Performance of Three to Five Poise Mold Powders with an Exothermic Addition

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Key words: Mold powders, Viscosity, Mold, Steel quality

1. Introduction

As part of a continuous improvement policy, United States Steel Corporation (U. S. Steel) decided to test some higher viscosity mold powders recommended by Shinagawa Advanced Materials Americas, Inc. (SAM Americas). Two types of steel were the focus for the quality improvement:

(a) Ultra Low Carbon (ULC) IF Critical Exposed Material - used for outside painted automotive surfaces (IF)

(b) Drawn & Ironed single reduced tin plate manufactured according to ASTM A624 (D&I)

Steel grades, such as critical exposed sheet steel for automotive exterior painted surfaces and drawn and ironed for two piece steel cans, require minimal finished coil inclusion levels. A 3 poise at 1300℃ high viscosity mold powder was tested on the IF steel grades as well as other ULC grades. A 5 poise mold powder was tested on the D&I steel grades, other low carbon grades, and steel grades with a carbon content above the peritectic range. The 3 poise mold powder was tested on 2 single strand straight mold casters (1st and 2nd) and on a straight mold twin caster. The 5 poise mold powder has been tested on an additional single strand straight mold caster (4th) and on a 2 strand curved mold caster. Both new mold powders exhibited enough quality improvement that they are now the standard mold powders for many grades on the 1st, 2nd, and twin casters. The quality improvements were realized over a variety of casting configurations and mold widths.

2. Background

As part of the United States Steel Corporation Gary

Works' sliver continuous improvement team, internal and external steelmaking diversion samples were collected from within the plant, outside processers, and customers. Analysis on over 180 samples showed that 58% of defects were related to mold powder entrapment. U. S. Steel's Research Department was contacted for possible improvement recommendations. An interplant comparison showed that Gary Works ran the lowest viscosity mold powders in the corporation. Flux vendors who supply Gary Works were contacted for powder recommendations with increased viscosities. Trial comparisons of current powders versus the recommended SAM Americas higher viscosity powders showed improvement in diversions in downstream processing units and at customer facilities. Similar trials were subsequently conducted with these high viscosity powders at other U. S. Steel plants. This report describes some of the findings from the mold flux plant trials.

3. Discussion

3. 1 ASTM Mold powder committee results

Historically, different mold powder suppliers and users have run a variety of compositional and melting tests to characterize mold powders. An ASTM Mold Powder committee was formed to evaluate these tests. To become an ASTM standard test, reliable, reproducible results must be achievable in different laboratories. The mold powder committee approved only two tests: ASTM C 1276‐(Standard Test for Measuring the Viscosity of Mold Powders Above Their Melting Point Using a Rotational Viscometer) and ASTM C 1444‐(Standard Test Method for Measuring the Angle of Repose of Free-Flowing Mold Powders). Both of these tests have since been withdrawn. The viscosity test was for determining the molten slag viscosity at specific temperatures. Other ASTM tests

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for molten glasses determine the temperature at which a given viscosity occurs. The mold powder committee found that all of the other tests did not give reproducible results from lab to lab. Some of the tests were not sufficiently reproducible within individual labs.

Especially problematic are any tests that don't involve some prior thermal treatment of the mold powder. Mold powders may consist of more than a dozen different raw materials of widely varying particle size distributions and bulk densities. This makes achieving a consistent pressed sample difficult whether using light pressure or extreme pressure when preparing the sample. Determining the chemical composition of mold powders by ICP or X-ray analysis of a pressed sample has not been nearly as accurate as using a melted sample.

Another ASTM committee on other metallurgical materials approved the ASTM E2050 (Standard Test Method for Determination of Total Carbon in Mold Powders by Combustion-Infrared Absorption Method). This test is still being used.

3. 2　Viscosity

The 3 and 5 poise stated viscosity is the aim viscosity at 1300℃ for the aim chemistry. There is, of course, some variation due to variation in the raw materials used. All of the testing that is reported here as resulting from the 5 poise mold powder was not from testing mold powder that was exactly 5 poise. The 3 and 5 poise value was determined by a viscosity testing setup that gives values in agreement with ASTM C1276. They were also calculated through an empirically derived equation. The 5 poise mold powder viscosity was measured at other facilities. Unfortunately, different production lots were measured at the different locations besides the differences in the measuring equipment. The measured results ranged from 3 to 6 poise at 1300℃. The calculated viscosity based on the measured chemistry of different production lots typically results in a narrower viscosity range. The mold powders selected for testing have a higher viscosity at 1300℃ than the standard mold powders. They also have a higher viscosity at the molten steel casting temperatures. The new mold powders have less tendency to crystallize and undergo a less dramatic increase in viscosity at the lower temperatures that are present in the flux film between the steel shell and the mold. Therefore, the new mold powders actually have lower viscosities at these lower temperatures.[1] The higher molten flux pool viscosity at the molten steel casting temperature makes it more difficult to entrain bits of the molten flux pool by the surface activity of the molten steel.

3. 3　Exothermic addition

The 5 poise mold powder raw materials include a moderate amount of raw material that undergoes an exothermic reaction prior to melting.[2] The reaction contributes about 75 calories per gram of mold powder to the temperature of the upper part of the mold. This is in addition to the contribution from the burning of the free carbon. This exothermic reaction initiates at about 560 ℃ and proceeds in a steady, sustained manner. Exothermic starter powders contain much higher levels of exothermic material and their reaction is designed to be quick and intense as compared with a running mold powder like the 5 poise powder. The new mold powders were formulated to minimize endothermic reactions.

3. 4　Practice

For the trials, no starter mold powders were required. Sometimes, a standard mold powder was used at the start of a casting sequence and then a switch to the new mold powder was done. Automatic mold powder feeders were used for most of the testing. In a few cases, mold powder granules from the 22 pound bags were manually pushed into the mold. The manual addition facilitated consumption measurements. The mold powder coverage goal was to have a minimum coverage of about 40 mm depth including the molten flux pool and the un-melted granules. Maximum coverage was recommended to be about 75 mm. The agglomeration process produces a wider range of granule size and shape than other granulation methods. This results in more efficient packing of the granules. As a result, with the same depth of coverage, there is more mass of mold powder in the mold with the agglomerated granules. At the end of casting, allowing the mold powder coverage to burn down was started earlier than with the standard mold powders. Not only do the new mold powders have more mass in the mold to be consumed, their consumption rate is slower. Therefore, more time is needed for their coverage to be depleted.

3. 5　Meniscus area temperature

In order to achieve optimum flotation of non-metallic inclusions and gas bubbles out of the molten steel, the molten steel temperature in the upper part of the mold needs to be maintained at a high enough temperature so that the molten steel viscosity is low enough to allow the inclusions to rise and be absorbed by the molten flux pool. ULC steel grades tend to have higher molten steel viscosities. Titanium additions can increase the molten steel viscosity further. The shorter freezing range of ULC grades is another factor that can restrict the flotation of inclusions.

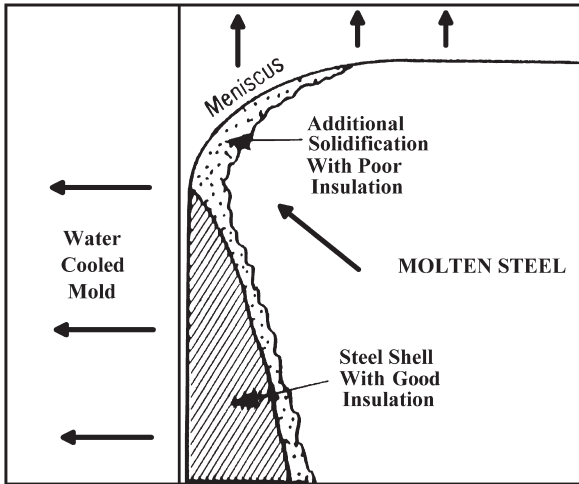Figure 1 below depicts the directions of heat flow within and out of the mold.[3]

Figure 1.   Effect of insulation on solidified steel shell.

Figure 2.   Typical melt pool depth frequency distribution.

The mold powder can affect the rate of heat removal by the mold through the characteristics of the flux film between the steel shell and the mold. Lower heat removal helps maintain the molten steel temperature. The mold powder can affect the rate of heat loss out of the top of the mold by its insulating characteristics. The better packing of the agglomerated granules restricts the upward convection of heat between the granules. The good insulating characteristics are only realized by maintaining sufficient mold powder coverage. If the molten steel temperature drops sufficiently in the meniscus area, additional solidification at the top of the desired steel shell can form an extended surface that can entrap inclusions and gas bubbles before they reach the molten slag pool. This extended surface can also lead to deeper oscillation marks on the cast surface of the steel and a more extensive "hook" solidification structure.

3. 6   Flux pool depth

The higher viscosity mold powders have a comparatively slower melting rate. With their lower consumption rate, faster melting rates would result in excessive molten flux pool depths and very little depth to the unmelted, insulating coverage. During the 3 and 5 poise testing, molten flux pool depths were measured at multiple points in the mold. The 2 wire method was used with a steel and an aluminum wire. The molten flux pool depths consistently averaged 9–11 mm for both mold powders. Figure 2 shows a typical molten flux pool depth frequency distribution.
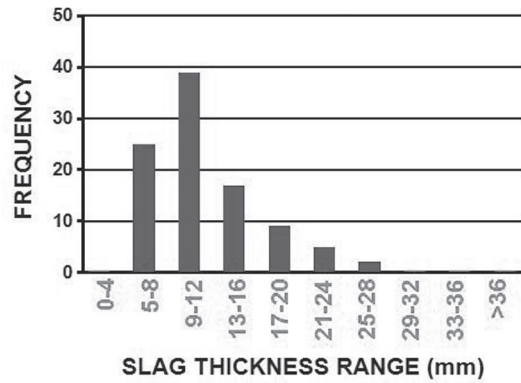
The data is from a single strand caster using the 5 poise mold powder for an entire tundish. The conclusion is that the molten flux pool depth was sufficient for providing mold to steel shell lubrication, and the molten flux pool depth was low enough such that a large portion of the mold powder coverage was composed of insulating unmelted powder.

3. 7   Heat removal calculations

There are three different calculations based on the water flow amount and the increase in the mold water temperature (ΔT) that are used to determine the mold heat removal rate.[4] BTUs per square inch per minute (BTUs/in^2/min) determines the rate that the mold removes heat over the mold surface. It does not consider the casting speed or the amount of time that the heat removal rate acts upon any specific surface area or volume of the steel being cast. BTUs/in^2/min does normalize (negate the variation of) for mold size. BTUs/in^2/min does measure what heat removal each section of the mold is incurring.

BTUs per pound (BTUs/#) of cast steel normalizes the heat removal for the steel throughput (tons per minute) which is determined by the casting speed and the mold width and thickness. BTUs/# is a good measure of how much heat has been removed by the mold towards solidifying the entire mass of steel being cast. However, the time spent in the mold is not intended to result in a fully solidified mass of steel as in ingot casting. BTUs/# does not measure well what heat removal each section of the mold is incurring. BTUs/# is not the preferred measurement to compare the heat removal for molds of different sizes.

BTUs per cast surface area (BTUs/in^2) also normalizes the heat removal for both the casting speed and the mold width and thickness. BTUs/in^2 is actually BTUs per minute removed by the mold divided by the square inches

per minute of cast surface area. The BTUs/in² calculation gives the heat removal amount for each mold surface as well as for the entire mold surface. The purpose of the time that the steel spends in the mold is to form a sufficiently thick and strong steel shell. BTUs/in² gives a measure of how much heat removal occurs towards building the steel shell. BTUs/in² is the preferred measurement to compare the heat removal for molds of different sizes and to compare the heat removal on different casters.

Data needed to calculate BTUs/in²:

1．Mold water flow rate for each mold section (gallons per minute)
2．Mold water ΔT for each mold section (°F)
3．Mold width (inches)
4．Mold thickness (inches)
5．Casting speed (inches per minute)

Procedure to calculate BTUs/in²:

1．Convert mold water flow rates from gallons per minute to pounds per minute by multiplying by 8.33 pounds per gallon.
2．Multiply the pounds per minute times the mold water ΔT for each mold section to get BTUs per minute.
3．For the broad faces, multiply the mold width times the casting speed to get the square inches of cast surface per minute. Some molds have 2 sections for each broad face so half the mold width is used.
4．For the narrow faces, multiply the mold thickness times the casting speed to get the square inches of cast surface per minute.
5．The BTUs per square inch for each mold section is obtained by dividing the BTUs per minute by the square inches of cast surface per minute. The minutes cancel out and BTUs per square inch of cast surface or just BTUs/in² remains.
6．To get the heat removal for the whole mold, add all of the BTUs/min and divide that sum by the total of all of the in²/min for all sections.

3. 8　Minimum heat removal

Most conventional thickness slab casters have a minimum heat removal standard target. This minimum is often expressed in BTUs/# and is used for all mold widths and tundish superheat temperatures. For high tundish superheat temperatures, the casting speed is reduced. For low tundish superheat temperatures, the minimum target is not reduced even though less heat removal would be needed. This keeps the practice simpler for the strand operators.

The BTUs/# minimum level has an equivalent BTUs/in² value that varies with the mold width. For the minimum mold width and the maximum casting speed at the 2 similar casters at U. S. Steel's Gary Works, the mini-

mum BTUs/# target converts to 25.6 BTU/in². For the maximum mold width and the maximum casting speed, the minimum BTUs/# target converts to 27.9 BTU/in². Since the goal was to operate with a low to moderate amount of heat removal, a lot of the observations during testing were directed towards maintaining a level above the minimum target.

4.　Results

4. 1　Heat removal results

The heat removal for the two new mold powders was measured. BTUs/in² was used to compare the heat removal results on the different casters. Since the 5 poise mold powder was used on all 5 casters, it will be used as the reference mold powder for reporting the results. The single strand, straight mold 2nd caster will be used as the reference caster. It was expected that the 3 poise mold powder would have higher heat removal than the 5 poise mold powder. For ULC and low carbon steel grades cast on the 2nd caster, this was verified as shown in Figure 3 below.
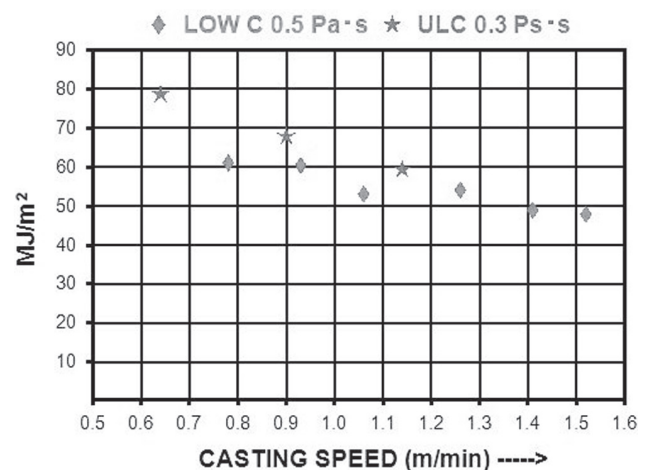

Figure 3.　Heat removal comparison for low C steels – 3 and 5 poise mold powder.

Although decreasing with speed, the BTUs/in² rate was still higher than the minimum target at the highest casting speed used during the new mold powder evaluation. The 5 poise powder was also used on high carbon steel grades. There was no significant difference in the BTUs/in² for either side of the peritectic range as shown in Figure 4 from the 2nd caster.
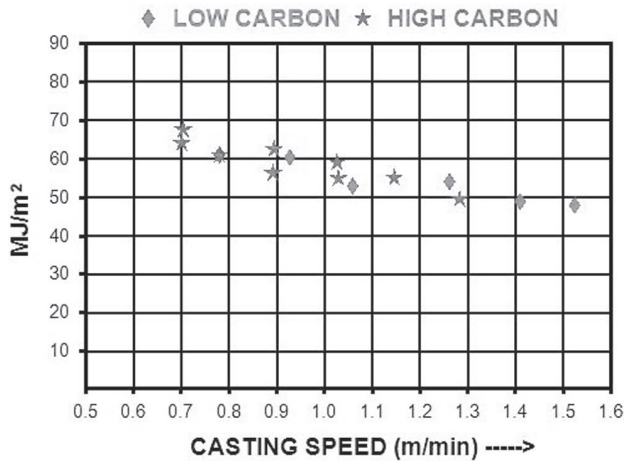
Figure 4.　Heat removal comparison for 5 poise powder - low and high carbon steel.

The 1 poise mold powder has been the standard powder for both low and high carbon steel grades. There was no significant difference in the BTUs/in^2 between the 1 poise and the 5 poise mold powders for high carbon steel grades cast on the 2nd caster as shown in Figure 5.
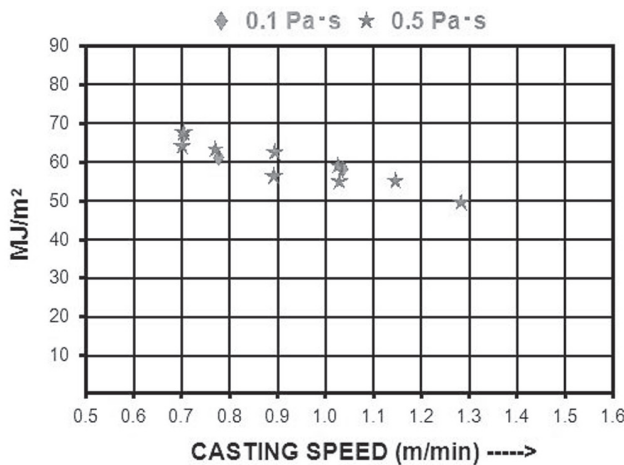

Figure 5.　High carbon steel heat removal comparison・1 & 5 poise mold powders.

By using either the 1 poise or the 5 poise mold powder, the heat removal from the molten steel by the mold is the same. Based on the premise that the 5 poise powder is better at insulating and restricting the heat loss out of the top of the mold, and its exothermic content, the molten steel temperature in the top of the mold should be higher with the 5 poise powder. The result should be fewer inclusions in the finished coils.

The 1st and 2nd casters are the same design and the BTUs/in^2 determinations were the same for the two casters. The 1st and 2nd casters have the largest range of possible mold widths. The SEN design is a major factor in the flotation of inclusions. It follows that the SEN

design will be less optimized for inclusion flotation for some of the mold widths used on the 1st and 2nd casters. Therefore, keeping the molten steel temperature elevated by low heat removal should be more important on the 1st and 2nd casters.

The twin caster has the smallest range of mold widths and the SEN design is optimized for its cast steel quality. It follows that low heat removal by the mold is less critical. The twin caster mold copper design does result in higher heat removal as compared to the 2nd caster as shown in Figure 6 for low carbon steel casting.
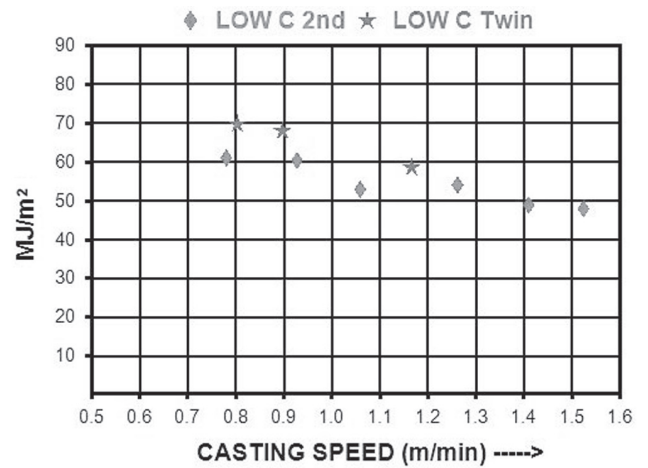

Figure 6.　Heat removal comparison for 5 poise mold powder・single vs. twin strand casters.

The mold copper design on the 4th caster results in slightly lower heat removal as compared with the 2nd caster as shown in Figure 7 below for low carbon steel casting with the 5 poise mold powder.
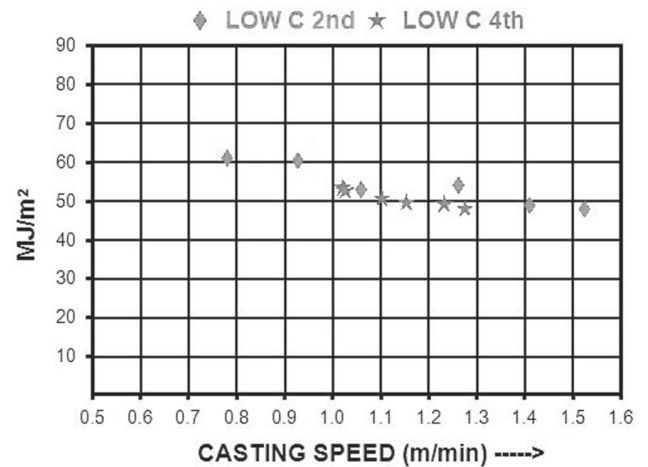

Figure 7.　Heat removal comparison for 5 poise mold powder・two single strand casters.

The mold copper design on the curved mold caster results in higher heat removal as compared with the 2nd caster as shown in Figure 8 for casting high carbon steel grades.
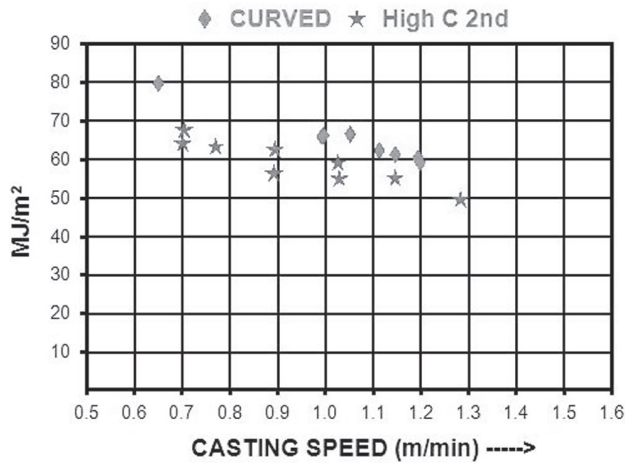

Figure 8. Heat removal comparison for 5 poise mold powder•straight vs. curved molds.

4. 2　Consumption

One of the concerns prior to testing the 3 and 5 poise mold powders was that the consumption might be too low. The consumption per cast surface area is one way to look at mold powder consumption. The flow (from the molten flux pool above the molten steel) between the steel shell and the mold should provide lubrication such that the highest peak of the friction force on the steel shell is less than the strength of the steel shell. As the flux film between the steel shell and the mold moves downward and exits the mold bottom, the flow should fully replenish the flux film, otherwise the character of the flux film will be inconsistent and result in less steady heat removal. The lower quality of heat removal can lead to crack sensitive steel grades having surface cracks. It can also lead to alarms when the thermal behavior of one or more thermocouples is inconsistent as compared with that of the neighboring thermocouples.[5),6)]

For slab casters, a 0.3 kg/m² minimum consumption target dates back prior to the conversion towards granulated mold powders.[7)] This minimum level includes mold powder that ends up in dust collectors and on the floor behind the mold. With granulated mold powders, much less mold powder is wasted and the consumption rate has been shown to be 10–15% lower as compared to fine powders with the same physical properties. Therefore, 10–15% less consumption than 0.3 kg/m² provides the same flow between the steel shell and the mold as with fine powders. Billet casters routinely have operated at

lower consumption levels. The lowest measured consumption rate was 0.27 kg/m² for the 5 poise powder. The slab surfaces did not indicate that low lubrication was a problem, and the steel grades tested are not prone to surface cracking. There was no increase in the frequency of alarms triggered by thermocouple behavior.

Another way to consider mold powder consumption is the amount used per weight of steel cast. A typical usage rate of one pound per ton of steel is often cited.[7)] Besides the physical properties of the mold powder like viscosity, the consumption rate is proportional to the positive strip time of the mold oscillation. All of the straight mold casters these mold powders were tested on use mold oscillation practices that result in shorter positive strip times as the casting speed increases. The effect of casting speed and mold powder viscosity is shown in Figure 9 below.
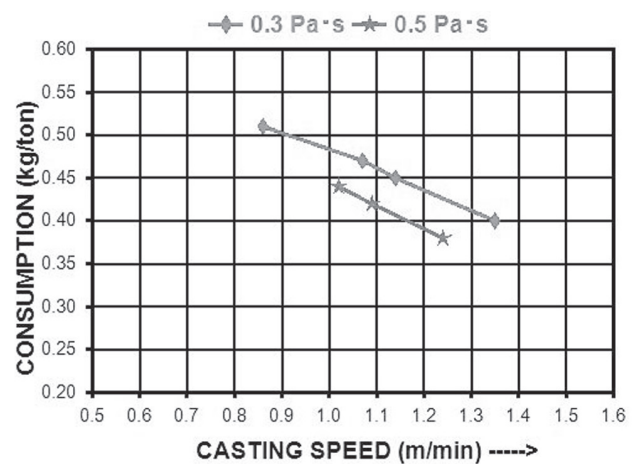

Figure 9. Consumption vs. casting speed for 3 & 5 poise mold powder.

As expected, the 5 poise mold powder showed lower consumption than the 3 poise mold powder, and the consumption rate decreased with higher casting speeds.[8)] It is typical that the consumption rate difference between two mold powders is about the same over a range of casting speeds. The 3 poise data is for four separate consumption measurements. The 5 poise data is for an average over four to five measurements.

An important result of the mold powder consumption is the removal of the molten steel impurities such as alumina that have been absorbed by the molten flux pool. If the consumption rate is too low, the alumina content of the molten flux pool will keep increasing during the casting sequence and the physical properties of the molten flux can change too drastically to provide sufficient lubrication for instance. Figure 10 shows the alumina content of the molten flux pool for both mold powders over several hours of casting. Both powders gave sufficient

consumption so that the alumina content remained within a fairly narrow range. The 3 poise mold powder alumina content data is from a twin casting sequence. The 5 poise mold powder alumina content data is from a single strand casting sequence.
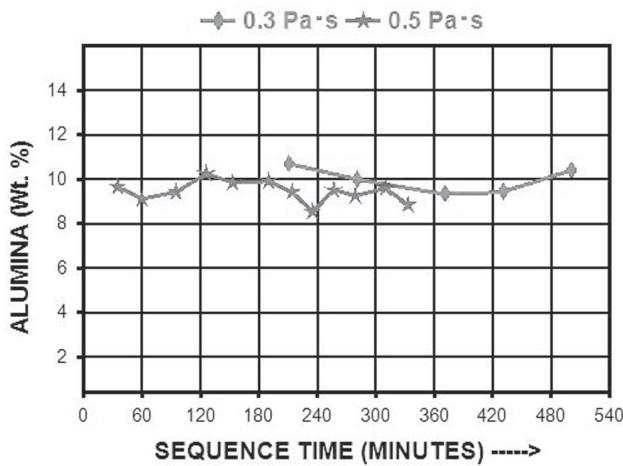

Figure 10.　Flux pool alumina content vs. cast time.

The pounds per ton consumption rate is also used to determine the mold powder purchasing cost per ton of steel. For the 5 poise mold powder testing, the standard mold powder has a viscosity of about 1 poise and an additional consumption of about 0.19 pounds per ton as determined through side by side casting on the twin caster. The 1 poise additional consumption percentage increases with casting speed according to Table 1. The consumption savings with the 5 poise mold powder increases with higher casting speeds.

Table 1　Mold powder consumption rates versus casting speed

Casting Speed （m/min）	1.02	1.24
5 poise consumption （kg/ton）	0.44	0.38
1 poise consumption increase	22%	25%

4. 3　Visual observations

As expected, the oscillation mark depths appeared to be shallower with the 3 and 5 poise mold powders. No actual measurements were performed. Also, the crease at the base of the oscillation mark appeared to be not as sharp with the new powders. When side by side testing of the 1 poise and the 5 poise mold powders on the twin caster was done, the SEN slag line erosion was noticeably less with the 5 poise mold powder. The zirconia in the SEN slag line is a potential source of inclusions, but it has not historically been a significant source at these casters. The SENs are usually changed due to alumina buildup

on the inside not due to slag line erosion. A thinner wall SEN could be used with the 5 poise mold powder, but the current SEN wall thickness is required for casting other grades with other mold powders.

4. 4　Quality results

The defect levels were reduced with both of the new mold powders tested. On comparison with the standard mold powder, on a percentage basis, the 3 poise mold powder gave less improvement than the 5 poise mold powder as shown by Figure 11. Both new mold powders exhibited enough quality improvement that they are now the standard mold powders for many grades on the 1st, 2nd, and twin casters. The quality improvements were realized over a variety of casting configurations and mold widths.
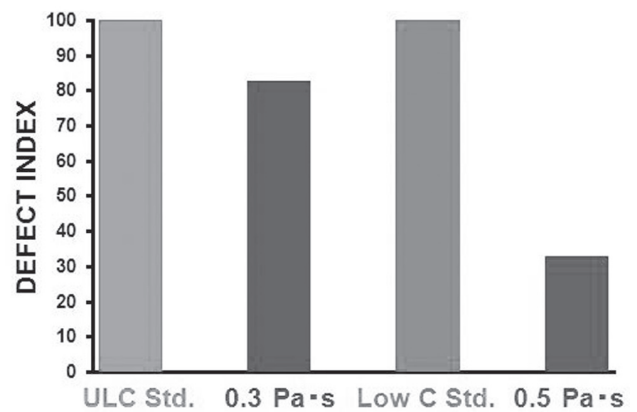

Figure 11　Defect reduction with the 3 & 5 poise mold powders.

5.　Conclusions

As part of a continuous improvement policy, United States Steel Corporation (U. S. Steel) decided to test some higher viscosity mold powders recommended by Shinagawa Advanced Materials Americas, Inc. (SAM Americas). Two types of steel were the focus for the quality improvement:

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straight mold casters (1st and 2nd) and on a straight mold twin caster. The 5 poise mold powder has been tested on an additional single strand straight mold caster (4th) and on a 2 strand curved mold caster. Both new mold powders exhibited enough quality improvement that they are now the standard mold powders for many grades on the 1st, 2nd, and twin casters. The quality improvements were realized over a variety of casting configurations and mold widths.

6. Acknowledgments

References

1) D. R. Larson, "Mold Powder Attributes," McMaster Symposium, 2006.

2) Y. Iwamoto, T. Suzuki, and B. He, "Granulated Exothermic Mold Powder," Shinagawa Technical Report No. 53, 2010, pp. 81-86.

3) D. R. Larson, "Criteria for Selecting Mold Powders to Optimize Continuous Cast Steel Quality," Industrial Heating, April 1986.

4) J. Shipman and H. L. Gilles, U. S. Patent 4006633 "Method and Apparatus for Determining Heat Removal from a Continuous Caster", April 22, 1976.

5) S. G. Thorton and N. S. Hunter, "The Application of Mould Thermal Monitoring to Aid Process and Quality Control when Slab Casting for Heavy Plate and Strip Grades," ISS Steelmaking Conference Proceedings Volume 73, 1990, pp. 261-274.

6) K. C. Mills, "The Performance of Casting Powders and Their Effect on Surface Quality," ISS Process Technology Division Conference, Washington, D.C., 1991.

7) D. R. Larson, "Thin Slab Casting Mold Powder Selection," Shinagawa Technical Report No. **37**, 1994, pp. 1-7.

8) R. J. Gray, "Behavior of Mould Fluxes During Continuous Casting," Report EUR 9495 EN, ECSC Contract 7210-CA/811, 1985.