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Research article

Foundry Coatings - Review

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A B S T R A C T

The main purpose of this publication is to present the founding stages of the foundry industry and its fundamental importance to the engineering sector. The second focus is to examine the technology of casting in sand molds and more specifically those based on no-bake process(chemically hardening). The auxiliary materials used for the production of sand molds and their importance for the quality of the final part-casting are examined in detail. Special attention is paid to refractory coatings, and in particular those with graphite filler, because of their wide application. The main chemical parameters are presented and the need to study their geometric and tribological characteristics and their influence on the quality of manufactured castings is emphasized. Until now, the author of the publication has studied the micro hardness, roughness, friability and gas permeability of refractory coatings, for which parameters no previous information on similar tests has been found. The research carried out was financed under phd project No. 222ПД0005-05 – TU Sofia, Bulgaria.

1. HISTORICAL PREVIEW AND TECHNICAL PARAMETERS

1.1 Historical preview

Since the evolution of mankind, people have used their intelligence and creative instinct to develop and optimize their work. They created bowls, tools and weapons from stones and wood that occur naturally in nature. Over time they discovered other elements such as gold, silver, copper and iron which were readily available in the form of nuggets and were easily melted with the help of firewood and charcoal and could be used to make various implements as desired and human needs. Therefore, in different eras, iron and copper became the most used natural materials.

Gold, silver, copper, iron, lead and tin have been known to man since ancient times. The basic process of melting the metals in a furnace, using casting patterns and solidifying the metal in the different types of moulds remains the same till today.

Metal casting (Fig. 1.) is a decisive factor that leads to the progress of any civilization. Important eras of prehistoric times are named after the metal that was widely used in that era. Some of the important eras and role of foundry are as follows.

- The Copper Age (7700-3300 BC)
- The Bronze Age: (3300-1200 BC)
- The Iron Age (1200 BC)
- The Industrial Era (18th century onwards)

Today, metal casting continues to be a complex process that requires precise chemistry and flawless execution. One of the main factors for the successful production of a casting is a correctly made mould. One of the most common mould making technologies is that by using sand, and the following pages will look at the main types of sand mould making technologies and their evolution towards the centuries [1].

Fig. 1 Metalcasting.

Clay moulds have been used in ancient China since the Shang Dynasty (ca. 1600 to 1046 BC). The famous Houmuwu ding (ca. 1300 BC) was made using clay moulding.

The Assyrian king Sennacherib (704–681 BC) cast massive bronzes weighing up to 30 tons and claimed to be the first to use clay moulds.

The Sand casting method was recorded by Vannoccio Biringuccio in his book published around 1540.

In 1924, the Ford automobile company set a record by producing 1 million cars, consuming a third of the total US die casting production in the process. As the automotive industry grew, so did the need for increased foundry efficiency. The growing demand for castings in the growing automotive and engineering industries during and after World War I and World War II stimulated new inventions in the mechanization and later automation of sand casting technology. . Improvements are being made in moulding speed, molding sand preparation, sand mixing, core manufacturing processes. . In 1912, the first sand mixer with individually mounted rotating blades was marketed by the Simpson Company. In 1915, the first experiments began with bentonite mixture instead of ordinary refractory clay as a binding additive to the moulding sand. This increases the strength of the forms in the dry and wet state. In 1918, production began on the first fully automated foundry to produce hand grenades for the US Army. In 1940, thermal regeneration of moulding sand and sands was applied. In 1952, the technology for making shell moulds with fine, pre-coated sand was developed. In 1953, the process of thermally hardening sand cores was invented. In 1954, a new binder came into use - water glass (sodium silicate), hardened with CO_2 from the surrounding air [2].

So far, important historical facts proving the importance of foundry technology and sand moulding in particular have been considered. In the following lines, attention will be paid to the main theoretical parameters needed to be clarified the actual need of research.

1.2 Technical parameters

Casting in sand moulds (Fig. 2) is a process in which the sand used for the production of the moulds is inserted repeatedly. At first glance, the processes of creating moulds can be defined as simple and complex, but the reality is different. To produce a quality mould or casting, many factors must be taken into account. The unit weight of the castings produced varies from a few grams to several tons. Almost all types of metals can be casted in sand moulds. The complexity of the relevant parts also varies widely - from castings with a simple configuration such as counterweights, to parts for hydraulic distributors with high accuracy requirements. Sand moulds have three important advantages over other technologies:

1. Economy,
2. Recyclability,
3. High refractory properties.

Sand casting is one of the few processes available for metals with high melting temperatures such as steels, nickel and titanium. Because of its flexibility, heat resistance, and relatively low cost, sand casting is the most widely used casting process.

Castings are produced by pouring liquid metal into the mold cavity . For casting to be successful, the cavity must hold its shape until the metal has cooled and solidified completely. Clean sand crumbles easily, but moulding sand contains a binding material that increases its ability to withstand heat and hold its shape. There are several basic types of sand mixes as follows:

- Bentonite mix (mixture of quartz sand SiO 2, ground coal, bentonite clay and water) for use without drying.
- Chemically-hardening mixtures, again produced mainly from quartz sand and various fasteners, as follows:
  - Resole resin (alkaline-phenolic) and catalyst esters,
  - Novolac resin (furan) and catalyst acids,
  - Cold box process, phenolic resin, isocyanate-based resin and amine gas catalyst,
  - Water glass with catalyst CO2 or esters
  - Others.

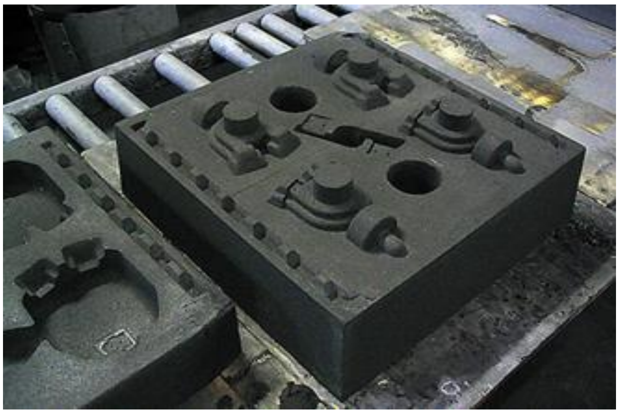

Fig. 2. Sand mould.

The main properties of moulding sand are the following:

- Strength -the ability of the sand mould to maintain its geometric shape under the conditions of mechanical stress.
- Gas permeability -the ability of the sand mould to allow the escape of gases and steam during the casting process.
- Moisture content -moisture content affects the strength and permeability of the mould: too little moisture content can cause spalling and gas voids in the casting.
- Fluidity -the capacity of sand to fill small voids. High fluidity creates a more precise shape and is therefore useful for detailed castings.
- Grain size -the size of individual sand particles.
- Grain shape- this property estimates the shape of individual grains of sand based on how round they are.

Three categories of grains are typically used in foundry sand:

1. Round-grained sands provide relatively low bond strength but good fluidity and surface finish.
2. Ribbed shaped beads have greater bond strength due to interlocking, but poorer fluidity and permeability than rounded ones.
3. Subangular grains are the middle ground. They have better strength and lower permeability than rounded grains, but lower strength and better permeability than angular grains.

There is another theory regarding the shape of the sand grains, according to which the oval shaped sand grains have higher strength due to their smaller surrounding surface compared to the ridged sand grains, because the smaller surrounding surface area requires less binder to be covered. That is, for an equal amount of binder, a mould made of spherical sand will have a higher strength.

- Flexural strength- the ability of the sand mixture to collapse under force. The higher flexural strength of the mould allows the metal casting to shrink freely as it solidifies without the risk of hot tearing or cracking.
- Refractory strength -the mould must not melt, burn or crack as molten metal is poured into it. Refractory strength measures the moulding sand's ability to withstand extreme heat.
- Recyclability -the ability of moulding sand to be reused (after crushing the sand) to produce other sand castings in subsequent manufacturing operations [3].

2. REFRACTORY COATINGS

In addition to the quality of the form, of determining importance for the good surface of the part is the refractory coating applied to the form before pouring the metal, because when pouring the form with liquid metal, its surface is subjected to thermal, mechanical and physicochemical effects. The oxidation products of the metal reacting with the materials contained in the mold form low-melting materials such as silicates that lubricate the quartz sand grains. This promotes the penetration of the metal into the internal spaces and the formation of mechanical scale, which is difficult to remove from the surface of the casting. Given that sand moulds and cores are highly porous, the production of quality castings is only possible by applying protective refractory coatings to the cores and moulds.

The main requirements for refractory coatings are minimum porosity and reduction of the physico-chemical reaction at the metal-coating contact. These refractory coatings are used to improve the quality of castings and reduce the cost of cleaning and machining the final part, because after coating, castings with smoother surfaces are produced because the coating fills the space between the sand grains, also after application of coating, easier peeling of a sand crust adhering to the details is observed, which is easily eliminated by shot blasting. The elimination of some defects such as metal penetration, veining, erosion, scorching is also observed (Fig. 3) [4].

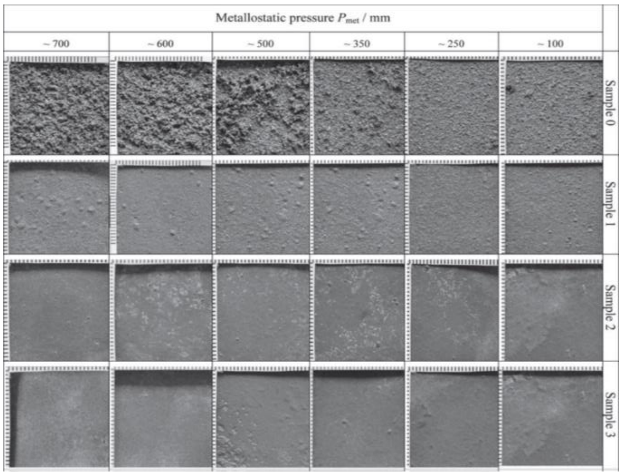

Fig. 3. Comparison of casting surface versus metallostatic pressure with and without refractory coating application.

2.1 Main features

A refractory coating must have the following characteristics:

- Sufficient refractory properties
- Chemical compatibility between the type of coating and the type of metal that will be cast in the mould
- Good adhesion
- Gas permeability
- Easy drying
- Durability of the layer after drying
- Good mixing properties
- Improve strength/
- Good storage stability
- Good coverage
- Good application properties according to the chosen method
- To achieve these characteristics, the refractory coating will consist of:
- Refractory filler
- Liquid carrier
- Binding agents
- Other Supplements- defoamers, wetting agents, biocides, etc. as shown in Figure 4.

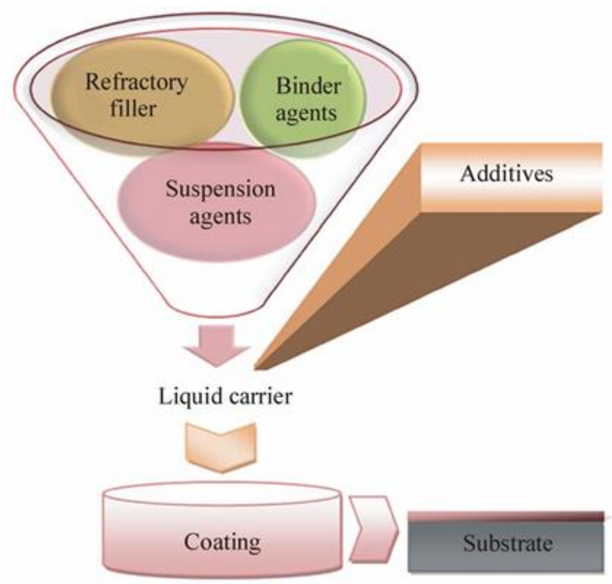

Fig. 4, Schematic of the components in the coating.

2.2 Graphite coatings

Graphite refractory fillers are the most common and are used for coatings in iron foundries and foundries for non-ferrous metals. Molten metal does not wet the graphite and sand grains coated with graphite coatings are resistant to metal penetration. This is the reason why graphite coatings are usually used for moulds and cores, except in steel castings. Coatings containing carbon constituents are not used on steel except for low carbon steels. The reason for this is that the steel is sensitive to the carbon content, and if there is the penetration of carbon, the properties of the steel will change. The graphite used is naturally flake type, silvery white appearance, fine powder. The use of graphite coatings improves the subsequent cleaning of the casting surface. The surface of the mould, on which the coating is applied, does not form pores through which liquid metal can penetrate. It is believed that the introduction of particles of graphite powder and subsequent firing fixes them and thus prevents their subsequent removal. Coatings based on graphite filler have the largest share of application due to the fact that they can be used for the widest range of metals - cast iron, carbon steels as well as non-ferrous alloys such as aluminum and bronze.

Regarding the liquid carrier a typical organic solvent-based or alcohol-based coating contains isopropanol (isopropyl alcohol) as a liquid thinner, which is released by burning the isopropanol. Other types of diluents are methanol, ethanol, hydrocarbons and chlorinated hydrocarbons. They dry very quickly. Isopropanol is recommended for use on large shapes and hearts. Isopropanol has good burning characteristics with a slow burn and moderate flame. This reduces the likelihood of overheating the sand surface and subsequent sand friability problems. Isopropanol is also technically acceptable - perhaps because it is compatible with a wide range of binders also used in the recipe of these coatings. Most of the organic solutions are air dried. These include carbon tetrachloride, methylene chloride, chloroethene and chloroform.. Due to the rise in isopropanol prices and due to the increased demand caused by the crisis caused by Covid 19, the subject of this dissertation is methanol alcohol, which remains most easily accessible and with the best indicators for its price [5].

2.3 Different way of application

Several variables dictate the choice of application method. Part geometry and size, appearance, and performance all influence the choice of coating method.

Other factors that influence the choice of application method are available painting facilities, space, climate and others. Some systems can be operated manually or automatically. Others require additional equipment, such as storage tanks or air supply. Different equipment can provide different coating parameters - viscosity, desired layer thickness. The complexity of the part determines with the greatest weight the method of application. This depends on the immersion time, number of applied layers and others. One factor that is important for all application methods is the transfer efficiency of the coating onto the mould/core. Transfer efficiency is the percentage of hard coating material used that is actually deposited on the surface . The amount of solvent in the coating is irrelevant. The higher the transfer efficiency the better as more coating material adheres to the heart/form and less is lost. Transfer efficiency ranges from 25% to 40% for conventional injection systems and up to nearly 100% for immersion. Much of the contamination and waste created by finishing operations can be reduced or eliminated by improving the transfer efficiency of the coating system [6].

The main ways of applying a casting coating to hearts or shapes are as follows:

1. Application with a brush or pad
2. Injection
3. Immersion
4. Watering

Brushing and tamping

Brush and pad coating is a method used in many foundries. The force caused by brushing helps to push the refractory particles into the pores of a sand surface, which is a desirable characteristic. A pad is the most useful aid in covering the inside of difficult pockets and corners. Both methods give non-uniform thickness of the coating as it also depends on the skill of the operator.

Sparying

It is a much faster medium for a wide range of applications used in foundries of all kinds. It is important to pay more attention to the composition of the coating, because there is less mechanical effort to force the particles into the pores between the sand grains. Solids selection and overall viscosity are more important when spraying than when applying with a brush or pad. Spraying is applied through specially designed fine spray guns. This method, as well as brush application, is characterized by difficulty in recoating in depth. One of the reasons for this is the back pressure air , which prevents the deposition of refractory in the cavities. The airless spray system helps to overcome this drawback. Airless spray has higher transfer efficiency.

Immersion

Dip coating techniques can be described as a process where the substrate to be coated is immersed in the liquid or coating and then withdrawn at a controlled rate under controlled temperature and atmospheric conditions. Coating thickness increases with faster drawn e . The layer thickness is determined by the buckling forces on the coating base as shown in Figure 6 .

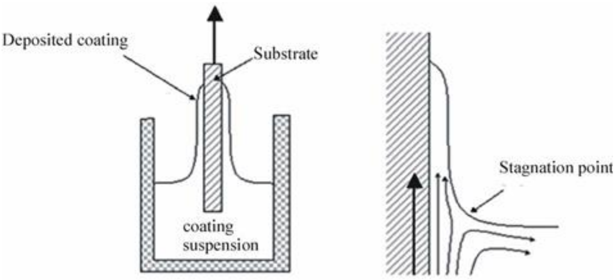

Fig. 6. Schematic diagram of the dipping process.

As soon as possible is the download, the more material remains on the mould/core surface as there is no time for the coating to flow back to the bath in which the immersion takes place. Immersion is usually used for cores and is well suited for automatic applications. This method improves high productivity and carryover ratio (almost 100%) by putting in relatively little work. The effectiveness of dip coating is highly dependent from the viscosity of the coating, which thickens on prolonged exposure to air unless carefully stored. The viscosity of the coating must remain constant in order to the quality of the deposited film also remains the same. To be maintain viscosity, solvent must be added periodically. This leads to an increase in the content of volatile organic compounds. Immersion is not suitable for parts with a hole or cavities. Other factors that determine dip coating performance includes coating density and surface tension. Better surface penetration is obtained than this with spray due to the pressure of the coating head in the dip tank. A uniform surface thickness is required to maintain dimensional accuracy and true reproduction on contour. Patchy coverage is worst when it works down like tears. This defect may be encouraged by nature of the surface to be coated, but is mainly due to the type of the suspending agent used in the coating. Tears and such coating defects are sources of high outgassing and casting can lead to defects [6].

Pouring

Pouring is a method of applying a refractory coating that can be described as wetting the molds or heavy cores with a hose at low pressure. In pouring, the mold or core is manipulated so that it is at an angle (20 to 40˚ to the vertical) in front of the operator and the coating is applied via a hose, as seen in Figure 7, starting at the top and in lateral motions progressively working down to **the** low part of the form. Dipping is usually used for large or complex shapes/odd shaped hearts that are difficult or impossible to dip. The spray coating process is easy to mechanize, requires little space, relatively low installation cost, low maintenance, and has low labor and operator skill requirements. The coefficient of transfer of the coating when pouring is over 90%. The thickness of the applied layer mainly depends on the viscosity of the material. This method eliminates the potential problems that occur with some of the other brush, spray, or dip application methods. Through this method, it is possible to create a surface layer and a secondary layer - the first serves as a barrier between the metal and the mold, and the second fills the pores of the mold between the sand grains, which leads to a reduction in the formation of defects such as veins and others [7].

Fig. 7. A mechanized pour coating system where the mold is placed at an angle.

2.4 Parameters of refractory coatings

In order to properly understand the behavior of the coatings, their characterization is required. The parameters that characterize the casting coating are discussed below.

Specific weight

Specific gravity is the unit weight per unit volume and is a quick test that allows conclusions to be drawn about the amount of solids and refractory components present in the coating. Knowledge of the specific gravity of the suspending agent and that of the refractory material is critical. The specific gravity also gives a good idea of the refractory content of the coating. Water has a lower specific gravity than 1. When used to thin a coating with a relatively higher specific gravity; the specific gravity of the coating is reduced [8].

Viscosity

Viscosity is a property of the coating that must be controlled during its application. Baume´ measurement is shown in figure 8 . the best test for evaluating coatings due to its high ratio with the dried residual layer on the core. There are several different methods of measuring viscosity. The most commonly applied in foundries is through a cup, as shown in figure 9 . The flow cup measure of viscosity requires the use of a cup with a specific hole size in the bottom to match the material being used. And the stopwatch is used when the cup is lowered into the coating and then removed from the surface of the coating after it is filled. The time it takes for the coating to drain through a hole is the viscosity in seconds.

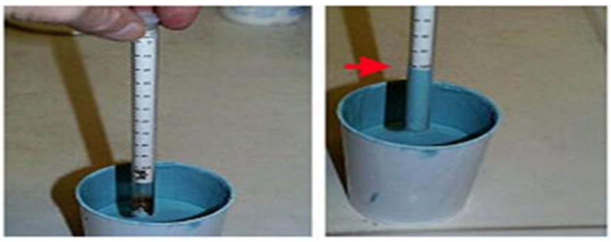

Fig. 8. Baume method.

Fig. 9. Viscosity flow cup.

Solid substance

The coating solids must be measured because they are the refractory materials that provide protection to the heart or form. The higher the percentage of solids, the more protection the coating offers. The solid content determines some other important coating parameters such as density, viscosity, thickness, coverage, etc. Therefore, knowledge of the amount of solids in the coating is very important for the reproducibility of these parameters. The percent solids content can be found by dividing the weight of the dried coating by the initial weight and multiplying by 100.

Coating thickness

Coating thickness is usually measured using a destructive test. To date, no reliable non-destructive test has been implemented. used by the foundry industry to measure consistency from the thickness of the coating layer applied to a core or mold. In some tests, the hearts are separated and measurements are taken under a microscope. In some other methods, the coating is removed from a flat surface on the core and the difference between the face of the core and the coated surface is measured. The surface layer size can be used as a reference for future comparisons and coating allowance decisions in casting design. There is a strong correlation between coating viscosity and coating thickness. However, measuring a thick dry coating layer has proven to be a difficult task, so the most easily applicable method is to measure the thickness of the wet coating layer using a wet film "comb" as shown in Figure 10. The combs for wet films may be used in accordance with the following standards; ISO 2808-7B, ASTM D 4414-A, BS 3900-C5-7B and NF T30-125. These combs have different lengths. These standards specify that the wet film comb is perpendicular to the substrate and the coating thickness is between the largest wet tooth value and the smallest dry tooth value. The wet coating layer thickness will correlate with the dry coating thickness if the volume and solids ratio of the coating are known. As a rule of thumb the thickness of the dry coating is 50% of the thickness of the wet coating. In dip coating, the thickness of the coating is mainly determined by the withdrawal rate, solid content (density), surface tension and viscosity of the liquid [9].

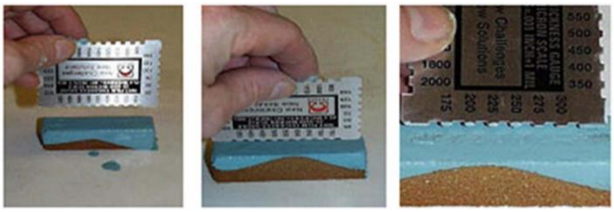

Fig. 10. Coating thickness.

Coating penetration depth

The depth at which the coating penetrates the heart is an important characteristic for its successful application. A coating that has not penetrated well enough into the mould/core will most likely separate easily from the sand surface. A coating that penetrates too much will break the heart. Coating Penetration is also a function of the density of the core itself - it is important whether it is dense enough to withstand the penetration of the coating or whether it is soft like a sponge and absorbs a lot of water. Evaluation of coating penetration is performed by cutting out a heart, with the coating applied and dried. The usual test takes into account the size of the sand grains. A normal level of penetration is 2 – 4 grains of sand. It has been found that this is not the most accurate methodology because the sand grain sizes vary from foundry to foundry. In addition, each lot of foundry sand has a different distribution of different grain sizes in it, which also makes the use of the number of sand grains inefficient. Lower surface tension increases the penetration depth of the coating. As the penetration of the coating increases, the thickness of the top layer decreases, and vice versa. Thermal expansion increases with the thickness of the top coating layer (surface layer). Therefore, an optimum thickness of the top layer is required in order to reduce the expansion defects of the casting made with these cores. This requires controlling the depth of penetration of the coating [10].

Gas permeability of the coating

The permeability of the coating is the amount of gas that can pass through the coating. Determining the level of permeability depends on both the type and amount of refractory materials used in the coating composition and the thick dry film deposited after drying on the mold/core. The permeability of the coating is measured using a laboratory permemeter. With a low-permeability coating, predicting the release of gases through certain areas of the heart is desirable. A high permeability coating is preferred. The permeability of the metal-form interface may be different from that previously measured because some of the coating constituents can rapidly thermally degrade leaving voids that result in higher permeability. Some can soften and stick together, resulting in lower permeability. A high-permeability coating will reduce the time required to remove degradation products and increase the rate of metal filling, which often leads to blistering and shrinkage defects. A low-permeability coating will slow down the metal velocity, which causes the molten metal to lose the necessary heat energy and result in improper or partial mold filling. Mold fill time was found to decrease with the permeability of the coatings. A standard approach to characterize the flexibility of porous materials is to use Darcy's law (Eq.), which relates volume flow and pressure gradients to the properties of fluids and porous materials:

where

K = permeability value in Darcy units,

μ = fluid viscosity in centipoise,

Q = volumetric flow rate, measured in cm 3 /sec,

L = length of the specimen in cm in the flow direction,

A = cross-sectional area of the specimen perpendicular the direction of the gas flow in cm2,

Δ P = (P 2 – P 1) = pressure drop across the specimen length,

P2 = pressure at the outlet side of the specimen in atmospheres spheres,

P1 = pressure at the inlet side of the specimen in atmospheres.

The equation is valid when KA/μL is a constant in laminar flow (slow viscous flow) i.e. for very small Reynolds number (Re) The upper limit is a value of Re between 1 and 10. At high Reynolds number, deviation from Darcy's law will be observed. The Darcian coefficient of permeability K indicates the ability of the porous medium to pass liquids. In reality, the permeability coefficient depends only on the properties of the porous medium. At high pressure, turbulent and inertial flow become increasingly dominant, so Darcy's Law is no longer valid. The transition from the linear (Darcy's law) to the non-linear regime is gradual as the Reynolds number increases. Therefore, the classic approach to macroscopically characterize the effect of inertia and turbulence on the flow through a real porous medium is to use the Forchheimer equation (equation 9), which includes parabolic parts in the considered equation-the effect of inertia and turbulence:

where

V = fluid velocity averaged over the total cross section of the porous sample (Q/A),

β = inertial parameter,

ρ = fluid density.

This equation macroscopically quantifies a nonlinear effect. Studies have shown that deviation from Darcy's law (which occurs at Re = 1 – 10) cannot be attributed to turbulence, but inertial forces are more suitable to explain the deviation. The role of inertial effects on such a transition at high Re from linear to nonlinear flow in the pore space was successfully-fully simulated in laminar mode without including turbulent effects. However, the random aspect of the pore distribution induces a highly heterogeneous local flow that becomes turbulent at high Re [11].

3. CONCLUSION

From the information provided, it is clear that the basic chemical and physical parameters of refractory foundry coatings are known to specialists in the field. A lack of information was found regarding the influence of the particle size in the refractory filler in the coatings on the penetration of the coating itself. There is also a lack of data on the relationship between the particle size, the depth of penetration and the erosion resistance of the layer deposited on the sand mold and the influence on the final appearance of the casting. The need for in-depth research on the above topics has been proven. That’s way there must be a bridge between the foundry and tribological science in order to prove that improving erosion resistance of the coating layer in the sand mould will help to produce casting with better surface and decrease the costs for cleaning and finishing procedures which is very important problem in the foundries worldwide.

Acknowledgement

Until now, the author of the publication has studied the micro hardness, roughness, friability and gas permeability of refractory coatings, for which parameters no previous information on similar tests has been found. The research carried out was financed under phd project No. 222ПД0005-05 – TU Sofia, Bulgaria.

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