THE SANTA FE SYMPOSIUM

The Revolution of CAD/CAM In the Casting of Fine Jewelry

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ABSTRACT

In recent years CAD/CAM has seen tremendous growth as an accepted technology in the jewelry industry. As jewelry manufacturers increasingly bring these new methods of design and materials into the daily production arena, the specific relationship between the various CAD/CAM technologies and the casting process has been an area of great challenge.

This paper compares the advantages of additive fabrication manufacturing methods, generally termed Rapid Prototyping (RP), and focuses on the new machine technologies available for producing jewelry quality models in this quickly changing field.

Finally, the materials and techniques used in the casting process specific to RP models are explored. Shrinkage rates, thermal expansion, burnout parameters, and surface treatments must all be considered differently from traditional wax model casting.

INTRODUCTION

We are all fortunate to live in interesting times for jewelry manufacturing—a digital age where fine jewelry becomes more science than art. Although the trends have always been moving toward automation for mass production, the development of master models has always remained the art of a modelmaker, who interprets the 2-D design rendering to create a 3-D model. In our current digital age, jewelry designers are now assuming the job of modelmakers through the use of CAD/CAM technology. The design freedom engendered by these digital tools and the speed with which a precise and repeatable 3-D model can be produced is truly a revolution in our industry.

Over the past five years, CAD technology has evolved phenomenally in the jewelry sector; the ability to design with CAD has become very affordable, and there now exist a growing variety of sophisticated output devices to create the 3-D models for casting. The term Rapid Prototype, or RP, (referring to the industrial stage of development it first served) has since been re-coined as a proper noun to describe these additive fabrication devices.Ultimately, the attainment of a high quality metal product is the objective in this sequence of processes. Yet thus far the relationship between RP models and investment casting outcomes is not widely understood in the jewelry industry. In order to produce an optimum casting, a qualitative analysis of models generated by the different RP systems must first be made in order to understand their fitness for design purposes. In addition, the suitability of the RP material in the particular casting process and the specific parameters that will apply to quality outcome both dimensionally and metallurgically, must be identified.

PURPOSE

The purpose of this paper is twofold: first, to present an overview of the latest RP machine technologies that are best suited to manufacture models for jewelry casting; and second, to present the findings of an experimental program undertaken to evaluate the performance traits of specific model materials in the investment casting process. It is our intent to offer information that will provide useful guidelines for jewelers working with RP technologies.

RP MACHINE TECHNOLOGIES

The RP Vocabulary: STL

As there are many types of CAD software, each of which uses a unique data format, a common data format was needed to communicate across RP machines. In the RP world, a 3-D object is best expressed as a polygonal surface referred to as ‘STL’ data format, or stereolithography, which is exported from most CAD software programs. The tessellated triangles that define the surface can vary in density based on export parameters in the native CAD. Faceting of surfaces can often be found on models if these parameters are not optimized on export.

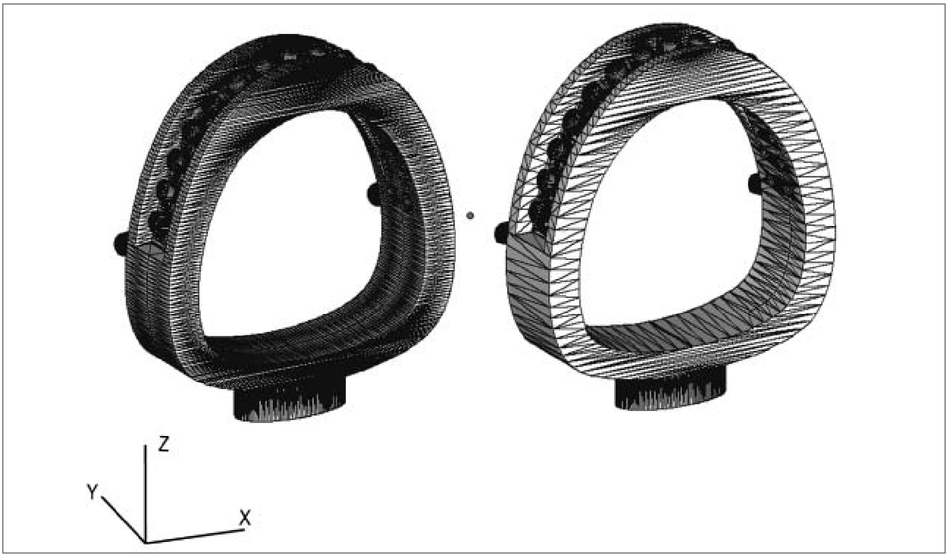

Figure 1 *Patterns with high (left) and low (right) surface faceting*

A valid STL file is a single surface or shell of the 3-D object to be built. There are, on occasion, exported STL files that contain multiple shells within the outer shell object. These anomalies are usually the result of human error in the design process, that are revealed fully in the exported data. In most cases, the RP vendor uses STL-specific software tools like MagicsRP™[1] to analyze and repair files before processing the model to the RP device.

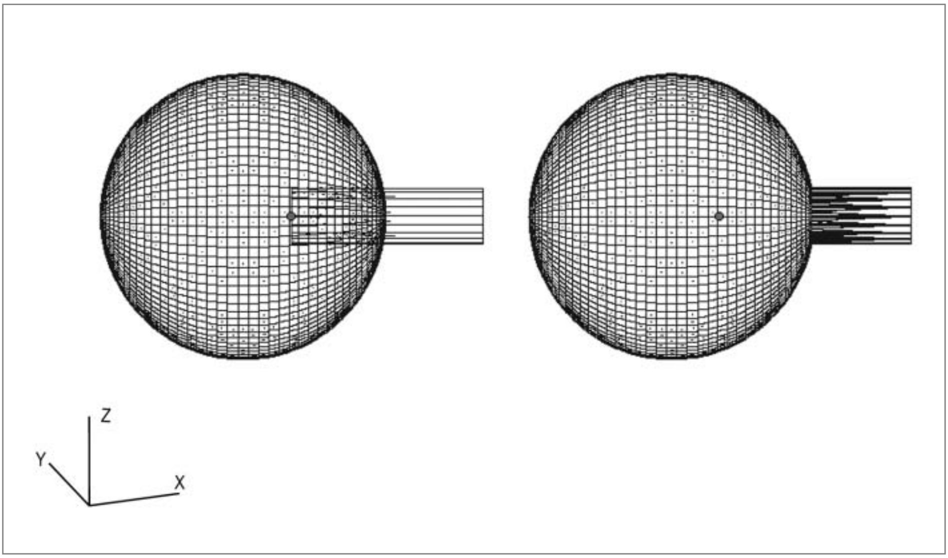

Figure 2 *Left object shown as two shells; right object shown as one shell*

Slicing and Sequential Layer Support

After verifying STL file integrity, the next step is to express the 3-D data in a layered format. The selected layer thickness and the orientation of the design about the Z-axis on the build plane are the two key elements in achieving the best results for each technology. For fine jewelry applications, the range of selection on the RP systems tested is from 0.0128mm to 0.0508mm. By parsing the STL dataset at specific height intervals in the Z-axis, we derive a new mathematical dataset for each layer of the object. The data is expressed in either a vector format for some RP systems or as raster- or pixel-based images on newer systems. The conversion of STL data to a sliced format is performed by each manufacturer's proprietary software. Examples are SLC, SLF and CLI data formats.

The orientation of the model build process is perhaps the most important aspect of the RP process. For the purpose of demonstration, let us presume to build a candy cane at various orientations. In Figure 3, we show the cane placed so that it is built with the fewest number of layers in the Z-axis. Since each successive layer is built fully upon the previous layer, there is no need for supplemental support to build this part. However, the stair-step effect across the entire build plane (Figure 4) is revealed. In the second orientation, with the cane in the standing position, the stair-step effect is minimized, moving up the longer side until reaching the arc of the cane. The downside of this orientation is that the shorter side of the cane provides no support to propagate the growth of this feature. In Figure 5, the need for an additional support feature is shown. As we reorient the part to a standing position in the U shape (Figure 6), we achieve the least amount of stair-step with no additional support required.

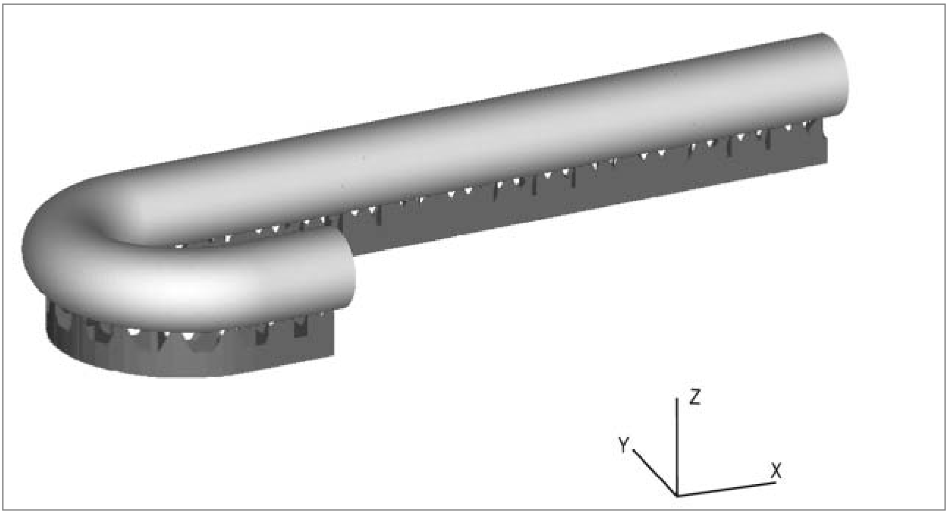

Figure 3 *Cane shown oriented at lowest Z height*

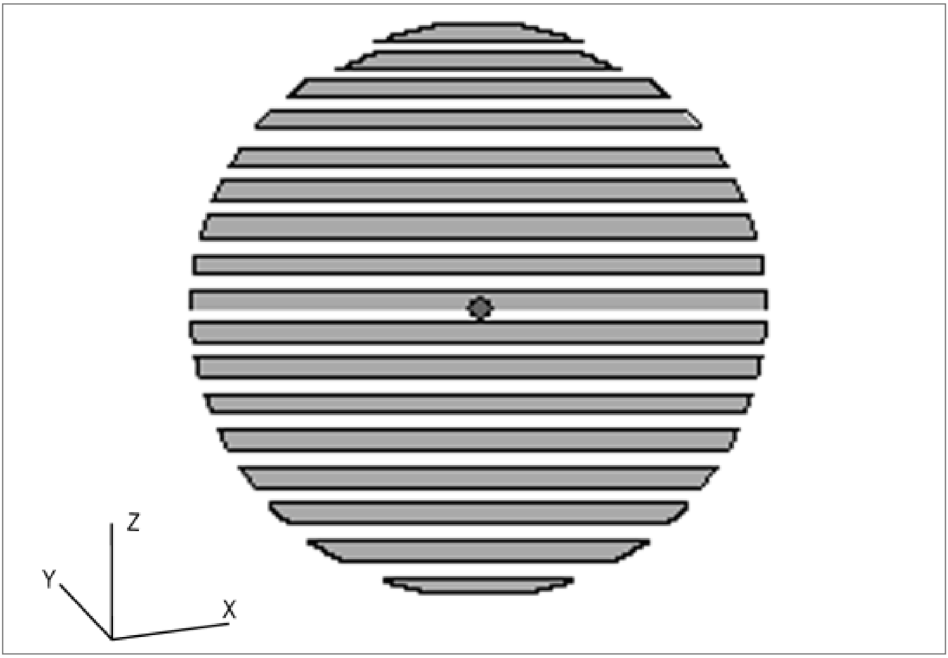

Figure 4 *Stair-step effect shown on candy cane sliced at lowest Z-height*

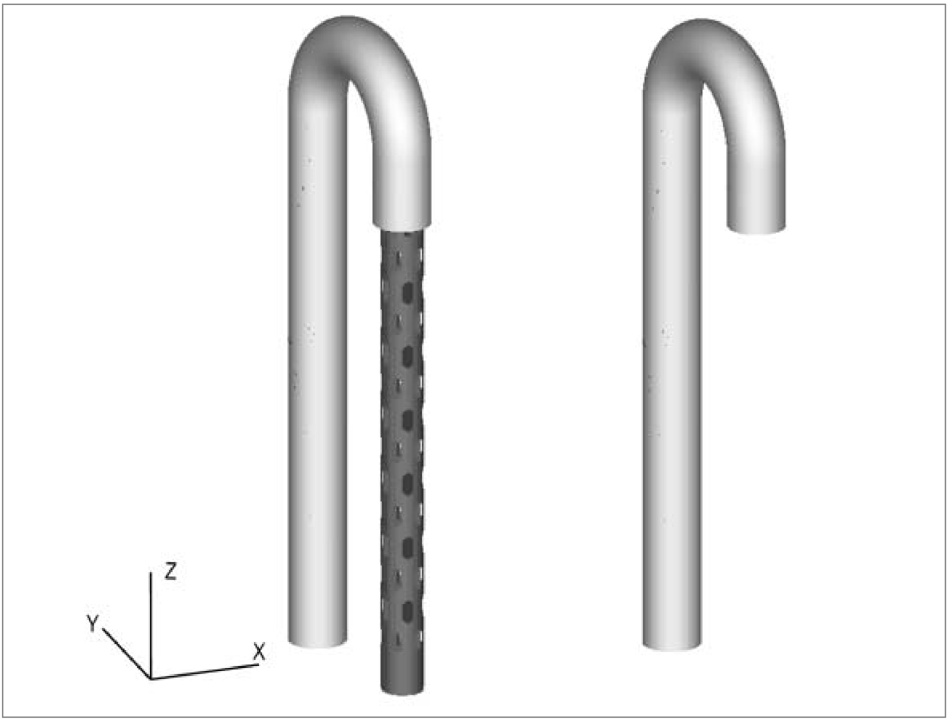

Figure 5 *Additional support feature to propagate shorter portion of the cane*

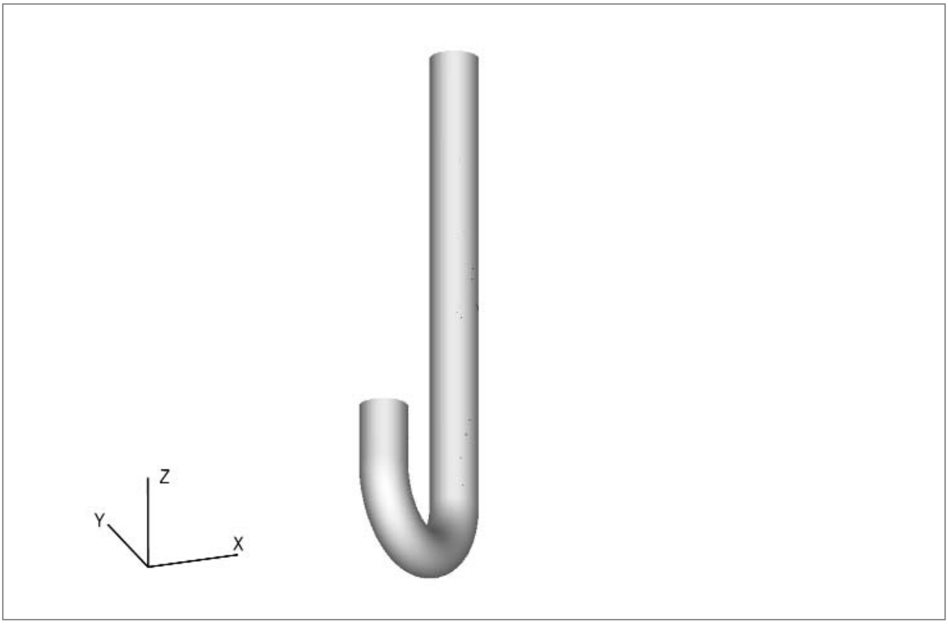

Figure 6 *Best orientation with least support and minimal stair-step effect*

In the systems we reviewed, support for each sequential layer can be achieved using two basic methods. On RP machines that use only one material, the support structures for island overhang features must be created as an integral part of the design, as shown in Figure 5. These added elements are then removed after the build process using mechanical means. The other alternative is to use a secondary material that is dissolved after the building process. The advantage of the latter is the creation of a net model from the design with little or no post-processing required. In the United States, this two-material RP process is licensed under the Helenski patent[2] to only two firms: Solidscape®, Inc. and 3D Systems®, Inc.

SYSTEM MANUFACTURERS

While there are a number of RP systems worldwide, we have limited the scope of our study to RP systems used primarily in the United States. We acknowledge that there are a small number of RP systems that may be in use by jewelry manufacturers, such as those produced by Z-Corp™, Objet™, Stratasys™, Sony® Precision Systems, and others. The selection of systems was based on popularity and on the number of U.S. domestic installations. It should also be acknowledged that there are several CAD systems bundled with subtractive milling products for jewelry production. These products were also excluded, since the study compares additive fabrication (RP) systems only.

This experiment was confined to dimensional and surface finish characteristics derived from a specific and proprietary casting process. Individuals or companies considering the use of RP technologies reported herein should perform due diligence, seeking the manufacturers' published specifications, fitness for use, and other factors, including but not limited to acquisition costs, operating costs, productivity, and staffing requirements.

Solidscape® T6x Bench Top 3D Printer (Sanders Process)
Operating Principle: Drop on Demand (DOD) Jetting of Thermoplastic

There have been several iterations of RP machines that use the Sanders Prototype process. Sanders Design International, Inc., founded in 1982 by Royden Sanders, was the original developer of the Sanders Prototype, Inc. patents[3]. Sanders later assigned ownership of these to Sanders Prototype, Inc. upon its formation in 1993. Sanders Prototype reorganized again in 2000 and became known thereafter as Solidscape, Inc. Sanders Design International, Inc. continued under a license agreement from Solidscape, Inc. to work in the field and further develop the technology. Limited numbers of advanced hybrid machines were produced by Sanders Design International until the company retired from the RP industry in late 2004.

The Sanders jetting process, now used solely by Solidscape, utilizes two-phase change materials: a low molecular weight thermoplastic for the build and a wax-based material for support. The materials are deposited one at a time by plotting a single line through vectors to define the outer perimeter and interior fill of the object on each layer. The process is repeated for jetting of the support material for subsequent layers.

The two jets are mounted on a gantry over the build platform. The motion of the jet carriage is controlled by reinforced rubber belts and is driven by stepper motors. At the completion of printing on each layer, the build platform is lowered to the desired layer thickness on a stepper-controlled lead screw. The gantry then moves to engage a milling tool from beyond the build envelope and proceeds to mill the interlayer to the defined Z-height layer thickness. Vacuum and brush mechanisms are also used to remove all particulates during the milling process. This provides a clean and smooth surface upon which the next layer can be printed.

At the completion of the entire process, the build platform is removed from the machine and heated from below sufficiently to remove the model from the build surface. The model is then placed in a heated bath that dissolves the wax support material while leaving the build material model intact.

3D Systems InVision™ HR 3D Printer
Operating Principle: Multiple Jet Modeling of UV Photopolymer/Wax

The Invision HR is a new addition to the MJM (Multi-Jet Modeling) series of RP devices from 3D Systems. As the name implies, the system utilizes an array of jets that deposit material simultaneously in a raster method. The first of the MJM series was the Thermojet system, introduced in 2000, which utilized only one material to build 3-D objects with integral support. The most recent addition, Invision, now provides two materials: one for build and one for support (using the Helinski patent). The system uses a movable build platform that passes under a fixed bank of jets as it travels along the X-axis. After first jetting the phase change photopolymer build material and then the wax support, the build platform positions itself under a UV light to partially cure the UV photopolymer. Once the polymer is sufficiently solidified, the build platform moves the model under a heated rolling device, or planerizer, which reduces the height of the layer by melting excess material, which is removed by capillary action. The process is repeated for each successive layer to completion. Then, the model is removed from the build platform and placed into a heated bath of paraffin wax. The paraffin wax dissolves the support material, leaving the user with a net object true to original 3-D design.

3D Systems Viper Si2™ SLA®
Operating Principle: UV Laser Solidification of Photopolymer

The Viper is an RP method that uses stereolithography to produce a model. This is a process that uses a UV-curable polymer resin that is solidified by a vector plotting laser; it was commercialized by 3D Systems in the mid-1980s[4]. For many years, this technology was considered too costly and inappropriate for investment casting of jewelry. It was not until 2001, with the introduction of the less expensive Viper model and a new acrylic resin called Accura® Amethyst™ that jewelry manufacturers began to incorporate SLA models in their CAD/CAM operations. The process begins with a vat of liquid photopolymer resin, with an elevator platform slightly below the surface of the resin. A UV laser is then drawn across the 5" x 5" surface, using a mirror array to define the perimeter and interior fill of the layer features as they solidify on contact with the first layer to the build platform. The elevator then lowers one layer height and the next layer is drawn on the liquid. This material solidifies on contact with the previous layer and the process continues in this manner. Since features can only be built on contact with previous layers or the build platform, additional support features must be included in the design to build overhanging features. Support structures are designed to be only as large as needed to propagate the overhang or island and are designed to be removed by mechanical means after the curing of the completed model.

Envisiontec® Perfactory® Mini
Operating Principle: DLP® Mask Solidification of Photopolymer

The Perfactory Mini was invented by the German engineer Hendrik John in 1999 and production systems became available in April 2003. The process uses a photopolymer resin that is solidified by the visible light spectrum using a mask system projected by the Texas Instruments DLP® (Direct Light Projection) chip technology. In lieu of the vat and elevator platform, the system uses a shallow glass tray or 'basement' to contain a minimal amount of resin for the layer build process. The build plate surface is attached to a stepper-controlled Z-axis lead screw, which allows it to be lowered into the material basement, thereby squeezing a thin layer of resin between the two glass surfaces. From beneath the basement a mask is projected, exposing the resin and solidifying the material with a short exposure time. The basement is treated with a silicone and/or teflon coating to allow for the release of the layer while adhering to the upper build plate surface. Thus, in this technology, the model rises up from the material basement instead of being lowered into a vat. By using variable optics in the Perfactory DLP Projector, the build envelope can be increased or decreased in size and in proportion to the desired pixel size being projected, making this system extremely flexible to achieve higher or lower part accuracy. For our study, we selected a pixel size of 0.040mm from the available range of 0.020mm up to 0.072mm currently in use for X/Y layer polymerization.

INVESTMENT CASTING CONSIDERATIONS

Having discussed the various output devices for 3-D casting models, we now turn to the process of transforming models into metal products through investment casting. The specific relationship between RP models and investment casting has been an area of great challenge as jewelry manufacturers increasingly bring these new methods of design and materials into daily production. In the sections that follow, we will endeavor to provide practical advice for achieving success with RP models in the casting process, from handling of the models through as-cast product.

Handling and Cleaning

RP patterns have a range of handling and cleaning issues specific to the particular material type. Proper techniques are critical to a quality outcome in the casting process. As a general rule, the following methods apply:

- *Solidscape:* These are the most fragile of the pattern types evaluated. Due to the material's tendency to oxidize, which can result in a breakdown of the surface quality, it is best to cast within one to two weeks. Where shipping is involved, it is important to pack very carefully to avoid even minor pressure on the model. Wax tree assembly using models with thin walls can be very challenging but can be overcome by an experienced assembler. Cleaning should be done only with a citrus cleaner such as D-Limonene or PC 205. Light filing or scraping with a blade can also be done, although caution should be used on the build lines where breakage is more likely to occur. The use of alcohol or acetone should be avoided as either will dissolve this material.

- *3D InVision:* Designs produced in this material are fairly strong and require only typical packaging, such as that which might be used with carving wax. This material is relatively new on the market and good data on hygroscopic tendency is not available, so it is best to avoid moisture during shipping and storage. Cleaning should be performed only with a citrus cleaner such as D-Limonene or PC 205. Hand cleaning can be performed with the same tools that one would use on carving wax patterns.
- *Envisiontec Perfactory and 3D Systems Viper:* These are the strongest materials of the group, requiring only minimal caution during shipping and assembling. Though durable, these materials are also hygroscopic; in order to maintain good dimensional stability it is best to ship and store with desiccant to prevent moisture absorption. Cleaning should be performed with industrial grade alcohol 95%, followed by a rapid rinse with a citrus cleaner such as D-Limonene or PC 205. As with 3D Systems' Amethyst® material, hand cleaning can be performed with the same tools that one would use on wax patterns.

Visual Inspection

Visual inspection of patterns is a critical step in the casting process and generally presents more challenges with the use of RP patterns than with traditional wax. Ultimately, the metallurgical responsibility for a quality piece rests with the caster; therefore, methods for adequate inspection must be addressed at this stage. As is the case with wax patterns, small voids and cracks can cause investment to break down (particularly in the vacuum process) and then combine with the molten metal, resulting in non-metallic inclusions and/or surface pitting in the casting. The visual inspection characteristics for the experimental group are shown in Table 1.

Table 1

Pattern Type	**Appearance**	**Visual Inspection**
Solidscape	Medium matte green or light blue	Defects are easily detected.
InVision	Medium dark blue	Dark color presents challenges.
Viper	Dark purple, glossy on one side	Inspection is challenging, especially on glossy side.
Perfactory	Dark, glossy, translucent orange	Challenging to inspect; translucency shows subsurface artifacts.

The best surface for inspection is a matte finish pattern with a medium to light color, such as is found with Solidscape. Clear patterns or those with a glossy surface are the most problematic for visual inspection, making it recommendable to incorporate finish sanding to facilitate inspection (as well as to smooth out any prominent build lines).

EXPERIMENTAL PROCEDURE

Attaining a high quality casting using RP patterns required us to look closely at the unique characteristics of these materials and the defects that can present with their use in the investment casting process. The two areas of focus that emerged through this analysis were dimensional expansion and burnout residue. The potential for expansion of RP patterns can be problematic as the necessity to predict dimensional outcomes such as ring size or setting size is obviously important. Reliable guidelines for various materials need to be established to avoid costly mistakes or compromise in the final design. Moreover, expansion in the burnout phase can cause investment cracking and failure in the core areas of settings, resulting in a metallurgically unusable product. Lastly, burnout residue trapped in the mold can create pitting and non-metallic inclusions in the casting.

In order to evaluate the key casting characteristics of specific RP patterns, a Design of Experiment (DOE) was conducted, using patterns supplied from Solidscape, 3D Systems, and EnvisionTEC RP machine manufacturers. The ring design chosen for the experiment was courtesy of David Trout at Coffin & Trout Jewelers, in Chandler, Arizona. The design is a medium-weight ring with flat shank sides for ease of caliper measurement and a large number of setting holes to enable a good evaluation of diameter behaviors through processing. The patterns were cast in 10% iridium platinum using a standard phosphate-bonded investment with ceramic shell face coats. Each casting tree contained two rings, and all lots achieved a 100% yield in casting. All assembly, investing, firing, casting and other parameters, with the notable exception of mold cleaning and burnout methods (shown in Table 2), were held constant in the experimental group. The only other variable was the pattern materials themselves. The following table identifies the parameters used:

Table 2

Lot Identity	**Flask Temp. (°C)**	**Pour Temp. (°C)**	**Burnout Method**	**Mold Cleaning Method**
Solidscape 1	850	1880	Standard	None
Solidscape 2	850	1880	Standard	None
InVision 1	850	1880	Standard	H_2O purge
InVision 2	850	1880	Compressed air flow	None
Viper 1	850	1880	Standard	H_2O purge
Viper 2	850	1880	Standard	H_2O purge
Perfactory 1	850	1880	Standard	H_2O purge
Perfactory 2	850	1880	Standard	H_2O purge

Following typical investment removal procedures, the castings were inspected for visual defects and a series of key dimensions were taken.

Dimensional Evaluation

In evaluating the dimensional accuracy of the RP systems tested we relied on a series of measurements that could be easily referenced in the original data file. In this manner, we could track variance from design specifications to RP pattern dimensions. Subsequent comparisons were also made between pattern measurements and the resulting metal casting. It is important to note that dimensional variations have been expressed both in numeric values and in percentages. It is the hope of the authors that these percentage values will help jewelry manufacturers to predict the scaling of designs required to compensate for yet another factor in the product development process. Figure 7 shows the locations for measurement used (indicated by letters A-E).

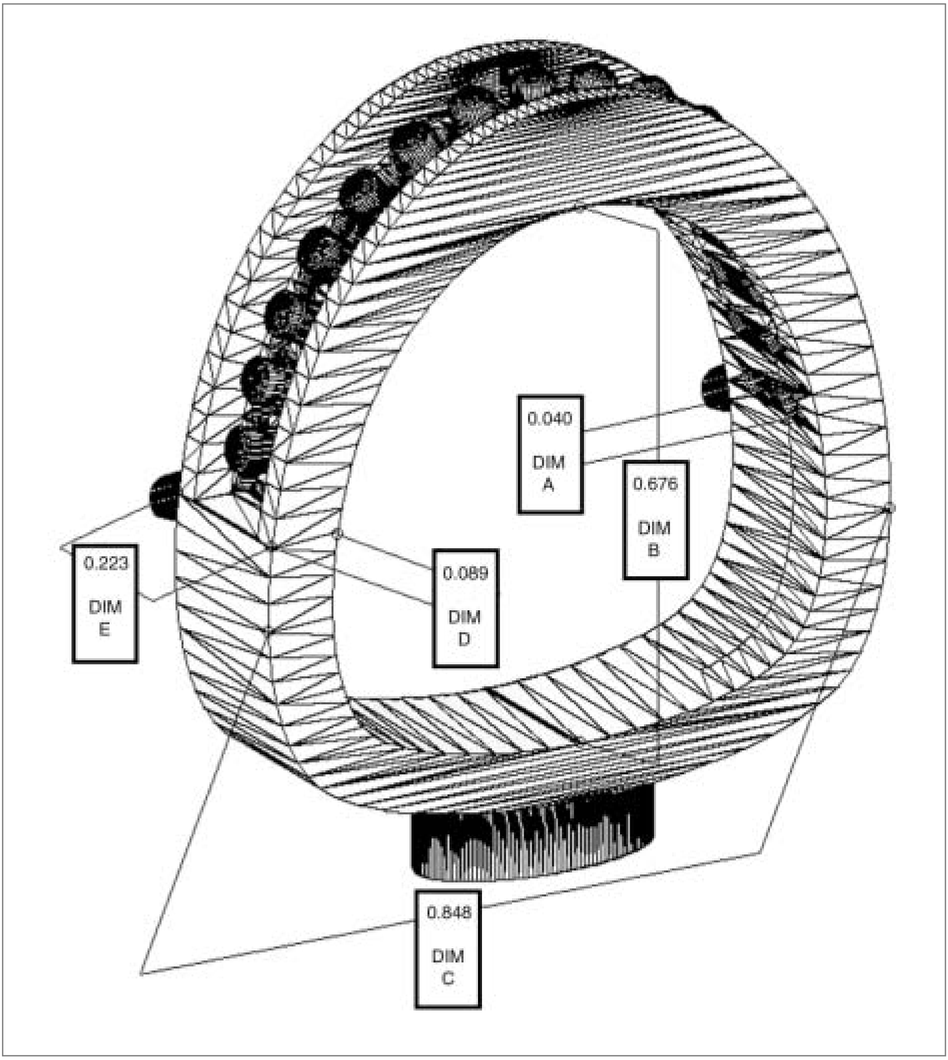

Figure 7 *Measurement locations*

In the table that follows, columns 2–4 indicate actual dimensions, columns 5–6 indicate the difference of file-to-pattern and pattern-to-casting, respectively. Column 7 specifies whether shrinkage, growth or zero movement in dimensional value was experienced between the pattern and casting. Column 8 indicates the percentage of shrinkage or growth (this is the number that should be evaluated when inputting the CAD file for pattern build when dimensions are critical). Shrink/growth rates must be correlated and then designated in the X, Y, and Z directions for these purposes.

Table 3

Dimensional Evaluation

1	2	3	4	5	6	7	8
Feature	**File**	**Pattern**	**Casting**	**Δ F–P**	**Δ P–C**	**Effect**	**Percentage**
Stone Hole (Dim. A)							
Solidscape	.040	.039	.039	-.001	.000	Zero	0.0
Invision	.040	.038	.036	-.002	-.002	Growth	5.2
Viper	.040	.040	.037	.000	-.003	Growth	7.5
Perfactory	.040	.038	.035	-.002	-.003	Growth	7.5
Shank ID (Dim. B)							
Solidscape	.676	.679	.672	.003	-.007	Growth	1.0
Invision	.676	.670	.657	-.006	-.013	Growth	1.9
Viper	.676	.676	.667	.000	-.009	Growth	1.3
Perfactory	.676	.668	.657	-.008	-.011	Growth	1.6
Shank OD (Dim. C)							
Solidscape	.848	.866	.859	.018	-.007	Shrink	-0.8
Invision	.848	.846	.845	-.002	-.001	*Shrink	-0.1
Viper	.848	.845	.844	-.003	-.001	*Shrink	-0.1
Perfactory	.848	.838	.837	-.010	-.001	*Shrink	-0.1
Shank (Dim. D)							
Solidscape	.089	.090	.090	.001	.000	Zero	0.0
Invision	.089	.090	.091	.001	.001	Growth	1.1
Viper	.089	.084	.086	-.005	.002	Growth	2.3
Perfactory	.089	.088	.091	-.001	.003	Growth	3.4
Shank (Dim. E)							
Solidscape	.223	.228	.223	.005	-.005	Shrink	-2.1
Invision	.223	.223	.223	.000	.000	Zero	0.0
Viper	.223	.222	.223	-.001	.001	Growth	0.4
Perfactory	.223	.221	.222	-.002	.001	Growth	0.4
Method: Mituoyo digital calipers/MagicsRP							
Unit of measurement: inches							

*Individual results must been seen in context with other dimensions. Even though shrink did occur in this isolated dimension, the thickness of the shank (Dim. D) was larger, indicating overall growth of the casting versus the pattern.

It should be noted that when the casting result for the inner diameter is a larger number than the pattern, this indicates shrinkage of the metal (metal is moving away from the investment). On the other hand, the inner diameter is smaller, this is due to expansion of the pattern and consequent enlarging of the mold cavity. This effect, which adds metal to the casting, can be seen in the shank ID (Dim. B).

The above results show consistent growth in the castings produced using the InVision, Viper, and Perfactory photopolymer patterns and, in contrast, consistent shrink or zero effect in the castings produced using the Solidscape thermoplastic patterns (with the single exception of the shank ID). Having established that these dimensional behaviors exist, we now turn to the different process features that may be responsible for such outcomes.

Moisture Adsorption

This section will concentrate mainly on the InVision, Viper, and Perfactory photopolymer patterns; since the Solidscape thermoplastic patterns presented minimal issues with dimensional growth, it is unlikely that significant moisture-related expansion took place in this material.

All photopolymer resins are subject to moisture adsorption. Given this hygroscopic nature of resins used in Perfactory, Viper, and InVision materials, there is a risk of dimensional expansion during shipping, storage and processing of the patterns. Wahlgren et al.[5], in their study of the effect of atmospheric humidity on photopolymer-based stereolithography (SLA) patterns, demonstrated that if humidity is in excess of 50%, linear expansion of SLAs is rapid for the first few days and levels off at about ten days. Humidity above 80% caused parts to grow for as long as two weeks. On the other hand, parts remained dimensionally stable in humidity of less than 30%.

While Wahlgren et al. looked at patterns in terms of time and ambient conditions in isolation from the remainder of the casting process, there are of course additional opportunities for the introduction of moisture, most notably during the investing procedure. Typical jewelry investment systems are either water- or acid-based. The system used at TechForm for this experiment was water-based. Since the elapsed time between pattern measurement, assembly and the commencement of investing in our study was relatively short, the exposure to pre-investment humidity, although present, was minimal. The investing process itself took place over several hours, with varying levels of moisture being introduced, first via the face coats, and second through phosphate-bonded investment procedures. An environment of controlled humidity in the range of 40% was present during face coat operations. As will be demonstrated in the next section, moisture alone is not likely to have caused all of the expansion shown in the above table.

Thermal Expansion

All materials expand with heat. As noted earlier, thermal expansion can result in cracking of the investment and/or core failures in setting areas and other diameters. Finning, ceramic inclusions and malformed features can all result from this type of failure.

The existence of thermal expansion in RP patterns is well documented in the literature. For example, Gouldson and Blake[6], in their study of ABS type RP patterns, observed an average percent linear expansion of 0.24% or .0024 inch when exposed to elevated temperatures. 3D Systems, in response to the problem of thermal expansion of their photopolymer patterns in investment casting operations, developed the QuickCast™ build style, characterized by a honeycomb-like internal structure that easily breaks down when exposed to heat in the burnout process[7]. In our study, evidence of thermal expansion during high temperature burnout was minimal in terms of shell cracking (where one would expect to see it), with only a minor amount of finning around the gate areas and some evidence of core failures in the setting areas, specifically on the Viper castings. Given that significant expansion was experienced in absence of shell cracking and that pre-investing pattern growth was not a factor, our investigations then focused on the investing/dewax stage of the process. It is worth pointing out that this particular phenomenon is not widely understood in the casting industry, and we were therefore compelled to do additional experimentation in order to find out where the growth was actually occurring.

Although dimensional growth was not evaluated in situ during investing and dewax/pre-burnout, it is now postulated that the bulk of the expansion took place during this phase. An experiment to approximate the conditions that photopolymer patterns are subjected to in these processes was performed using an electric kiln set initially at the peak temperature experienced during the setting of the solid mold investment (29°C), and then set at the dewax/pre-burnout temperature (150°C). A moist environment designed to emulate the solid mold investing process was created by wrapping each photopolymer pattern in a paper towel moistened with water. Table 4–6 depicts the results of this experiment.

Table 4

InVision Pattern (held 1 hour @ 29°C in DRY environment)

Measurement	Start Dimension	End Dimension	Difference
Shank width	.224	.225	.001
Shank ID⟶gate	.172	.173	.001
Shank OD	.850	.851	.001
Setting wall	.038	.038	.000
Shank ID	.672	.671	-.001
Unit of measurement: inches			
Method: Mituoyo digital calipers			

Table 5

InVision Pattern (held 1 hour @ 29°C in MOIST environment)

Measurement	Start Dimension	End Dimension	Difference
Shank width	.225	.225	0
Shank ID⟶gate	.172	.172	0
Shank OD	.850	.852	.002
Setting wall	.038	.039	.001
Shank ID	.672	.668	-.004
Unit of measurement: inches			
Method: Mituoyo digital calipers			

Table 6

InVision Pattern (held 1 hour @ 150°C in MOIST environment)

Measurement	Start Dimension	End Dimension	Difference
Shank width	.225	.226	.001
Shank ID⟶gate	.172	.173	.001
Shank OD	.850	.855	.005
Setting wall	.038	.039	.001
Shank ID	.672	.671	-.001
Unit of measurement: inches			
Method: Mituoyo digital calipers			

The above results point to the combination of temperature and moisture as the cause of highest dimensional growth during the investing/dewax stage of the process. Given the strength and low ductility of the face coats after setting, one would expect cracking of the shell upon thermal expansion of the patterns, but not overall growth without cracking, as was observed in the experimental group. This finding indicates that expansion of the face coats after drying occurs as a result of moisture introduced by the solid investment backer. Therefore, we hypothesize that the face coats are softening upon contact with the solid investment and allowing the thermal expansion of the patterns to occur without fracturing shell surfaces. This softening of the face coats has been observed in previous experience at TechForm, although documentation of dimensional impact was not evaluated. This hypothesis should be confirmed with additional testing.

Investment Reactions

Aside from the potential for adsorption during investing, negative reactions with investment were not observed in the experimental group. It is important to note, however, that although acid-based investment was not used in our experiments, it is generally acknowledged that these types of investments are not compatible with Solidscape thermoplastic patterns for traditional platinum casting. Castings will display significant breakdown of surface finish as the acid-based investments react with the chemistry of the thermoplastics.

Burnout

The experimental group is segregated with respect to burnout techniques (Table 2). Solidscape thermoplastic patterns consistently exhibited very clean burnout without the need to introduce special processing for evacuation of residual ash. Conversely, the clean burnout of InVision, Viper, Perfactory and all other types of photopolymer RP patterns can be challenging. Accordingly, this issue is the subject of much discussion in the casting industry worldwide. Photopolymer resin that does not fully burn out results in oxides and other residues forming on the inside of the investment, which will appear as negatives or “pits” in the cast surface of the metal.

Proprietary techniques, ‘magic’ pattern coatings, elevated and sustained temperatures, mold cleaning and increased air circulation top the list of methods formulated to address this significant concern. It is important to note that the particular investment material and burnout oven being used in a given casting process will influence which of these methods will work best. The following is a list of possible techniques for elimination of residues and attenuation of thermal expansion:

- *Pattern coating:* This can be some form of spray or paste wax. The purpose of wax-coating is to inhibit moisture adsorption, provide a layer of low melting material to relieve stress on investment during thermal expansion of the pattern (although for this purpose it must be relatively thick) and to prevent bonding of residues on the interior of the shell.

- *Mold venting:* This method involves the creation of small airways in the investment that are connected to the pattern to facilitate airflow during burnout. The airways must be filled in a subsequent operation following burnout to prevent molten metal from escaping during casting.
- *Mold washing:* This method is not suitable for most jewelry investments because it involves exposure of investment to liquid following burnout. For this process, the mold must be brought down to room temperature, purged with water or other liquid, and refired before casting. It is best to consult with your investment supplier before attempting this technique, as some investments will break down through the cooling process and subsequent exposure to H_2O.
- *Burnout temperature:* Photopolymers generally require high burnout temperatures. Although precise melting temperatures and flashpoints for all materials were not available, clean burnout requires temperatures that go beyond these initial measures of pattern decomposition. The firing curve used for the experimental group reached a maximum of 950°C and was held for a period of four hours at that temperature. Time at temperature (dwell) may be a factor towards achieving clean burnout, although this specific variable was not included in our experiment. 3D Systems recommends sustaining a temperature of 982-1093°C for a period of three or more hours when burning out their Quickcast™ photopolymer-based material as a possible method to minimize burnout residual[8].
- *Burnout airflow:* In repeated tests conducted at TechForm using compressed air channeled directly into the mold, increased airflow has been shown to aid in clean burnout of photopolymers to a greater or lesser extent, depending upon the material. The InVision Visi-Jet® material in particular benefits greatly from this technique, with results in this study equaling the mold-washing technique in terms of metallurgical quality. The type of burnout oven used also plays a fundamental role in the oxygen content. For example, a gas oven will generally have a lower amount of oxygen but greater air circulation. Conversely, the electric oven will have greater oxygen but lower air circulation in the absence of a fan mechanism.
- *Flashfire ovens:* These are not commonly used in the jewelry industry, but have proven to be very beneficial for the burnout of photopolymers. This method involves subjecting the mold to initial temperatures in the range of 800°C to encourage burnout of the patterns before thermal expansion of the pattern has a chance to occur. The types of investment that can withstand this type of 'shock' are limited and should be researched before attempting this method.

SURFACE FINISH

Perhaps the most significant aspect of the modelmaking process for jewelry is the achievement of a pristine surface finish. In terms of ensuring profitability, mass production is more reliant on this stage of product development than any other factor. CAD/CAM can address issues of design symmetry and small feature definition that are difficult to achieve in handmade patterns. However, no RP system has come close to achieving an acceptable surface finish for production directly off the machine. In every case, the plastic pattern, the resulting metal casting or both need to be polished and chased to achieve a pattern ready for the production molding stage. For the purposes of our study, we have focused on the smaller features such as prongs and setting holes where hand polishing is the most difficult. In these critical areas, where relative dimensional accuracy is also required for stone setting, the degree of polishing required to optimize a surface can affect the pattern's fitness for production. It is at this level of utilization that relative accuracy and surface finish become critical to success.

Solidscape T6x Benchtop Printer

The Solidscape process relies on vector plotting to define the surface of the pattern. In Figures 8 and 9 we note the vertical lines that are created on the outside perimeter surface. These lines are actually the positions of vectors and represent the short 'stop/starts' at each vector and the hysteresis that takes place in the rubber drive belts as they respond to the plotting event. It should be noted that this effect only seems to occur on the larger features where acceleration is higher. On the smaller features we cannot find evidence of any the hysteresis effect.

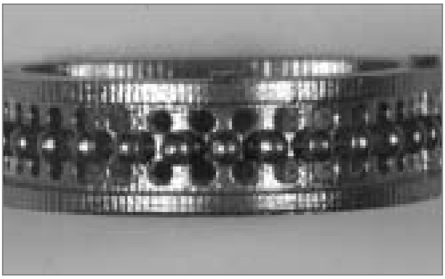

Figure 8

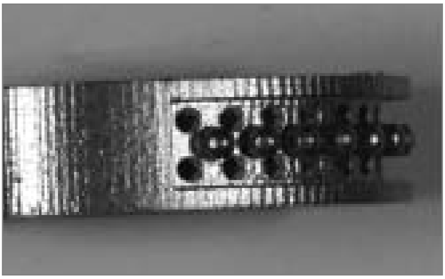

Figure 9

We note next the setting holes where the Solidscape material did not exhibit any malformation. All holes are round and there is no indication of finning or investment breakdown. The prongs in Figure 10 have a relatively smooth surface finish and will require little work to achieve an acceptable model quality.

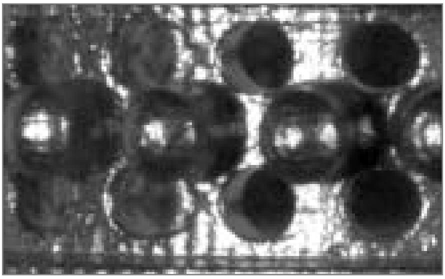

Figure 10

Envisiontec Perfactory Mini

The Perfactory uses the Texas Instruments DLP chip to create each layer all at once in a raster- or pixel-based printing method. Unlike a vector system, this method uses a pixilated representation of the layer object, which creates a stair-step effect on the X and Y axes as well as those found normally in the Z-axis. With the use of different optics on the Perfactory, a smaller pixel can be achieved that reduces this effect. Whereas there is little of the effect shown from the top view in Figure 11, the effect is easily seen in both Figure 12 and in the enlarged version shown in Figure 13.

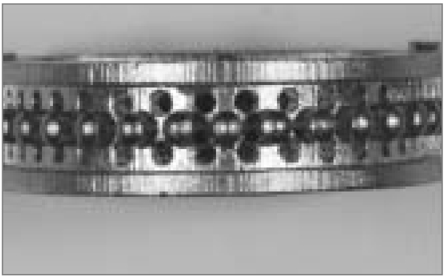

Figure 11

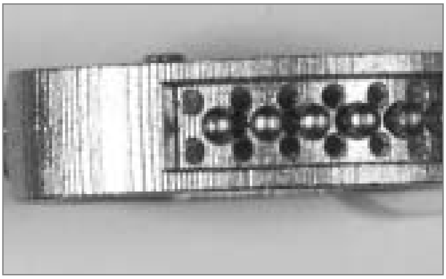

Figure 12

The prongs in Figure 13 appear to have a relatively smooth surface finish and will require little work to achieve an acceptable model quality. The setting holes show slight finning but are otherwise suitable in terms of form and functionality.

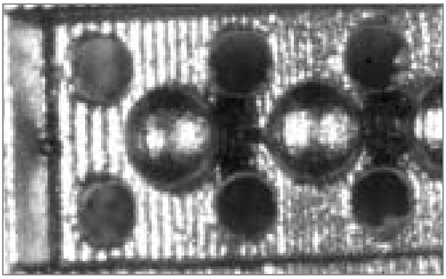

Figure 13

3D Systems Viper Si2

The Viper Si2 relies on a photopolymer that cures very quickly when exposed to a vector-plotting UV laser. The process provides a smooth surface finish in model form. Unfortunately, in our casting results, there were several instances of shell failure with the Amethyst™ material. In Figure 14, we find malformation of setting holes and finning. In Figures 15 and Figure 16, there is also a large metal positive created from shell failure. There is also evidence of finning on several setting holes, indicating pattern expansion.

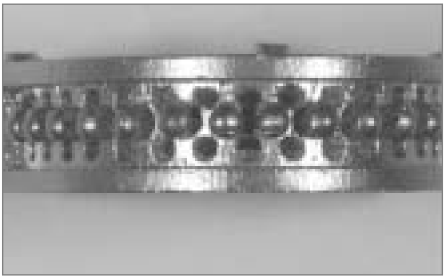

Figure 14

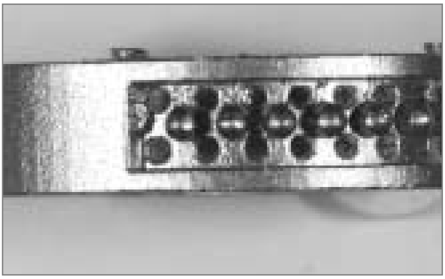

Figure 15

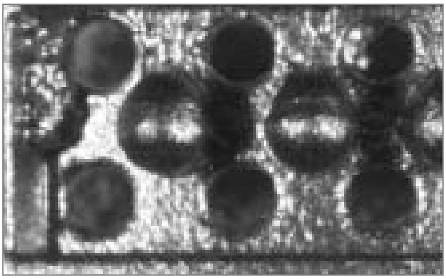

Figure 16

3D Systems InVision 3D Printer

The InVision uses the Multi-Jet Modeling system to print each layer in a raster format. This is expressed in dots per inch (DPI), which are visible under magnification. In Figures 17–19, we note a uniform and significant texture on all surfaces. There were no obvious signs of shell failure positives or burnout ash residue.

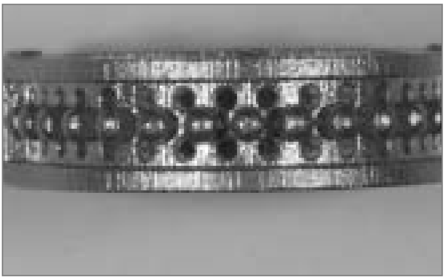

Figure 17

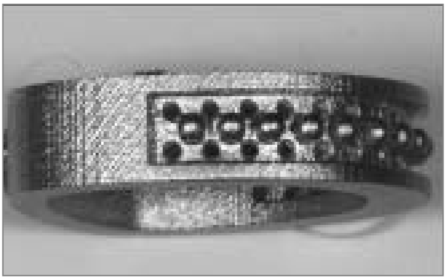

Figure 18

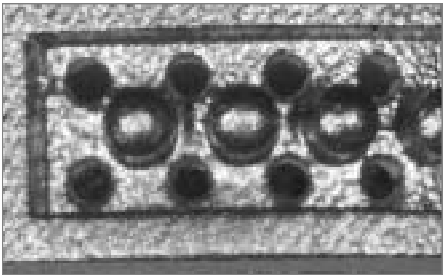

Figure 19

CONCLUSIONS

CAD/CAM technologies generally, and RP patterns specifically, have a very important role to play in the future of jewelry production. An understanding of the unique characteristics of working with these materials and processes is crucial to achieving a quality product. Beginning with individual RP machine technologies and continuing with careful attention to each step of the casting process, from pattern preparation through dimensional and burnout needs, one can successfully make the best choice for individual designs and casting processes.

Further studies are needed to dial in the dimensional impacts of the various RP pattern materials with greater precision. In addition, different investment systems should be tested to check concurrence with the results presented in this paper. Nevertheless, we believe that guidelines for the behavior trends of the different materials clearly emerged in this study, and as such, provide a useful tool to jewelers in estimating shrink and expansion of final castings.

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