Refractory Coating Technology: A Review

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ABSTRACT

Application of refractory coatings in foundry is very essential as they significantly enhance the surface finish of castings. Coatings applied on mould cavities, cores or patterns (as in lost foam casting) fill the tiny spaces in between the mould sand particles, solidify and render the mould surfaces smooth before pouring the liquid metal. The resulting enhancement of the surface finish of the casting has brought about an indisputable conclusion that there can be no acceptable casting without the application of refractory coatings. The casting production is considered as a backbone and influencer of the development of global economy as the level of industrialisation in each country is a reflection of the practical attention given to casting production. The demand for casting products has been on the increase over the years leading to increase in demand for refractory coatings. The indispensability of refractory coatings in casting production necessitates understanding the nitty-gritty of coating production technology which expectedly calls for a comprehensive review. The information provided in this study would undoubtedly serve as a handy summary of refractory coating production in relation to casting surface finish enhancement.

KEYWORDS

Refractory coating
Casting
Refractory material
Characterisation
Binder
Additive

1. INTRODUCTION

Application of foundry coatings, otherwise known as refractory coatings, in foundry is very essential as they enhance the casting surface finish. Applying refractory coatings in mould cavities brings about creation of a high thermal integrity barrier between the mould and the liquid metal making the thermal shock experienced by the sand system to reduce (Nwaogu and Tiedje, 2011). This thermal shock causes surface defects like veining, erosion, metal penetration, rat tail, burn-on, and scab. However, these defects are significantly reduced through the use of refractory coatings.

In the traditional casting processes, as cavities are created in moulds, when the molten metal fills the cavity and solidifies, it is discovered that the surface roughness is usually very high as a result of tiny spaces in between the mould sand particles. Refractory coatings occupy the gaps in the mould sand particles, making the surface of the cavities and cores smooth, thus giving the castings a better surface finish (Nwaogu and Tiedje, 2011). Similarly, castings made through evaporative pattern casting (EPC) otherwise known as lost foam casting without employing refractory coatings have very high surface roughness as is in the case of traditional casting processes. Thus, refractory coatings are equally employed in EPC and are applied on the foam patterns before they are buried in the mould to bring improved surface finish (Omidiji, 2018). A significant role is played by the refractory coating in the vaporisation of the evaporative patterns, the filling of the molten metal and casting formation (Luoyang Liushi Mould, 2019).

Recently, the global economy with its developmental trends was analytically studied (Holtzer, *et al.,* 2012). It was discovered that the nations with leading economic growth take the lead in casting production. The demand for casting products has been on the increase over the years (Foundry Planet.com, 2023). In fact, the trends towards electrical vehicles and light weight production will induce a rising aluminium foundry production. Similarly, it has been confirmed that in the last few years, the demand for steel casting has equally been on the increase in sectors such as oil, gas, mining, power, and agriculture (Mathov, 2022).

Most machine components and spare parts are products of casting. For instance, in the agricultural, petroleum, power, automobile, defence, electrical, ship building, railways, cement, food processing, ceramic and refractory industries, the vital machine components and spare parts are products of casting. The fact that the global economy has not graduated from depending on the foundry industry to thrive cannot be overemphasized. The very fact that people extensively depend on metallic products today indicates how indispensable casting products are. Without casting, metallic products cannot exist as every metal product begins from ingot, a product of casting. (Nwigbo, 2019). Thus, metals cannot exist without casting; without metals many products would be non-existent. It is therefore an accomplished fact that acquiring casting technology is necessary for self-reliance through economic prosperity. In an attempt to industrialise a nation, the indispensability of foundry should generate a great concern (Patrick and Akintunde, 2017). Yet, as important as foundry is, it cannot be effectively carried out without the use of refractory coatings. Omidiji (2018) showed the indispensability of refractory coatings in foundry when he emphasized conclusively that there can be no acceptable casting without the use of refractory coatings. Increase in demand for casting products has invariably increased the demand for refractory coatings.

Not much research has been done recently in the area of application of refractory coating technology in casting despite its indispensability. Thus, this paper aims at examining the length and breadth of refractory coating technology including recent research activities and alternatives to the various coating components considering factors such as availability, cost and efficiency. The indispensability of refractory coatings in casting production therefore calls for a comprehensive review.

2. VARIETIES OF REFRACTORY COATINGS

Refractory coatings are broadly categorized into two based on their applications, namely, dry application and wet application. Coatings applied wet are further divided into carbon-based and carbon-free coatings. Refractory coatings for wet application can be divided on the basis of their carrier systems as aqueous carrier-based and organic solvent carrier-based (Figure 1).

2.1. Coatings applied dry

Plumbago is the refractory material for dry application most commonly used. Other materials less frequently used are white

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talc, wheat flour and mica. The coatings are usually blown or shaken onto mould surfaces from open-mesh cloth bags (AFS, 1962).

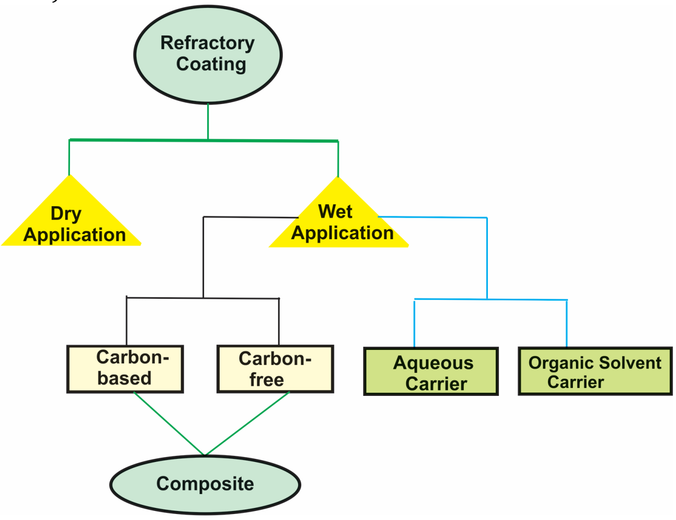

Figure 1: Varieties of Refractory Coatings (Nwaogu and Tiedje, 2011)

2.2. Coatings Applied Wet

Coatings for wet application can exist either in paste or powder form. The moisture of the sand enhances the coating adherence on the substrate. Anthracite, coke, graphite or a combination of two or more of the aforementioned refractory materials is the main constituent of carbon-based coatings. Carbon free coatings may contain mica, zircon, silica, talc, olivine, clay, or a combination of two or more of the materials (AFS, 1962). Coatings may contain both carbonate and non-carbonate raw materials in an attempt to reap the synergetic advantage.

3. QUALITY ISSUES IN FOUNDRY COATINGS

The quality of castings can be depicted in good surface finish and minimum or no defect. Several variables contribute to the quality of castings. Some are coating related while some are not. Variables affecting the quality of castings that are coating-related include the coating material constituents, viscosity, coating thickness, liquid absorption capability, percentage solid, casting method, gas permeability and particle size. Several studies recommended 75 μm as the particle size of the refractory coating in order to obtain the best surface finish of the casting (Kumar, *et al.*, 2008, Nwaogu and Tiedje, 2011).

3.1. Characteristics Of Refractory Coatings

High refractoriness, optimum porosity/permeability and reduction in the physico-chemical reactions at the metal-coating interface are the basic requirements for foundry coatings (Kascheev *et al.,* 1982). Coating high refractoriness ensures that it is able to withstand the high temperature of the molten metal while optimum permeability minimizes air entrapment. Other characteristics include good adhesion to the mould or core surface leading to prevention of spalling on drying, ability to dry fast, no tendency to blister, scale or crack on drying, minimum core strength degradation, stability in storage, good suspension and remixing properties, and good spread (Nwaogu and Tiedje, 2011).

3.2. Applying The Refractory Coating

Refractory coatings are commonly applied through dipping, spraying or swabbing of the substrate. The method adopted depends on the part geometry and size, as well as ease of application. To obtain almost uniform thickness, spraying is the best of the three methods since in reality it is difficult to obtain constant coating thickness for all cavities, cores or patterns as the case may be (Omidiji, 2018). Uniform coating thickness is desirable as it gives room for uniform permeability. Spraying is recommended where patterns are without inner channels while dipping is recommended for patterns with inner channels of complex shapes (Pacyniak, 2008). In the dipping method, there is much variableness in thickness while in the swabbing method, the brush used may make marks on the pattern thereby creating unwanted marks on the castings. After applying the coating, its excess is allowed to flow off, giving the coating uniform thickness, and hence uniform permeability (Patrick and Akintunde, 2017). The denser the pattern in evaporative pattern casting (EPC), the thinner should be the coating to improve permeability. Yet, the danger is that thinner coating may result in metal penetration. Using coarser sand or a higher vacuum level can enhance the removal of the products of pattern decomposition.

4. CONSTITUENTS OF REFRACTORY COATINGS

The three major constituents of a refractory coating are refractory filler, binder and additive (Figure 2). Sometimes where high casting surface finish is not a must, a refractory coating may contain just the refractory filler alone (Omidiji, 2018). As the three major constituents of a refractory coating are usually in powder form, for wet application, there is need to add a solvent to enhance the deposit of the coating on the substrate. The foregoing necessitates the addition of a liquid carrier as a coating constituent. Other coating constituents termed enhancing agents are added to improve effectiveness, suspension stability and durability. Enhancing agents include wetting agents, anti-fermentation agents, dyes and suspension agents (Beauvais, *et al.,* 1988). Thixotropic agents are also enhancing agents added so that the coating will not drip down from the substrate which may be the mould, core or pattern in case of EPC (FOSECO, 1999). Foundry coatings can vary from one country to another as a result of the use of local materials (Shroyer, 1958, FOSECO, 1999).

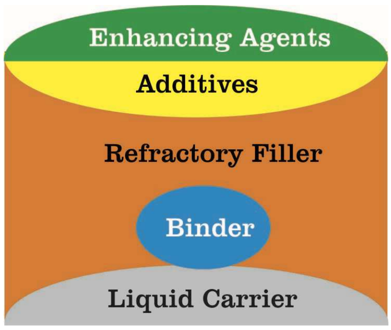

Figure 2: Refractory Coating Components

4.1. Refractory Fillers

Refractory fillers are materials that are highly refractory mainly as a result of their high melting points (Moore, 2001, Pirkle and Podmeyer, 1998). A very significant characteristic of a refractory material is its refractoriness defined by the American Society for Testing and Materials (ASTM) as "the capability of maintaining the desired degree of chemical and physical identity at high temperatures and in the environment and condition of use" (Nwaogu and Tiedje, 2011). Very significant while considering the refractoriness of a material is its melting temperature which is the maximum temperature of use (Hlavac, 1982). In a refractory coating, the refractory material is dispersed in binder and constitutes the skeleton of the coating film. It significantly dictates the viscosity, density, hardness and permeability of the coating film. The higher the percentage of the refractory filler in a coating, the higher are its viscosity, density and hardness while the less its permeability.

4.1.1. Characteristics of refractory materials

Refractory materials have several characteristics which include high melting points resulting in high refractoriness, not being wetted readily by the liquid metal, chemical inertness with the liquid metal, having consistent PH, absence of volatile elements that could produce gas while being heated, low thermal expansion and being compatible coating constituents including chemical binders. A refractory material should be void of impurities. Its particle size and particle shape as well as particle size distribution (PSD) should be suitable. The particle shape of a refractory material which determines the mechanical properties of the refractory coating significantly depends on a parameter called the aspect ratio. The aspect ratio is the ratio of the average diameter to average thickness of the particle. As the refractory particle aspect ratio increases, the coating reinforcing effect also increases. The PSD of a refractory material shows the amount per weight or volume of particles in percentage smaller than a given size. Grinding the refractory material automatically alters its PSD. Fine particles improve impact strength whereas coarse particles could result in fractures or cracks because under loading they serve as points of high stress concentration (Houssa, 2003). Refractory materials are of diverse properties; their choice in foundry depends on the type of metal used in casting.

4.1.2. Existing refractory materials

There are several examples of refractory materials which include silica, zircon, graphite, mica, chamotte, magnesite, chrome magnesite, and olivine. Few of the foregoing refractory materials are described as follows.

i. **Silica flour:** This is a common refractory material containing the mineral called quartz. Its chemical formula is SiO_2. It has a density of 2650 kg/m^3 and a coefficient of thermal expansion of 19mm/m with a melting point of 1700°C (Hlavac, 1982). It is slightly acidic (pH 4.5 - 6.5) with a thermal conductivity between 9.5 and 12.5 W/mk (Ulrich and Molesky, 1998).
ii. **Zircon flour:** This is a refractory filler of high refractoriness resulting from its high melting temperature (2727 °C). Some of its other sterling qualities are its low coefficient of thermal expansion (3.2 mm/m) and it is not being readily wetted by molten metal (Aftab, *et al.,* 2019). It is basically used for coatings while casting steel. The chemical formula for zircon is $ZrSiO_4$ (Zirconium silicate). It has a high density of 4500 kg/m^3. It is slightly acidic (PH of 5.5), and has a thermal conductivity of 12 to 15 W/mK).
iii. **Talc:** This has the chemical formula of $Mg_3Si_4O_{10}(OH)_2$. It is a hydrous magnesium silicate mineral. It is the softest material on Mohr's scale of hardness with Mohr's hardness of 1 (Yekeler, 2004). Its density ranges between 2600 and 2800 kg/m^3. Its other characteristics include high melting point (1500 °C), low hardness, adhesion capability, low electrical conductivity, chemical inertness and high thermal conductivity (Ariffin, 2000). It is platy, organophilic and hydrophobic (Acimovic-Pavlovic, 2007).
iv. **Graphite:** as a refractory material is not wetted by molten metal and so it resists metal penetration when used to coat moulds. It is thus commonly used as refractory filler in casting (AFS,1962)
v. **Mica:** This is a plate-like crystalline aluminosilicate (Gan, *et al.*, 2001). The seven important mica minerals are muscovite (potassium mica), paragonite (sodium mica), lepidolite (lithium mica), phlogophite (magnesium mica), lepidolelane (iron mica), biotile (magnesium iron mica), and zinnwaldite (lithium iron mica). The most common mica mineral is muscovite. Both muscovite and phlogophite are the only types of mica that are of commercial importance. As a result of its lamellar plate-like nature, mica used as refractory filler in foundry mould or core coatings reduces or completely eliminates finning defect in castings (Pirkle and Podmeyer, 1998).

4.2. The Use of Binding Agents in Refractory Coating Production

The binding agent is one of the major constituents of a refractory coating. Binding agents hold the particles of the refractory fillers together and also enhance the attachment of the coating matrix to the substrate (Nwaogu and Tiedje, 2011). The lower the refractory filler particle size, the higher is the amount of the binding agent needed in a refractory coating matrix. Examples of binding agents used in refractory coating production are bentonite and kaolin.

4.2.1. Bentonite

Bentonite, named after Fort Benton who once had much of it, is an old swelling absorbent type of clay. It is common globally. Its ability to absorb large amounts of water increasing its volume by up to eight times makes its site not suitable for road or building construction (Jackson, 1997). However, its cohesiveness makes it useful as a binder and as an additive to improve the plasticity of kaolinite for pottery. The three types of bentonites are sodium bentonite, calcium bentonite and potassium bentonite.

4.2.2. Kaolin

Kaolin is also called China clay. It is a rocky material which is rich in kaolinite and halloysite, where kaolinite is a soft earthly mineral, a form of clay with the chemical formula $Al_2Si_2O_5(OH)_4$ (Pohl, 2011). As a result of the presence of iron oxide, kaolin is coloured pink, orange or red in many parts of the world. Kaolin is an essential constituent in the production of China porcelain and is widely used in the manufacture of paint, rubber, coated paper, food additive, cosmetics, toothpaste, refractory coatings and several other products. It is a very refractory aluminium silicate as a result of its fairly high melting point of 1770 °C. However, this temperature drops quickly as impurities increase.

4.3. Coating Additives

Additives are substances added to refractory coatings to improve their quality. Sometimes a refractory coating may have just refractory filler as its constituent with the exclusion of other components (Omidiji, 2017). However, to improve the quality of refractory coatings, additives such as bottom ash and fly ash are added where both bottom ash and fly ash are residues resulting from combustion of coal mineral (Dale, 2023). In an industrial context, bottom ash is one of the four coal combustion residuals, the other three being fly ash, flu-gas desulfurization, and boiler slag (EPA, 2021). The ash that falls to the bottom of the combustion chamber of the boiler is referred to as bottom ash while fly ash is the portion that flies up the chimney.

4.4. Liquid Carriers

Refractory coatings for wet application employ liquid carriers which may be aqueous (water) or volatile organic liquid carriers. Examples of organic liquid carriers are alcohol-based carriers which include methyl alcohol (otherwise called methanol), isopropanol and ethanol. While the refractory coating employing an aqueous carrier must be dried after application, the ones employing organic-solvent carriers can dry rapidly on their own or may be ignited so that it dries due to its combustion (Pursall, 1970)

5. CHARACTERISATION OF REFRACTORY COATINGS

Characterisation of foundry coatings is necessary to ascertain their behaviour and quality with respect to their constituents. Parameters used to characterise refractory coatings include viscosity, specific gravity, solid content, Baume parameter, coating thickness, colloidal stability, permeability, wettability, core degradation, surface tension and coating penetration depth

(Nwaogu and Tiedje, 2011). Some of the foregoing characteristics are highlighted thus.

5.1. Specific Gravity

Specific gravity of a coating is defined as the ratio of its density to the density of a reference material. The reference material commonly chosen is water. The coating specific gravity could make inferences to be drawn as regards the refractory components and the total solids the coating comprises (Cast TIP, 2010). The refractory material can easily be kept in the suspension agent having similar specific gravities (Pursall, 1970).

5.2. Viscosity

Viscosity is a measure of the flow properties of a fluid. It describes flow resistance. It expresses the magnitude of a fluid internal friction. In other words, viscosity measures resistance of a fluid to deformation at a given rate. Informally, viscosity of a fluid is indicated by its thickness. Its SI unit is Newton-second per square metre (NS/m^2), Pascal second or poiseiulle. Viscosity can be measured through different methods including the use of viscometer and flow cup measure (Nwaogu and Tiedje, 2011)

5.3. Baume' Parameter

The Baume' test is quick and easy. The test is carried out using a hydrometer consisting of thin glass tube closed at both ends, with one end enlarged into a bulb containing mercury or fine lead shot (Nwaogu and Tiedje, 2011). The glass tubular end contains a calibrated scale in degree of Baume. The coating sample is first mixed thoroughly and the hydrometer is then floated in the coating. The Baume degrees are then read on the hydrometer scale directly the moment it is no more sinking (Baker, 2002). Coating viscosity can be presented in degree Baume as Baume number is directly proportional to viscosity (Winardi and Griffin, 2008). The specific gravity of the coating and the Baume scale of numbers are related.

5.4. Solid Content

The solid content of a coating is a measure of the quantity of refractory materials in it. The refractory materials protect the mould and core. The higher the percentage solids, the more protection the coating gives. The solid content also dictates the density, viscosity, thickness, and coverage which are important coating parameters (Nwaogu and Tiedje, 2011). Determining the solid content of a coating enhances reproducibility of the aforementioned properties. It is therefore necessary to measure the solid content of the coating. This is achieved using equation 1.

$$Sc = \frac{Wd}{Wo} \text{ x } 100\% \quad (1)$$

Where Sc is the percent solid content of the coating; W_d is the weight of the dried coating; W_o is the original weight of the coating.

5.5. Colloidal Stability

Colloidal stability describes the formation of uniform suspension of the particles in the coating matrix. The resistance of the particles to aggregation determines the stability. The sedimentation rates give the understanding of the formation of uniform suspensions. It is assumed that the particles are spherical in shape making it possible to apply Stokes' Law. The sedimentation rates can be calculated by equating gravitational and frictional forces (equation 2)

$$\frac{dx}{dt} = [(\frac{4\pi}{3}r^3)(\rho - \rho')g]/6\pi r\eta = [2r^2(\rho - \rho')g]/9\eta \quad (2)$$

Where r = refractory particle radius; ρ = coating density; ρ' = refractory material density; η = coating viscosity; g = acceleration due to gravity

For a particle of density ρ, relative molar mass (M), surface tension ($^\gamma$) and radius (r), the pressure difference across the curved surface, P_r, compared to that across a flat surface, P_o, is expressed through equation the Kelvin equation, as presented in equation 3 (Wright and Sommerdijk, 2001).

$$RT\ln(P_r/P_o) = 2Y\rho rM \quad (3)$$

5.6. Coating Thickness

All the available tests for measuring coating thickness are destructive in nature. Sometimes, the coating thickness is measured with the aid of a microscope after sectioning the core (Ramrattan and Joyce, 2009). It has been discovered that the coating thickness is strongly related to its viscosity (Baker, 2002. Nwaogu and Tiedje, 2011). Generally, dry coating thickness has proved difficult to measure. However, wet coating thickness can be measured more easily. The wet coating layer thickness is usually measured with the aid of the elcometer wet film 'comb'.

5.7. Coating Permeability

Coating permeability is the measure of the amount of gas that can pass through the coating on drying after being applied on the substrate. This is dependent on the amount and type of the refractory materials contained by the coating. It also depends on the dry film thickness deposit. The permmeter is the instrument for measuring the permeability of a coating. The higher the coating permeability, the less is the time it takes the degradation products to escape. It was reported that mould filling times increased with decreasing coating permeability (Chen and Penumadu, 2008).

Darcy's law (equation 4) is the standard used to characterise the permeability of porous materials. The law shows the relationship between pressure gradients and volumetric flow with the properties of the fluid and porous materials.

$$k = \mu QLA(\Delta P) \quad (4)$$

where, k= permeability value in units of Darcys; μ = viscosity of the fluid in centipoises; Q = volumetric flow rate measured in cm^3/sec; A = cross-sectional area of the specimen perpendicular to the direction of gas flow in cm^2; $\Delta P = (P_2 - P_1)$ = pressure drop over the specimen in atmospheres; P_2 = pressure at outlet side of the specimen in atmospheres; P_1 = pressure at inlet side of specimen in atmospheres.

The equation is valid when KA/μL is a constant in the laminar flow region implying small Reynolds number (Anderson, 1966, Sogabe, 1992, Wang and Liu, 2004). However, deviation from Darcy's law is observed at a high Reynolds number. The Darcian permeability coefficient K shows the ability of the porous medium to transmit fluids.

6. RECENT STUDIES ON THE DEVELOPMENT OF REFRACTORY COATINGS

Bauer *et al.* (2009) developed corrosion resistant coatings for typical materials used in aggressively high temperature environment like incinerators and cement plants. There were four different coatings developed: One was ferritic, two austenitic and the last one was nickel based. They employed several coating techniques like Nickel plating and pack cementation. The samples (both coated and uncoated) were examined for corrosion resistance in two process environments, namely, hot gas corrosion environment and molten salt environment (hot corrosion). Nickel plating showed better result for the ferritic material than pack cementation. Prstic et al. (2012) developed zircon-based foundry coating for application in EPC. Optimization of the coating composition was attained with controlled rheological properties by applying various coating components (Prstic et al. 2012). Prstic et al. (2014) investigated "refractory coatings based on refractory fillers (talc, cordierite, zircon and mullite) for application in EPC". Design optimization of the coatings as well as their consequent synthesis was achieved by applying different kinds of coating components and altering the coating production procedure.

Omidiji et al. (2016) made varieties of silica-kaolin refractory coatings. Silica flour was the refractory filler while kaolin was the binging agent. Ratio method was used to form basis for the factorial design of experiment which led to nine runs. The carrier used was methyl alcohol at 99% concentration. Pouring temperature was observed as a process parameter alongside the mix ratios of the coatings. They characterized the coatings using differential thermal analysis and x-Ray diffraction. The gating system was designed and the casting was done. They used a digital profilometer to take the measurement of the surface roughness. In conclusion they observed that the mix ratio 90 % silica flour – 10 % kaolin produced the lowest value of surface roughness and the lowest material loss in the DTA test. The best casting produced was correspondent to 650oC pouring temperature. Omidiji (2017) developed a refractory coating from locally available silica sand and kaolin. Silica flour was the refractory filler while kaolin was the binder. Fly ash was added as an additive.

In an attempt to determine the quality of the refractory coating, he made three varieties of the refractory coating and used them in coating moulds. The Taguchi's L9 orthogonal array was used for the experimental design. Molten aluminium metal pouring temperatures were chosen as 650oC, 700oC and 750oC. He concluded that pouring temperature had the highest influence on the mechanical properties of the castings, followed by the refractory filler (silica sand), additive (flyash) and binder (kaolin). Aftab et al. (2019) verified the effects of linseed oil-, zircon- and magnesite-based coatings on the surface finish and hardness of manganese steel castings. A plain mould (without any coating) was used as the baseline study. In the course of preparing the coatings from the refractory materials, the zircon powder was dissolved in isopropyl alcohol (C3H7OH) in a proportion of 26 % to 74 % - forming a paste. The magnesite coating was similarly prepared. The wet coatings were then applied using a spray gun. The coating was dried with the oxyacetylene burner at each spray pass. That was repeated several times to ensure that a thick coating was not made at once to avoid the problem of trapping residual water or moisture. The surface of the bare mould casting showed a very irregular surface as a result of lack of coating which should have filled up the holes. The casting showed metal projections, making their way through the sand mould's surface roughness. There were also gas entrapments resulting from the residual moisture left in the sand mould. Both microporosity and macroporosity resulting from the action of metal shrinkage and gas entrapment during solidification were shown by the surface of the linseed oil casting. The main defect in the cast was hydrogen entrapment. Slag presence was also apparent. There was porosity in the surface of the casting produced in zircon-coated mould. However, the surface finish of casting using zircon coating was smoother than the two previous ones.

7. CONCLUSIONS

This comprehensive review encompasses the basics of refractory coating production including facts about its components such as refractory fillers, binders, additives, liquid carriers and enhancing agents. The handy information provided will help foundries and coating manufacturers to identify the right parameters and their alternatives to enhance the effectiveness of refractory coatings in bringing about castings with improved surface finish. Besides, researchers are encouraged to delve into development of high-grade refractory coatings to cater for the growing demand for foundry products and coatings as recent research activities in coating production are an eye-opener to the possibility of harnessing abundantly available refractory materials and other coating constituents in form of mineral resources in the development of refractory coatings.

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