Teresa Frye
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Teresa Frye is the owner and President of TechForm Advanced Casting Technology. In the early 90's her firm introduced high-temperature casting methods from the aerospace industry to jewelry manufacturing. A leading expert on jewelry casting and a prolific researcher, she has published technical papers and articles worldwide. Her publications have appeared in Platinum Metals Review, The Santa Fe Symposium on Jewelry Manufacturing Technology, MJSA Journal, and JCK Magazine, among others. She has also presented her research at numerous jewelry industry venues across the globe.
Ms. Frye's company, TechForm Advanced Casting Technology, provides platinum castings to a broad customer base, including many top jewelry brands in the US. To further the sharing of technical information, in 2008 she founded the Portland Jewelry Symposium, an annual educational conference that specifically serves the educational needs of manufacturing jewelry retailers.

Today's jewelry manufacturers are incorporating digitally produced casting models into their production processes at levels never seen before. Machine costs have dropped dramatically, and makers now have a wide variety of 3D printers and materials from which to choose. None of these are qualitatively identical, and there is a significant body of evidence, both anecdotal and documented, indicating that materials used in digital production have varying degrees of success in investment casting. The root causes of related defects are not fully understood, leaving the industry plagued by speculation and a variety of home grown methods aimed at addressing these problems.

Through the use of controlled studies, we first explore the burnout behaviors of several mainstream materials, followed by an evaluation of dimensional movement experienced by these materials when subjected to investing and firing. Casting defects will be tracked to their root causes through dimensional analyses and observations of defect morphology in cast product.

“A Study of the Effects of Digitally Produced Casting Models on Casting Quality”

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INTRODUCTION

The study of the casting behaviors of digital model materials is nothing new. Since the inception of these technologies in the early nineties, a great deal of effort has gone into developing materials that not only allow us to see and feel a 3D object in its plastic form, but also perform well as a casting model for a variety of metals. What we have learned through past research is that virtually all of these materials behave differently from one another in the casting process. Some products, such as 3D Systems QuickCastÔ build system, have been extensively researched and publications abound that can help us understand how to get the best cast product. Other materials are either too new or are simply lacking in published research. This work is intended to take some of the mystery out of the equation, giving jewelry designers and casters better tools to use in finding the material that best suits their individual needs.

Note: The authors do not endorse any particular product used in the study. The associated machines and materials are very complex and conclusions about them cannot be accurately drawn from analysis of data from this study alone.

DIGITAL MODEL MATERIALS

The mainstream materials used in digital model production fall into three classes based upon their chemical properties and are categorized in this study as either photopolymer (light curing), thermoplastic (jetting technologies), or wax based (CNC milling). Injection wax, although not digitally produced, has been included as a baseline from which to draw comparisons. Table 1 is a list of the model materials used and their respective classifications.

Material Class	Material ID	DIGITAL Method
Photopolymer	A	Light Curing 3D Print
Photopolymer	B	Light Curing 3D Print
Thermoplastic	C	Jetting 3D Print
Polymeric (Milling) Wax Green	D	CNC Milling
Polymeric (Milling) Wax Blue	E	CNC Milling
Polymeric (Milling) Wax Purple	F	CNC Milling
Polymeric (Milling) Wax Orange	G	CNC Milling
Wax-Hydrocarbon Resin Green	H	Rubber Mold Injection

Table 1 Model Materials

TEST GEOMETRY & ALLOY CHOICE

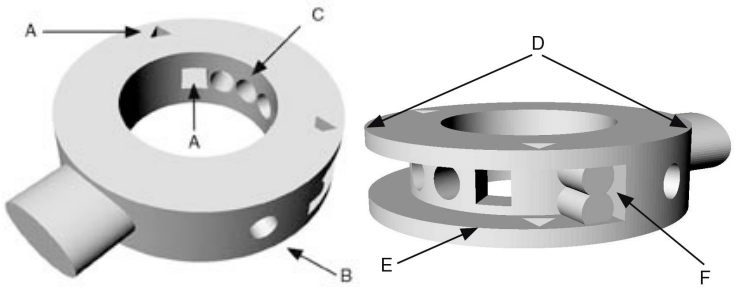


Figure 1 Test Geometry

For our experiments, we created a test geometry that was designed to encourage failures typically seen in investment casting of digital model materials (Figure 1). Deep holes, sharp angles, and complex recesses set in a heavy torus shape were chosen as likely to initiate failures based upon our past experience. The following is a brief summary of the test geometry features chosen:
Sharp Angle (A): Regardless of model material, sharp angles can create havoc in the casting process due to the weakness created in the shell/investment by the tension of a 90°angle. One can hypothesize that this condition would be magnified when dealing with a high rate of expansion in the model material; internal pressure applied to an already weakened system would likely fail earlier than casting with minimally expansive materials.

Deep/Blind Holes (B&C): Excessively deep setting holes cause problems for several reasons. First, the investment inside does not have great mass and is therefore weaker by nature. Second, it may be difficult to get a very dense core as material may enter the blind hole imperfectly, e.g. air may become trapped in the bottom or bonding of the investment to the model is incomplete. Lastly, and most importantly for our study, the long, narrow core may be pressed upon in a concentric manner by expanding model material.

Heavy, Sharp Edged Torus Shape (D & E): Our observations in production have been that heavier pieces have a greater tendency towards investment failure. The greater mass may increase stress on investment not only dimensionally, but also in terms of heat retention and force of the metal as it enters the mold cavity at high speed.

Complex Recess (F): With this type of geometry one can imagine forces being exerted upon the investment in a number of ways. Features that are located very close to one another only have a thin “wall” of investment between them. If significant model expansion takes place while the investment is still in the green state, this thin and relatively weak wall may collapse and the two features will then join together as one.

Alloy: 90% Platinum 10% Iridium was our alloy choice due to its high density and the high flask and pour temperatures that must be used in casting. These extreme parameters naturally challenge casting quality and therefore are good indicators of robustness when looking at performance of model materials relative to one another.

BURNOUT EXPERIMENTS

The first set of experiments we undertook was aimed at understanding the amount of residual ash that the various model materials left following burnout. We used two vessels; one covered to imitate the restricted air flow of a typical casting flask, and one uncovered for free flow of air (Figure 2).

Figure 2 Burnout Vessels – Full Air

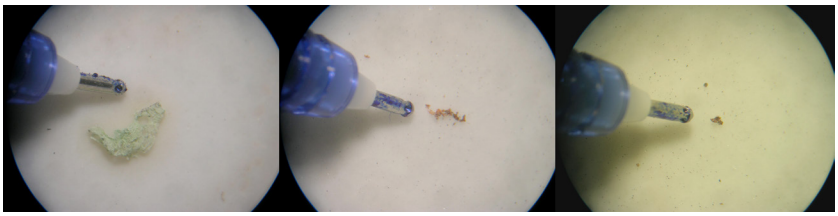
Material		Deformation	Boiling/Burn Temperature	Residue Full Air	Residue Restricted Air
Photopolymer	A	425°C - 450°C	~450°C - 475°C	5	4
Photopolymer	B	275°C	~450°C	9	8
Thermoplastic	C	110°C	~175°C	3	2
Milling Wax Green	D	125°C	~350°C	5	1
Milling Wax Blue	E	100°C	~350°C	5	2
Milling Wax Purple	F	125°C	~350°C	4	1
Milling Wax Orange	G	150°C	~390°C	3	1
Injection Wax Green	H	75°C	~240°C	4	1

Table 2 Burnout Results

Note: 1= lowest amount of ash; 10 = highest amount of ash. See Figures 3 through 6 for examples.

Clearly, the most interesting finding in this phase of our study was the relative sparsity of ash residue when using the covered vessel. Our assumption had been that the greater exposure to air and the potential for circulation presented by the open vessel would result in a lesser amount of ash. Surprisingly, the result was opposite. Even for the photopolymers, the amount of residue was somewhat reduced by covering the vessel. Further experiments with actual casting flasks should be pursued in light of this finding.

In summary, all materials left some degree of residual ash in burnout. The lowest degree of ash was found in the orange wax, and the highest degree was found in Photopolymer B. Figure 3 depicts the volume of ash in context with the tip of a pen. Based upon this result, we will look for corresponding defect morphology in the casting correlation study that follows.



Photopolymer Green Milled Orange Milled

Figure 3 Ash Residues – Full Air

MODEL THERMAL EXPANSION MEASUREMENTS - BACKGROUND

In the 2005 study “The Revolution of CAD/CAM in the Casting of Fine Jewelry”1 by Adler and Fryé, it was demonstrated that significant thermal expansion of models was taking place, particularly in the class of materials called photopolymers. Expansion was physically demonstrated by the observation that casting dimensions for product produced from photopolymer models were larger than those of the models themselves. The mold cavity had clearly enlarged, in theory because expansion of models (and consequently the mold cavity) occurs while investment is still in the flexible green state. This growth, as was demonstrated in the 2005 study, takes place in both the investing and burnout procedures. What was not fully understood at that point in time, however, was the rate at which various digital models expand and how this rate translates into casting quality. For example, what is the impact of growth onset

as it relates to overall burnout time? Do materials that expand earlier cause more damage, or is later expansion more harmful to our investment? In order to answer these questions, we set out to assess the amount and rate of thermal expansion experienced by mainstream model materials.

MODEL THERMAL EXPANSION MEASUREMENTS – METHOD

The first avenue towards understanding thermal expansion of our digital materials was to conduct phone and internet research to determine whether such information already existed. We contacted manufacturers of 3D printers and CNC wax producers. We searched the internet, but in the end found very little information, confirming that original research would be needed to capture data and draw comparisons. The next step was to find a reliable method of taking measurements of materials at elevated temperatures. In order to gauge the rate and amount of expansion in typical burnout conditions, we needed a temperature resistant and very sensitive measuring device. Our research and discussions with testing labs specializing in such measurements indicated that the most reliable method for measuring thermal expansion of photopolymer resins and wax would be through use of a dilatometer. Unfortunately, further investigation ruled out this method due to the high cost of purchasing a dilatometer or performing such work at an outside lab on a large number of different materials.

A second more cost efficient method was devised using a steel fixture, dial gauge, and quartz probe. (Figures 4-5) The fixture consists of four major components that are constructed out of steel. The first piece is the “base” of the fixture, the thickness of which is important to keep it from warping during thermal cycling. The next two pieces, plates “A” and “B”, hold the models in place. The plates were ground flat on both legs to keep them true to the base of the fixture and to properly hold the models during the test. Plate “A” was twice as tall as plate “B”, which allowed it to extend higher than the models. This provided a flat surface to rest against and forced model growth to go in only one direction; this also put the clamping force in the middle of plate “A” so that the model did not tilt forward, eliminating the risk of a gap between fixture and model. (Any gap would show as negative growth during thermal cycling because it would allow the model to move away from the probe and not towards it.) The last piece is the “quartz guide”, a piece of 16-gauge piano wire that has a loop bent at one end and is locked in place at the other end by a set screw, allowing it to be set at the appropriate height. The purpose of the quartz guide is to keep the quartz probe from resting on plate “B” during the test and allowing it free movement during thermal cycling.

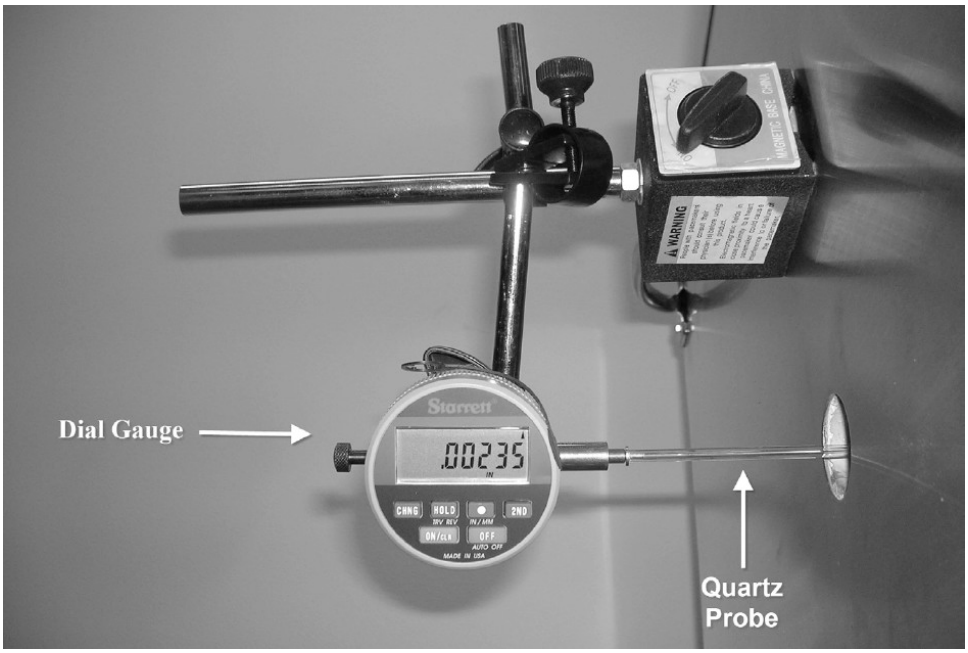


Figure 4 - Kiln Exterior - Dial Gauge & Quartz Probe

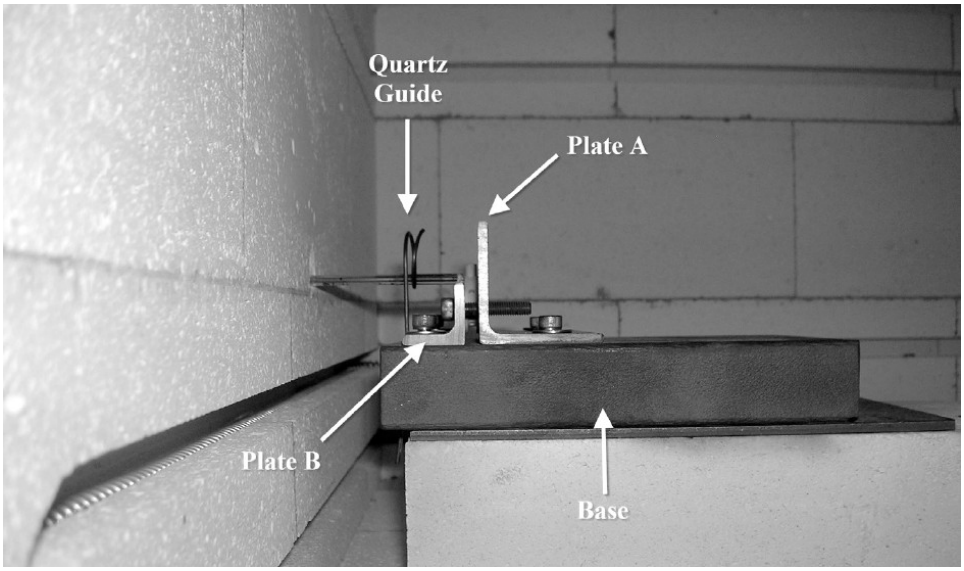


Figure 5 Kiln Interior – Quartz Guide and Holding Fixture

TEST SET-UP

When clamping the models in the fixture, the model was placed in between the two plates and the screws were hand tightened so that the model was loose. Models were positioned so that the inner diameter was at the top of plate "B" with the sprue stub facing up. The clamp was then tightened, but caution was taken so that the model was not crushed or warped. After the model was clamped, the fixture was placed in the burnout oven. A digital dial indicator with a range of .250" and an accuracy of .00005" was used to measure the model expansion during the thermal cycle. A .150" diameter by 8" quartz probe was fitted with a machined adapter to fit the dial indicator. The blunt end of the probe was placed flush with the models for testing. After the fixture was placed in the burnout oven, the quartz probe was fed through the viewing hole and guide. The fixture was then moved forward so that the probe was in contact with the model and a reading of ~.02000 was achieved on the dial indicator. A gauge was used to measure the distance between the fixture and the burnout oven wall, and to true it up as well. After the fixture was trued up in the burnout oven, the door was shut and the dial indicator was zeroed out. Next, the probe was pulled back slightly and allowed to spring back in contact with the model. This was done three times confirm the probe's return to zero.

THERMAL CYCLE

All models went through a series of temperatures in 25ºC increments. Each step was allowed to reach temperature and dwell for ten minutes before logging the dimension. Milling wax and thermoplastic models, which have relatively low melting points, started the thermal cycle at 50ºC. The photopolymer materials, which have higher melting points, started the cycle at 100 ºC. Thermal cycling ran until negative growth was observed, indicating that the models had started to melt and deteriorate.

MODEL THERMAL EXPANSION MEASUREMENTS – RESULTS

The following graphs depict the readings taken by our quartz probe fixture assembly. While measurements in thousandths of an inch are reported, this should not be seen as a statement of absolute growth in the models, but rather as a plot of the quartz probe movement generated by each material. Even though this method is relatively accurate, our test results cannot ignore the possible impact of fixture thermal expansion and human touch in the exact placement of the probe. In addition, temperature increments and elapsed time were not identical to firing curves, and the fact that models had not been invested for the test leaves out the potential impact of water absorption and other dynamics inherent in the investing operation. We therefore rely more heavily on the relative rather than the absolute when interpreting the probe movement charts.

INJECTION WAX

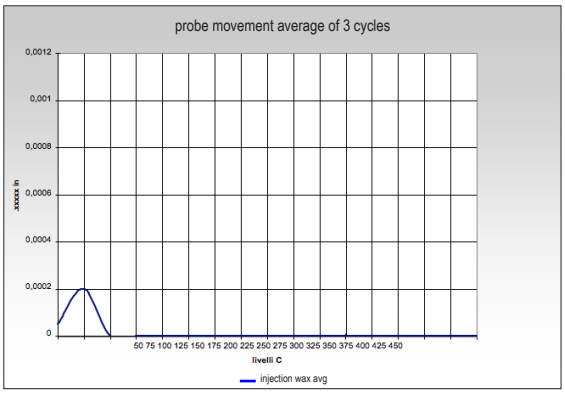


Figure 6 Injection Wax Probe Movement
Material H: Low Expansion and Melting Temperature

MILLING WAX

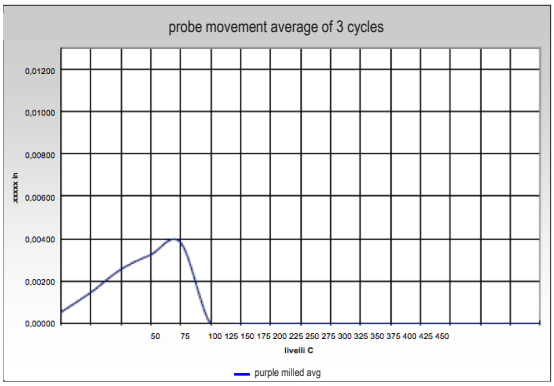


Figure 7 Purple Milled Wax Probe Movement
Material F: Moderate Expansion and Melting Temperature

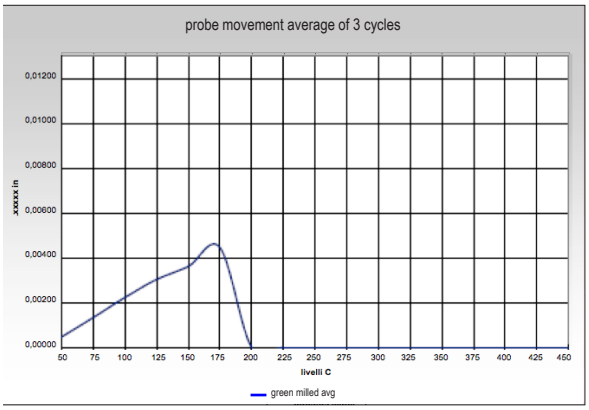


Figure 8 Green Milled Wax Probe Movement
Material D: Moderate Expansion and Melting Temperature

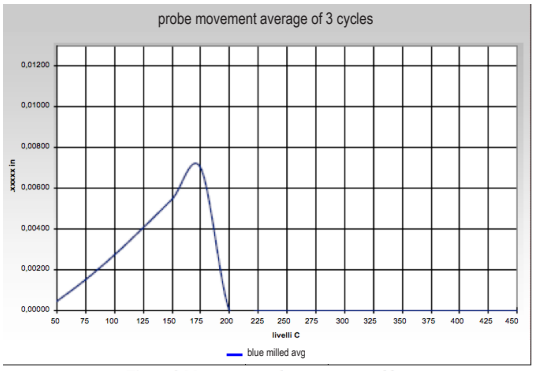


Figure 9 Blue Milled Wax Probe Movement
Material E: Moderately High Expansion and Moderate Melting Temperature

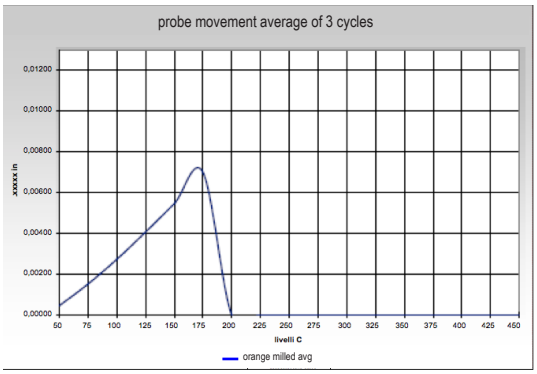


Figure 10 Orange Milled Wax Probe Movement
Material G: Moderately High Expansion and Moderate Melting Temperat

WAX THERMAL EXPANSION SUMMARY

Table 3 Wax Thermal Expansion Results

Wax Type	Probe Movement	Peak Temperature
Injection Wax Green H	0,00025”	75°C
Milling Wax Purple F	0,00400”	175°C
Milling Wax Green D	0,00425”	175°C
Milling Wax Blue E	0,00700”	175°C
Milling Wax Orange G	0,00725”	200°C

As shown in Table 4, the injection wax had the least amount of probe movement. Also of note is the considerably lower melting temperature. In theory, this material at .00025 probe movement should cause little stress on the investment and casting results should generally be good.

Milled wax results, on the other hand, were a bit surprising with probe movement up to .00725” on the blue sample, indicating expansion approaching what we will see in photopolymers. The manufacturer of the green, purple, and blue materials used in this study notes that all of their milling waxes are chemically similar wax/plastic hybrids with varying amounts of additives depending upon the desired hardness characteristics. The blue wax, which is also used for hand-carving, is the softest of the group; purple is midrange, and green is the hardest. Given the significant amount of probe movement on all of the milled waxes, we would expect some degree of investment stress to take place during the dewax and burnout phases.

THERMOPLASTIC THERMAL EXPANSIONI

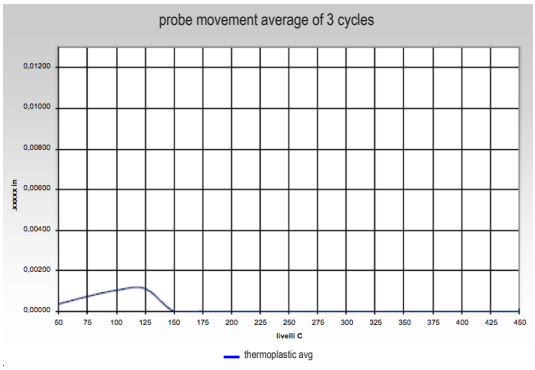


Figure 11 Thermoplastic Probe Movement

Material C: Low Expansion and Moderately Low Melting Temperature

Material	Probe Movement	Peak Temperature
Thermoplastic	.00115	125°C

Table 4 Thermoplastic Expansion Results

The results from the single thermoplastic material tested show that very little expansion is taking place, in fact less than all of the milled waxes tested and only slightly more than the injection wax. This sample reflects a relatively low melting temperature of 125°C and probe movement of slightly more than .001". This result concurs with our production observations that castings produced from this thermoplastic material do not typically exhibit casting defects with origins that are suspect for model expansion such as finning and core failures.

PHOTOPOLYMER THERMAL EXPANSION

Photopolymer models are well known for having a higher degree of thermal expansion when compared to most waxes and thermoplastics. In the book "Rapid Prototyping: Laser Based and Other Technologies"2 authors Venuvinod and Ma state that resins, being thermosets, do not melt at lower temperatures and will continue to expand during the initial burnout phase. Our results confirm this with probe movement for photopolymers ranging from .009" on the low end up to .012" on the high end..

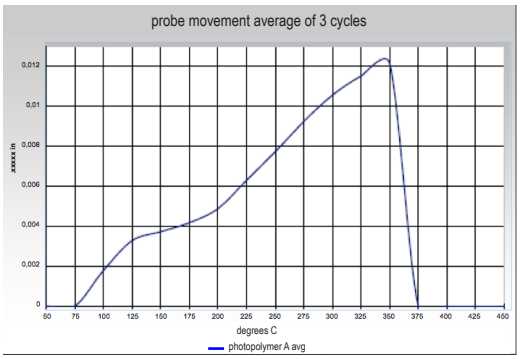


Figure 12 Photopolymer A Probe Movement

Material A: High Expansion and High Melting Temperature

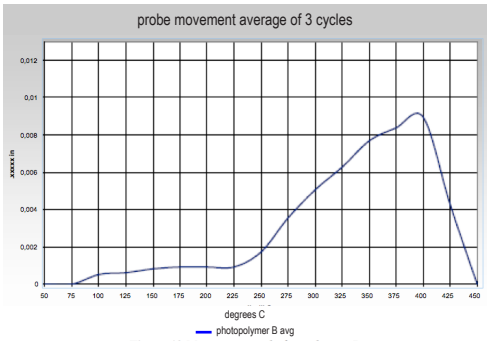


Figure 13 Photopolymer B Probe Movement

Material B: Moderately High Expansion and High Melting Temperature

Material Type	Probe Movement	Peak Temperature
Photopolymer A	0,01200”	350°C
Photopolymer B	0,00925”	400°C

Table 5 Photopolymer Expansion Results

Not surprisingly, both photopolymers showed significant probe movement. The remarkable finding in these tests is not so much the amount of expansion as the temperatures at which expansion peaks. Compared to our wax and thermoplastic categories with peak expansion at 200°C, our photopolymers keep expanding well up into the 350° - 400°C range. This combination of higher expansion over a longer period of time clearly distinguishes photopolymers from our other materials in terms of investment interactions.

MODEL THERMAL EXPANSION - CONCLUSIONS

Our results reflect a range of probe movement on the low end of .00025 for the injected wax and on the high end of .012 for Photopolymer A. Clearly, we have a broad range of model behaviors interacting with the investing and firing processes. In order to better evaluate the potential impact of these various levels and rates of expansion, we will now context them with investment dynamics, followed by a casting correlation study.

INVESTMENT CONSIDERATIONS

Most materials expand with heat. This phenomenon is caused by an increase in the average space between the nuclei of atoms when more energy is present. Consequently, during burnout Mother Nature gives us not only the expansion of the model materials to consider, but the expansion of investment materials as well. Investment type may also be a critical factor not only in terms of expansion, but also in terms of strength. The stronger investment is in its green state (prior to and during firing), it might be said that the more likely it is to hold up to the pressure exerted upon it during the initial burnout curve. In order to evaluate this interaction, we first sought information on thermal expansion of two common investment types. The following graphs, courtesy of investment supplier Ransom & Randolph, depict thermal expansions of their gypsum and phosphate bonded investments marketed under the trade names Ultravest® and Astrovest™.

PHOSPHATE BONDED INVESTMENT EXPANSION

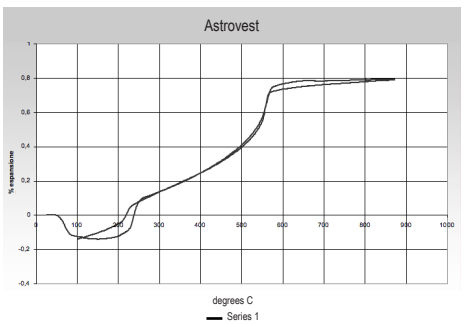


Figure 14 Astrovest™ Thermal Expansion Low to Absent at Key Model Expansion Temperatures

As we can see, the phosphate bonded investment starts out the curve with shrinkage and then starts to expand at 225°C. Notably, the expansion occurs well after all of our wax and thermoplastic categories have reached their peak expansion temperatures. Therefore, investment expansion is not a concern for these materials. The photopolymers, on the other hand, expand up to the range of 350 to 400°C. As a result, model expansion is simultaneous with investment expansion. Although the total investment expansion is relatively low at ~0.3% in the photopolymer melting ranges, it is worth noting that this phenomenon is occurring. While the precise impact this dynamic might have on investment failure is not clear from our experiments, it should nevertheless be kept in mind as a possible contributor.

GYPSUM INVESTMENT EXPANSION

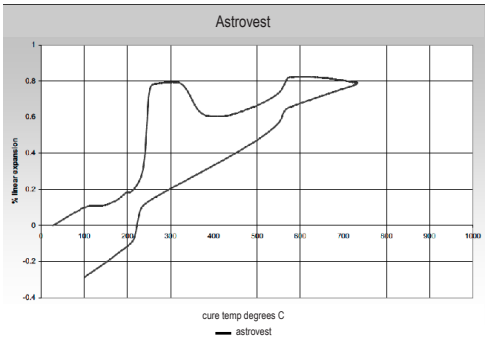


Figure 15 Ultravest® Thermal Expansion. Relatively Low at Wax and Thermoplastic Key Expansion Temperature; Relatively High at Photopolymer Key Expansion Temperatures

The gypsum investment exhibits an expansion curve very different from the phosphate bonded. Expansion starts out very slowly then suddenly spikes at 225°C. Again, this is not a concern for our wax or thermoplastic categories as they have already begun to melt below this temperature. The photopolymers, however, are not so lucky and continue expanding beyond gypsum's peak of 0.9% starting at 260°C, then falling slightly to 0.7% at photopolymer melting temperatures. As noted above, this would indicate that simultaneous expansion is occurring between the photopolymers and the gypsum investment.

PHOSPHATE BONDED COMPRESSIVE STRENGTH

In addition to thermal expansion, we also wanted to look at the strength of investments at our key model expansion temperatures. For the phosphate bonded investment, strength increases as the temperature rises, therefore the risk of failures may potentially be mitigated by increasing strength. The graph below demonstrates the compression strength in psi of Ransom & Randolph's Astrovest™ product at our key model expansion temperatures. Astrovest™ continues to increase in compressive strength as the firing curve proceeds, topping out at 600 psi in the fully fired condition.

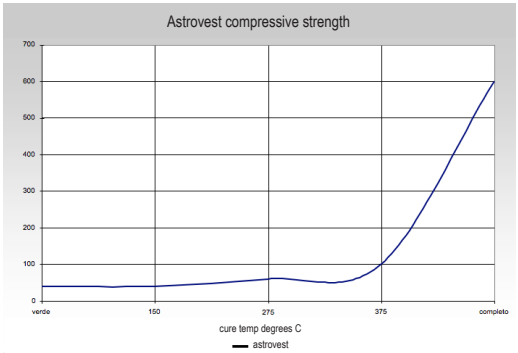


Figure 16 Astrovest™ Compressive Strength. Relatively Low (40 to 100 psi) at Key Model Expansion Temperaturesdel modello

GYPSUM INVESTMENT COMPRESSION STRENGTH

The compressive strength curve for gypsum investment is essentially reversed from phosphate bonded. Our gypsum sample was at its strongest in the green state (400 psi) after a 2-hour set time. As the firing curve proceeds, it becomes weaker, bottoming out at 100 psi in the fully fired condition. Nevertheless, at our critical model expansion temperatures of 150°C, 275°C, and 375°C gypsum still maintains a higher compressive strength than the phosphate bonded. Although casting studies were not performed on gypsum investment for this paper, it would be interesting to pursue this experimentation in light of the differing compressive strength curves of these two investment types at model-critical expansion temperatures.

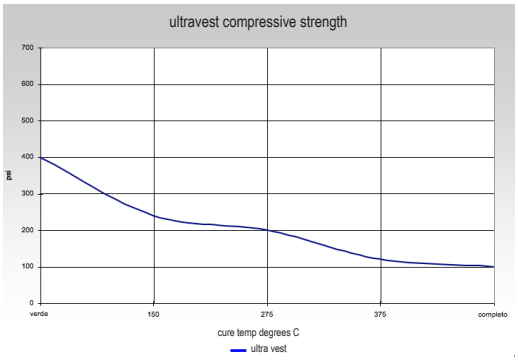


Figure 17 Ultravest Compressive Strength.
Higher Than Phosphate Bonded at Key Model Expansion Temperatures

CASTING CORRELATION

Once thermal expansion of the model materials and investments had been analyzed, we proceeded with experiments aimed at correlation of these results in cast product. For these experiments, the alloy choice was 90% Platinum 10% Iridium, and for investment we utilized a ceramic shell system combined with a phosphate bonded platinum investment. This type of ceramic system produces a strong interface for the various model materials and subsequent casting—although as our thermal expansion experiments have demonstrated, all of the model expansion takes place well before either shell or phosphate bonded investment reaches sintering temperatures and maximum strength.

When launching our casting experiments, we hypothesized that model materials demonstrating greater probe movement in our thermal expansion experiments would be more susceptible to investment failure. In addition, those materials that left a greater degree of ash residue in our burnout experiments might exhibit surface negatives with morphologies similar to that of the ash.

As discussed earlier, the type of design features most vulnerable to model expansion tend to be very deep setting holes or recesses where the investment “core” is thought to collapse from concentric pressure applied as the model walls around the core expand. In this sense, once the compressive strength of the investment is exceeded by the pressure exerted on it by the expanding model, a breaking down of the core occurs. The resulting defect is normally a blend of metal and investment that partially or totally fills the void where the core had been. This type of defect seriously compromises the quality of the casting, and adding insult to injury, it typically renders the affected metal unsafe for direct recasting due to the contamination of metal from investment. In some cases, the investment core can totally break free (fully in tact) and relocate to another area of the casting. This type of defect, which we will call “core relocation”, (Figure 26) reveals a precise imprint of the core’s shape in a location that should be composed of solid metal. For our casting correlation study, we produced six identically sprued trees. Three trees contained wax-based materials, and three contained thermoplastic and photopolymer materials. The flask and pour temperatures were identical for all six trees. The following photos depict casting results experienced by the various model materials.

INJECTION WAX

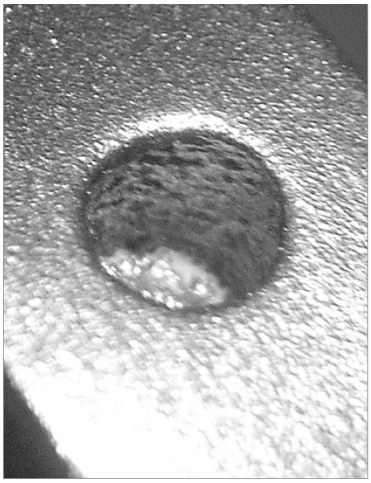


Figure 18

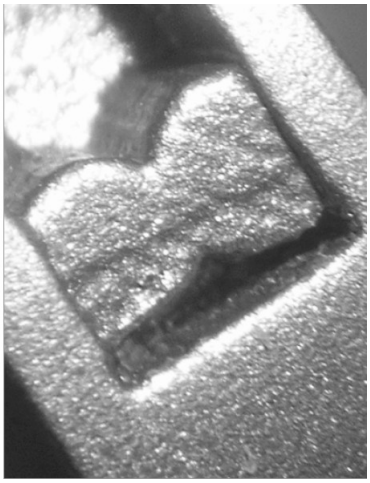


Figure 19

The injection wax (Figures 18 and 19), exhibiting very little expansion and having a relatively low melting temperature, performed very well in casting. Even the features we specifically designed for investment stress cast cleanly without evidence of defects.

MILLED WAXES

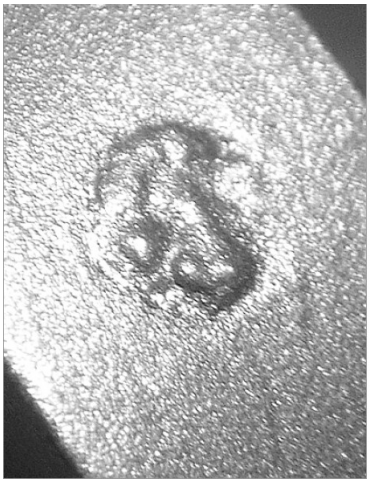


Figura 20

Figura 21

All milled waxes experienced problems in the features designed to test investment stress. Shown here are results from the Green Milling Wax, however, all milling waxes exhibited similar defects. Note the investment failure in the blind hole shown in Figure 20, as well as the failure of the thin wall of investment adjacent the prongs in the channel shown in Figure 21. In looking at these features, one can imagine the expansion of surrounding model material pressing against the relatively weak investment until the point of fracture.

THERMOPLASTICS

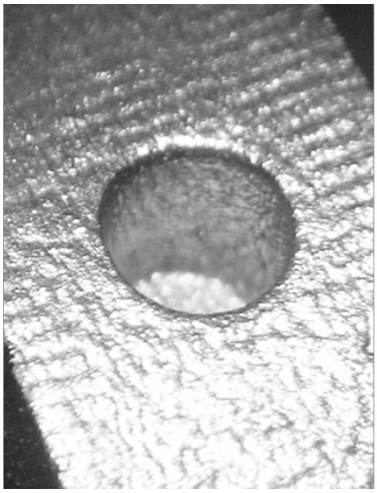


Figure 22

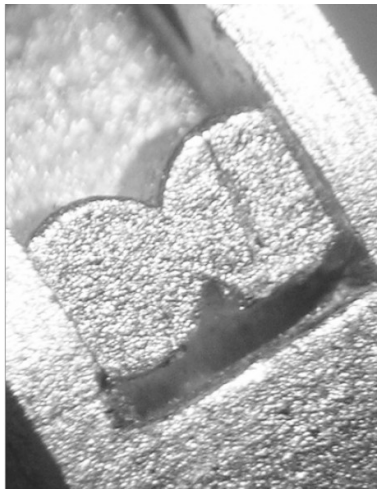


Figure 23

The thermoplastic material (Figures 22 and 23) offers additional evidence that lower expansion properties correlate with higher casting quality in difficult features. As we cansee from the picture, the areas that presented challenges in the milled waxes cast very cleanly in the thermoplastic.

PHOTOPOLYMERS

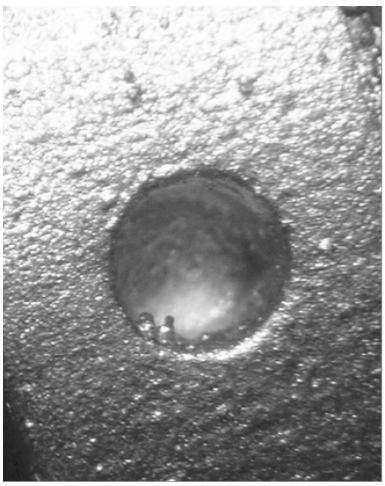


Figure 24

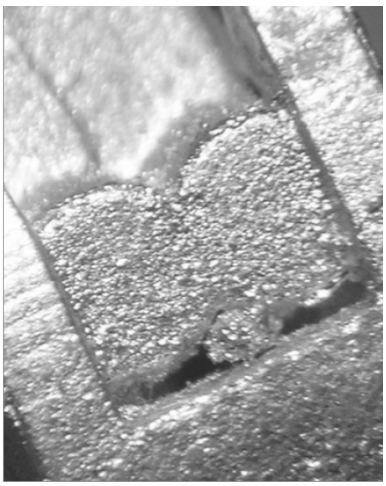


Figure 25

Castings from the photopolymer patterns produced mixed results. As we can see from Figure 24, the hole cast relatively cleanly. We can see some areas of investment infiltration, however, these are largely superficial. Figure 25 shows a breakdown of investment in the wall adjacent to the prongs and, in addition, the castings exhibited fins on the edges of the shank and prongs. Given the high level of probe movement in comparison with injected wax and thermoplastic, this result supports our theory that higher levels of expansion promote investment failure.

CORE RELOCATION

This phenomenon is occasionally seen in production casting and is quite devastating when it occurs. In our experiments, core relocation occurred on one of the milled wax trees. It was not clear from which particular material the core originated, as all milled wax patterns on this tree had some degree of investment failure. Figure 26 shows the embedded ceramic core that had relocated to the bottom of the tree.

In addition, one Photopolymer A piece experienced significant core relocation at the base of the shank. This defect is highly suspect as resulting from pattern thermal expansion as it is rarely seen in injection wax or thermoplastics in our production experience. Our experimental results also add support to the theory that expansion is the root cause of such defects.

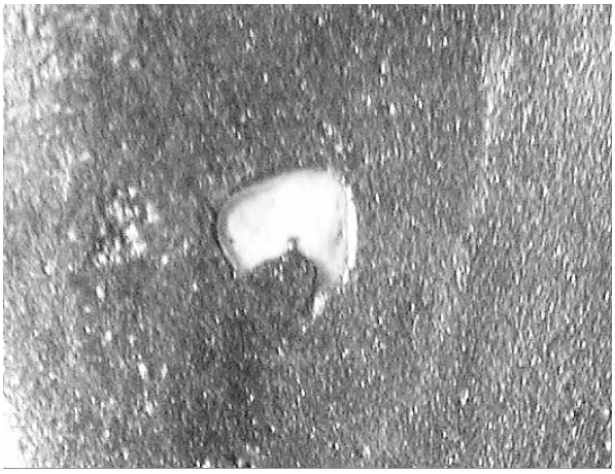


Figura 26

ASH RESIDUE

Although significant degrees of ash were found in our burnout experiments, we were not able to correlate any specific casting defects to the morphology of the ash. One possible reason may be that the ash scatters into smaller particles not easily detectable on the ascast surface because of their size. Another might be that upon contact with the molten metal much of this ash floats into the sprue system. In any event, we did not find ash residue to be a significant contributor to surface defects.

CONCLUSIONS

The majority of digitally produced model materials present casting challenges in designs that have sharp edges, deep setting holes, and small detailed areas that inherently possess thin cross sections of investment between features. The only digital model material that did not experience casting problems in our test geometry was the thermoplastic. This was attributed to its low melting temperature and low thermal expansion relative to the other materials. In essence, it would appear that the thermoplastic material behaves very similar to injection wax during burnout.

The cause of investment failures generated by other digital model materials, as demonstrated by this research, relates primarily to expansion of pattern materials during the investing and burnout operations. The strength of investments at temperatures that coincide with expansion of most digital models is insufficient to withstand fractures, particularly in complex CAD geometries.

Jewelry designs engineered for the particular digital model material that will be used in an important consideration for success in casting. The challenging features utilized in this study can all be modified to better accommodate the expanding materials. The addition of radii on sharp edges and decreased depth in setting holes and channels will help facilitate success in materials that expand early in the firing curve.

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