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Judging the Effect of Penetration and Mil Thickness on Core Wash Performance in PUNB Steel Applications

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ABSTRACT

This study investigated the relationship between mil thickness, penetration, and wash performance in a high temperature, no-bake molding application with steel. It was found that the depth of wash penetration strongly correlates to the performance of the core wash. With a single coat of wash, mil thickness was proved to be inversely proportional to penetration and was found to correlate negatively to wash performance. A statistical discovery was made that wash penetration is a significant driving factor of wash performance when a single coat is applied. This research statistically defines how penetration and mil thickness are related to each other and how they affect wash performance. Findings made in this study may be utilized to eliminate the need for multiple coats of wash and to better determine the ideal wash Baumé or specific weight for different wash compositions.

Keywords: wash, penetration, mil thickness, application parameters, Baumé, phenolic urethane no-bake, PUNB, steel application

INTRODUCTION

Core wash is a very critical material to any no-bake foundry, but when it comes to steel, it becomes even more critical due to the high pour temperature of many steel alloys. Throughout the foundry industry, there are many different schools of thought in relation to core wash and what type of application method is the best. Among the most common methods, there is painting with a standard paintbrush or a handheld mop-like utensil, flow-coating, dipping, and spraying, among others. Whichever wash application method that is chosen, the main goal is for the wash to be applied onto the mold in a way that reduces the potential for defects related to adherent sand. There are other secondary goals such as: throughput improvement, cost reduction, etc. The performance of wash is largely based upon the composition of the wash, chemically and physically, as well as how it applies to the mold with which it interacts. The properties as to how the wash applies to the mold are known as the application parameters.

The application parameters that are typically studied are the depth of wash penetration and the wet mil thickness upon application. The mil thickness can be loosely defined as the amount of buildup of core wash on the surface of the mold. Mil thickness is typically checked using a card style measurement device, which is often distributed by major core wash producers. A common wet mil thickness test is AFS 4403-13-S as outlined in the AFS "Mold and Core Test Handbook."[2] Wet mil thickness is checked prior to drying of a water-based wash or ignition of a solvent-based wash. Penetration is the depth that the refractory from the core wash seeps into the mold or core. Penetration is normally checked after the wash has dried or flashed off by cutting a core or mold and analyzing it under a microscope to determine how deep the wash seeped into the core or mold. Application parameters have been a point of contention among metalcasters for a long-time, there are many different opinions as for which application parameter is more important or critical to quality. There has also been debate about which combination of application parameters is optimal for wash performance, whether it be less penetration, more mil thickness, vice versa, or high amounts of both.

The goal of this study is to definitively answer how wash application parameters relate to core wash performance in a high temperature, phenolic urethane no-bake (PUNB) steel application. Specifically, penetration and mil thickness were investigated individually to determine whether they have a significant difference on wash performance, and if that effect is positive or negative.

RELATED WORK

A large amount of research has been done over the years on core wash, and as such, there have been several large-scale studies conducted which encompassed the application parameters. In Research Report no. 112, the Steel Founders' Society of America (SFSA) reported that wet thickness control of the coating is critical in order to prevent drying cracks in the refractory. Drying cracks in the refractory allow for metal to penetrate underneath the layer of refractory, which can lead to adherent sand defects and other undesirable casting conditions.[1] Researchers at Western Michigan University (WMU) correlated the amount of coating solids to the thickness of the proud layer. Their research indicated that by doing a better job at controlling the coating solids, it may be possible to reduce variability in the thickness of the proud layer. It was also observed that the penetration of the coating into the sand was higher at a lower percentage of solids in the research conducted by WMU. This research established the link between the thickness of the coating mixture, the variability of the proud layer, and the penetration depth of the coating into the sand.[3]

METHODOLOGY

The study was conducted utilizing a custom-built, four impression test pattern that produces four test castings. The test casting is a 12 in. (30.5cm) diameter disc that is 3 in. (7.6cm) tall with four 2 in. (5cm) diameter pin cores in the middle of the cavity, it is extremely similar to a Gertzman test casting. Each impression has a 6 in. (15.2cm) diameter by 8 in. (20.3cm) tall exothermic round neckdown riser sleeve on it. Two molds were made for a total of eight test castings and 32 pin cores were made to fill those test molds. The layout of the test pattern is shown in Figure 1.

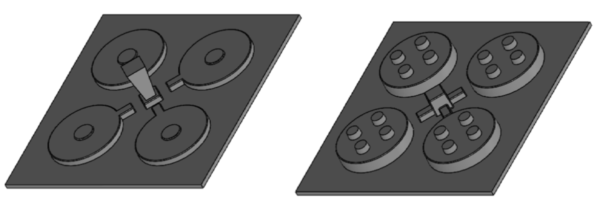

Figure 1. A CAD model showing the layout of the four-impression test pattern.

The molds and cores were made from 100% thermally reclaimed silica sand. The resin mixture for molds and cores was 1.2% resin, with 55% Part 1, 45% Part 2, and 3% Catalyst. The sand was tested to verify all parameters according to official procedures outlined in the "Mold and Core Test Handbook."[2] A sieve analysis conforming to AFS 1105-12-S, a Loss-on Ignition (LOI) test conforming to AFS 5100-12-S, and a Grain Fineness Number (GFN) test conforming to AFS 1106-12-S were performed.[2] The sand was determined to have a LOI of 1.16%, 0.03% fines present, and a GFN of 58.28 for the specific mixture used for the test.

Wash testing was conducted utilizing two different mold washes, both solvent-based, one containing an alumina-based refractory (Wash A) and one containing a zircon-based refractory (Wash Z). Both washes were run at varying densities which were measured with a Baumé stick, the test for measuring wash density conformed to AFS 4409-15-S, as outlined in Reference 2. Each wash was run at four different Baumé levels, 65be, 58be, 54be, and 50be. At each Baumé and with each wash, four pin cores were dipped into the wash, the wash on the cores was ignited, and then all four cores were placed into the same impression on the test mold. The Baumé and wash type of the cores was denoted in a table with a sample number and letter, which was also carved into the same mold cavity that those cores are in. This allowed the number and letter to be cast into the part, which allowed for traceability throughout the process. At each Baumé and with each wash, a dogbone style test coupon was dipped into the wash (Fig. 2). The wash on the test coupon was mil thickness tested in three locations.

Following the ignition and drying of the wash on the dogbone test coupon, it was placed into a zippered storage bag labeled with the corresponding sample letter and number of the wash that it was dipped in. Once the application was complete, the dogbones were cut in the thin section in the middle of the dogbone and checked for depth of penetration using a stereo microscope. The penetration data was obtained by counting the number of grains from the surface that refractory was found to cover.

Figure 2. The dog bone test coupons after dipping.

The two test molds were poured out of a single heat of stainless-steel conforming to ASTM grade HD at 2800F (1538C). The molds were poured through the downsprue and filled to the top of the riser. The castings were allowed to cool in the mold for a total of 16 hours and were then removed from the mold. Following shakeout, the castings were inspected for any undesirable defects that would compromise the test and it was determined the castings contained no such defects. The castings were all blasted in a single cycle, and the flashing was then removed. The cored holes were then studied and rated on a scale of one to five. Once the evaluation of the castings had concluded, an in-depth statistical analysis was conducted upon the application parameters and the casting scores to determine how each application parameter affected wash performance.

RESULTS

The sample marking scheme is shown in Table 1.

Table 1. Sample Key

Sample	Wash Type	Baumé
1A	Wash Z	65
1B	Wash A	65
1C	Wash Z	58
1D	Wash A	58
2A	Wash Z	54
2B	Wash A	54
2C	Wash Z	50
2D	Wash A	50

EFFECT OF BAUME AND WASH TYPE ON APPLICATION PARAMETERS

The data table containing the measurements of mil thickness is shown in Table 2.

Table 2. Mil Thickness Measurements

Wash Key	Mil Thickness (Mils)		
	Sample 1	Sample 2	Sample 3
1A	10	12	14
1B	6	6	6
1C	6	6	6
1D	7	6	6
2A	7	6	6
2B	5	5	6
2C	4	6	4
2D	6	4	4

The mil thickness appears to be, overall, very similar between the alumina-based wash and the zircon-based wash when tested at the same Baumé level, the only notable exception being Wash 1A being considerably thicker than Wash 1B. A two factor ANOVA with 0.05 level of significance and replication was conducted on the mil thickness of all of the samples. The goal of the analysis of variance was to determine if wash selection, Baumé, and both in conjunction with one another have a significant effect on the mil thickness observed.

The ANOVA indicated that there was a significant difference between Wash A and Wash Z, Wash Z having a higher amount of average mil thickness than Wash A with a P-Value of 0.0007. There was also a significant difference between Baumé levels, finding a P-Value of 8.16E-6 with the average mil thickness decreasing as the Baumé decreased. There was also a significant difference in terms of interaction between Baumé and wash type, having a P-Value of 0.00016.

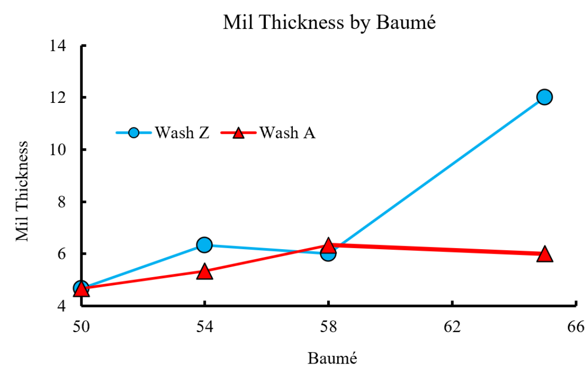

Figure 3. A graph showing the relationship between Baumé and mil thickness.

Penetration data was collected and tabulated as shown in Table 3.

Table 3. Penetration Measurements

Wash Key	Penetration (Grains)		
	Sample 1	Sample 2	Sample 3
1A	2	2	2
1B	3	2	2
1C	3	3	3
1D	4	2	3
2A	4	3	3
2B	3	4	4
2C	4	3	5
2D	3	4	5

From this data, a two-factor ANOVA with 0.05 level of significance and replication was conducted on the samples. The ANOVA for the penetration data showed that the type of wash did not have a significant effect on the level of penetration. The Baumé level did have a significant effect on the level of penetration, at a P-Value of 0.004. The interaction between Baumé and wash type did not have a significant effect on the amount of penetration.

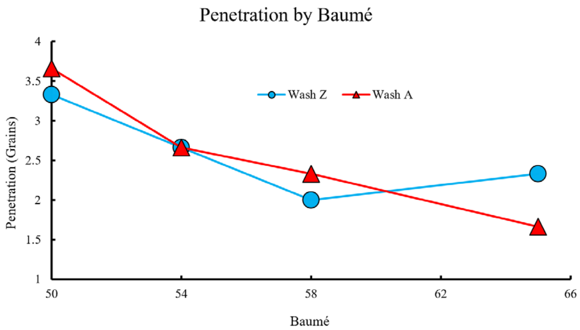

Figure 4. A graph showing the relationship between Baumé and penetration.

CASTING ANALYSIS

The castings were analyzed and numerically ranked according to the following scale. One denotes a casting surface with a large amount of adherent sand and a very poor surface finish, five denotes a casting that is almost spotless, with very little burn-in and a high-quality surface finish.

Beginning with Sample 1A, Wash Z at 65 Baumé, the casting showed a large number of drips and runs and undulations in the casting surface due to buildup of refractory from the mold wash (Fig. 5). There was also the presence of adherent sand in the sharp corners of the cavity, it was rated 2.

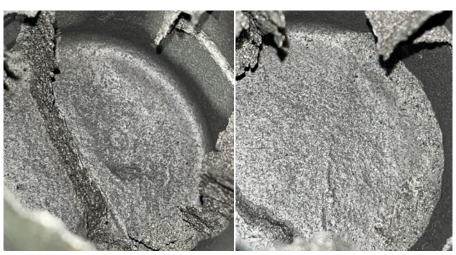

Figure 5. Sample 1A, Wash Z at 65 Baumé.

In Sample 1B, Wash A at 65 Baumé, there was a large presence of adherent sand in the sharp corners of the cavity, though no drips or runs were present (Fig. 6). The amount of sand in the areas containing adherent sand was significantly larger than what was seen in Wash Z, so it was rated 1.

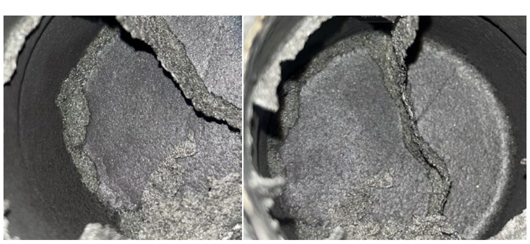

Figure 6. Sample 1B, Wash A at 65 Baumé.

In Sample 1C, Wash Z at 58 Baumé, there was little adherent sand remaining post blast, and some minor surface undulations (Fig. 7). This cavity was rated 3.

Figure 7. Sample 1C, Wash Z at 58 Baumé.

In Sample 1D, Wash A at 58 Baumé, there was little adherent sand remaining post blast and no presence of drips/runs in the cavity (Fig. 8). Wash A performed very similarly to Wash Z at this Baumé but with slightly better surface quality, so it was rated 4.

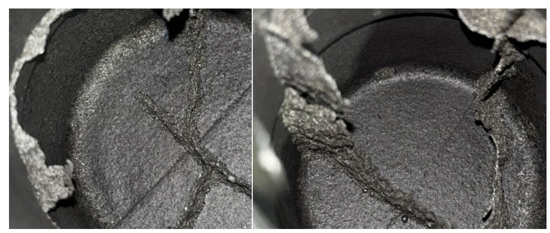

Figure 8. Sample 1D, Wash A at 58 Baumé.

In Sample 2A, Wash Z at 54 Baumé, there was a presence of adherent sand in the corners of the cavity and a grainy type of surface finish (Fig. 9). The cavity was rated 3.

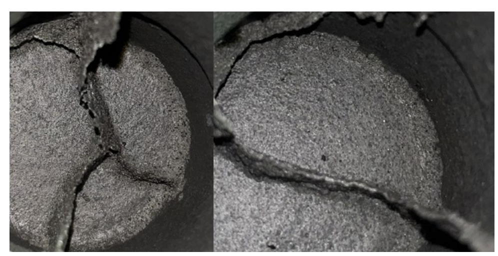

Figure 9. Sample 2A, Wash Z at 54 Baumé.

In Sample 2B, Wash A at 54 Baumé, there was almost no presence of adherent sand anywhere in the cavity, the areas were almost completely clean except for a few minor exceptions (Fig. 10). There were no drips or runs and the surface finish was very high quality. This cavity was rated 5.

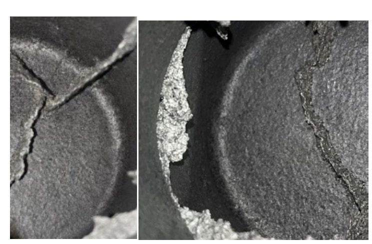

Figure 10. Sample 2B, Wash A at 54 Baumé.

In Sample 2C, Wash Z at 50 Baumé, there was some minor amount of adherent sand in the corners of the cavity, though far less than Wash Z at any other Baumé tested (Fig. 11). The surface finish was of high quality as well. This cavity was rated 5.

Figure 11. Sample 2C, Wash Z at 50 Baumé.

In Sample 2D, Wash A at 50 Baumé, there some adherent sand present in the corners of the cavity, however not a large amount (Fig. 12). The surface finish was poor, very grainy and contained some imperfections. This cavity was rated 3.

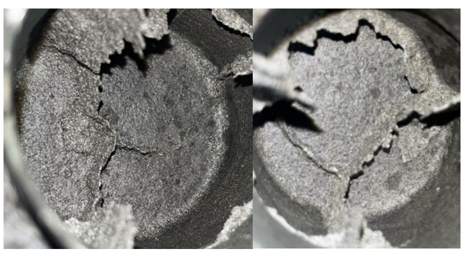

Figure 12. Sample 2D, Wash A at 50 Baumé.

Table 4. Summary of Properties and Score

Wash Key	Penetration	Mil Thickness	Casting Rating
1A	2	12	2
1B	2.33	6	1
1C	3	6	3
1D	3	6.33	4
2A	3.33	6.33	3
2B	3.66	5.33	5
2C	4	4.66	5
2D	4	4.66	3

In order to determine that there is a significant difference between Baumé levels, two ANOVAs at a 0.05 level of significance were conducted on the application parameters, one on the penetration and one on the mil thickness. The ANOVA on penetration found an F critical value of 2.65 and an actual F value of 3.23, meaning that the difference between Baumé levels is significant, and there is factor effect.

On mil thickness, the ANOVA generated an F critical value of 2.65 and an actual F value of 17.36, meaning that there was a significant difference between Baumé levels and a factor effect for mil thickness (Table 4).

A correlation analysis was conducted to correlate the application parameters to the casting score. Three separate correlation analyses were performed, the first one was on Wash Z only, the second one was on Wash A only, and the third one was on both washes together. The correlation analysis correlated penetration level, mil thickness, and the casting score. Wash Z showed a strong positive correlation of 0.927 between penetration and casting score, and a strong negative correlation of -0.809 between mil thickness and casting score. Wash Z also showed a strong negative correlation between penetration and mil thickness, with a value of -0.941. The correlation analysis for Wash A showed a strong correlation of 0.637 between casting score and penetration, and a mild negative correlation between wash score and mil thickness with a value of -0.155. Wash A also showed a strong negative correlation of -0.831 between penetration and mil thickness.

When both washes were analyzed together, there was a strong positive correlation of 0.747 between penetration and casting score, a negative correlation of -0.459 was found between mil thickness and casting score. Altogether, mil thickness and penetration had a negative correlation with a value of -0.789 (Table 5).

Table 5. Summary of Correlation Results

Wash Type	Correlation Between	Correlation Score
Wash Z	Penetration to Casting Score	0.927
Wash Z	Mil Thickness to Casting Score	-0.809
Wash Z	Penetration to Mil Thickness	-0.941
Wash A	Penetration to Casting Score	0.637
Wash A	Mil Thickness to Casting Score	-0.155
Wash A	Penetration to Mil Thickness	-0.831
Both	Penetration to Casting Score	0.747
Both	Mil Thickness to Casting Score	-0.459
Both	Penetration to Mil Thickness	-0.789

Linear regression was attempted in order to determine if it was possible to predict the casting score based upon the application parameters. All regression was completed with a 0.1 level of significance, due to the few number of data points. For mil thickness, the generated regression equation was as follows (Eqn. 1):

$$Score = 7.85 - 0.787(Mil\ Thickness) \qquad \text{Eqn. 1}$$

The R Squared value was 0.169 with an adjusted R Squared of 0.003, indicating a very poor fit. The P-value was 0.13 for the intercept and 0.36 for the regression, indicating that the regression was insignificant. The graph is shown in Fig. 13.

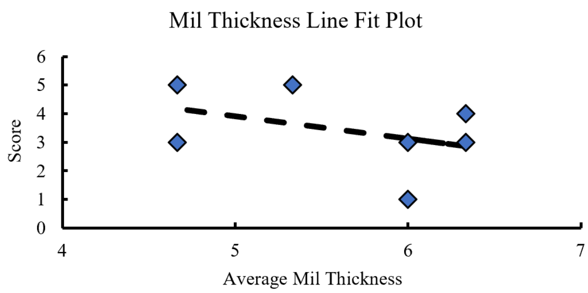

Figure 13. A line plot showing casting score as a function of mil thickness.

Linear regression for penetration generated an equation as follows (Eqn. 2):

$$Score = 1.65(Penetration) - 2.07 \qquad \text{Eqn. 2}$$

The R Squared value was 0.516 with an adjusted R Squared of 0.419, indicating an okay fit for the regression model. The P-value for the intercept was 0.43, and for the regression was 0.069. Indicating that the intercept was insignificant, however the regression was significant. The line plot is shown in Fig. 14.

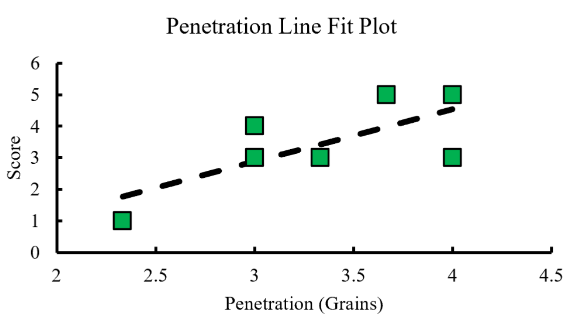

Figure 14. A line plot showing casting score as a function of wash penetration.

CONCLUSION AND DISCUSSION

Taking a deeper dive into the statistical analysis and looking at the results closely yields many significant findings in terms of how the application parameters of core wash influence its performance in the casting process.

Across all of the correlations, it is shown conclusively that penetration and the quality of the casting are heavily related in a positive manner. There is also indication that mil thickness and casting score are negatively correlated, particularly in Wash Z, however not as much in Wash A. This is likely due to Wash A having considerably less mil thickness than Wash Z at 65 Baumé, which may be skewing the results. An important consideration is that the correlation analysis showed mil thickness and penetration to negatively correlate, which implies that they are inversely proportional. This opens up the possibility that the mil thickness negatively correlates to the casting score due to the penetration being low at the given Baumé level.

The mil thickness regression is both an extremely poor fit and insignificant, which implies that mil thickness is not the driving factor of wash performance, whether the relationship between mil thickness and casting score be proportional or inversely proportional. However, the penetration regression was significant, and it was a good fit. The intercept was not a good fit, but that is likely due to the fact that it would cross the axis well outside of the range of Baumé levels tested in this experiment. The significance of penetration regression implies that penetration is a key driving factor of wash performance.

The greatest takeaway that can be made here is that given a single coat of mold wash, penetration is the most critical application parameter to wash performance. Penetration not only positively correlated to the wash score, but it also was able to build a reasonably accurate and significant regression model, which implies there is more than only correlation, but causation as well. Mil thickness negatively correlates to wash performance within the scope of this test, but it does not appear to cause poor wash performance, rather it correlates due to its inversely proportional relationship with penetration when using a single coat of wash. All of the above conclusions hold true for both the alumina and zircon-based washes utilized in this test.

While penetration is the driving factor for high quality wash performance and should be maximized, it should be done within reason. There does come a point at which the pursuit of additional penetration becomes a fruitless endeavor and can have a negative effect on quality. Looking at each of the Baumé levels in this experiment, the penetration gradually increased as the Baumé decreased.

This is all well and good, but at some point on the Baumé spectrum, the concentration of the refractory in the coating is diminished to the point at which it can no longer properly protect the metal from the sand.

There can also be issues with surface gas due to reactions between metal and still wet alcohol deep within the sand at lower Baumé levels which can somewhat be seen in Sample 2D from this experiment. From this research, these issues seem to begin to around 4-5 grains of penetration, and the best wash performance in this experiment occurred when penetration was around 3-4 grains.

While this research does indicate that penetration is a driving factor of core wash performance, it does not indicate why penetration is so important to performance. However, based upon previous work, it can be hypothesized that it has something to do with preventing liquid metal from getting underneath the refractory layer. SFSA Research Report No. 112 indicates that drying cracks in the proud layer can allow for metal to slip under the refractory, causing metal penetration and other adherent sand defects.[1] In theory, with higher amounts of wash penetration, it is less likely that metal can get underneath of refractory and cause metal penetration and adherent sand defects due to the refractory being present deeper underneath the surface of the core/mold.

One can also deduce this based upon the relationship between wet mil thickness and wash penetration being inversely proportional. If a large amount of wet mil thickness can cause cracks in the outer refractory layer, then as the mil thickness is reduced and the wash penetration is increased, the risk of cracks forming in the outer refractory layer is reduced. However, these hypotheses are untested at this point, further research is required to fully understand how wash penetration contributes to surface quality.

Though this test was run under very specific conditions, it is believed that the findings from this research will also apply to other ferrous applications and with other types of no-bake sand and binder systems. The area in which this research would not apply is in applications in which multiple coats of wash are utilized, as the first coat of wash is the one that drives the penetration, and any additional coats of wash are meant to add mil thickness. However, it is possible that these findings could be leveraged to eliminate the need for multiple coats of wash in certain situations, which would save time in production and reduce the quantity of wash usage. It would also not apply in any other type of molding method besides no-bake.

ACKNOWLEDGEMENTS

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