Intercoat Drying and Shell Properties

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ABSTRACT
Intercoat drying is an important step in the investment casting shell building process. The amount of water removed after each shell layer has been shown to have a large influence on mold properties. Unfortunately we do not have a clear understanding of how much water needs to be removed. We also do not have a reliable method for relating dryness measurement to the amount of water remaining in the mold. This study was conducted as an attempt to establish the relationship between degree of dryness, mold properties and the dryness measurement method.

INTRODUCTION
If you were to ask an experienced shell process engineer how long you need to dry each layer, hopefully they would respond by saying “it depends”. It depends on the drying conditions, binder system, shell thickness and drying difficulty. There are no simple answers.

But there should be a straightforward process for determining the required dry time. This paper will demonstrate a testing protocol that can be used to relate dryness to mold properties.

BACKGROUND
Intercoat dry time can affect shell throughput and casting quality. Excessive dry times may severely limit the output of the shell room whereas under-drying may lead to dewax cracking or metal leakage at cast. The ideal dry time will produce high quality molds in the shortest period of time.

The amount of water that needs to be removed during drying is the subject of some debate. At a minimum, the drying step must be long enough to initiate binder gelling or the layer will slough off upon re-dipping.

The binder gel point is dependent on the binder particle size, polymer type and polymer percentage. Generally speaking, a small particle binder will begin to gel at around 45% concentration [1, 3]. The percentage of water that must be removed to begin binder gelling is dependent on the initial binder concentration. Assuming no polymer is used, a slurry with 20% silica will require about 70% water removal. For a slurry with 30% silica, only 50% of the water must be removed. (Figure 1)

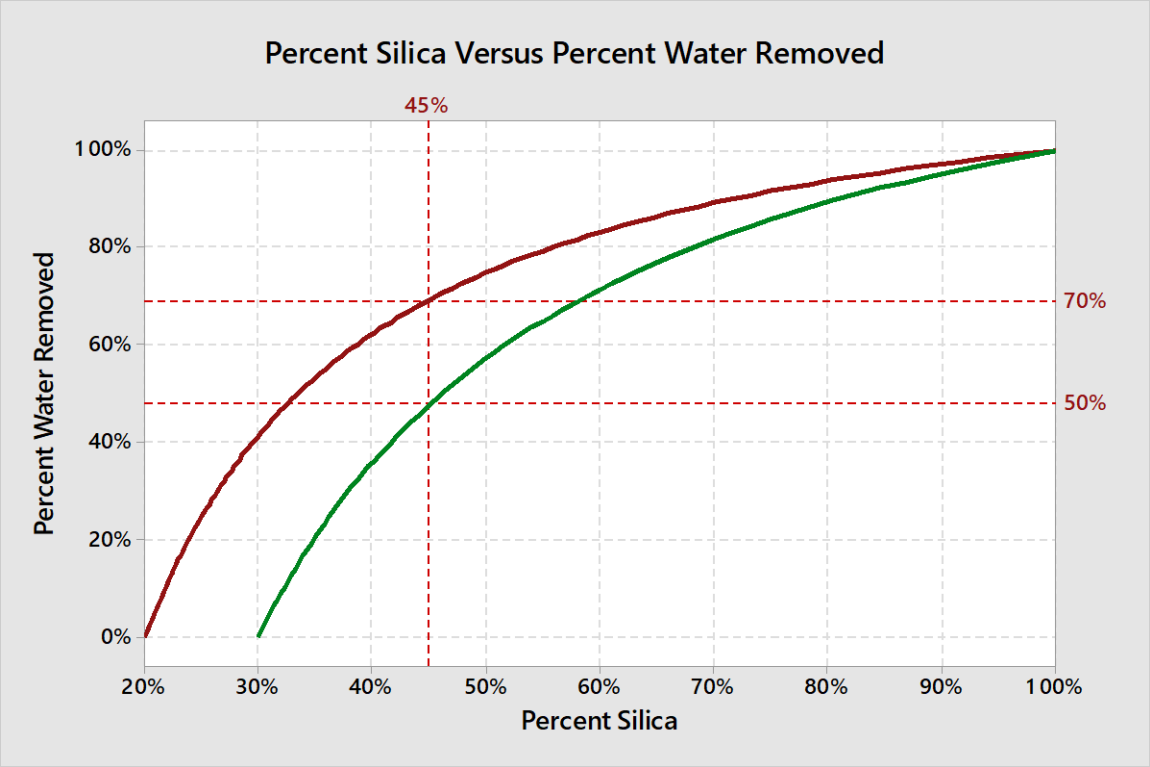

Figure 1. Water removal versus percent silica with 45% as the assumed gel point

Mold Dryness and Mold Quality

There have been many studies published relating casting quality to mold dryness. Here is a sampling of these studies:

Halsey showed that green strength increases as the percentage of solvent is removed and the probability of cracking during dewaxing is reduced as the amount of solvent is removed.[12]

Dalgetty and Mills showed that both green strength and fired strength increased with the extent of drying.[11]

Jackson showed that increasing intercoat drying reduced the amount of mold breakage at pour and improved casting quality in difficult to dry areas of the mold.[4]

Wright and Jackson conducted a three factor DOE to measure the effects of backup layers, dry time between dips and post dip drying on dewax cracking. *The DOE results showed that autoclave dewax results improved when dry time (between dips) and backup layers were increased.* The confirmation trial again showed the time between dips (3 hours versus 5 hours) significantly improved dewax results.[10]

In general, as more water is removed after each layer, mold properties and casting quality improve - but only up to a point. Data from many different researchers has shown that the relationship between water removal and strength is non-linear. A plateau in strength (**strength plateau**) appears to occur where additional water removal does not increase strength. (Figure 2)

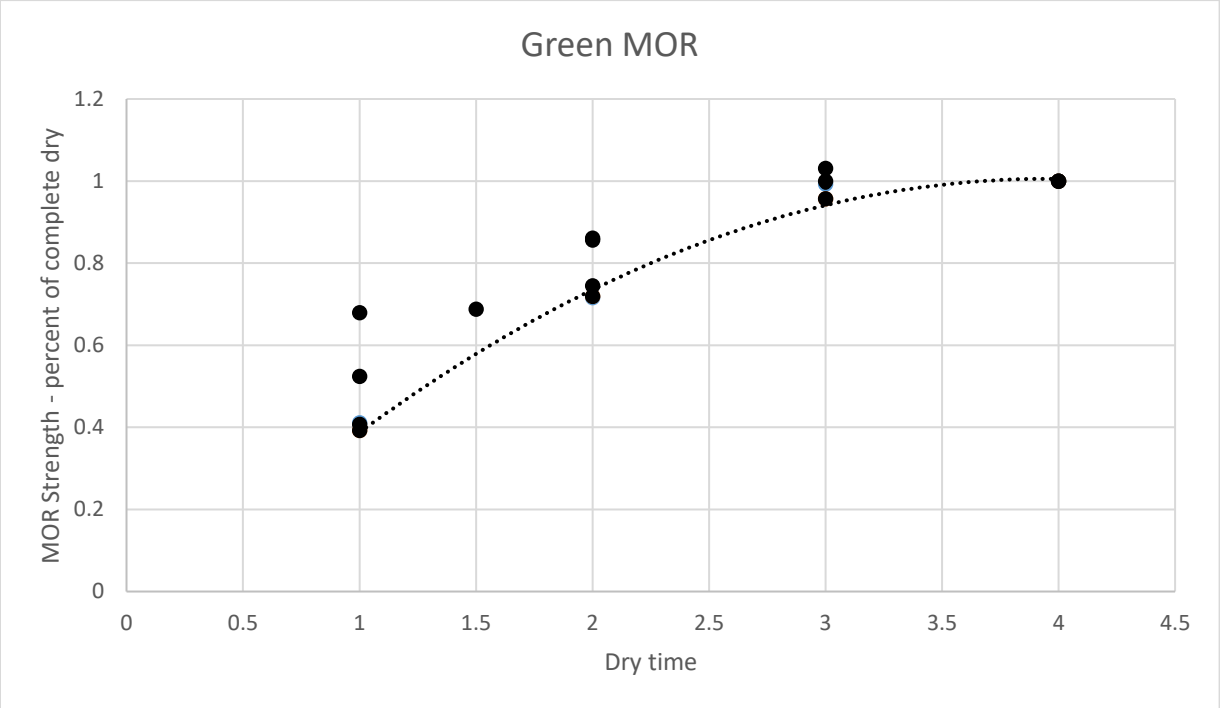

Figure 2. Green strength of different shell systems with large and small particle binder and no polymer[7]

Dryness Measurement Methods

What is the best way to measure mold dryness? The ideal dryness measurement method will be capable of accessing difficult to dry areas of the mold, provide dryness level in real-time and can be directly or in-directly related to mold properties. The industry uses several different dryness measurement methods.

Temperature

One method of measuring the progression of mold drying is by temperature. This technique uses the effect evaporative cooling (latent heat of vaporization) has on mold temperature. During the initial stages of drying there is plenty of water at the surface of the mold. Evaporative cooling of this surface water will reduce the temperature of mold to that approaching the wet bulb temperature. As drying proceeds and water volume is reduced, it becomes more and more difficult for the remaining water to migrate to the surface of the mold. When the speed of water transmission to the surface limits the evaporation rate, the

mold temperature will begin to increase. When the mold temperature is equal to the dry bulb temperature, there is almost no water remaining in the mold.

The degree of dryness is determined using the ***recovery temperature.*** Recovery temperature is simply the difference between the mold temperature and the dry bulb temperature at the point of re-dipping. (Figure 3) A mold dried to a 1 degree recovery temperature will have more water removed than a mold dried to a 6 degree recovery temperature.

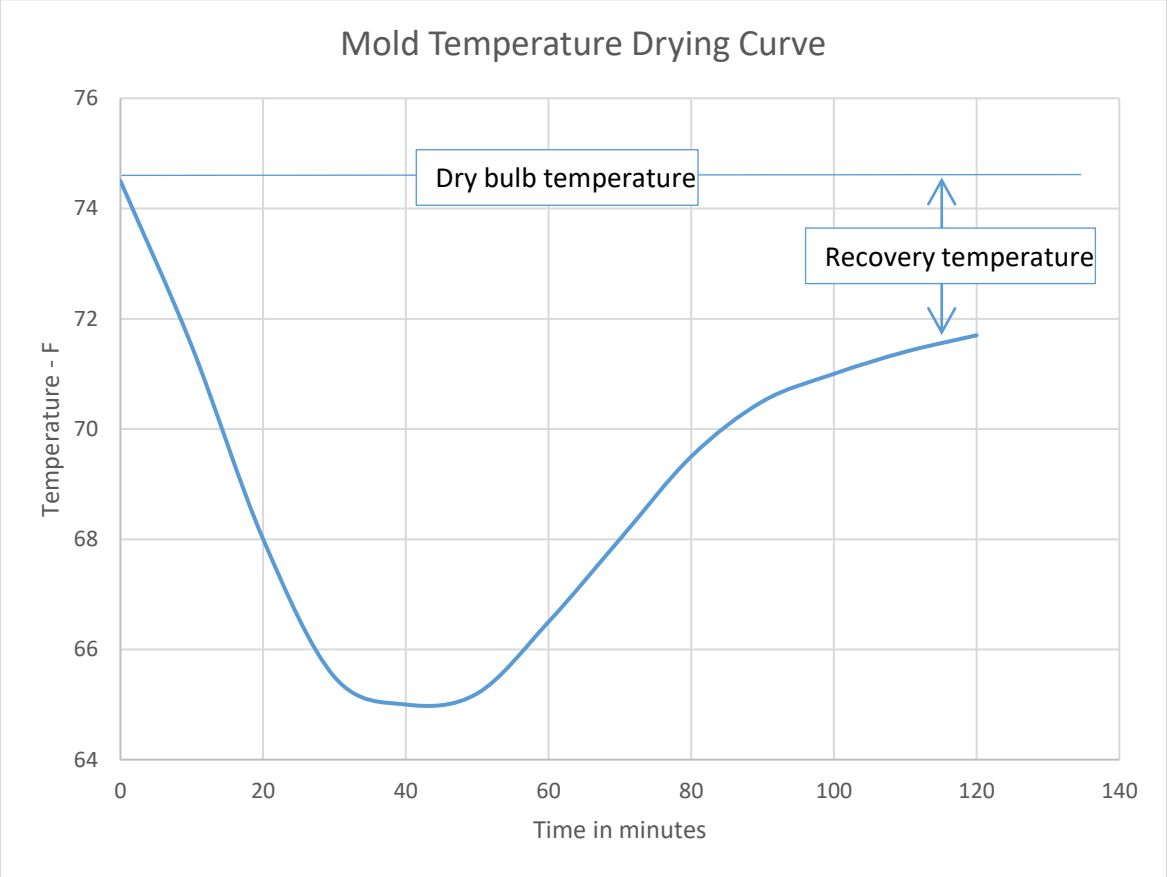

Figure 3. Mold temperature drying curve. This curve shows a 2.8 degree recovery temperature

The relationship between the recovery temperature and degree of dryness is dependent on the drying conditions (temperature and relative humidity). Molds dried to a 1 degree recovery temperature at 50% relative humidity will have more remaining water than those dried to a 1 degree recovery at 20% relative humidity.

Temperature by embedded thermocouple

An embedded thermocouple can be used to measure a distinct area of interest that might not be accessible using other methods.

Temperature by infrared pyrometer

The temperature of the exterior of the mold can be measured using an infrared pyrometer. This is a low-cost method for line-of-sight temperature measurement.

Temperature by thermal imaging

A thermal imaging camera can be used to provide a temperature profile of the mold.

Conductivity

Another method of measuring mold dryness is by electrical conductivity (or electrical resistance). Dry ceramic is a very poor conductor of electricity whereas wet ceramic is a good conductor [1]. By plotting conductivity over time we can determine when the mold (area of interest) is dry. The relationship between water content and conductivity is non-linear with large conductivity changes occurring at the later stages of drying. This method is very good at detecting the drying endpoint but may not be able to detect the strength plateau. (Figure 4)

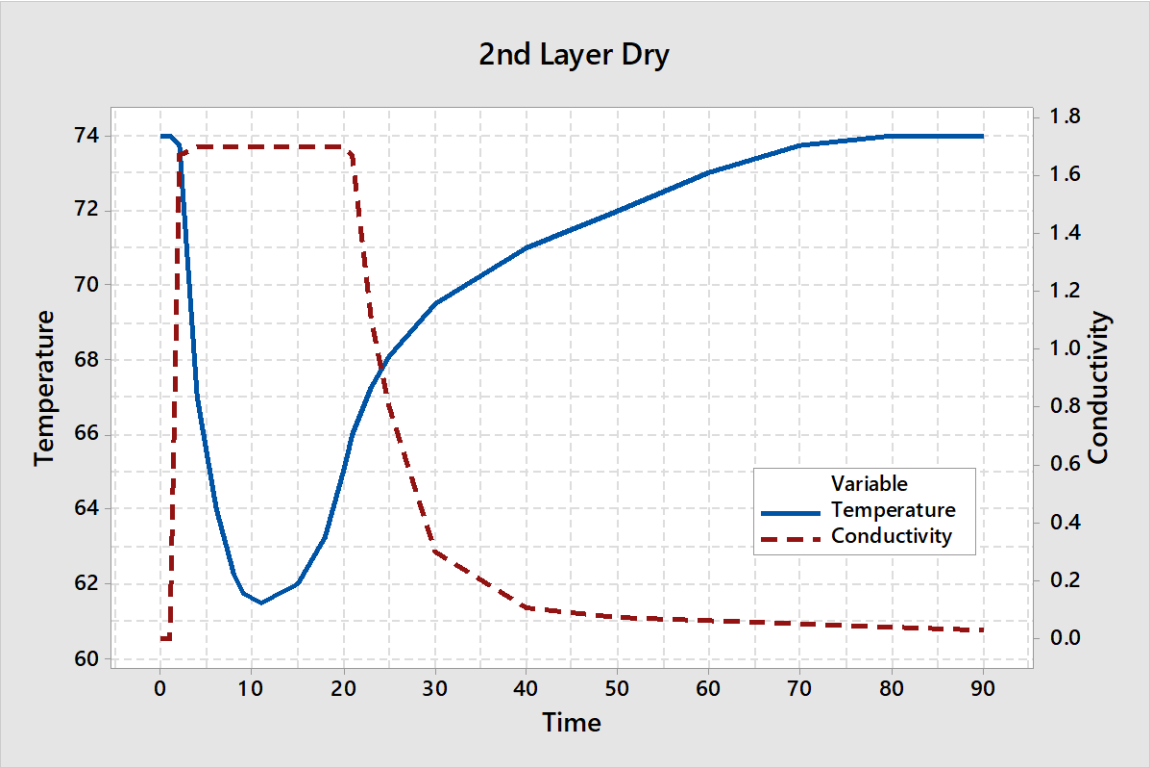

Figure 4. Conductivity and temperature on 2nd layer

Since conductivity is a measure of moisture level between a pair of bare wires, it will not only detect when a mold is dry but will also detect when binder re-wetting occurs. Unfortunately, as more layers are applied there is a larger and larger time lag between immersion and

conductivity change. In one example, it took approximately 250 minutes for the binder to completely wick through a 6 layer shell. (Figure 5)

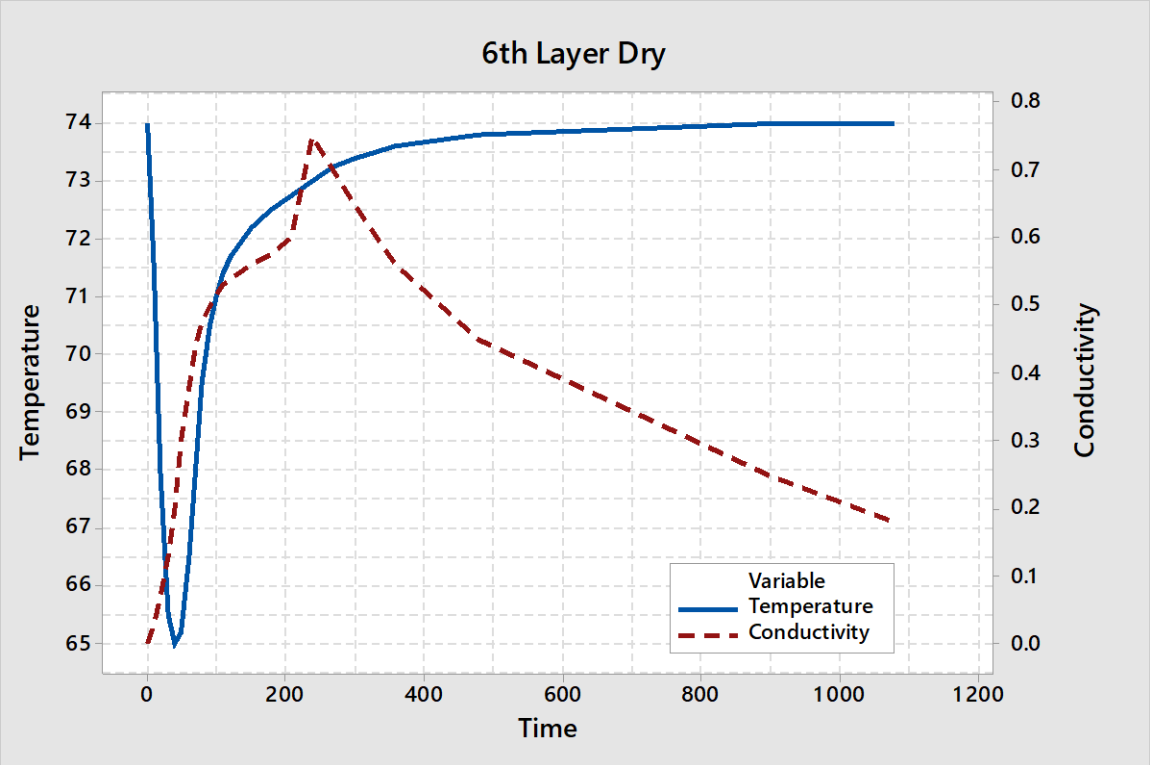

Figure 5. Conductivity and temperature on 6th layer

Weight Loss

Measuring water weight loss is another method of monitoring the progression of drying. By plotting mold weight over time, the drying rate can be determined. (Figure 6) This method can be effective for monitoring the dryness of molds that dry uniformly. Unfortunately, most molds do not dry uniformly.

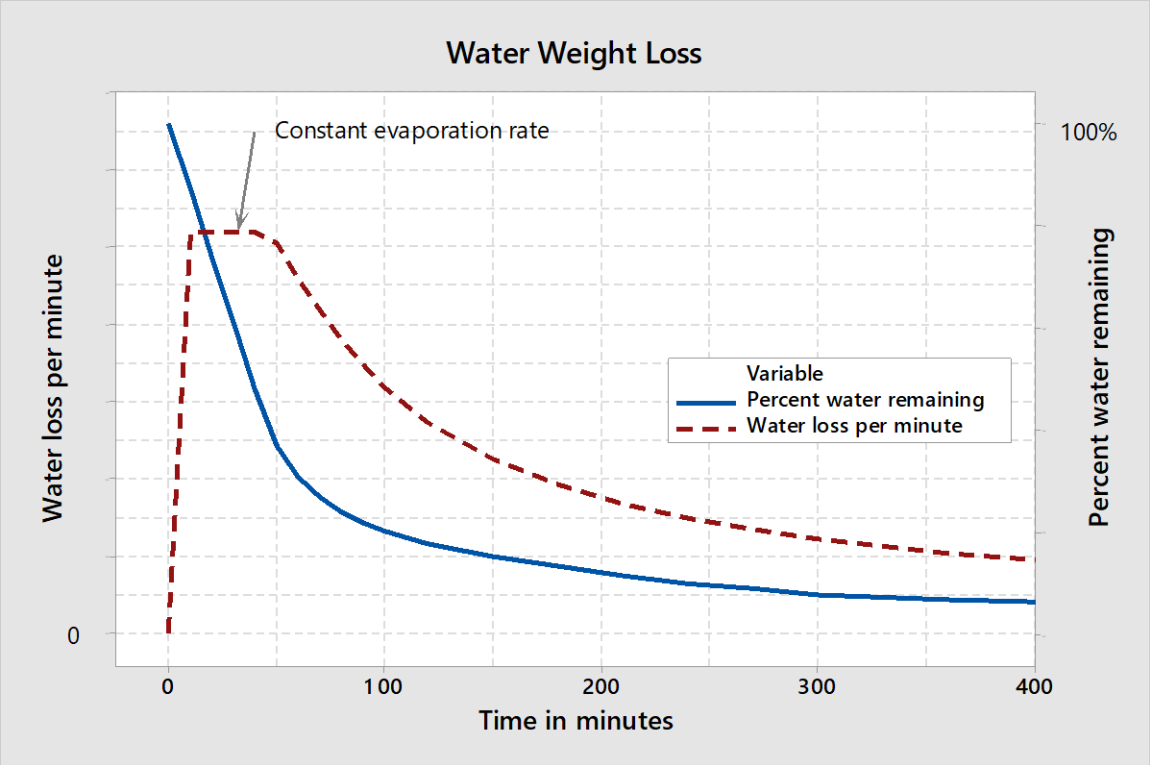

Figure 6. Percent water remaining and water loss rate

Humidity

Another method of monitoring degree of dryness is by measuring the internal humidity of the mold. (Figure 7) This method uses a special digital sensor that is embedded in the wax pattern. The sensor is enclosed in a cap with one end protected by a waterproof, breathable fabric which allows the vapor to come in contact with the sensor.[8]

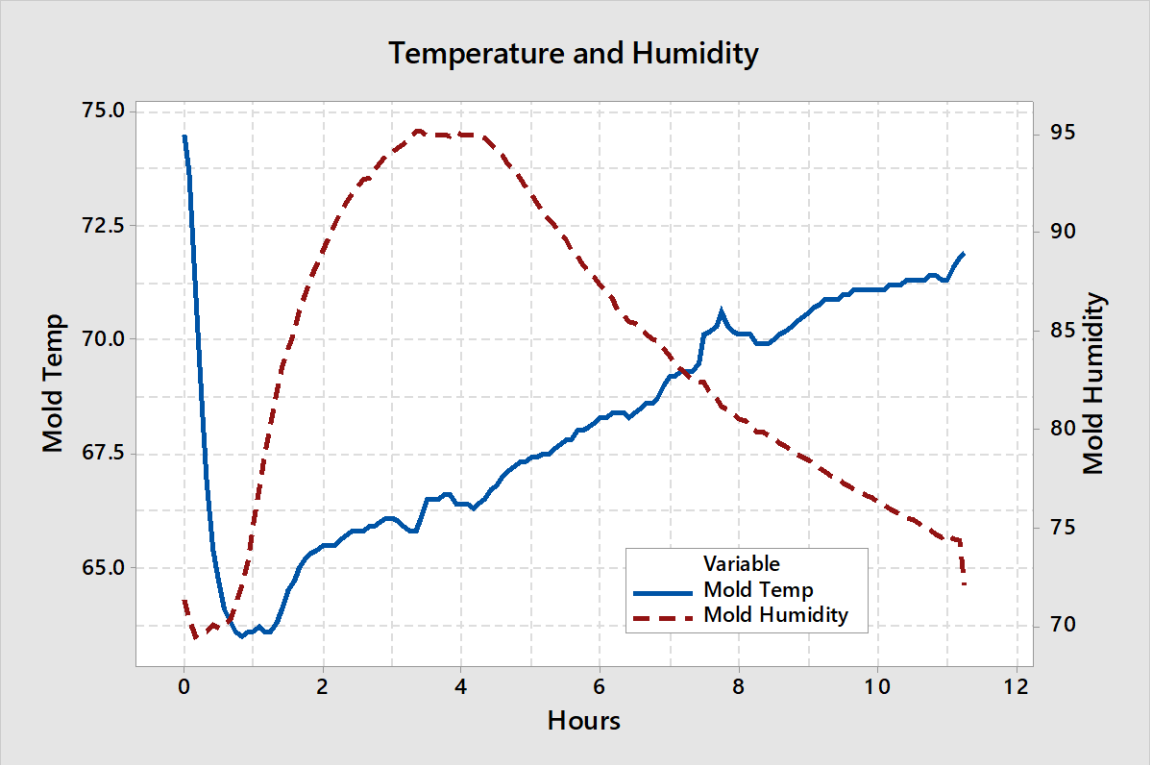

Figure 7. Temperature and humidity of a mold during drying

Dryness Indicators

Dryness indicating dyes have been used in investment casting slurries for many years. These dyes change color from yellow-green to orange-yellow with approximately 17% water remaining[3]. It may be difficult to detect the color change on some refractory systems.

Theories on Mold Strength Improvement through Moisture Removal

Why should drying each layer beyond the binder gel point increase the strength of the mold? It is believed that moisture removal between layers affects mold strength in two different ways: ceramic shrinkage and binder re-wetting.

Ceramic Shrinkage

Immediately after the application of a layer, the ceramic particles in the slurry are separated by the binder solution. As water is evaporated, the amount of liquid separating the ceramic particles is reduced, causing the slurry layer to shrink. Shrinkage of the slurry layer will continue until the ceramic particles come in contact with one another. The point where ceramic shrinkage is complete is known as the critical moisture content. Jackson showed the critical moisture content to be approximately 30% volume percent of remaining water.[2]

Depending on the refractory system, binder size and binder concentration, complete ceramic shrinkage might require additional water removal beyond that necessary for colloidal silica gelling. It is believed the application of shell layers prior to complete ceramic shrinkage will produce a weak, low density mold.

Jackson demonstrated two distinct stages of drying: the constant rate stage and the falling rate stage. In the constant rate stage the water evaporation rate is uniform and the slurry layer continues to shrink. Upon reaching the critical moisture content, slurry shrinkage is complete and the falling rate stage of drying begins[2]. The falling rate stage is characterized by an ever decreasing evaporation rate.

The actual percentage of water that needs to be removed to insure complete ceramic shrinkage is dependent on the slurry refractory particle size distribution and binder system. It is believed that, at a minimum, molds must be allowed to dry beyond the constant rate stage but this is only speculation. (Figure 8) Hopefully, MOR bar testing will provide additional insight on the relationship between the drying stages and strength.

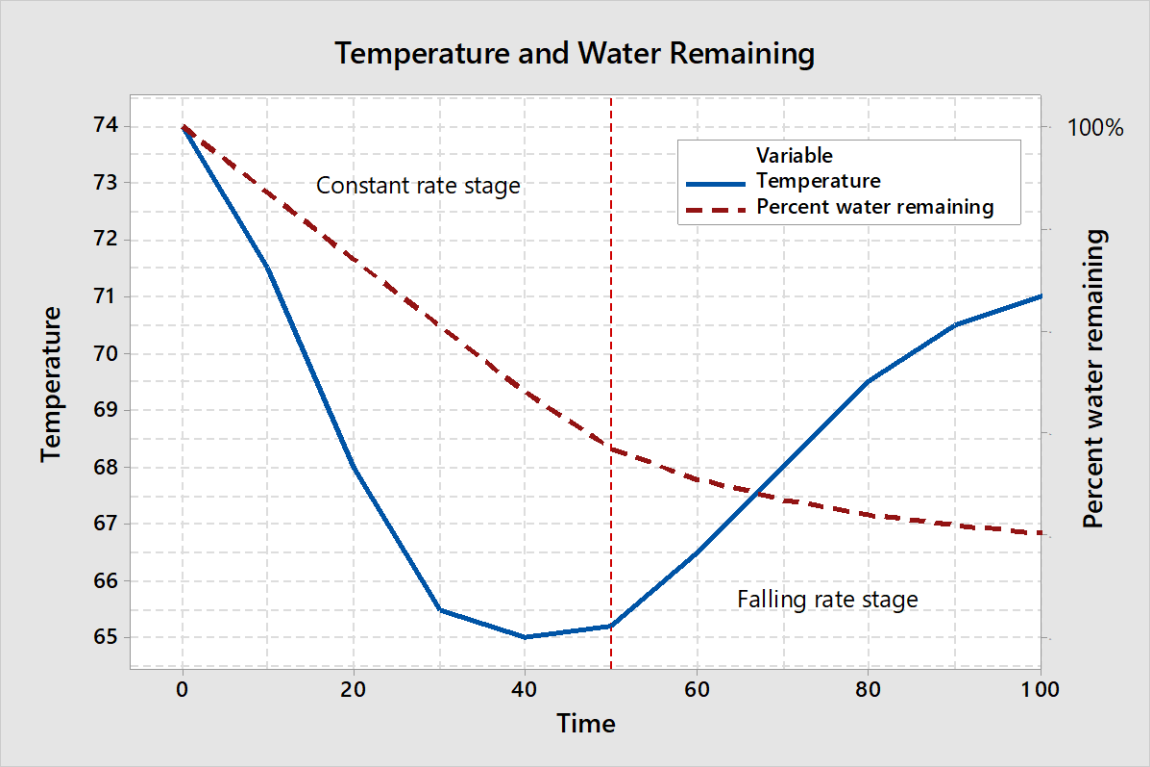

Figure 8. Expected relationship between mold temperature and stages of drying

Binder Re-wetting

There is a great deal of anecdotal evidence pointing to binder re-wetting as another reason for the strength improvement. The theory is that each layer deposits additional binder in the voids of the previous layers and the amount of strength improvement is directly related to the amount of re-wetting that occurs.

In order for the binder to wet previous shell layers, the pores must be open and free from water. Therefore, strength improvement is directly related to pore space available for re-wetting and the ability of the binder to wet these open pores.

Studies Supporting the Re-wetting Theory

Jackson stated "On subsequent redip, moisture is free to soak into the partially dried coats." In the discussion following the paper, J. Hockin from Electronicast asserted that "the increased strength is due to more drying between coats. Back penetration of the binder is important."

Leyland speculated "The main limitation to efficient drying is due to soak back of water from slurry re-wetting the shell mould during dipping…. The study highlighted that water would re-wet the last 4 coats applied to the shell mould due to soak back."

Snow demonstrated that "Immersion time in the slurry can affect soak-back and hence drying." His work showed a 7 layer mold immersed for 40 seconds took 138% longer to dry than one immersed for 10 seconds.[3]

Snow presented data showing the difference in dry time as effected by use of wetting agent. The use of wetting agent in backup slurries increased the dry time by 158% compared to one without a wetting agent.[3]

Additional insight can be gathered from United States Patent 5,927,379, *Infiltration Method for Producing Shells Useful for Investing Casting* by Yasrebi et al. This patent demonstrated a method of infiltrating a mold with colloidal silica binder after the shell was complete. In their work they showed the degree of binder infiltration was dependent on time in binder, pressure, flour particle size, binder particle size, shell porosity, thickness of the refractory layers and thickness of the entire shell. They showed the ability to triple the green strength of a mold using the infiltration process.

It appears that if the binder can wick into previously dried shell layers, there will be some degree of strengthening that will occur. But even if we remove all of the water from each layer, the binder may not wet all of the open pores.

It should be noted that these two concepts are ***still only theories*** as to the reason the strength improves with additional moisture removal.

TESTING METHODOLOGY

Okhuysen said *"*Many studies have been performed where the strength dependence of the mold material has been linked with the amount of drying of the shell material. Unfortunately these studies measured moisture content indirectly… thus a correlation between the actual moisture content in the shell and its strength should be developed." [6]

In order to construct the relationship between degree of dryness and mold properties, the test had to produce specimens at many different dryness levels. In addition, testing had to relate the dryness measurement method to the percent water remaining. The dryness measurement method used in this test was recovery temperature. Percent water remaining was obtained by back-calculation.

Test Layout

- A total of 6 MOR bars and 4 cone molds were produced for each level of dryness. An embedded thermocouple was attached to one of the specimens for each drying condition.
- The specimens were re-dipped when the embedded thermocouple reached the required recovery temperature.
- The samples were weighed three times each layer, after slurry, after stucco and after drying.
- Upon the completion, the samples were dried for a minimum of 24 hours prior to green strength testing.
- Cone molds were dried for a minimum of 24 hours prior to autoclave dewaxing. The cone molds were evaluated for cracks after dewaxing and after firing.

RESULTS

Testing was not complete at the time of paper submission. The results will be presented at the 2018 Investment Casting Institute Technical Meeting.

DISCUSSION

Adequate intercoat drying is a critical step in producing consistently good molds. Incomplete mold drying can contribute to dewax cracking, metal leakage during pour and dimensional variation. Excessive drying may limit the capacity of the shell room.

This paper showed various methods for measuring mold dryness and one approach for relating degree of dryness to mold properties. By using this technique, any shell specialist will be able to scientifically determine the ideal dry time for their shell system and drying environment.

REFERENCES

1. J. Jackson, 'Drying Ceramic Shell Molds', 25th Annual Meeting of the Investment Casting Institute, 1977, paper 8
2. J. Jackson, 'The Role of Drying in Shell Mold Preparation and Dewaxing', 28th Annual Meeting of the Investment Casting Institute, 1980, paper 12
3. J. Snow, D. Scott, 'Shell Drying – Water Based' 46th Annual Technical Meeting of the Investment Casting Institute, 1998, paper 8
4. J. Jackson, 'Ceramic Process Control Through Design of Experiment', 41st Annual Technical Meeting of the Investment Casting Institute, 1993 paper 5
5. M. Guerra, 'Effect of Binder Selection on Drying of Recessed Areas in a Shell Mold', 57th Annual Meeting of the Investment Casting Institute, 2010, paper 15
6. V. Okhuysen, 'Investment Casting Shell Mold Drying Model', AFS Transactions 2004, paper 04-137.
7. M. Guerra, 'Fast Processing Water Based Binder System', United States Patent 5,629,369.
8. J. Markee, I. Nassar, 'Utilizing Modern Technology to Optimize Shell Drying' 60th Annual Technical Conference of the Investment Casting Institute, 2013
9. M. Yasrebi, D. Sturgis, W. Kemp, M. Springgate, D. Nickolas, 'Infiltration Method for Producing Shells Useful for Investment Casting', United States Patent 5,927,379.
10. J. Wright, J. Jackson, 'Shell Improvement with Wide Distribution Slurries'", 45th Annual Technical Meeting of the Investment Casting Institute, 1997, paper 13.
11. Dalgetty, B. Mills, 'The Effect of Drying Times on the Strength of Investment Shell Molds,' 11th Annual B.I.C.T.A. Conference, 1971
12. G. Halsey, 'Some Factors Influencing the Dewaxing of Ceramic Shell Molds', 10th Annual B.I.C.T.A. Conference, 1970
13. S. Leyland, Ian Smith, 'Implementation of a Water Based Shell Mould Investment Casting Process', 9th World Conference of Investment Casting, San Francisco, 1996