Transforming the Fused Silica Shell System at Texas Precision Metalcraft & Tech Cast LLC with the 3M™ Fused Silica Rapid Cast System

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1.0 ABSTRACT

The investment casting industry has shown tremendous advancements in improved materials, processes and improved castings over the decades. Mid twentieth century refractory use after World War II was focused upon alumino silicates and zircon, with eventual incorporation of fused silica for improved dimensional control and improved shell knockout. Fused silica distributions were next widened with improvements in slurry flow and shell building. In the twenty first century fused silica slurries further incorporated additives for strength, edge building and small reduction in the numbers of required applied dips. Perhaps like most industries, investment casting professionals benefit from the advancements of those who pioneered before us and reach further for additional advancements in both slurry and shell properties. Today, the industry has a number of quite excellent slurry systems to choose for their shell building.

The team at 3M has introduced a new somewhat revolutionary slurry system that will offer a great leap forward in improving how foundries build better investment casting shells.

This new slurry system is equally adept at thin shell build while also building thickness and strength. This is due to a new application of thixotropy to investment casting slurries. A second benefit of this system is the reduced need for constant attention to liquid level adjustments. A third and often overlooked benefit is a dramatic improvement in shell knockout, greatly reducing and often eliminating the need for caustic cleaning.

3M has been working with both Tech Cast, LLC and Texas Precision Metalcraft (TPM) during the development of the new slurry system. Throughout the development cycle a number of changes, enhancements and controls were established. TPM and Tech Cast ran numerous head to head trials each against a different, well known and excellent performing baseline slurry system. TPM introduced the new slurry system to full production in their hand dip line in March. TPM has experienced a reduction of backup dips and improvement

in shell throughput time across all parts. TPM has also reduced knockout time, rough clean blast time, and has fewer parts that require caustic cleaning.

2.0 BACKGROUND

Before we define thixotropy, one must consider a pseudo plastic fluid. A pseudo plastic fluid is similar in that it acts less viscous with applied shear, but here there is no time dependency. The reader will immediately identify with common brands of tomato ketchup which do not flow well when simply inverted over one's "French fries". A degree of shaking is required to induce sufficient shear to get the ketchup to flow out.

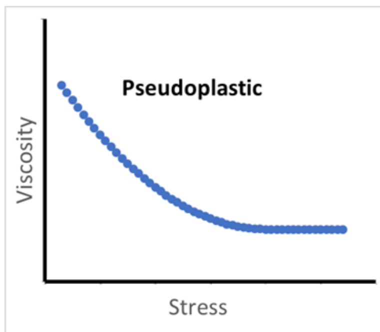

Fig. 1. Pseudo plastic Fluid Performance

Thixotropy adds one additional variable, that of time. The Oxford dictionary describes this as the property of becoming less viscous when subjected to an applied stress and is a function of time as well. This is shown for example by some gels which become temporarily fluid when shaken or stirred. For this reason, a thixotropic slurry is pseudo plastic as well. Fig. 2 below shows what a thixotropic fluid might look like.

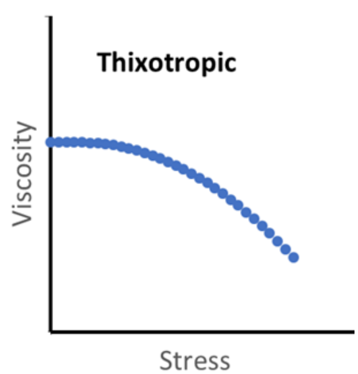

Fig. 2. Thixotropic Fluid Performance

Typical investment casting slurries are much more "Newtonian" in flow. This means that the slurry's viscosity will remain constant regardless of the amount of shear applied. These fluids have a linear relationship between the applied shear stress and the measured viscosity. Now, few fluids are truly Newtonian, including investment casting slurries; however, this description applies fairly well to typical foundry slurries.

Midway has been investigating rheological additives for years when one day a few years ago, during testing of one slurry blend, an unexpectedly thick slurry appeared to result. At first the slurry appeared unusable. However, with some experimentation it was discovered that when a wax pattern was submerged and slowly removed, a very thick and relatively uniform slurry layer resulted. With some experimentation it was discovered that the dual nature of this slurry could be quite advantageous providing both thick slurry coverage while also providing the ability to cover pattern detail. This dual nature was seen to occur with the application and removal of shear stress. The thixotropic precision investment casting slurry was born!

As the reader has likely already wondered, "how does one measure/ control viscosity of a thixotropic slurry?" The lab at Midway measures this with a digital Brookfield Viscometer; however, very few foundries have this type of relatively expensive equipment. The norm for investment casting slurries has always been Zahn or ISO dip cups. These of course will not work at all with thixotropic slurries. As a result, a new method of measuring and controlling solids content and flow of these slurries was required. A simple agricultural plastic 50 ml syringe is used to take up approximately 50 ml of slurry. The syringe is inverted with open tip up and tapped to allow any bubbles to move to the tip. Once the bubbles are located there, the plunger is depressed to push out the bubbles and reduce the slurry volume to 30 ml. The syringe is then placed 2" above a concentric circle 'target' pattern (Fig. 3) and the slurry is pushed out smoothly and somewhat rapidly to form a uniform diameter of slurry. The operator then waits 30 seconds for the gel structure to re-form in the slurry and the flow to slow. The diameter of the slurry is then recorded. This is the variable that is controlled.

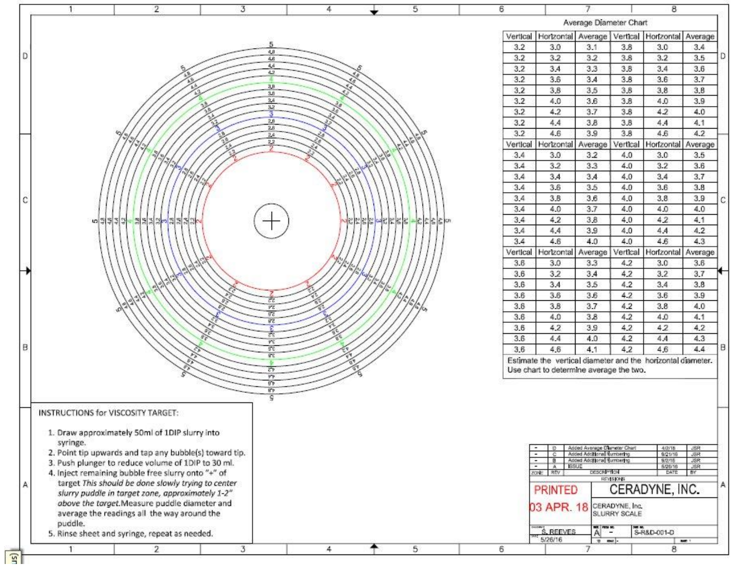

Fig. 3. Target Viscosity Tool.

The flow of the 30 ml of slurry was altered with gradual additions of colloidal silica to 'thin' the slurry as a foundry would to adjust their slurry viscosity. A reasonable linear relationship between slurry density (e.g. solids content) and slurry diameter was realized as seen below in Fig. 4.

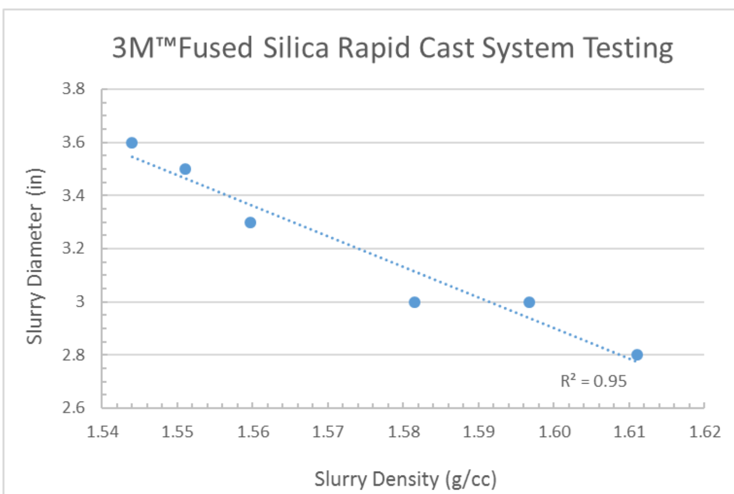

Fig. 4. Slurry Control Relationship

This seems to be a crude method to control the slurry performance. However, this has proven to be a simple, rapid and very inexpensive method to for viscosity control. It does not require any more time that a standard dip cup method. Operators have commented they prefer it over the dip cup method used on normal investment casting slurries.

3.0 THE TPM EXPERIENCE

TPM has been using basically the same fused silica-based shell system for 8+ years. We evolved from a 'non-engineered' system to try various 'engineered systems' and settled on a relatively low zircon prime with a fiber enhanced backup system. Over that 8 years span we have constantly tweaked our formulas to make incremental improvements and test various theories. We were 100% hand dip and we had a very good shell process.

For reference TPM is a commercial job shop with parts ranging from a couple ounces to about 40 pounds. Our trees range from 1/tree setups to 250+/tree setups and average 35-75 pounds pour weight in just about any air melt ferrous alloy, and several copper-based alloys.

The baseline dipping process was:
Prime – low zircon (~35%) / FS slurry and zircon sand
Intermediate – low zircon/FS slurry and 50/100 sand
B/U 1 – fiber-based slurry and 30/50 sand
B/U 2 – fiber-based slurry and 30/50 sand
B/U 3 – fiber-based slurry and 30/50 sand
Seal – fiber-based slurry

About 60% of our product uses the above dip process and 30% uses one less B/U. <10% were special parts (prototypes, especially large parts) that got an odd ball dip procedure.

This produces a very robust shell. When combined with our engineered 100% virgin wax we experience no shell cracking and no leakers. Almost no one at TPM knows what a shell crack looks like.

Yet we still entertained testing a new shell – more on why later.

Before moving forward, it needs to be made clear that TPM Co-Author, Jeff Crape, did the lion's share of the work during the 18+ months that we worked on this slurry development. Jeff is our plant manager and has both theoretical and hands-on skills that make him about the ideal person to run a dip trial.

We were approached in Nov 2016 about running some tests on a new back up slurry that had shown promising lab results but need to be tested in a production environment. We agreed to run some shells and help evaluate the results. Materials were delivered December of 2016 and we started making mixes.

The original theory was this slurry would allow us to have a single back up dip on most (maybe even all) of the parts we make. We agreed to run 2 trees from most production orders in the new slurry. Comparative weights were recorded for every dip before slurry (dry shell), after slurry (before sand) and after sand. We wanted to evaluate wet and dry component weights.

There were issues with the product at the high initially viscosity that we tried (2.8 on the disc chart). We noticed some non-wetting of previous dips which resulted in some air bubbles and poor adhesion. We tried to pre-wet but this was not very successful either. After lots of trial and error testing we eventually reduced the viscosity to 3.5 on the disc chart. At this viscosity we were able to pre-wet successfully, when we thought it was needed based on part geometry.

It needs to be noted that standard hand dipping practices that our team used which were well suited for standard slurries were not the same for the new slurry. The wetting and draining were different and required some different techniques than normal. This required some work with operators to be sure they did not just dip by muscle memory.

These initial single back-up shells were holding up after flash fire and then as we poured. However, the shells looked very thin and it was nerve wracking to watch a heat as you just knew a shell was going to burst open – but they did not. Still we decided this was too thin and we needed a thicker shell to be more robust. It was at this time that we decided the single b/u dip was too aggressive. We decided we would focus on reducing the number of dips from three to two back-ups and seal.

It should be noted that this new slurry was expected to have no settling affects so it did not require constant agitation in the tank. However, our rotating tanks were set to always rotate. So, we were in constant mixing mode. At about this time had a serendipitous discovery.

We had just dipped a shell and weighed it. We then stopped the rotation of the slurry tank and dipped the next tree and weighed it. Tree #2 was a full pound heavier after just 1-2 minutes of no rotation. We tried to dip another tree and another and another and the weight stayed consistent with the rotation off for the rest of the shift. Going forward we determined to rotate the tanks overnight and turn them off at the start of first shift and not rotate all day. With the non-rotating slurry pot, the shell thicknesses increased.

We continued to weigh three shells (as described previously) from the fiber-based control trees and the from the new slurry trees. The weights were statistically close enough in our minds to decide the two systems yielded a very similar shell weight.

In March we decided to go all in and dip all production from the new slurry. Note that during this time we did always run one tree in the fiber-based slurry as a control for comparison.

As of the end of July, our findings were as follows:

- Trees Processed - 4000+ trees in our highly variable product mix successfully dipped and poured.
- Reduced one out of three standard back-up dips (from 3 to 2) on 60% of our product.
- Throughput time in the shell department was decreased by a full day.
- Faster shell knockout (varied by part but averaged about half the time).
- Shells knocked out cleaner resulting in less time in blasting (about 20% on average).
- Need for caustic cleaning was greatly reduced if not eliminated.
- Slurry viscosity held constant all day without adjustments.

This last point needs clarification. We found that when we verified the viscosity in the morning we could dip all day, without the need for frequent liquid additions and monitoring. We confirmed the viscosity on the target ring chart, and just dipped all day. After a weekend we might have to add a little water to adjust for evaporation.

In June, TPM had our new robotic dip cell installed. We decided to try and transfer the new slurry to the dip cell knowing we might have some challenges as we were going from fluidized beds in hand dip to rainfall in robotic dip and our shells would get thinner again. With the learning curve associated with robotic dipping, creating programs, determining dry times, and adjusting to rainfall sanding; the added variables of the new slurry were more than we wanted to tackle at the time. So, we have switched back to the fiber-based slurry for robotic dipping which will allow us to get all the bugs worked out on operating our new system. first. After initial draining the coating was uniform. However, our base program used quick motions throughout the stucco application. This caused the slurry to shear-thin again which reactivated the draining. Best advice here is for smooth and fluid motions to minimize the induced shear. These movements would have only one up and one down angled motion. We also learned that some of the best results were achieved when the slurry tank rotation slowed and then stopped for about a minute before the cluster of trees was introduced.

Our future plans are to eventually move all parts to robotic dipping and become excellent at this. Then we will re-look at the new slurry when we can focus on a single variable at a time.

As you recall we had a very good and robust shell system as baseline, yet we went into what was about a year and a half of testing of the new slurry. We think that it is important for foundries to team up with our suppliers and do the work and spend the time and energy etc. to test new ideas. We never know when this new idea will be a big game changer. Foundries cannot sit back and expect our suppliers to come up with these new innovations and perfect them in a lab, we have to step up and be a part of the solutions and do our part to succeed and sometimes fail in order to advance our process and our industry. We had great success in hand dip and our entire team was educated and become better at what we do and became more in tune with the nuances of how our dipping could improve. I do not doubt that some months from now we will be back in saddle to figure out if the new slurry is the right answer for TPM in robotic dipping and we will put in the due diligence to try and make it happen.

4.0 THE TECH CAST EXPERIENCE

Tech Cast, LLC has been using an engineered, fused silica, shell system for 20+ years and a large particle colloidal silica binder for the same time span. About 8 years ago, Tech Cast started using the 3M™ Fused Silica Advanced Shell System WDS3 shell system with a high zircon prime all applied by robot. Tech Cast is a commercial job shop with a large range of capability. Castings made at Tech Cast range from weighing a few ounces to upwards of 500 pounds at the largest. The average pour weight experienced is between 100 and 150 pounds in a diverse range of alloys including duplex and super duplex stainless steels.

The shell building/dipping process ranges based on the final pour weight of the mold. Each part has its own unique shell building recipe. Typically, a mold receives the following coats:

Prime	– zircon/low fused silica slurry with zircon sand
Intermediate	– 3M™ Fused Silica Advance Shell System WDS3 with fused silica stucco (50x100)
Backup	– WDS3 with fused silica stucco (30x50)
	– Number of backup coats applied dependent on a casting’s size and shape.
Seal	– WDS3

Approximately 60% of all jobs have under 6 backup coats applied with the remaining 40% receiving 6 or more backup coats. The expectancy of 1 coat of the new slurry (made with 3M™ Fused Silica Rapid Cast Flour and 3M™ Rapid Cast Accelerator) being equivalent to 2 coats of our baseline WDS3 drove the desire to test this system. It was expected that this system would reduce lead times across the board, but be especially beneficial for the larger parts. All jobs go through an autoclave dewaxing process following shell building.

The testing at Tech Cast was broken into 3 phases. Phase 1 consisted of hand dipping several parts with complex geometries to prove the system was a viable option to be incorporated into the robot line. With the success of Phase 1, Phase 2 was setup to evaluate and improve the robot dipping sequence. Phase 3 was a production heavy stage setup to test the slurry’s longevity and approximate the turnover rate for mixing.

To complete Phases 2 and 3, Tech Cast converted the seal dip rotating tank for the rapid cast slurry. The transition required writing new sequence programming for the robots to properly dip, coat, and drain molds in this tank and move on to the stucco application sequences.

During Phase 2, for each tree run through the slurry, Tech Cast either ran a side by side shell building comparison to current processing or used recent data collected from previous parts to verify the new shell before dewaxing. Shell weight comparisons showed that the new system's shells were heavier than ones built under current conditions. The 3M™ Fused Silica Rapid Cast System also built a less consistent shell thickness from the top to the bottom of the molds. There was also an initial period where the slurry would continue to drain after stucco application leaving the molds with an unusual appearance.

From this data, the draining and stucco application techniques were revised. Longer up draining resulted in a more uniform shell thickness from top to bottom. The post-stucco application draining was something not experienced with 3M™ Fused Silica Advanced Shell System WDS3, so it took some tweaking to alleviate. Modifications were made to the programming of the stucco application sequencing within the robot program used for dipping. With the draining and stucco application sequences revised, molds were more uniform from top to bottom, and the post stucco application draining problem was eliminated.

All jobs run through rapid cast were given unique recipes based on their current recipes. In fact, half of the total number of backups were applied. For example, if a WDS3 recipe called for 8 backup coats, 4 backup coats of rapid cast were applied. If the recipe called for an odd number of backup coats, the number of coats in rapid cast was rounded up (five baseline coats of WDS3 became three coats in rapid cast). Seal coats were applied in each respective tank, so if the job was going through the WDS3 recipe, it was sealed in the WDS3 tank, and the inverse was true for rapid cast.

Phase 2 of testing yielded the plot shown in Figure 5 below which summarizes collected shell weights for both WDS3 (blue/left) and rapid cast (orange/right). There was some variation in the shell weights attributed to the process of refining the application and draining of the slurry and the application of stucco. Weight differences between the WDS3 and rapid cast shells was minimized through further process refinement. In most cases, no significant weight savings were observed when using the rapid cast shell system.

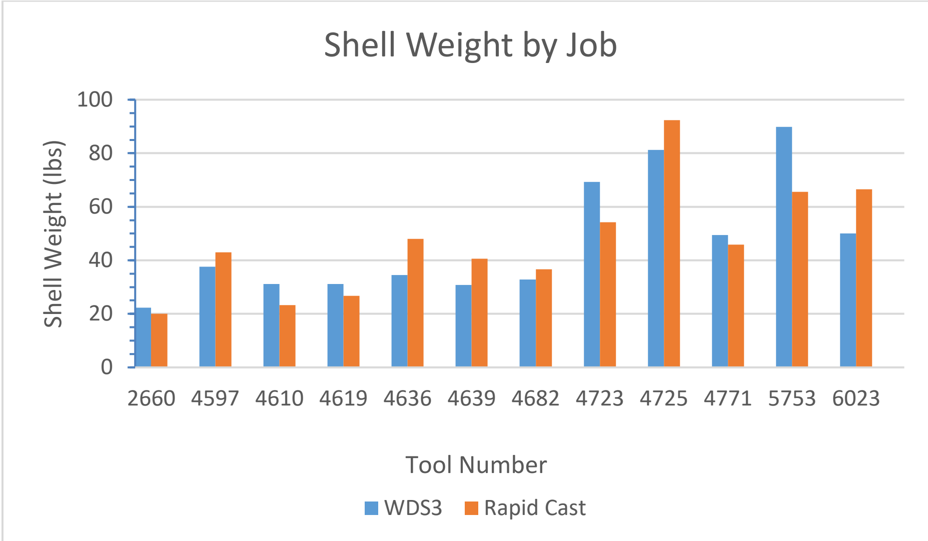

Fig. 5. Shell Weight Comparison (3M™ Fused Silica Advanced Shell System WDS3 vs. 3M™ Fused Silica Rapid Cast System)

Mold geometry and surface area were likely factors on how each mold is affected by the rapid cast shell system. Figure 6 below shows the distribution of the shell weight increase per backup layer applied. It is broken down by the number of equivalent WDS3 backup coats applied to the job. On average, an increase of 83% was observed. In some cases, increases of 100% or more were observed validating the approximate "2 to 1" shell system. Through further draining and stucco application refinement, it is believed the weight per layer increase average would be brought from 83% to 100%.

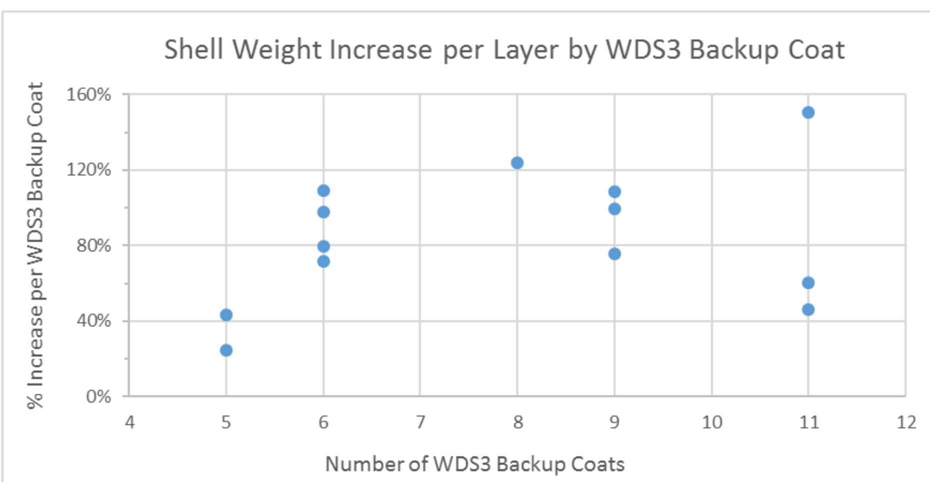

Fig. 6: Weight Increase per Coat

During Phase 2, mold dryness studies were completed to ensure each mold was dry before applying another coat. From experience, Tech Cast knew a wet shell typically leads to a thinner final shell. Rapid Cast dry times were collected using a J&J Mold Dryness Indicator (from J&J Electronics). Overall dry time for the 3M™ Fused Silica Rapid Cast System was longer than that of the 3M™ Fused Silica Advanced Shell System WDS3, but this was an expected outcome due to the per layer weight increase that can be directly correlated to an increase in per layer thickness applied. It appeared there was less soak back with the new slurry. While this phenomenon was not fully understood, it suggested the dry times for rapid cast could be standardized with less concern for geometrical and size differences between jobs.

From the results of Phase 2, Tech Cast went right into Phase 3, which was an extended robot test. The extended robot test meant approximately 20% of all production currently moving through the facility was slated to use the new slurry system. During Phase 3, all expedite orders and rapid prototype orders were run through the rapid cast shell system.

Phase 3 showed the capacity and lead time potential that rapid cast provided. Of course, capacity potential increases with the reduction of lead time per mold in the shell room. Lead time is defined as the time from the application of the first backup coat to the application of the seal coat. Figure 7 below shows the reduction in theoretical lead time per the number of equivalent WDS3 coats. Theoretical values were based on the assumption that jobs receive each coat as specified by the shell building sequence recipe. For example, if a recipe calls out four WDS3 backup coats with an eight-hour dry time per coat, the theoretical lead time value for this job is 32 hours (4 coats x 8 hours/coat). A positive value in Figure 7 refers to a decrease in the theoretical lead time for shell building if the job were to be switched from WDS3 to rapid cast. On average, a 15.7% reduction in theoretical lead time was observed when rapid cast recipes were created and compared to the original WDS3 recipes.

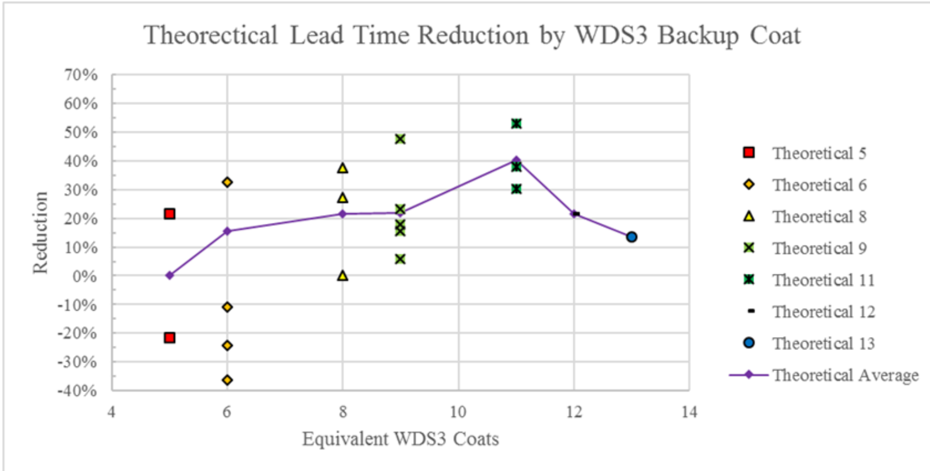

Fig. 7. Theoretical Lead Time Reduction between 3M™ Fused Silica Advanced Shell System WDS3 and 3M™ Fused Silica Rapid Cast System.

The theoretical values are unrealistic in a real-world application as the dry times do not account for system down time, system inefficiencies, and conveyor travel time. To take into account all possible variables related to lead time, data was collected from the robots in the form of time stamped data points representing the exact moment a job received each backup coat. The time stamped data was collected for all rapid cast jobs as well as their WDS3 equivalents. Figure 8 shows the observed lead time reduction for each job. A 28.4% reduction in actual lead time was observed when jobs were run through the rapid cast system slurry versus the WDS3 slurry. The 28.4% was the overall average reduction in lead time across all jobs run through rapid cast.

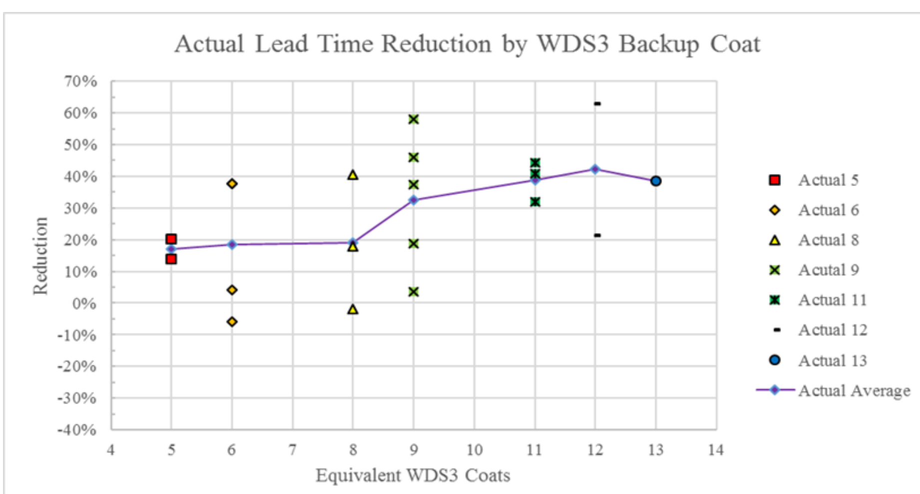

Fig. 8. Observed Lead Time Reduction by Equivalent WDS3 Backup Coats

Figure 9 shows the comparison of average theoretical to average actual lead time reduction with trend lines applied to each data set. From all lead time data, a trend emerged showing lead time reduction increased as the equivalent number of 3M™ Fused Silica Advanced Shell System WDS3 backup coats increased. This means the more coats a job receives; the lead time reduction will be more significant when the job is completed using the 3M™ Fused Silica Rapid Cast System shell.

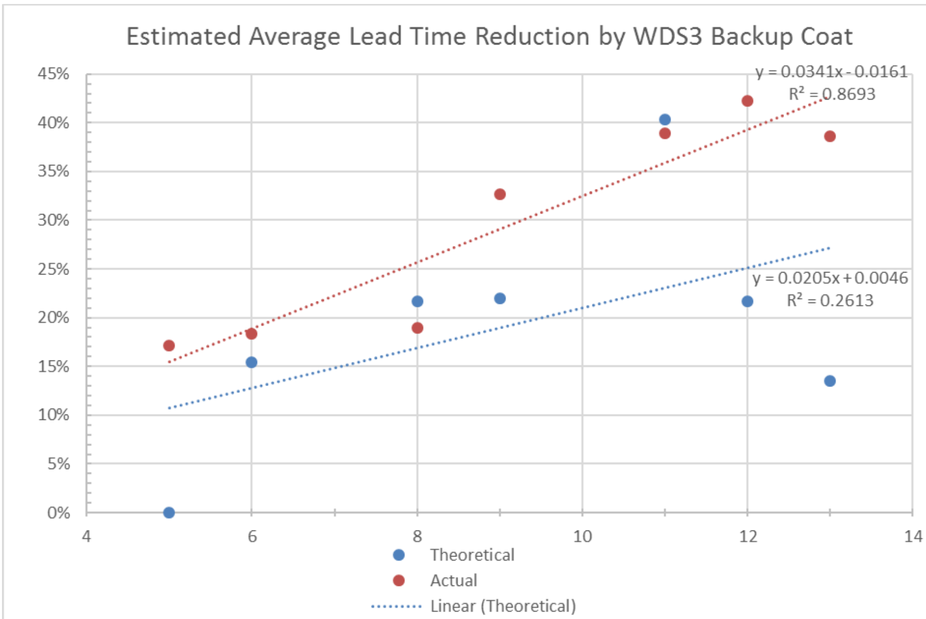

Fig. 9. Average Lead Time Reduction by Equivalent WDS3 Backup

By the end of Phase 3, Tech Cast was able to make the following observations:

- Approximately 200 trees were processed focusing on the larger molds and all showed at least 30% reduction in lead time through the shell room.
- There was an increase in need for cleaning of the fluidized stucco bed.
- Rapid Cast seal coats acted as both an equivalent WDS3 coat and traditional seal coat.
- Stucco embedded into the rapid cast slurry. This reduced the amount of stucco that could be brushed off of a dry mold compared to WDS3.
- Reduced soak back lead to more predictable and uniform dry times.

With 3M™ Fused Silica Advanced Shell SystemWDS3, the stucco bed required cleaning once a week. The slurry made with 3M™ Fused Silica Rapid Cast Flour and 3M™ Rapid Cast

Accelerator tended to have more carry over into the stucco bed which resulted in more nuggets accumulating at the bottom of the bed. Cleaning was done 3 to 5 times per week during Phase 3 to ensure parts were not broken in the fluidized stucco bed due to the increase in nugget accumulation. This did inhibit production and increase robot down time, but the increased through put from the use of rapid cast accounted for the additional down time.

For Tech Cast, the rapid cast shell system is best used for large molds, complex geometries, and prototypes. Large molds are classified, in this case, as molds requiring eight or more backup coats. The large molds benefit most of the benefits of the rapid cast system. Standardized dry times reduce the likelihood of a mold needing to be skipped due to recipe dry times being longer than the time taken to complete on conveyor revolution. With larger molds, the “2 to 1” slurry replacement associated with rapid cast was more often observed than with smaller molds. Both the standardized dry times and the “2 to 1” shell build lead to a 30% or more reduction in lead time.

Geometrically complex parts, such as impellers and valve bodies, benefit most from the standardized dry times. Due to the internal geometries of these parts, dry times using the WDS3 system have been observed to be upwards of 24 hours. With the rapid cast system, soak back during dipping was observed to be minimal through the dry studies completed. Reduced soak back means each coat dries approximately the same amount of time. Lead times are more predictable, and jobs are less likely to be skipped due to extended dry times.

Prototype molds most benefit from the reduction of lead time. These molds typically require additional backup coats compared to molds of similar pour weights because of the nature of autoclaving the printed patterns. The extra backup coats greatly extend the lead time of the jobs through the shell room. With the rapid cast system, prototype molds have seen an average reduction of lead time of 30% with some showing a reduction of close to 50%.