A SURVEY OF INVESTMENT CASTING TECHNIQUES FOR HIGH-TEMPERATURE ALLOYS

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INTRODUCTION

This paper explores the various bonding systems for lost wax casting technology for high-temperature alloys. This technology is widely used in the jewelry, dental, art, and industrial markets (which includes a wide range of sub-markets from automotive to aerospace). While focusing on the different bonding systems, this paper also covers the two widely used application technologies for the lost-wax casting of solid (block) mold and ceramic shell. Various properties are investigated and discussed, including the strengths and weaknesses of the different investment types and processes. Topics include pattern and flask setup, mixing, bench cure, and burnout. It also covers other investing technologies that encourage jewelers' creative inclinations and open new possibilities to further their art or advance their craft. This technical knowledge will benefit manufacturers by refining an existing process or discovering something new for implementation.

Table 1: Investment bonding types evaluated in this paper

	Jewelry Phosphate Bonded	Dental Phosphate Bonded	Ethyl Silicate Bonded	Sodium Silicate Bonded	Two-Part Acid	Ceramic Shell with a Suspended Slurry
Typical Industries	Jewelry (Pt, Pd, Steels)	Dental, Removable Partials (CoCr, NiCr)	Dental (CoCr, NiCr)	Jewelry, Medical Device, Braces (Pt, Pd, Steels)	Jewelry, (Pt, Pd, Steels)	Commercial, Areospace, Automotive, Medical Device
Flask Preperation	Metal Flask	Flaskless Mold	Metal Flask	Metal Flask, Absorbant Base	Metal Flask, Absorbant Base, Absorbent Liner	No Flask
Liquid Portion of Investment	Water	Binder with User Controlled Water Dillution	Ethyl-Silicate and Acid Binder	Water	Acid Binder with Specific Water Dillution	Colloidal Silica Pre-Mixed Slurry
Mixing Method	Planitay Mixer (Hobart)	Vacuum Mix	Hand Spatulate	Planitay Mixer (Hobart)	Planitay Mixer (Hobart)	Hand Stir
Typical Pattern Material	Wax	Wax and Resin	Wax	Wax and Resin	Wax and Resin	Wax

GENERAL TIPS FOR JEWELRY AND DENTAL INVESTMENTS

(not including ceramic shell)

- Use deionized water when instructed to use water.[1]
- Control water and powder temperature. Typically, at room temperature for best results.[1]
- It's essential to keep all equipment clean of dried investment materials to prevent any contamination that could affect the quality of the mold.
- Ensure access to a properly functioning vacuum pump. Test by placing water in a vacuum chamber, pulling a vacuum, and reaching a rapid boil in 20 seconds.
- The mold must have a minimum clearance of ¼ in. on the sides and 1 in. at the top and bottom of the pattern.
- While some of these investment types are more commonly used for applications other than jewelry, rest assured that all instructions are carefully adapted to suit the specific needs of the jewelry casting industry.
- The alloy manufacturer can provide mold temperature guidelines for casting. Once the mold has been held at this temperature based on the burnout cycle, it is ready for casting.
- Allow the mold to cool before attempting to devest. Do not quench in water. Some investment types will devest easily by tapping on the metal flask with a hammer-like tool. Sandblasting is appropriate for further cleaning up the casting.

JEWELRY PHOSPHATE BONDED INVESTMENT

Phosphate-bonded investments are not all the same. Some can be strong in the green state, while others are weak. Various factors can be adjusted to achieve the desired strength, porosity, and expansion. The refractories and additives in this investment type compensate for the alloy shrinkage through thermal expansion.[2] The jewelry phosphate investment was designed so that it would not get too hot when setting. Therefore, this investment type is weak in the green state but gains considerable strength during firing. This investment can be difficult to devest because of the mold's post-fired strength.

Figure 1: An example of a conventional wax set-up on a rubber base

Flask Preparation

Because this investment type was developed long before plastic or resin patterns were commonly used, the best results come from using wax patterns. Resin patterns often lead to flashing as the mold is not strong enough to withstand resin expansion. Set up the patterns in a conventional manner using a rubber base, as shown in Figure 1, a metal flask, and a flask collar. These investment types do not use a flask liner.

Investing

This type of investment is mixed with only water because the binders are all included in the powder. In contrast, later discussed in this paper, investment types require additional binders like colloidal silica, ethyl-silicate, and others. Adding just water is beneficial as there is less room for error while measuring just one liquid. Measure water and powder and prepare a mixing unit with a wire whip. Add all the powder to the water immediately and hand mix for about 30 seconds. Mechanically mix for about 1.5-2 minutes. Place the whole mixture under a vacuum until it boils and breaks. Do not leave the flask under vacuum for longer than 1 minute. Pour investment down the side of the flask, avoiding the pattern. Fill the flask until the pattern is covered; do not fill it completely. Place the flask under a vacuum for about 1 minute. Do not leave the flask under vacuum for longer than 1 minute. Top off the flask and allow it to bench cure for 2 hours. This type of investment is highly fragile in the green state, so handle it carefully. Ensure the flask is placed in a vibration-free zone to prevent disturbances.[3]

If an investing machine allows mixing and pouring under a vacuum, most of the mixing time should be used before filling the flask.

Mold Stripping and Burnout

Carefully remove the base and collar from the flask to avoid disturbing the mold. Then, following the burnout cycle, place the mold in a room-temperature oven, as illustrated in Figure 2.[3]

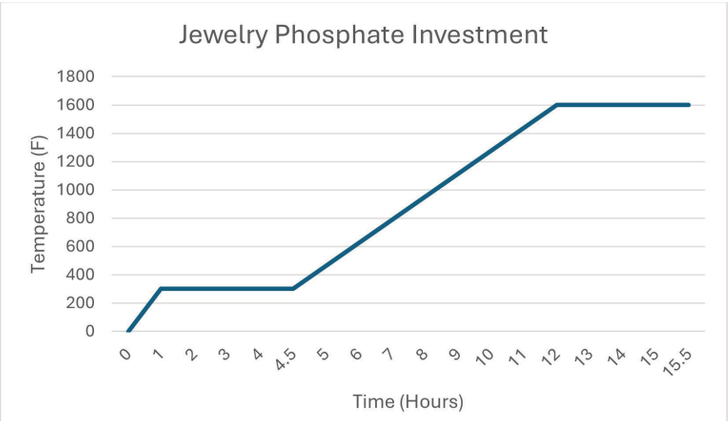

Figure 2: The typical burnout cycle for the jewelry phosphate bonded investment

Other Tips

Phosphate investments typically have a shorter working time compared to gypsum-based jewelry investments.[2] If additional working time is needed, place the investment and water in a refrigerator before investing. This slows down the chemical reaction that causes the investment to set.[1]

DENTAL PHOSPHATE BONDED INVESTMENT

This type of phosphate-bonded investment is very strong in the green and post-fired states, making it useful with printed resin patterns. Due to the mold's porosity, this investment type performs well with flash fire burnout. These characteristics make this investment type preferred when a quick turnaround is needed. This overall process is only about 90 minutes for a 3x3 flask.

Figure 3: An example of a conventional setup with resin patterns on a rubber base

Flask Preparation

This investment type supports wax and resin patterns. The patterns can be sprued conventionally, as shown in Figure 3. However, this investment type performs better with a removable flask.

Investing

Use deionized water alone or mix with colloidal silica with appropriate dilution to adjust for desired expansion results. A higher concentration of colloidal silica results in more expansion.[2] The standard dilution ratio is 86 mL of expansion liquid and 14 mL of deionized water. Add powder to the liquid and mix under vacuum for about 1 minute at 250-350 rpm. If the RPMs is increased, decrease the mixing time accordingly to prevent the working time from diminishing. Slowly pour the investment around the pattern on a vibration table to decrease the chance of air bubbles. Once the flask is filled, place the mold in a pressure vessel for the remainder of the set time if desired. Do not disturb the mold during the bench cure.[4]

Figure 4: The dental phosphate bonded flaskless mold with the top and bottom trimmed before entering the oven

Flash Fire Burnout

Allow the mold to bench cure for 20 minutes. Remove the base, flask, and flask collar. Because this mold is strong in the green state, before placing the mold in the oven, using a model trimmer or rasp to remove 1/8 in. layer from the top and bottom of the mold is good practice. This will open the pores of the mold and aid in rapid moisture release during the flash fire. The stripped and trimmed mold is illustrated in Figure 4. Place the mold in a preheated oven at 1500-1700°F (816-927°C) for one hour minimum, as shown in Figure 5. A flask-less mold is preferred for this method to allow moisture to escape quickly. After the hour has passed, bring the oven temperature to the appropriate casting temperature if needed.[4]

Ramped Burnout

A less aggressive burnout may be preferred for several reasons. As shown in Figure 5, a larger mold will need this longer initial hold at a lower temperature. Burning out the mold overnight may also be beneficial on a certain workflow day.

Allow the mold to bench-cure for one hour. Remove the base, flask, and flask collar. Before placing it in the oven, wet the mold by running it under room-temperature water for about one minute while trimming off 1/8 in. layer from the top and bottom of the mold. The stripped and trimmed mold is illustrated in Figure 4. Then, place the mold in a room-temperature oven and follow the ramped burnout cycle illustrated in Figure 5.[4]

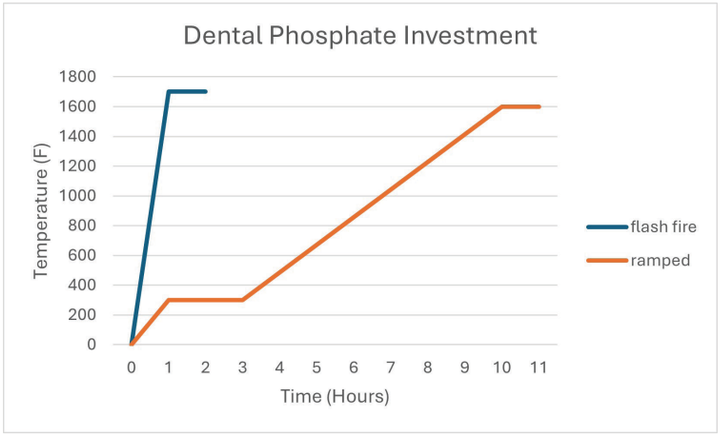

Figure 5: The flash fire and ramped burnout cycles for the dental phosphate bonded investment

Devesting

Due to the mold's strength, the devesting process may be more complex than other investment types. While holding the casting button, tap on the button with a hammer to release most of the investment.

ETHYL SILICATE INVESTMENT

Ethyl silicate bonded investments use silicic acid gel binders to bond refractory materials together. This binder is created by precisely measuring the components to foster the proper hydrolysis reaction.[2] After hydrolysis, this binder is stable for three days when refrigerated and sealed.[5]

Flask Preparation

This investment type prefers wax patterns as it is not strong in the green state. Resin patterns can lead to flashing. Sprue the patterns in a conventional manner with a rubber base, a metal flask, and a flask collar.

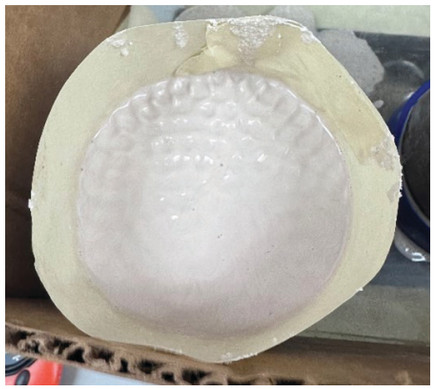

Figure 6: A representation of the ethyl silicate investment on the vibration table before the investment is set

Investing

Thoroughly mix all powder and binder liquid. This should only take about 1 minute. Pour the mixture into the flask on a vibration table, carefully pouring down the side while avoiding the pattern. Allow the investment to set for 9-20 minutes while still on the vibration table. Ripples should be visible to ensure the vibration is strong enough, as shown in Figure 6. The investment begins to set in a spongy manner and then becomes very hard. After vibration, allow the mold to bench-cure for an additional 30 minutes.[5]

Figure 7: Both images show the ethyl silicate mold after it has set. Left: The gelled and cracked top layer; Right: the mold after the top layer has been peeled away.

Burnout

The top layer of the mold will have small cracks where it has become spongy. This layer should be peeled or flaked off, as shown in Figure 7. Carefully remove the base and collar from the flask to avoid disturbing the mold. Place the mold into a cold furnace and follow the burnout cycle outlined in Figure 8.[5]

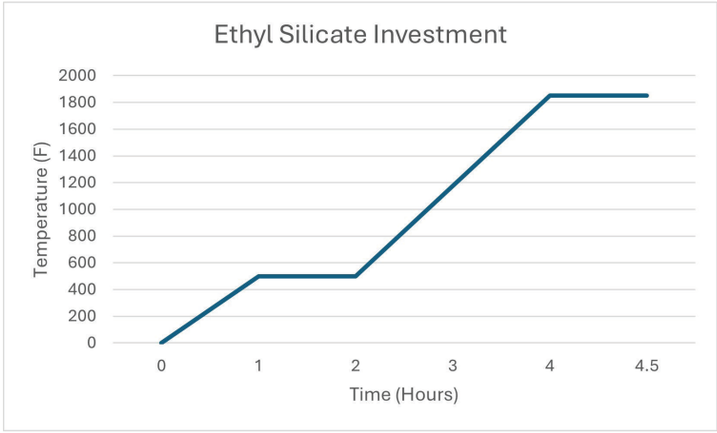

Figure 8: The typical burnout cycle for the ethyl silicate investment

SODIUM SILICATE INVESTMENT

This investment is typically used for very small and detailed medical device steel castings, such as orthodontic brackets. It can also be used to cast platinum-based and other high-temperature alloys. This type of investment is simply mixed with water instead of other binders typically required for other platinum investments. This is a benefit, as there is less room for error while measuring the liquid portion. Another advantage is that it can be used with plastic and resin.

Flask Preparation

Using an absorbent base, cut a small hole in the base paper under the sprue button to ensure complete wax burnout. Attach the metal flask to the absorbent paper with sticky wax shown in Figure 9. Place the collar 2-3 in. (5.1-7.6 cm) above the top of the metal flask. Place the absorbent base and flask on top of a piece of wood or a layer of cardboard for extra support.[6]

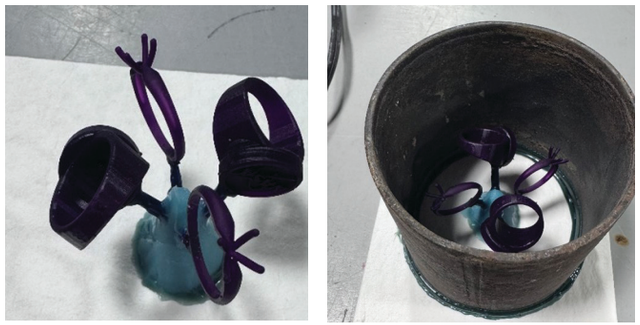

Figure 9: Both images show an example of a conventional setup with resin patterns on a wax button and absorbent paper base. Right: metal flask attached to the absorbent base with wax

Investing

Add some powder to the water and begin mixing by hand. Using a paddle attachment on the mixing unit set to the lowest setting, slowly any remaining powder. After mixing for 2 minutes, scrape the sides of the bowl to ensure all powder is incorporated into the water. Mix for 12 minutes to fully wet out the powder. Place the entire mixture in a vacuum until it rises and breaks. Pour the investment onto the side of the flask with a small stream, avoiding the pattern. Fill the flask slightly above the pattern. Place the flask in a vacuum and allow it to boil for 45 seconds with vibration. Fill the flask to .5 in. above the metal flask.

After investing, an overnight bench cure is required for 14-16 hours in a warm, dry room.[6]

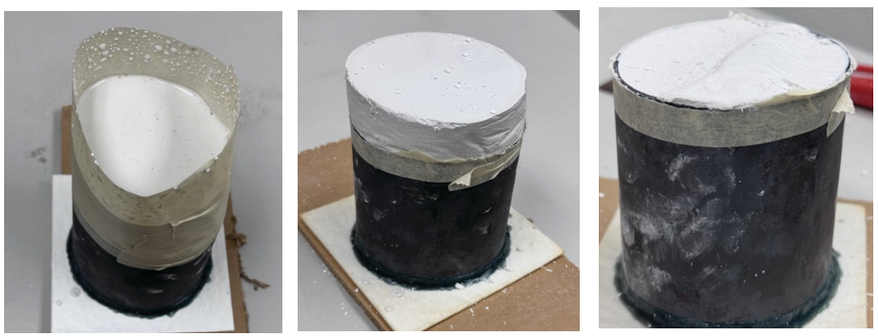

Figure 10: Left: the layer of liquid formed at the top of the set investment; center: after the excess liquid is decanted and the collar removed; right: after the excess investment is removed from the top of the flask.

Flask Stripping and Burnout

The investment will settle in the flask, and a layer of liquid will form on top. Decant the excess liquid. Let the mold dry for approximately one hour, then remove the collar. Carefully trim off any investment material left above the flask. Figure 10 shows all these steps. Follow the burnout cycle from Figure 11.[6]

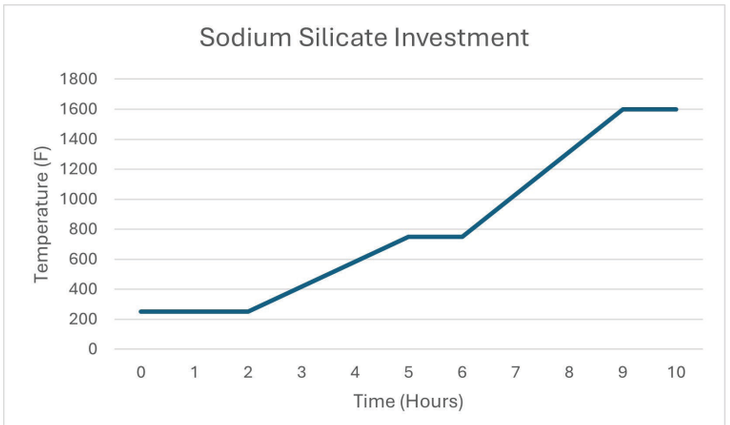

Figure 11: The typical burnout cycle for the sodium silicate investment

TWO-PART ACID INVESTMENT

A concentrated acid binder is to be combined with the refractory powder. These investments need to settle out and do not set like other types. The acid binder allows for a lower water-to-powder ratio. This is advantageous, as less water must be absorbed, decreasing the time needed for the mold to set.

Flask Preparation

Place an absorbent liner on the inside of the metal flask walls, ensuring about ¼ in. of the flask remains uncovered at the top and bottom. Use an absorbent base and cut a small hole in the base paper under the sprue button to ensure complete wax burnout. The metal flask is attached to the absorbent paper with sticky wax, as illustrated in Figure 12. Position a flask collar 2-3 in. (5.1-7.6 cm above the top of the metal flask.[7] Place the absorbent base and flask on top of a piece of wood or a layer of cardboard for extra support, mirroring the setup described in the Sodium Silicate Investment section.

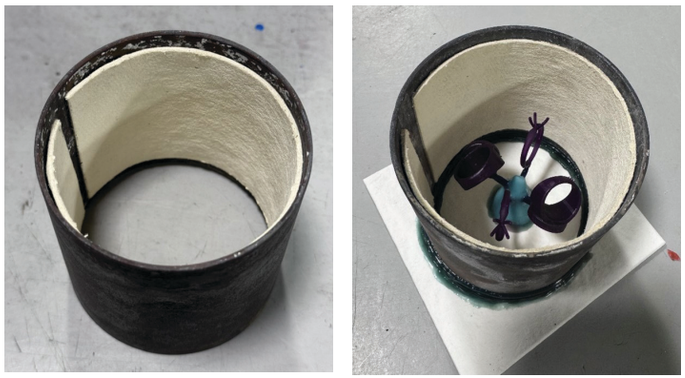

Figure 12: Left: The absorbent liner on the inside of the flask; right: The flask attached to the absorbent base with a resin pattern

Investing

Dilute the binder appropriately. Place the binder and water in a mixing unit and slowly add part of the powder. Continue to add powder slowly while mixing. Once all the powder is mixed into the binder, mix for an additional 15-20 minutes. Place the entire mixture in a vacuum until it rises and breaks. Pour the investment down the side of the flask with a small stream, avoiding the pattern. Fill the flask slightly above the pattern. Place the flask in a vacuum and allow it to boil for 45 seconds with vibration.[7] Fill the flask past the absorbent liner, over-filling past the edge of the flask slightly.

Figure 13: The mold after it has set, with a still glossy surface, as the mold does not appear traditionally set

Bench-cure in a warm, dry space for five hours or until the mold is "set", as shown in Figure 13. This investment will not set in a typical manner and can liquefy slightly with agitation.[7]

Flask Stripping and Burnout

This requires careful handling as the mold is extremely weak. Remove the collar and shave any excess investment from the top of the flask, as shown in Figure 13. Follow either burnout cycle shown in Figure 14.[7]

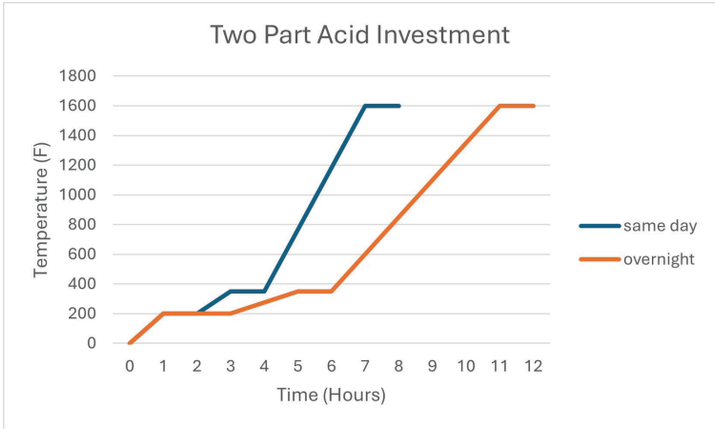

Figure 14: The same-day and overnight burnout cycles for the two-part acid investment

CERAMIC SHELL WITH A HIGH-TEMPERATURE SUSPENDED SLURRY

Common ceramic shell terms include:

- Binder - colloidal silica binder is a suspension of solid amorphous silicon dioxide particles in water.
- Binder solids - silicon dioxide and other ingredients in high-performance binders that bind refractory materials and sand to form a shell.
- Refractory – a fine powder-like heat-resistant ceramic material.
- Slurry – a combination of binder and flour materials.
- Stucco – sand applied to an investment mold after it has been freshly dipped in a slurry and drained.
- Primary slurry - used to apply the initial coat(s) to the pattern. These coats determine the surface finish of the cast metal.

- Backup slurry - used to apply shell coats after the primary to build up a shell with adequate strength and thickness to withstand the stress in the process.
- Viscosity – the resistance of a substance to flow, the thickness or thinness of the material.[8]

Slurry Makeup
Using a pre-mixed slurry eliminates the risk of operator error in adding the proper amounts of flour to the binder. This also eliminates the labor, mixing equipment, and time costs. A suspended slurry can be remixed or stirred in minutes if needed. The need for continuous mixing is also eliminated as a benefit to the potential loss of power supply. This suspension can be maintained for months without mixing.[8]

Control
The slurry should be protected from freezing, as this will irreversibly impact it, making it unusable. Viscosity should be checked at the beginning of the day before use, and the density and total solids of the slurry should also be checked regularly. High refractory solids can cause shell cracking and make the shell difficult to remove.[9]

Figure 15: An example of a conventional set-up with wax patterns on a wax base. There is a screw placed into the wax base as something to hold onto during dipping.

Pattern Setup
A ceramic shell with a wax pattern is recommended. The setup resembles a typical jewelry setup with a base and sprues. To properly dip the pattern into the slurry, there needs to be a section to hold onto that will not be covered in the slurry material. In this specific example, a screw was inserted into the wax base shown in Figure 15. The wax could also be extended as a place to hold while dipping. A clip is used to hang the mold while drying.

Figure 16: The shells in the green state are fully built with the final seal coat.

Application Recommendation
Stir the slurry before each dip. Once blending is complete, the mixture should appear creamy. Patterns must be clean of contaminants before dipping. A lid should be placed on the slurry to prevent water evaporation between dips.[10]

Dipping Process/Shell Building
The first dip is essential to ensure the best surface finish possible. This first dip is called a primary coat. Air bubbles or gaps in the slurry on the pattern need to be eliminated to achieve the desired surface finish of the casting. The typical dipping sequence involves immersing the cleaned pattern in the slurry, draining it until a uniform coat is formed with no dripping, and then applying the stucco sand. Fine zircon sand should be used for the first coat. The stucco sand can be applied using the following methods:

- Rainfall: sifting or sprinkling sand over a freshly dipped and drained pattern.
- Fluidized bed: Compressed air passes through a porous stone or plate, evenly disturbing air through a bed of sand, allowing

a pattern or mold to be immersed fully.

- Cat box: Place the freshly dipped and drained mold on an open bed of sand with moderate side walls, flipping the sand by hand onto the mold.[8]

The mold is left to dry in a low moisture, room temperature area. The shell needs to be thoroughly dried before moving on to further dips. When the shell's temperature is the same as the surrounding environment, it is dry. If the shell's temperature is lower than the surrounding area, it needs more time for the moisture to evaporate entirely. This can be checked with an infrared temperature gun. Once the prime dip has dried, the mold will be ready for the next dip. The first dip of the backup slurry is very similar in that the slurry coat should be even and allowed to drain correctly. The stucco for the backup dips should be coarser sand. The sand must be a fused mineral like fused silica or an aluminosilicate, not regular quartz. This process will continue until the shell is built to the appropriate thickness. This specific process was one prime coat and four backup coats with stucco. The final dip is called the seal. This final dip is done without any stucco; it is only slurry. This final dip is shown in Figure 16 when dried. In total, six dips of slurry were used for this process. This indicates that the dipping process took three days.

Shell and Solid Mold Hybrid Application

Hybrid techniques have been used in the investment casting industry for decades, from World War II and continuing into at least the 1970s. Some forms of this technique are still used today. The most common pre-coats used sodium silicate, ethyl silicate, or colloidal silica binder and refractory powders appropriate for the given application. A wax or plastic pattern is dipped in this slurry mixture. A fine zircon stucco sand is then applied using one of the above-mentioned methods: rainfall, fluidized bed, or cat box method. This process can be used with one or two coats and set to fully dry for about 24 hours before backing up with an appropriate investment. Between the 1940s and 1970s, at least three phosphate-bonded refractory investments were available with high permeability and were strong enough to withstand a rapid, high-heat burnout. This is not as common today but is still used with a colloidal binder slurry and phosphate-bonded backup material for high-temperature alloy casting.[11]

Burnout

This ceramic shell application can be burned out with a flash fire, as shown in Figure 17.[12] This is a significant benefit, as the shell-building process can take a few days.

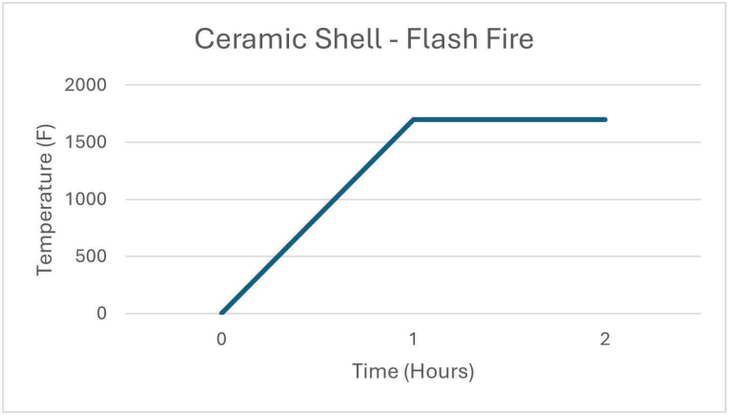

Figure 17: The flash fire burnout cycle for ceramic shell

Figure 18: The shell mold after the metal was cast

Devesting

Small cracks may appear in the shell immediately after casting, as shown in Figure 18. This is normal because the alloy freezes quickly after casting. The cracks will have no impact on the casting. Once the shell has cooled, tapping on the mold with a hammer-like tool will loosen it from the casting.

SUMMARY

Each bonding type has pros and cons. Table 2 shows the time used for each process from the start of investing until casting. This breakdown is specific to each product process evaluated in this paper.

Table 2: Time needed for each product process evaluated in this paper

	Jewelry Phosphate Bonded	Dental Phosphate Bonded	Ethyl Silicate Bonded	Sodium Silicate Bonded	Two-Part Acid
Working Time	5-6 mins	5-7 mins	9-20 mins	12 mins	20 mins
Bench Cure Time	2 hrs	20 mins	30 mins	15-17 hrs	~6 hrs
Burnout	15 hrs 30 mins	1 hr	4 hrs 30 mins	10 hrs	12 hrs
Typical Time from Investing to Casting	18 hrs	1 hr 30 mins	5 hrs 30 mins	27 hrs	19 hrs

	Ceramic Shell
Dipping Process (6 Coats)	2 days ~ 3 hrs between dips
Burnout	1 hr

There are many investment casting options to produce the desired casting. By showcasing these differing methods, the hope is that jewelers can find new ways to improve their craft. With varying technologies that have been around for decades, there are always different options to attempt. Each bonding method has distinct advantages and drawbacks. Bonding methods may work very well in one case, while they may cause too many hurdles to overcome in other cases. While a phosphate investment provides a quick turnaround, the desire may be a need for a longer working time. A sodium silicate bonded investment may help with this need. With each of these technologies laid out broadly, the hope is that there is a match for any desired process outcome.

ACKNOWLEDGMENTS

I want to thank Daniel Nixon, R&R's President, for developing the idea behind this research project. I want to thank R&R for allowing me the opportunity to do this study. I want to thank Ralph Carter, R&R's Product Development and Quality Control Manager; Mike Hendricks, R&R's Vice President of Technology; Allison Richards, R&R's Marketing Director; and Amber Meach, R&R's Digital Technology Laboratory Specialist, for all their support and encouragement.

REFERENCES

1. R. Carter, "Effects of Water Quality and Temperature on Investment Casting Powders," *The Santa Fe Symposium on Jewelry Manufacturing Technology 2000*, ed. Eddie Bell (Albuquerque: Met-Chem Research, 2000)
2. Phillips, Ralph W., Skinner's Science of Dental Materials, 9th ed., W.B., Saunders Co., 1991 pg 406-411.
3. "Astro-Vest® Investment," Ransom & Randolph, Toledo, OH, US, Accessed: 9/26/24, https://www.ransom-randolph.com/_files/ugd/cc5f22_c730c5a8f13e4538b9cd20b491a26aea.pdf
4. "Biovest® Investment," Ransom & Randolph, Toledo, OH, US, Accessed: 9/26/24, https://www.ransom-randolph.com/_files/ugd/cc5f22_c730c5a8f13e4538b9cd20b491a26aea.pdf
5. "Chromex™ Regular Investment," Ransom & Randolph, Toledo, OH, US, Accessed: 9/26/24, https://www.ransom-randolph.com/_files/ugd/cc5f22_019ca74402564af480a7ad8afd2becc1.pdf
6. "SC-PT Investment," Ransom & Randolph, Toledo, OH, US, Accessed 9/26/24, https://www.ransom-randolph.com/_files/ugd/cc5f22_0cefe7fcead7465b8a00d08f69977f0c.pdf
7. "Platinum Investment & Binder," Ransom & Randolph, Toledo, OH, US, Accessed 9/26/24, https://www.ransom-randolph.com/_files/ugd/cc5f22_6ff263c0778e4e009564c3052183e4a3.pdf
8. "Ceramic Shell Investment Casting an Introduction," Ransom & Randolph, Toledo, OH, US, Accessed 12/1/24, https://www.ransom-randolph.com/_files/ugd/cc5f22_d496cc4dd1664bfab5786d933817d9cb.pdf
9. "Slurry Control." Ransom & Randolph, Toledo, OH, US,

Accessed 12/1/24, https://www.ransom-randolph.com/_files/ugd/cc5f22_665b1054d01b4689881b1c048e5cff68.pdf

10. "SuspendaSlurry® FS Material" Ransom & Randolph, Toledo, OH, US, Accessed 12/1/24, https://www.ransom-randolph.com/_files/ugd/9d0704_2991efaf37044e09adc8a72060c8ea22.pdf
11. "Investments & Ceramic Shell Refractories for Investment Casting," The Ransom & Randolph Co., pg 201-205, 251.
12. "FlashFire Dewax Method," Ransom & Randolph, Toledo, OH, US, Accessed 12/1/24, https://www.ransom-randolph.com/_files/ugd/cc5f22_4f9c7f876b0f498faabf9750000bdbe1.pdf