EFFECT OF DIFFERENT COATINGS ON THE SURFACE FINISH AND HARDNESS OF MANGANESE STEEL CASTINGS

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Abstract:

The quality of finished surface of castings is mostly dependent on a number of factors including the mould chemistry, preparation of mould& types of coating applied, melt temperature and pouring techniques etc. The selection and application of coatings on the surfaces of mould cavities and cores is important since the surface & subsurface defects, in general, are attributed to thermal, mechanical and physicochemical reactions during pouring and solidification of the molten metal.

Depending upon the chemistry of castings, appropriate coatings are selected with a view to suppress the interfacial reactions. The present research demonstrates that the selection of coatings and mould preparation conditions etc., during the production of Manganese-steel castings, does have bearings on the quality of finished surfaces of castings. The findings are useful to develop basic guidelines to enhance the quality of surface finish. Advanced techniques, such as SEM, were used to analyze the coatings and the surfaces of castings. Hardness testing on castings was also performed.

1. Introduction

Foundry coatings for the preparation of mouldsarecommonly employed with a view to produce castings with quality surface finish. There is a general perception that the surface finish of castings depends largely on sand particle grading, - and hence it is supposed that a proper selection of a particular grade of sandwould be the only requirement to get better surface quality. Beside this, there are other factors to be considered, such as the use of appropriate coatings[1].

A mouldis subjected to mechanical,thermal, and physicochemical phenomena during compaction and pouring of liquid metal into it. Considering that the sand moulds and cores are highly porous, the production of castings in these materials without surface defects is possible only with protection of the surfaces of moulds and cores with refractory coatings[2]. The fundamental requirements for the refractory coatings are minimum porosity, high refractoriness and reduction of the physicochemical reaction at the metal-coating interface (lubrication, solution, penetration)[1,2]. Further improvement from the coatings leads to thecleaner and better peel of sand at shakeout and elimination of certain defects such as metal penetration, veining, erosion, sand burn-in etc.,thus reducing subsequent fettling operation & machining costs[3, 4].

In local foundries, a variety of coatings are employed – the most common ones are Zircon, Magnesia, and linseed oil.Magnesite coating, however, is gaining more popularity world over.

The objective of this work was to demonstrate that the selection of coatings and mould preparation conditions etc., during the production of Mn-steel castings, does have bearings on the quality of finished surfaces of castings. Scanning Electron Microscopy (SEM) was used to analyze the coatings and the interfacial products. Since the practices vary widely from foundry to foundry, it is difficult to rationalize the conditions, the work presented here, never-the-less, shall provide some insight as well as basic guidelines. Undoubtedly more systematic research is required to establish standard conditions and best coating material for the production of Mn-Steel castings with quality surface finish. A small contribution was also made towards finding the impact of refractory coatings on the hardness of the Mn-Steel castings because the wide application of Manganese Steel actually owe to its extreme anti-wear properties.

2.Moulding Sand Composition

Although there are many new advanced technologies for metal casting, the sand casting process remains one of the most widely used one for economic reasons. It can be attributed to low cost of raw materials, application to a wide variety of castings with respect to size and composition, and the possibility of recycling the moulding sand.

The general composition of green mould is:

- silica sand (SiO2), or chromite sand ($FeCr_2O$), or zircon sand ($ZrSiO_4$), 75 to 85%
- bentonite (clay), 5 to 11%
- water, 2 to 4%
- additives, 1.5 to 2%

Process factors like moisture content, green compression strength, permeability and mold hardness, significantly affect the casting defects including those present on the surfaces of any castings/products. If the strength of the sand is not good, it causes the cracking of the mould upon pouring of molten metal. If the permeability of the sand is not reasonable, hot gases cannot easily vent off through the mould, creating minute to larger sizes blow holes inside the castings. Inappropriate moisture content leads to inability of good bonding between the sand particles. Thus, the quality of the molding sand mixture significantly affects the quality of the castings.

The composition of green sand used at the local foundries is:

- Silica sand, 85-90%
- Bentonite, 6-7%
- Water, 3-4%

The sand containsupto 30% reclaimed sand, with addition of bentonite and water in appropriate proportion, for maintaining good bonding strength. This practice needs to be optimized, as excessive recycling would lead to a substantial reduction in the properties of the sand mold and as a result increase the number of casting rejects. About 93.3 mass% of one-time recycled molding sand, 5 mass% of bentonite, and 1.7 mass% of water gave optimum strength and permeability to green sand[5].

Thelocal foundries, however, use the recycled sand falling in the following composition range:

- new silica sand, 60-70%
- recycled silica sand, 15-30%
- bentonite, 6-7%
- water, 3-4%

Generally, the face of the mould cavityis made of the new silica sand composition (Silica sand, 90%; Bentonite, 6-7% and water, 3-4%.) whereas the rest of the mould is composed of: mixture of recycled silica sand, up to 30%; new silica sand, 60%; bentonite, 6-7% and water, 3-4%. The reason for using the above compositions is to ensure the best mould quality (in terms of strength and permeability) as well as to get better surface finish. Unused sand, free from any combustion products, contributes to achieve above mentioned purpose. Finally different types of coatings are applied over the mould to enhance the surface finish. Some of the well-known properties are stated in the next section.

3. Properties of Refractory Coatings

The literature survey carried out during the study revealed that a variety of refractory coatings such as those listed below are used in steel foundries[6, 7]:

- Silica Sand
- Zircon
- Olivine
- Kaolin Clay
- Magnesite
- Chromite
- Talc
- Chamotte

The main characteristics of theserefractory coatings are stated below[2]:

- Sufficient refractory properties to cope with the metal being poured
- Good adhesion to the mould wall
- Be permeable to minimize air entrapment
- Be fast in drying
- No tendency to blistering, cracking or scaling on drying
- Good suspension and remixing properties
- Minimize core strength degradation
- Provide adequate protection against metal penetration
- Good stability in storage
- Good covering power
- Good application properties by the method chosen

Table 1 provides a comparison of various parameters for different coatings in order to provide basis of selecting the most appropriate coating material that would best serve the surface finish of steelcastings.Only refractory coatings with more modern and frequent applications have been shown in the table and other coatings have not been recognized due to their very poor competency in properties w.r.t. the mentioned coatings.

The importance of each property[8] of refractory coatings is described as follows:

- High refractory temperature: Hinders sand burns and enables casting of high melting point metals to be produced
- Low thermal expansion: Strengthens the mould against thermal and mechanical stresses and helps in producing accurate castings free from scabbing defects

Table 1. Properties of refractory coatings for steel

	Chromite	Silica Sand	Chamotte	Zircon	Magnesite
Chemical Formula	$FeCr_2O_4$	SiO_2	40% Al_2O_3, 30% SiO_2, 4% Fe_2O_3, 2% MgO and CaO combined	$ZrSiO_4$	$MgCO_3$
Melting Point (˚C)	1850	1700	1780	2727	1850
Thermal Expansion (1000 mm/m)	0.007	0.019	0.0052	0.0032	0.014
Density (g/cm^3)	<3.22	2.65	≈ 2.6	3.22	2.96
Chemical Nature	Basic (pH 7.5-9.5)	Acidic (pH 4.5 -6.5)	Slightly Basic (pH 7.8)	Acidic (pH 5.5)[24]	Basic (pH 8.5 – 9.5)
Thermal Conductivity (W/K/m)	9-15	9.5-12.5	6-9.5	12-15	20-30
Wettability with Molten Metal	No wettability	Easily wetted	No wettability	Not easily wetted	No wettability

- Greater density: Prevents metal penetration into the intergranular spaces of the mould
- Highthermalconductivity: Promotes quick formation of a solidified metal layer and helps in producing castings with a fine grained structure
- Basic chemical nature: Manganese Steel is compatible to a basic environment. With this context, refractory coatings with high pH values do not chemically react with manganese steel

The densities, wettability properties and pH natures (except Silica Sand and Zircon) of all coatings are almost similar (except for Silica Sand having high wettability with the molten metal); silica sand and chamotte are however less dense. The difference inthem now lies in other of the properties. The pouring temperature of the liquid melt (Manganese Steel) is usually 1600 ˚C. The highest refractory temperature is shown by Zircon, the others' though are close to the pouring temperature, but still are above it. Since the mould temperature (after pouring the molten metal) will be nowhere above 1600 ˚C; with the addition of proper additives or binding agents to the filler material, none of the refractory coatings may face decomposition due to high temperatures. Thermal conductivity is a very important property of refractory materials, since it helps in quick formation of a solidified metal layer. We can see that Magnesite has the highest thermal conductivity of all. Zircon's thermal conductivity is half to that of Magnesite, and Chamotte has the least.

The thermal expansion factor is a very critical one. The mould material, i.e. Silica sand in this case, has its own thermal expansion, and the coating material adherent to it has its own. If there is a mark difference between the thermal expansions of the mould material and the coating, they will split from each other[9]. Due to this splitting and cracking, the metal will enter these gaps and form thin fins on the surface of the casting. Silica sand has a thermal expansion of 19 mm/m. Among all of the tabulated refractory coatings, Magnesite has the closest thermal expansion (of 14 mm/m) to that of Silica sand.This implies that there are least expectations for surface

defectslike fining, veining and other metal penetration related defects, to form on the surfaces of Manganese steel castings – if Magnesite coatings are used. However, experimentation had to be done to check out the effect of the contemporary refractory coatings (on surface finish of Manganese Steel castings) being used commonly, i.e. Zircon and Magnesite; along with two controls set - defined in the following section.

4. Experimental Procedure

For Mn-Steel castings, the following types of coating materials are generally employed in the local foundries:

a) Linseed Oil
b) Zircon Powder
c) Magnesite Powder

The experimental scheme for the present work also used these coatings in addition to plain mould (without any coating) for the baseline study. It is noted that Zircon powder and Magnesite powder coatings are the most popular types of coating for the production of Mn-Steel castings. The refractory coatings used in the experiments were obtained from a local firm dealing with foundry related consumables.

Linseed oil is also used at different foundries asa spray on the green sand mould's cavity (before it is baked). It enhances the compactness and strength of the cavity's face, through binding the sand particles together. Linseed oil, generally, serves as a binding agent.

The green sand was prepared by mixing 90% silica sand with 6-7% bentonite clay and 3-4% water, in a sand muller machine, at a speed of 900 rpm. The wet sand was well compacted in the copes and drags by ramming. A wooden pattern, of 1 x 2 x 1 inches, was used to make the mould cavity.

The Zircon powder was dissolved in isopropyl alcohol (C_3H_7OH), in a proportion of 26% to 74% – forming a paste. The Magnesite coating paste was also prepared in the similar way.

During the experiment, all the wet coatings (including linseed oil) were applied using a spray gun, and each time a pass with the spray was made, the coating was dried with the oxyacetylene burner torchfor 4 to 5 minutes, and then the next pass was made - and the coating again dried. This was to ensure that a thick coat was not made at once; as thick refractory coats do not easily dry up and either residual water or moisture is trapped in them[12].The longer the refractory coating takes time to dry; it penetrates deeper into the mould and cores – drastically reducing their strength and the ability to handle the core[10, 11].

The longer drying time for coatings may lead to various problems like gas cavities, blow-holes, pin-holes and scabs[12]. It was observed that most foundriesdo not have a designated method for determining when a mould or core is completely void of any moisture. It is subjectively determined by the operator when he thinks that the coating is completely dry or not.

The four moulds prepared were dried as per methods described below:

Mould 1
- Baked in Oven at 450˚C for 4 hours (24hrs oven cooling)
- No coating applied

Mould 2
-Linseed Oil coated
-Baked in Oven at 450˚C for 4 hours (24hrs oven cooling)

Mould 3
-Baked in Oven at 450˚C for 4 hours (24hrs oven cooling)
-Zircon coated, dried by burner torch

Mould 4
-Baked in Oven at 450˚C for 4 hours (24hrs oven cooling)
-Magnesite coated, dried by burner torch

Manganese Steelof the following composition (Table 2), melted in an induction furnace was poured into the mould cavity at 1600 ˚C:

Table 2. Mass Percentages of elements in Mn-steel

C	Mn	Cr	Fe
1.1 %	12%	1.7%	Bal.

The pouring rate for all moulds was kept constant and the pouring time was about 5 seconds. The ambient temperature was around 45˚C. After the filling wascompleted, the moulds were left to cool at the atmospheric temperature for 1.5 hours - all at a constant cooling rate.Subsequently, the mould boxes were opened and all the four castings were placed in a shot blasting machine for 15 minutes on each face.

5. Results and Discussion

Optical micrographs ofall the four castings' surfaces are shown in Figure 1 (a tod).

The surface of the bare mould casting (Figure 1a) showed a very irregular surface. The sand mould had no coating on it; therefore the mould cavity's surface is expected to be irregular - as no coating had filled the pits and voids present in it. The casting shows metal projections, making their way through the sand mould's surface roughness. Gas entrapments also appear on the surface owing to the residual moisture left in the sand mould. The EDS results of this specimen revealed that a $SiO_2$and MnOlayer had also formed at the surface of the casting.

Figure 1a. Casting without coating (top left)
Figure 1b. Casting with Linseed Oil (top right)
Figure 1c. Casting with Zircon (bottom left)
Figure 1d. Casting with Magnesite (bottom right)

The surface of the Linseed oil casting (Figure 1b)showed both microporosity and macroporosity, caused by the combined action of metal shrinkage and gas entrapment during solidification[15]. Hydrogen entrapment seems the main defect in this casting. Apparently, the overall surface smoothness is better as compared to the casting shown in Figure 1a. Presence of slag was also apparent on the surface. The casting produced in Zircon coated mould (Figure 1c) showed porosity on its surface. There was also an appearance of a dark metal oxide layer, possibly of MnO, according to the EDS results. However, the surface finish of casting using the zircon coating was smoother than the prior discussed two castings shown in Figure 1a and 1b.

The casting produced in Magnesite coated mould (Figure 1d),showed refractory erosion on casting surface due to sand mould erosion – which had in return formed a defective surface (at some points). In addition, inclusions were also observed to be present on the surface of castings[16]. Presence of silicates was also apparent on the surface. In literature[22], EDS results testify the fact that when metal is poured into moulds, in places where the coating has worn off or is incorrectly applied, the reaction of manganese oxidation (due to oxygen present in the atmosphere inside the mould cavity) and penetration of manganese vapors occurred. Due to the higher affinity of Mn to O than that of Fe, the formation of Manganese Oxide, MnO occurs, which reacts strongly with the constituents of sand, SiO_2. As a result of this reaction, silicates of a general formula $Mn_nSi_mO_{2m}$ are formed[23].

6. Testing & Characterization

Scanning Electron Microscopy (SEM) was done on the castings to have a closer look at the surface finishes. Energy Dispersive X-ray Spectroscopy (EDS) was performed to examine the compositions of the refractory coatings – zircon and magnesite – to form a further basis of conclusions for the results obtained.SEM and EDSwas also performed on the core of the castings.The analytical SEM used was JEOL JSM-6490A equiped with Oxford Instruments EDS system.Hardness testing was also performed on the castings, using the Rockwell Machine.

6.1 SEM of Surface Finish of Castings

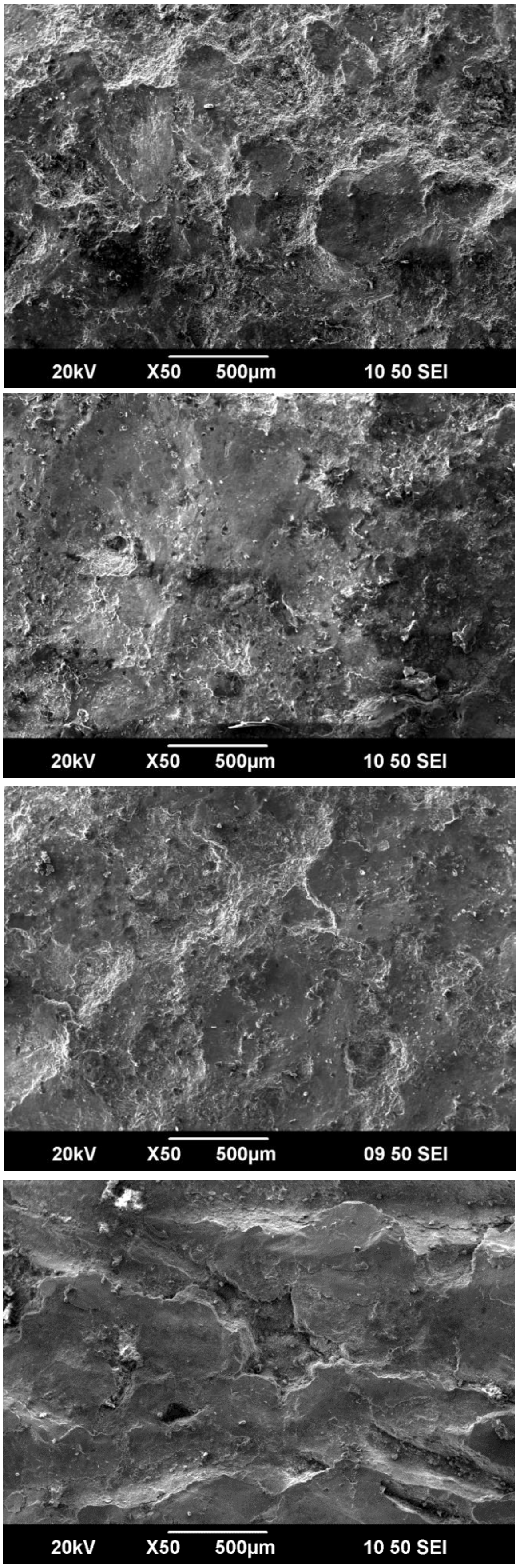
SEM of all the four castings, with various coating conditions, were studied at various magnifications. Typical variations in the surface structures are as shown in Figure 2 (a-d).

Figure 2a reveals the surface irregularities on the bare mold casting surface caused by the interaction between the molten metal and the moulding sand (devoid of any protective coating). Microporosity is also evident at some locations.

In Figure 2b, the surface of the casting made using Linseed oil, has a lot of microporosity in it – owing to gas entrapments. Upon the pouring of molten metal on a linseed oil coating causes a release of volatileorganic compounds from it[17]. When the molten metal starts to fill in the mould cavity, the organic coatingmay also block the evaporation of the volatile matter, leading to gas entrapment. Shrinkage on the surface, at some places is also visiblein the SEM image.

The surface of the casting produced in Zircon coated mold (Figure 2c) has a lot of microporosity on it, but the surface smoothness is better thaneither of the plain or linseed oil coated mold castings.

The best surface appears to be achieved in the casting produced with Magnesite (Figure 2d). It has the most planar surface, with the least microporosity; however, there are locations of eroded sand casting defects.



(a) (b) (c) (d)

Figure 2. (a) SEM image of plain casting, (b) SEM image of Linseed Oil coated casting, (c) SEM image of Zircon coated casting, (d) SEM image of Magnesite coated casting

6.2 EDS of Refractory Coatings

The EDS results (Table 3) of Zircon Powder revealed the following elemental analysis:

Table 3. Mass % of elements in Zircon powder

Element	Mass Percent
C	22.69
O	38.83
Mg	24.62
Al	0.36
Si	3.07
Ca	5.55
Zn	3.20
Zr	1.68

The weight percentage of Zr in Zircon powder is as low as 1.68%. Whereas, there is a very high composition of Mg in it which could be either in the form of MgO or $MgCO_3$, and there are very low abundances of SiO_2 and Al_2O_3.

In a previous research on refractory coatings[2], it is claimed that good quality Zircon flour should contain a minimum of 64% of zirconium oxide (ZrO_2), 30 to 35% silica and a maximum of 0.5% of combined TiO_2& Fe_2O_3.It is obvious that the refractory coating available locally, is in fact very impure, and a meager amount of Zris present probably in the form of $ZrSiO_4$, in a sea of MgO and/or $MgCO_3$.

The EDS results (Table 4) of Magnesite powder revealed the following elemental analysis:

Table 4. Mass % of elements in Magnesite powder

Element	Mass Percent
C	19.25
O	41.73
Mg	30.75
Si	1.20
Ca	7.07

The proportions of elements in Magnesite largely resemble to that of Zircon powder, except for it does not contain Zr in it. According to the measured composition, the magnesite powder mainly consists of $MgCO_3$.

According to a general opinion of foundry industry, in Pakistan, Zircon is providing the best surface finish to Manganese Steel castings. Magnesite coatings are a new, improved technology in the world of Manganese Steel casting foundries. It is confirmed by some research work[18] practiced on Manganese Steel using Zirconium, Magnesite, Corundum based coatings, all compared against a casting without using any coating on the mould wall -revealed that Magnesite provided the best surface finish. Based on these facts, we can claim that the reason behind the ambiguous results obtained in this research were mainly due to the false compositions of the refractory coatings.

6.3 EDS of the Cores of Castings

We intended to find out the chemical composition of the Manganese Steel castings using EDS, to check if it confirmed to the composition of Manganese Steel found by the volumetric method (carried out at the 'Chemical Analysis Lab' of the foundry) – i.e. 11.9% Mn, 1.1%C and 0.7% Cr. The castings were sectioned with a *Metkon METACUT – A 350 ABRASIVE CUTTER*. The mass percentages of the elements are shown below (Table 5):

Table 5. Mass % of elements in Mn-Steel Castings

	Mn-Steel Casting Composition			
Elements	Bare mold	Linseed Oil coating	Zircon coating	Magnesite coating
Si	0.48	0.74	0.57	0.62
Cr	1.65	1.97	1.31	1.70
Mn	11.03	11.16	11.65	12.26
Fe	Bal.	Bal.	Bal.	Bal.
Zr			0.11	

It is found that the contents of Cr and Mn in the Manganese Steel were in sync with thefoundry chemical analysis.But the volumetric method of finding chemical analysis is not reliable at all times; it is always preferable to make accurate tests (e.g.with EDS and C analyzer) to make elemental analysis. We can also see that in the Zircon coated mold casting, there has been a diffusion of Zr from the Zircon coating, into the Manganese Steel when it was poured into the mould cavity.

6.4 Hardness Testing

Hardness tests were performed on all four castings on their cast surfaces, and also on the sectioned surfaces. The Rockwell Machine was used to measure the mean hardness values. The results are tabulated (Table 6) as follows:

Table 6. Hardness values of Castings

	Surface (HRC)	Core (HRC)
Plain Casting	135.67	103.5
Linseed Oil Coated Casting	108.33	111
Zircon Coated Casting	127.5	108.83
Magnesite Coated Casting	119.17	117.67

The hardness of the surface is greater as compared to the core of the castings, in general. The high undercooling (ΔT) at the mould wall causes the surface of the casting to solidify first, followed by the slow cooling in the core of the casting[19]. The surface of the casting also undergoes a quenching effect due to being closest to the surrounding environment as compared to its core. The greater the quenching effect, the higher is the hardness of the surface. The greatest hardness values are achieved by the specimens that were cast without any coating and with zircon coating. These effects can also be correlated to the thermal conductivities(as mentioned in section 3).The greater the thermal conductivity of a coating, the greater will be the heat transfer across the mould wall[8]. Zircon coating has contributed to a greater hardness value to the surface of the casting, as compared to the Magnesite coating. Surface hardness is also attributed to the types of casting defects on the surface. The higher is the amount of oxide layers, the higher is the hardness. Oxide layers are ceramic in nature, enhancing the brittleness on the surface, and hence, the hardness[21].

7. Summary

Improving the surface finish of castings is a big dilemma of foundry industries. To smoothen up the surfaces of castings and making them free of any casting defects, refractory coatings are applied to mould cavities and cores. Differentiated various refractory coatings upon various properties like: density, pH nature, thermal expansion, thermal conductivity and refractory temperature; out of which Zircon and Magnesite provided the best combination of all of the properties that make a refractory coating suitable to give the best surface finish to castings. But after experimentation it was revealed that there is much more to getting good surface finishes for castings, than just applying refractory coatings. Above all features that will be addressed in the following, it is undeniable that proper ramming of the sand mould is enough to get good surface quality of castings.

Metal projections and casting defects were evident in almost all of the castings. Though optimum ramming of the sand mould was done (during the experimentation), the grain size of the sand has a very big effect on the compaction of the sand mould. The smaller the grain size, the greater is the compression strength and permeability of the sand mould – influencing the surface roughness of castings[5] by minimizing it.

Foundry variables like pouring temperature and pouring velocity also have an impact on the surface finish of castings. Very high pouring temperatures cause enhanced gas entrapments, leading to blowholes[20]. Decreasing the pouring temperature of Manganese Steel would not be a good approach to solving this problem, as it may cause solidification of melt before casting. If the mould box is a bit hot/warm, then a lower pouring temperature may be a possible remedy. High pouring velocities also cause sand erosion to occur, and the specimen size we dealt with was very small.

The castings made in the experiments were light section castings, of weights well below 10 kg. If thicker coats are applied to thin sections, then though the resistance to metal penetration will increase; however, there is a resultant loss of dimension and surface smoothness with thick coat applications[14]because chances increase that with each layer applied, the thickness is not uniform. It is therefore advised to use thin coating thicknesses for light section castings for enhanced surface improvements. Brittleness of the refractory layer also increases which may break if pouring velocity is high (as in these experiments).

The impurity of the coatings was one of the major reasons that deteriorated the casting quality. It is advised that the phase composition of refractory coatings should always be tested after their production (by manufacturers) and procurement (by the foundry industries). The elemental composition of refractory coatings certainly affects their properties like thermal conductivity, thermal expansion etc.

Lastly, it should be noted that the mould cavities were made with a wooden pattern. Better surface finish of castings would be expected to appear with aluminum patterns [13].

Nonetheless, despite all the flaws in various domains, it is apparent that the magnesite casting has a very high potential of serving as a refractory coating which can provide the best surface finish to Manganese Steel castings – as it was seen in the SEM result (Figure 2d). However, the appreciable results of Zircon coating can never be underemphasized.

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