A one-part silicone mounting adhesive is used to mount the aluminum mounting plates to the ceramic test model. The adhesive manufactured by General Electric is RTV162. As shown in figure 11, the



Figure 8. Sintering of cast ceramic model in electric fired kiln to 2150°F.



Figure 9. Sintered ceramic test model.

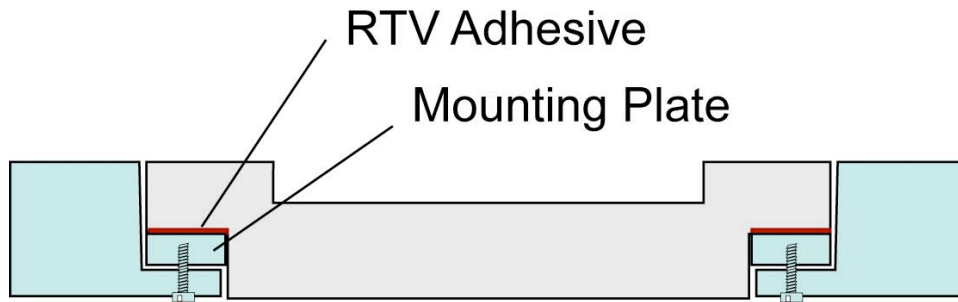


Figure 10. Diagram of ceramic plate mounting configuration.

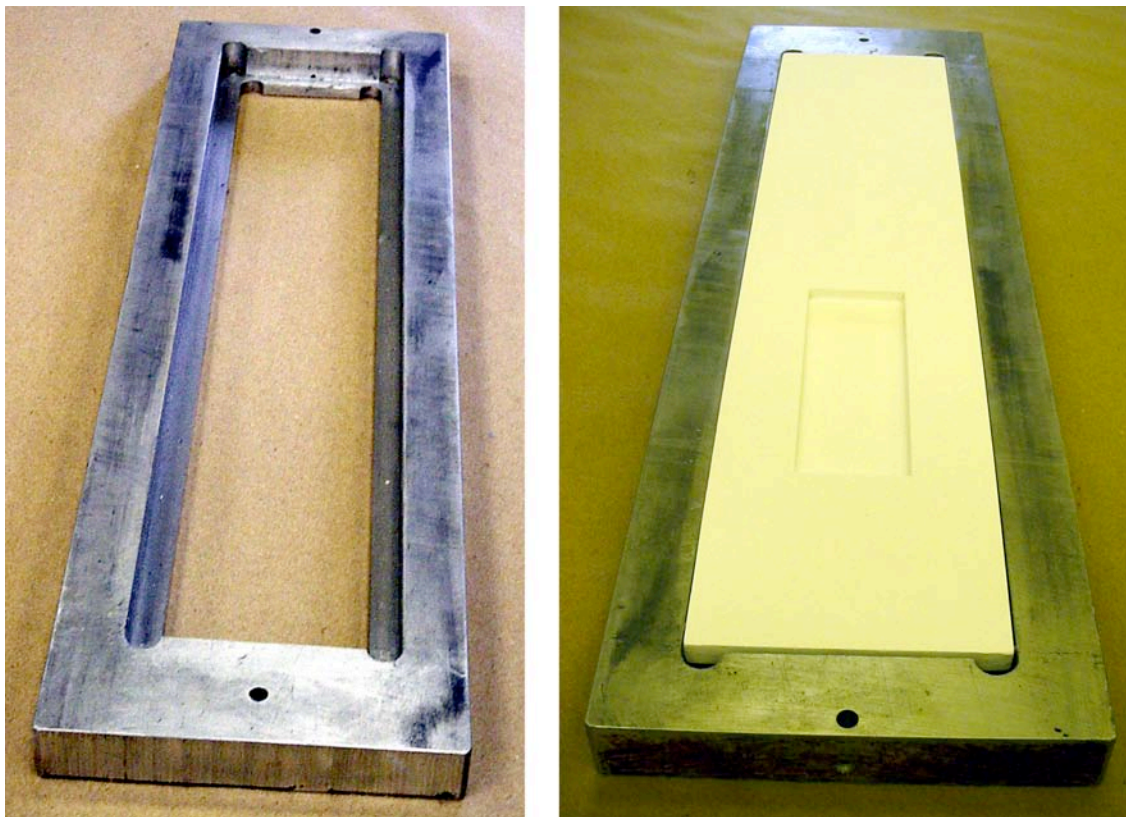


Figure 11. Fixture for aligning mounting plates and setup with ceramic model.

mounting plate and ceramic test plate are stacked in the alignment fixture for accurate alignment. Prior to assembly, the mounting surface of the aluminum plate is sand blasted, cleaned with acetone solvent and primed with a metal/ceramic primer. Silicone adhesive is applied to both surfaces, plates are stacked in the alignment fixture and 15 pounds of weight are set on top to hold the surfaces overnight. Assembled mounting plate on the bottom of the test ceramic is shown in figure 12.

Machining Slots and Attaching Plenum Box

As illustrated in figure 13, one configuration used a vacuum plenum on the lower surface of the ceramic test plate to provide suction to the test cavity, simulating the loss of a wing carrier panel resulting in a breach in the cold structure of the vehicle. This vacuum plenum is attached using the same silicone adhesive as used for the mounting plates. A suction gap is first machined into the cast ceramic plate prior to assembly using a diamond cutting tool. After machining the suction gap the ceramic plate is taken back up to temperature in the kiln (to 1200°F) to remove water absorbed from the cooling fluid used in the cutter. The mounting plates and plenum box are then bonded as described previously.

Phosphor Coating and Application of Fiducial Marks

After fabrication, flat plate cavity models are coated with a ceramic phosphor coating for surface temperature measurements and fiducial markings applied for imaging coordinate registration. The techniques for ceramic phosphor coating and fiducial markings are documented by Buck, Powers et. al., 2005, for fabrication of 0.0075 scale Shuttle Orbiter test models. In addition to the phosphor powder mixture described for the Orbiter models, the mixture used in coating the flat plate models also incorporates a glass resin matrix material (organic silicon oxide precursor) processed in the dry mixture and pyrolyzed at 1200°F to form a uniform aggregate of the two phosphor powders (ZnCdS: Ag, Ni and La₂O₂S:Eu). The composite dry particle size is less than 100 micron (170 mesh sieve). Since this powder does not mix well directly with aqueous based binders and it tends to become airborne easily, it has also been wetted with ethyl alcohol for improved mixing and safe handling. In the coating process 68 grams of this phosphor powder mixture is again wetted with deionized water, then mixed in suspension with 100 grams of colloidal silica binder (Nyacol 215) and airbrushed on a test model with a Paasche type H airbrush with a #5 spray nozzle. Figure 14 shows a finished plate-gap model (configuration 57, diamond shape) with phosphor coating and fiducial markings.



Figure 12. Lower side of ceramic model with attached aluminum mounting plate.

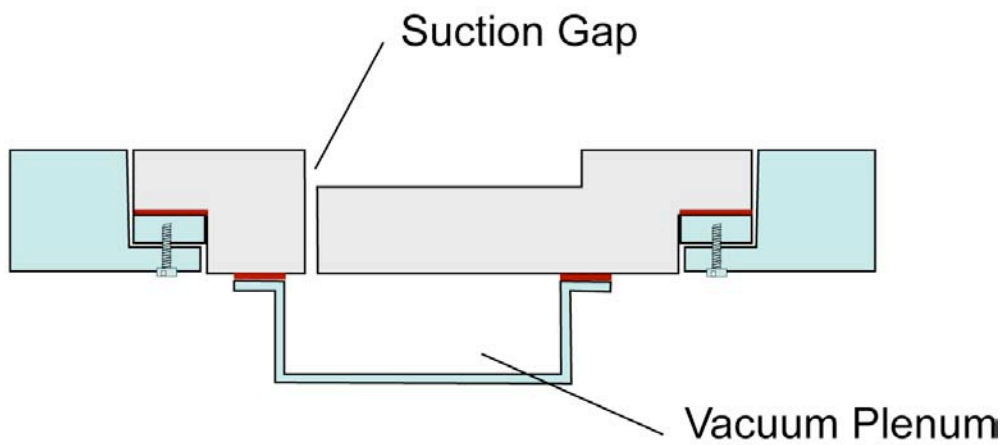


Figure 13. Diagram of plenum box mounted on lower plate surface for gap suction.

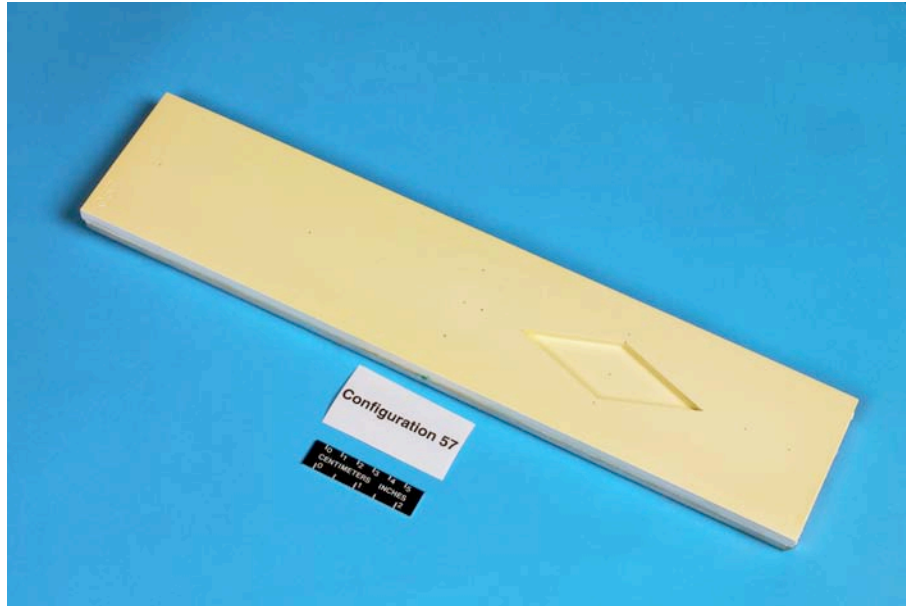


Figure 14. Finished plate-gap model (diamond shape) with phosphor coating and fiducial markings.

Summary

These are the methods, materials and equipment used in fabricating the flat plate test models for Shuttle return-to-flight aeroheating experiments at NASA Langley Research Center. This document stands as supporting material for OEAN-0405-004, 2005, by Everhart et al., documenting those test results.

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