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Evaporative Pattern Casting (EPC) Process

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Abstract

The chapter provides details of operations and activities in evaporative pattern casting (EPC) Process. The process was developed in the year 1956 to tackle some of the inadequacies of the traditional sand casting processes but has in itself some challenges that should be taken care of if sound castings would be obtained. The challenges come mainly from the evaporative pattern employed as pattern material in the process. The material makes the process to be sensitive to process variables such that proper and adequate control should be ensured to have castings of sound integrity. Some of the known process variables are pouring temperature, refractory coating, vibration and pattern and molding materials. In the whole the EPC is known to have edge over the traditional sand casting methods.

Keywords: pattern, molding, casting, variables and coating

1. History of evaporative pattern casting (EPC) process

Evaporative pattern casting (EPC) Process is a sand molding process that makes use of evaporative patterns produced industrially by steam molding or machined out from a block of expandable polystyrene foam (EPS) [1, 2]. The pattern is buried in the sand mold and the melted casting material is poured into the mold without removing pattern, unlike the traditional sand casting method that makes use of wooden, plastic and metallic pattern which is removed from the mold before molten metal is advanced.

It was in 1956 that Shroyer made a documentation of his work on EPC where green sand was used as the molding material [3]. The author machined a shape from expanded polystyrene (EPS) and supported it inside a flask with bounded sand. Another researcher called Flemmings

came up in 1964 to use unbounded silica grains for the process [1]. Foundry men later came to differentiate between the two; calling the first the full mold and the second the lost foam processes. The subtle difference only lied in the use of bounded (green) sand and loose sand.

The process became known to foundry men in 1958 and many trade names have been formed to describe it [3]. They include styrecast, replicast, full mold, lost foam and evaporative process. A distinguishing feature of this type of sand process is that an evaporative pattern made of polystyrene foam is used [4]. It is coated with a coating developed from a refractory material usually silica or zircon sand before being buried in the mold. It is not removed from the mold once it is buried.

After 1964, some works have been done by researchers to understand the variables that affect the process. Some works in the automotive industry have also been done. General motors have produced a number of automotive components with the method. This started in the year 1980 and they are still in the use of the process. The full mold process unlike the conventional sand casting process uses patterns and pouring system, which retains the pattern in the mold, thus justifying the title full mold [5]. The term 'evaporative' stands as a family name for all the trade names that have so far been coined out for evaporative pattern casting processes. This is because the pattern evaporates when there is contact between it and liquid metal; all the features are replicated [6].

2. Introduction

By evaluation and practices, the process is known to take care of intricate and complex shapes without the use of cores; this is not achievable in traditional sand casting methods. The surface finish of the castings produced has an edge over the ones of green sand method. Very slender elements are produced with ease using EPC which is very difficult in other sand casting methods. Precision in terms of dimensional accuracy is better [7].

With the trend in the automotive industries; where engine blocks and cylinder heads are made with aluminum alloy, the evaporative pattern casting process has found a place for effective production. This has opened up endless research opportunities aimed to improve on the use of metal alloy components obtained by EPC.

Patterns used in EPC process are produced locally by machining them from blocks of polystyrene material and industrially by steam molding of the beads. The ones produced industrially are for mass production. The commonly used pattern material is expandable polystyrene (EPS). Polyalkylene carbonate (PAC) is used to manufacture ferrous castings [3]. Another material that is used for EPC is the poly methyl methacrylate (PMMA). Metal tooling with techniques that have been developed for industrial packaging is used. Precision machine tools are required for EPC process. The tooling material is aluminum alloy. It is used because of its exceptional properties which are not found in other alloys. The properties include good thermal conductivity, good erosion resistance, fair strength, light weight and good surface finish upon machining.

The process of producing pattern material is regarded as polymerization. In local development of EPC Process, the patterns are cut manually using knives, blades, pre-heated wire etc. and then smoothened out by emerald paper. At times when parts are to be joined together, the use of glue is employed. Juice from rubber plant can as well be used to join patterns. After the production of the pattern and it is assembled with the gating system, it is coated with refractory material which may be wet (slurry) or dry. The coating provides a barrier between the flowing molten metal and the molding sand to prevent metal penetration. Other benefits are offered. An example is the quality of casting surface produced.

The gating system assembled with the pattern is informed by the weight of the casting to be poured. Immediately the pattern that is coated is dry, it is taken and buried in the mold. Care is taken so that the coating layer is not peeled off. Molding sand is packed into the molding flask and rammed carefully so that the pattern is not distorted and the mold is poured. After solidification, shake out process follows and cleaning of the casting is done. The molding sand is entirely reclaimable. The process offers many benefits to both the casting producers and users in terms of time reduction and low cost in the production of the patterns and low cost of purchase of pattern materials.

Mold production entails the placement of the coated pattern assembly in green sand and rammed to obtain compaction of the grains. In the full mold, green sand is used as molding material. Things required in mold production are: molding sand, molding boxes, pattern and vibration. Following vibration, the mold is prepared for casting, which may simply involve the location of a pouring basin above the sprue entrance. However, to prevent fluidization/erosion of the sand during pouring, caused by the evolved gaseous pattern decomposition products, mold weights may be necessary, or the top of the box may be covered with a plastic sheet and a soft vacuum applied [3].

When pouring the liquid metal into prepared molds, it must flow full right from the pouring cup on top of the sprue in the gating system down to the mold cavity [8]. This offers advantages in that the mold would not collapse, the sprue evaporates completely, air aspiration is avoided and sound casting is obtained. The pouring rate is determined by the density of the foam, permeability of the sand and casting material. Gating design is therefore done carefully to achieve sound castings. The elements of gating system include pouring cup, down sprue, sprue base well, runners, ingates and risers. Careful design of each of these elements brings about soundness in castings. The gating ratio is informed by the type of material to be cast. For aluminum alloys, non-pressured gating ratios like 1:2:4, 1:3:3 or 1:4:4 is used [8]. This refers to the cross-sectional areas of the choke, runners and ingates. For the ferrous materials, pressurized gating ratios are used like 4:3:1, 2:1:8, 1:1:4 and 1:2:1 [8].

Once liquid metal is poured in EPC mold both physical and chemical reactions start to occur. EPC is known to be influenced by many variables. The combination of these variables determines whether sound casting would be obtained. The process begins by mold filling with the liquid metal, followed by transfer of heat energy from the liquid metal to the evaporative pattern in the mold. The flow of liquid metal to make contact with the pattern is also observed and when it eventually makes contact, decomposition of the foam begins, leading to pyrolysis

products [2]. Pressure in the mold is built up as a result of these products and reactions. The pressure determines what quality of the casting that would be obtained [9, 10].

As a unique technique to produce integrated components which otherwise must be cast in several parts, it has drawn great interest from both academia and industry [10]. Efforts have been made over the years to understand variables and physico-chemical activities that significantly affect the process and initiate means of monitoring and controlling them. These research efforts have enabled rapid growth of EPC production around the world [6]. This has cumulated to the increase of the products of the process in the automotive and similar industries. Researches are still on-going to maximize the benefits.

It has been observed that the EPC offers many advantages over the traditional/conventional casting processes. One of the advantages is that it eliminates the requirements of cores for internal structures because foam patterns which are produced by steam molding in industrial set-up or machined from a block of polystyrene are shaped desirably to bring out the casting. This machining method also allows several parts to be assembled and makes complex casting designs possible. Other advantages include increased dimensional accuracy, saved material and costs as castings produced with the process require minimal fettling.

In EPC Process the molding sand is reusable because no binders are used, which makes EPC a more environmentally friendly process [11]. This process also eliminates issues like dewaxing and mold firing that occurs in the lost wax process. It has been shown that the mechanical properties of lost foam castings and full-mold castings have cutting edge over those of other sand castings [11]. Other attractive features include near-net-shape casting, elimination of parting lines and excellent surface finish. **Table 1** shows a comparison among the various casting processes on labor cost, equipment and surface finish. Studies show that all ferrous and nonferrous metals have been successfully cast using EPC process.

Type of process	Labor cost per unit	Equipment cost	Surface finish μ m CLA	Accuracy mm	Minimum section mm
Sand (green)	Medium	Low	500–1000	± 2.5	5.0
Shell	Low	Medium	100–300	± 0.25	2.5
Centrifugal	Low	Medium	100–500	± 0.7	8.0
Investment	High	Medium	25–125	± 0.06 –25	0.6
Die casting gravity	Low	Medium	100–250	$\pm 0.4 + 0.05$ per 25 mm	2.5
Die casting low press	Low	Medium	40–100	$\pm 0.05 + 0.05$ per 25 mm	1.2
continuous	Low	High	100–200	± 0.12 per 25 mm	8.0
EPC	Low	Low	60–300	$\pm 0.05 + 0.05$ per 25 mm	1.0

Source: [10].

Table 1. Summary of casting processes.

One outstanding advantage that EPC process offers is that there is minimal number of rejected castings. It could then be inferred that there is a saving on cost of purchase of furnace fuel used in firing and melting and energy to remelt the scraps or rejected products is reduced. The casting material is also optimized as it does not end in scraps; sound castings are produced with them.

In overall evaluation EPC should be preferred to the traditional casting methods. Therefore in where energy supply is not adequate the foundry engineer could make use of the EPC for these afore mentioned benefits and the rapid production of the patterns with less energy expended unlike the patterns used in the conventional methods where large amount of energy is expended.

With the advantages and benefits that the process offers, not all foundries are known to embrace it. However, predictions have been made that soon very many foundries would use the process; looking at it from the perspective of automotive industries. It is believed that if the process parameters that affect the EPC process are properly monitored and controlled and there is proper gating system design and melting and pouring practices, defect free castings should be obtained [5].

In order to obtain castings with good surface finish free from defects researchers both in industries and academia are giving attention to both experimental, modeling and theoretical studies of the variables known to influence the process [2, 6, 12–17]. It has been recognized that the pyrolysis products are the main source of defects in EPC [11, 18].

The EPC process is very sensitive and known to be complex because of the very many variables that affect it. Experiments and research efforts have not been able to adequately quantify certain parameters like the heat transfer coefficient existing between the liquid metal flow and the decomposing foam. Therefore a range of the coefficient has been proposed to be 40–160 W/m² K [10, 19].

According to Mohammed [20] computational models and simulations have been developed to further understand the interactions of various variables in EPC process in order to help reduce defect formation in the castings [9–11, 21–24]. Since the heat transfer from the molten metal to foam pattern plays a very important role, models without sufficient consideration of the foam pyrolysis process do not capture the effect of process parameters on the defect formation in the castings.

3. Evaporative pattern casting (EPC) process steps

Clegg [3], Acimovic-Pavlovic [12] and Kumar et al. [6] outlined the basic steps in the EPC Process. All the activities are diagrammatically illustrated in **Figure 1**. It is of interest to see the steps simply outlined but every step needs to be carefully monitored and controlled because of the physico-chemical interactions in the steps coupled with the process parameters that are involved for the purpose of producing consistent and high quality castings.

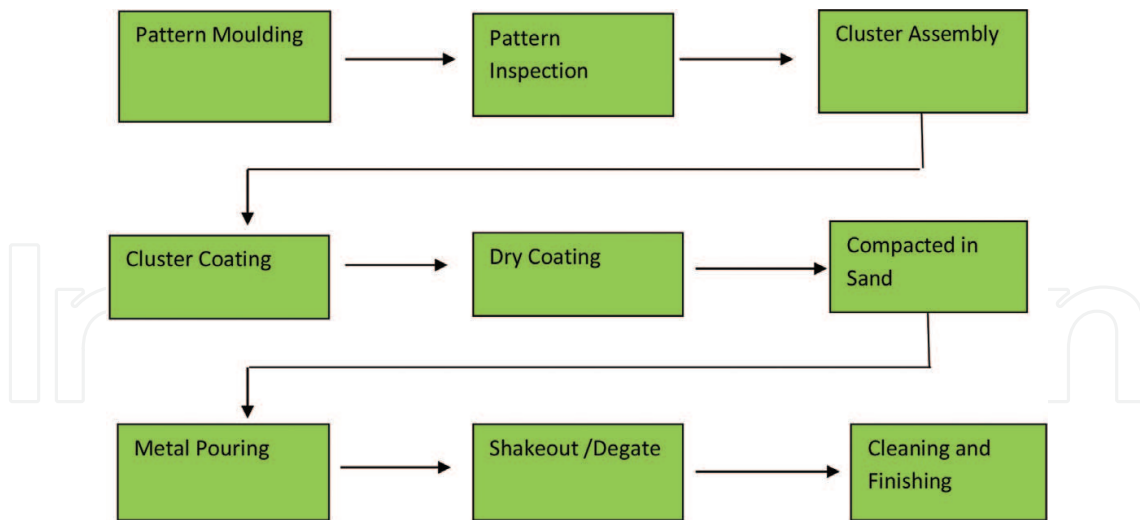


Figure 1. Steps of EPC process. Source: [10].

The very many variables of EPC process grouped into six categories have made the process to react to changes that occur in the system. The combined and individual effects of these variables sometimes produce significant effects on the process and its products [11, 25]. The chain of systems observed to make castings by EPC process are divided into two main classes

- a. Evaporative pattern production, assembly and inspection
- b. Casting production and inspection

The first division is a six-step operation. The step 1 is the pattern molding. This is done industrially by injection process. Beads of polystyrene foam are injected into molding machine under pressure. The foam material together with the amount of applied pressure for compaction determines the density of the polystyrene pattern that would be employed for casting. This is an industrial option. On the other hand, patterns are machined from a block of polystyrene foam with a device called heated wire. Step 2 is the inspection of the patterns produced industrially or manually. Dimensional accuracy and correctness of the shape are inspected at this level. Distortion of the patterns is avoided. This is paramount to the EPC Process. Many a time, EPC Process involves casting of intricate shapes such that a shape will be broken into segments and patterns will be produced for these segments. The patterns of the segments are joined together with glue. The joining process is referred to as cluster assembly which is step 3. To provide ability to withstand thermal energy from advancing liquid metal and prevent sand penetration in evaporative pattern castings, refractory coating which is made from highly refractory materials is sprayed on the patterns. Step 4 takes care of this. The patterns are left to dry. The drying period is within a matter of seconds; maximum 15 s. This is possible because of the reducer/carrier which is usually methyl alcohol at 99% concentration that is employed in the transfer of the coating to spraying the pattern. The drying process is done in step 5. Step 6 deals with compaction of the coated patterns in the sand mold. The sand mold is prepared with molding sand usually river sand whose grain fineness number has been determined and some other properties which molding materials should have like green strength, refractoriness, hot strength and so on. Immediately the bed is laid, the pattern is put

inside the molding flask then it is filled with molding and backing sand. The pattern is not removed from the mold.

The second division deals with casting production and inspection. Three steps are involved. The step 1 deals with metal pouring. Casting materials are charged into the furnace and allowed to melt. Each metal has its melting temperature. The foundry man takes the melt from the furnace with pouring equipment and pours into the prepared mold. Solidification of the casting takes place inside the mold. Step 2 takes care of shakeout and de-gating of the casting. The process of removing the casting from the mold is the shakeout while removal of sprue, runner bar and ingates from the casting is the de-gating. Step 3 which is the last of all sees to the cleaning and finishing of the casting. Here brushes are employed to clean by removing sand attached to the casting. Unnecessary projections are also cut off.

4. Advantages and disadvantages of (EPC) process

From an environmental and economic perspective, one of the principal advantages of EPC Process is the fact that the casting sand can be reused. This is not so with the traditional green sand casting method as it will require chemical treatment to maintain the properties of the molding sand with will have negative impact of the environment when the sand is finally disposed. The process offers manufacture of complex shapes without the need for cores which must be provided for in production of holes and passages when green sand mold method is used. EPC Process does not present lines that separate molds into several parts which are called parting lines. Based on these afore, researchers have sub mitted that the process reduces machining cost and energy use.

Even with the advantages that researches have outlined which include good surface finish, high dimensional accuracy and reduction in cost of production which make the EPC process to be competitive [26]; it is not without its disadvantages. It is true that the process offers good surface finish but it is subject to the surface of the pattern. The pattern density has significant effect on the quality of casting produced with it. The density values of the patterns vary due to level of compaction of the beads by steam molding. The foams, if not carefully handled may be distorted or permanently damaged. On the whole the disadvantages recorded in the process are associated with the EPS [13, 26].

5. Problems and challenges in EPC process

EPC Process is known to offer many advantages over the traditional sand molding processes like rapid production of patterns and at low costs. However, there are pronounced disadvantages and problems that have been identified. These problems are known to occur because of the sensitivity of the Process to the variables. The chemistry of decomposition of the polystyrene foam which is used as the pattern material is vital in the overall success. The pyrolysis

products therefore must escape from the molds as fast as possible to have castings free of defects.

Some problems are associated with the process majorly referred to as casting defects [10, 27]. The EPS foam pattern undergoes a series of complex reactions: collapse, liquefaction, vaporization and depolymerization. Kumar et al. [6], Molibog [28], Wang et al. [29] and Shivkumar et al. [30] showed that the pyrolysis liquid and gaseous products are potential defect sources like blow holes and the effective elimination of these degradation products is important to produce quality castings. Common EPC defects such as internal porosity, folds and surface defects are all pyrolysis product related.

Variable like refractory coating, pattern density uniformity, and pouring temperature are critical factors affecting formation of defects in the castings. Porosity defects are created when a fast moving metal front engulfs portions of the foam pattern which form voids in the solidified castings. Folds are caused when two streams of molten metal meet and pyrolysis products at the metal front prevent the two streams of metal from fusing. Surface defects are present at the surface of the casting, and are a result of foam pyrolysis products trapped at the metal-coating interface.

6. Applications of evaporative pattern casting process

The application of the EPC process is dynamic. It has been applied in the production of aluminum and its alloys. Iron founding also makes use of the process for production of various products. Magnesium and its alloys are now being cast using the method. The first public recognition of the application of the process was in 1980 when General Motors produced some automobile components with it [6, 7, 31]. Aluminum railway valve body, aluminum cylinder head, pipe fittings and shaft hubs are now being produced by foundries in Canada, Italy, USA and Netherlands [32].

7. EPC process parameters

EPC Process is relatively new and from works of researchers, many process parameters have been known to affect/influence the process. It is also believed to be very sensitive as these variables affect the soundness of the castings produced by it. In both local and industrial applications of the process, difficulties have been encountered [10]. The difficulties have led to casting defects. Some of the process parameters are the patterns, pattern coating, pouring temperature, vibration, gating ratios and geometry of components.

7.1. Patterns in EPC process

Patterns are made of expanded polystyrene foam; poly methyl methacrylate and polyalkylene carbonate [10]. The materials are light in weight. They must be carefully handled after

production to avoid distortion. The expanded polystyrene is used for aluminum and its alloys; it is not used in iron founding because of the defects that it causes for the casting. It is known that the materials have different density values and this has effects on the quality of castings produced [33]. It is then required that there must be consistency in the material used as pattern for consistent quality in terms of the mechanical properties and the microstructures of the castings. It is observed that the pattern used in EPC is in sharp contrast to the ones employed in the traditional sand casting methods where wooden, metallic and plastic materials are used to create cavity in the molds and then removed before pouring casting material into the molds.

7.2. Pattern properties

Xuejun [10], Clegg [3], Kumar et al. [6] and Behm et al. [13] observed that the properties of the pattern significantly affect the casting quality. Xuejun [10] and Liu et al. [34] also showed that to a very large extent, defects caused in castings are attributed to the non-uniformity in pattern density. Consistency should be observed in the properties of the pattern, especially, the density which is a result of the bead compaction [35]. The density affects the flow of molten metal expected to displace the pattern material buried in the sand mold when the compaction of the beads of one side is different from the other side. Instead of having uniform flow of molten metal, the metal tends to flow to low density areas, thus causing folds and foam inclusion in the casting because metal flow faster in the area of low density showing low bead compaction. The decomposition of the patterns may be by scission or unzipping; a number of reactions are involved in this before completion and patterns rejected usually become environmental problems [10, 36, 37].

7.3. Pattern coating

Pattern coating which is a mixture of refractory material and binder or many a times only the refractory material, when applied on patterns, forms a solid layer on the pattern when it is dry. The coating must be permeable to allow gas to escape into the surrounding; otherwise the gas would be trapped, causing defects in the castings [38]. Houzeaux and Codina [31] showed that the escape of the gas from the mold is subject to coating applied on the foam. Chen and Penumadu [11] posited that mold filling times decreased with permeability of the coatings.

Depending on the type of coating, the time to fill the mold with the liquid metal is affected. The gas generated must escape continuously from the mold to avoid defects. The pyrolysis products are the main causes of defects in EPC Process [39]. The release of the gas products should be in a timely manner; if they are too fast, it leads to mold collapse because of pressure drops such that the coating layer is no longer supported and could not therefore bear the weight of the sand. An ideal pattern coating must allow gaseous and liquid foam degradation products to be transported out of the casting in a timely and balanced manner. Variables such as coating material, percent solid, viscosity, liquid absorption capability, coating thickness and gas permeability affect the quality of casting" [10, 16, 20].

The application of the pattern coating must be carefully done on the pattern to ensure that it is consistent [40]. If the coating is applied wet, the wettability must be consistent. If it is applied

dry, the thickness must be consistent [41]. This will allow for controlled liquid absorption and gas permeability. The coating layer provides clean and smooth surfaces on the castings because it is easily removed.

As regards the particle size of the refractory coating, Kumar et al. [2] and Nwaogu and Tiedje [38] had recommended 200 meshes (75 μm) in their research. In reality, the particle size can be reduced to 65 μm . This gives good surface finish to the castings produced with it. The surface roughness obtained in the castings when the coatings are used is subject to the type of casting method employed. With ceramic investment casting process, Singh et al. [42], obtained 2 μm surface roughness but with sand casting method 10 μm to 50 μm was obtained [38].

Usually one of the three methods; spraying, dipping, swabbing, is used to apply the refractory coating to the surface of patterns. Spraying has proved to be the most effective in that uniform spread of the coating is obtained leading to almost uniform thickness. In reality constant thickness cannot be obtained for all patterns. The dipping process will not give uniform spread of the coating. There is great variation in the thickness that would be obtained. In the swabbing, the brush used in the painting makes marks on the pattern thereby reproducing the marks on the castings produced with it.

7.4. Structure and thermal degradation of foam pattern

Polystyrene was discovered in Germany in 1839 by Edward Simon and is a derivative of petroleum produced by polymerization of monomer styrene. The chemical structure of the polystyrene contains only carbon and hydrogen atoms with benzene ring attached to it and it is then classified as hydrocarbon. The chemical formula is $(\text{C}_8\text{H}_8)_n$. The polymerization process of producing the foam is illustrated in the **Figure 2**. In EPC Process, thermal degradation of the polystyrene occurs at elevated temperature.

Kannan et al. [43], Liu et al. [34], Barone and Caulk [44] and Mirbagheri et al. [9] had studied the thermal degradation of Expanded Polystyrene Foam (EPS) used for EPC Process. The authors had advanced physical and kinetic models for the degradation of the polystyrene foam applied in EPC Process. In the physical model as a result of heat energy transferred from the liquid metal to the solid foam, there were formations of pyrolysis products at the reaction site.

A number of physical models were proposed [14]. The physical models advanced that the composition of the mixture of degradation products is a function of the time that the products reside in the interface before escaping out through the coating and sand [43]. Worthy of note is

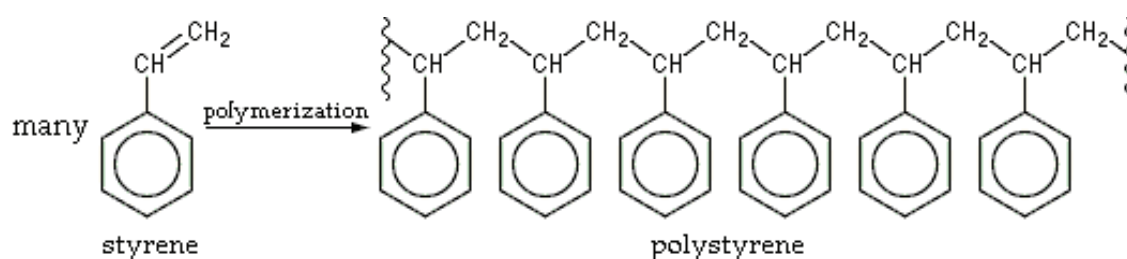


Figure 2. Polymerization process.

the proposal of Molibog [28] who had advanced that there is a three-phase kinetic zone in the metal-foam interface. Molibog's proposal is shown in **Figure 3**.

From the available literature, it was observed that at the initial stage, as temperature increased, the polymer retained its structure without any changes until the temperature reaches the glass transition temperature (T_g). T_g is the temperature at which the molecules begin to vibrate. This is the initial stage of translational movement.

Immediately the temperature is raised above the T_g the molecules of the polymers increase in vibration and its viscosity reduces. A point of collapse of the polymer beads is reached when the temperature is increased further. Partial depolymerization of the polymer chain is achieved as the temperature proceeds. The products of the depolymerization include monomers, dimers and other oligomers [10]. Usually, with EPS, the beads collapse at a temperature about 120°C and its volume decreases to $1/40$ of its original size. The degradation process known with the EPS occurs by random scission. The C-C bonds contained in the polymer break down at different locations [45]. It has been noted that at 160°C , the beads which are expanded by team molding to produce the EPS melt, forming viscous substance, consisting of depolymerized products. At various temperatures, the products are formed and they are known to undergo further fragmentations. Finally at about 750°C , the gaseous products formed contain styrene, toluene (C_7H_8), benzene (C_6H_6), ethylene (C_2H_4), acetylene (C_2H_2) and methane (CH_4) [45]. The properties of expanded polystyrene (EPS) and poly methyl methacrylate (PMMA) thermal degradation are summarized in **Table 2** [10].

In iron founding, lustrous carbon defects are known to occur by using EPS as the pattern material. It is to this end that alternative is provided called poly methyl methacrylate (PMMA) as the pattern material. This is capable of eliminating the defects known with EPS. The

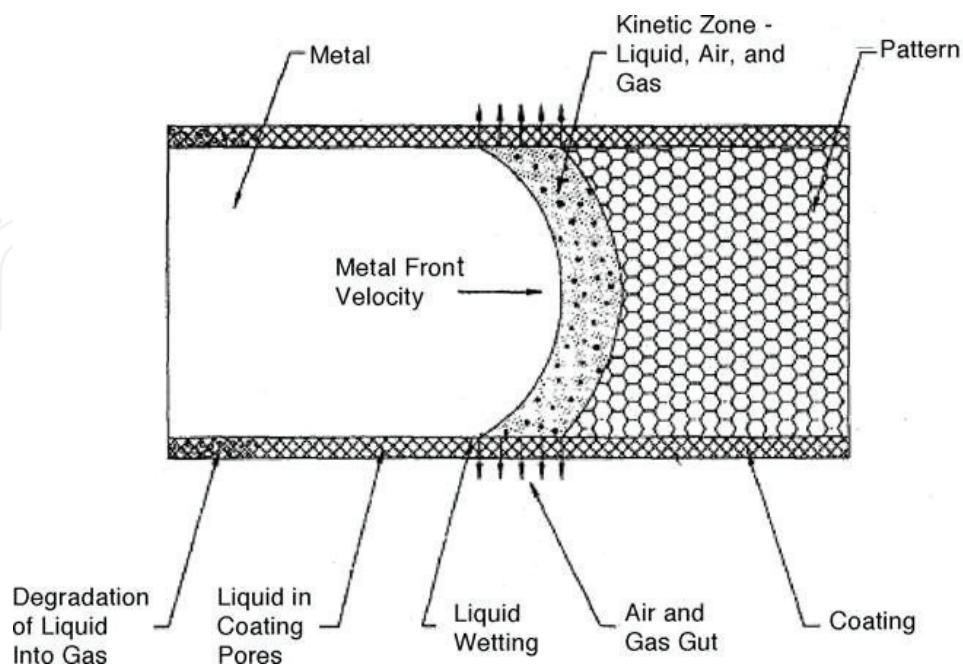


Figure 3. Schematic of the foam degradation process. Source: [43].

properties of the PMMA are included in **Table 2**. The PMMA is known to undergo degradation by a process called unzipping. Research efforts to eliminate completely or at least reduce the lustrous carbon defects of the EPS in iron founding have yielded positive results by the invention of other polymers such as polyalkylene (PAC) and copolymers of the EPS [3].

7.5. Molding practices in EPC process

After the patterns have been produced by injection molding as applied to industrial method or machined out from block of polystyrene, they are assembled with the gating systems design for the patterns and coated with refractory material. Time is given to allow the refractory material to dry. The patterns with the gating systems are then taken and positioned in the molds and supported with green molding sand and rammed carefully. The ramming is necessary to provide rigidity for the molds so that they would not collapse when molten metal is poured. The patterns with the gating systems buried in the molds are not removed like those in traditional sand casting methods. When the liquid metal is poured, the patterns and gating system evaporate leaving only the castings at solidification. The schematic of the pattern-gating system assembly positioned in the mold is shown in **Figure 4**. The thermal energy helps foam patterns to decompose and leaving desired dimensional casting products. As the metal replaces the foam pattern, the process involves a series of complex foam reactions: collapse, liquefaction, vaporization, and depolymerization. The degradation products are vented through the coating layer into the surrounding sand.

The quality of castings in the EPC process is strongly affected by the elimination of liquid and gaseous products produced by the foam pattern [27, 34, 46, 47]. If the foam pattern pyrolysis

Thermal properties	EPS	PMMA
Glass transition temperature (°C)	80 to 100	105
Collapse temperature (°C)	110 to 120	140 to 200
Melting temperature (°C)	160	260
Starting temperature of volatilization (°C)	275 to 300	250 to 260
Peak volatilization temperature (°C)	400 to 420	370
End volatilization temperature (°C)	460 to 500	420 to 430
Heat of degradation (J/g)	912	842
Rate of vaporization at 750°C (Kg/s.m. ²)	0.77	0.61
Rate of vaporization at 1300°C (Kg/s.m. ²)	0.18	0.31
Gas yield at 750°C (m ³ (STP)/Kg)	0.23	0.273
Gas yield at 1300°C (m ³ (STP)/Kg)	0.76	0.804
% Viscous residue at 750°C	61	32
% Viscous residue at 1400°C	15	3

Source: [10].

Table 2. The characteristics of EPS thermal degradation.

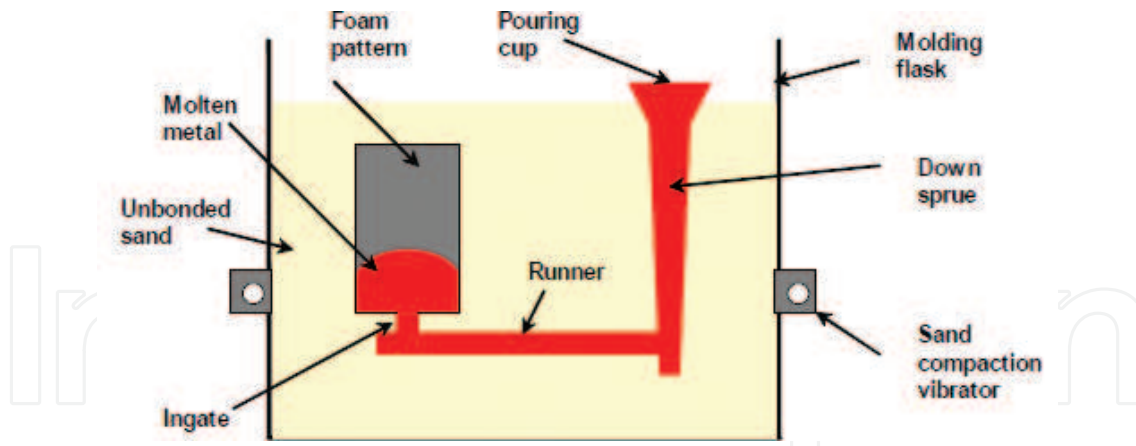


Figure 4. Schematic of molten metal pouring in EPC process. Source: [10].

products cannot be effectively eliminated from the casting, they can cause various defects [19, 48]. After the castings cool down, they are shaken out, de-gated, cleaned and inspected for quality. These final procedures are similar to those used in conventional casting process.

7.6. Vibration

Vibration of the sand around the pattern to obtain the optimum density and compaction of the mold is a critical feature in the successful production of castings by the EPC. The vibration characteristics are critical since the sand must be caused to flow into internal cavities and undercuts for good compaction. The frequency, amplitude and intensity of vibration, direction of movement impacts, shape of the container and the point at which the vibration is applied all influence the quality of the castings. [49] reported that applying vibration during solidification is an effective way for grain refinement. Vibration can modify the solidified microstructure by promoting nucleation and thus reduce the grain size and lead to a homogenous microstructure. The frequency can be of range 10 to 60 Hz, the amplitude ranges from 0.11 to 0.45 while the intensity which is quantified as force ranges from 80 to 12,000 N.

7.7. Characteristic behaviour of molten metal in prepared molds

To eliminate mold erosion in sand molding processes, it is important that gating and feeding system is designed and constructed for the particular casting that would be produced. It is the gating system that will eliminate turbulence that may occur as a result of the pouring of the liquid metal into the prepared mold. It enters the mold by gravity.

In EPC, immediately the liquid metal contacts the buried polystyrene foam, it begins to decompose and violent gas escapes from the mold through vents that have been provided. Physical and chemical reactions begin to take place inside the mold. The gas evolving develops a back pressure to resist the advancing liquid metal; by this a kinetic zone is established. The molten metal displaces the foam because of its high temperature; resulting in pyrolysis products like monomers and emissions toxic to human [13]. All the products formed in the mold have been established as potential causes of defects in castings obtained by EPC process

[6, 43, 45, 49, 50]. Attempts have been made to study comprehensively the behaviour of the liquid metal poured into EPC molds. Some researchers have employed x-rays to study the physico-chemical reactions taking place at the sites. Attempts have been made to model and simulate the interactions that have been known to occur for possible predictions. However, difficulty still exists to quantitatively/qualitatively represent that behaviour of the fluid in the mold.

7.8. Pouring temperature

This refers to the temperature at which the liquid metal is poured into the mold. It is one of the pouring material variables. By experimental determination, it has been established that pouring temperature has significant effects on the mechanical properties of the castings obtained by sand molding processes, EPC inclusive. Usually, it is at high temperature that the casting material is melted in the furnace. Once the casting material melts, the prepared mold is poured. By experiment, it is determined that some aluminum alloys when poured into EPC mold at 650°C, quality casting is obtained [50, 51].

Effects of pouring temperature on the mechanical properties and microstructures of casting can be studied by observing a range of values and levels are taken within the range when the casting material is poured at the levels, opportunity is provided to compare results in terms of visual and mechanical examination of the casting obtained. The visual examination reveals some defects on the surface of the casting if they are existing. Surface roughness can as well be measured. The mechanical examination reveals the mechanical properties in terms of impart, tensile, creep, % elongation, hardness and elasticity [52]. These provide evaluation of the casting to know if it is of good quality. Sometimes the effect of the pouring temperature is examined on the grain refinement.

Each casting material has the temperature range at which it must be poured. Therefore the temperature is measured to determine the pouring range. Usually a k-type chromium-nickel thermocouple is employed to take the measurement. It has a grinded junction. Other forms of thermocouple can be used. The pouring temperature because of the high thermal energy that it has is responsible for the dissociation of H₂O in the molding sand, thereby producing H₂ which escapes from the mold and the decomposition of the evaporative patterns used in EPC process [31].

7.9. The gating system

Molten metal is poured into already prepared mold through a gating system. The gating system designed for a casting is informed by the weight of the casting. There are a number of parts that make up the gating system. Pouring basin is a reservoir at the top of the gating system that receives the stream of molten metal poured from the ladle. Next to the pouring basin is the sprue which usually tapers down to the sprue base well. The sprue usually in the form of a cone has an exit diameter determined by employing the formula for the area of a cone [53].

The sprue base well is usually taken to be five the size of the cross-sectional area of the sprue exit [8]. The choke informs what the cross-sectional areas of the runner bar and ingates will be

by employing the gating ratios. Pressurized and non-pressurized gating ratios are used; pressurized for the ferrous castings and the non-pressurized for the light alloys such as Al-alloys. The runners and ingates convey the molten metal to the cavity of the mold or the polystyrene pattern buried in the mold in the case of EPC Process. Riser is an important part of the gating system. Its function is to feed the casting during solidification so that no shrinkage cavities are formed.

There are many types of gating system designs; top, bottom, side and step. Jain [54] and Rao [8] posited that side gating system enjoys the advantages of both the top and bottom gating designs. However, gating system should be used based on the shape of component to be produced. For example the bottom design is best for the cylinder. **Figures 5–7** show the top, bottom and side or parting line gating designs. These gating systems must be designed, constructed and assembled with the patterns and positioned in the mold ready for the pouring of the liquid metal. Rao [8] provided an insight into the pouring rate of molten metals with respect to their weights poured into already prepared mold. This assists the foundry engineer to determine the rate of flow of liquid metal which can ultimately be used to determine the pouring time. **Table 3** gives the pouring rates of some metals [8].

7.10. Review of specific work on EPC process

Sands and Shivkuman [55] demonstrated the influence of refractory material porosity on mold filling in the EPC process by changing coating thickness. The demonstration showed that mold filling times decreased with the permeability of the coating. From practical perspective, the gas permeability of the refractory coating has been a critical factor in the EPC process for casting soundness control [2].

Behm et al. [13] submitted that EPC process does produce quantities of airborne emissions that are known to be toxic to humans. He further argued that little is known about how individual process variables- coating, pattern thickness, pouring temperature, pouring time, vibration etc. impact the quantity and makeup of these' emissions. This fundamental knowledge may lead to a more environmentally responsible process by reducing the airborne emissions from EPC process. A limitation known with EPC which has not been totally eliminated by experiments is blow hole formation.

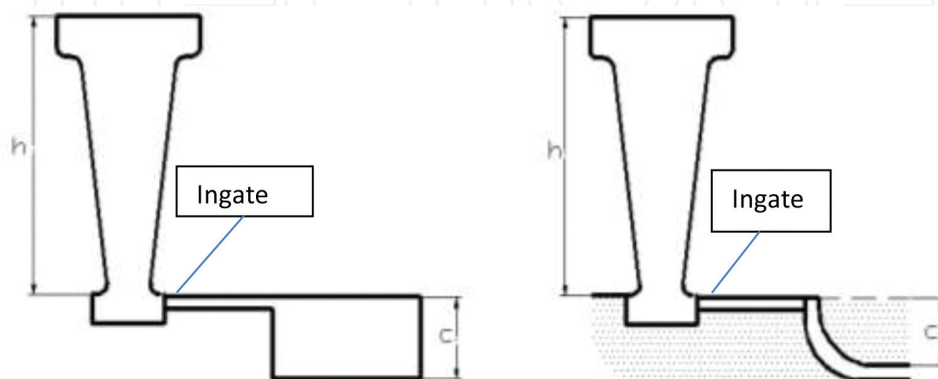


Figure 5. Top gating system.

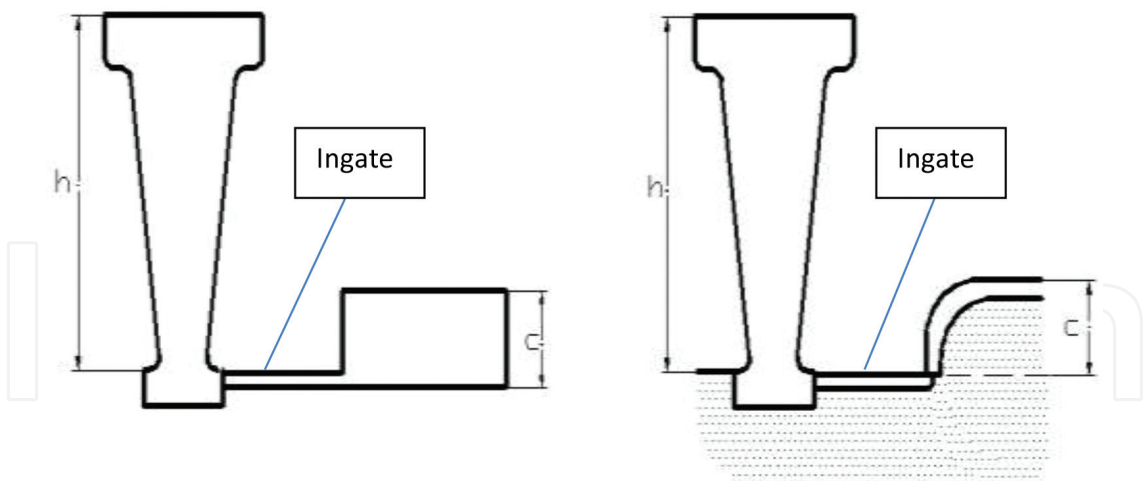


Figure 6. Bottom gating system.

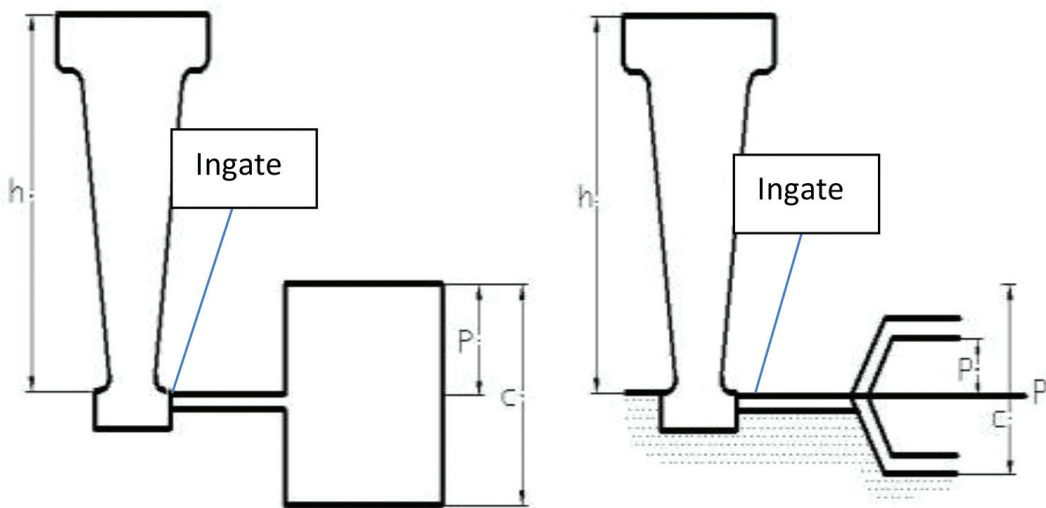


Figure 7. Parting line gating system.

Metal	Pouring rate in Kg/s for castings of mass, Kg			
	Up to 10	10–50	50–100	100–500
Pig iron	1.1	1.5–2.0	3.0–4.0	3.5–6.0
Steel	1.2–1.4	1.9–2.5	4.0–5.0	4.5–7.0
Aluminum alloys	0.25–0.3	0.5–0.7	1.0–1.3	1.2–2.0

Source: [8].

Table 3. Pouring rate of metals.

This provides a platform to make some analysis on the variables that may have weighty results on the soundness that would be produced using EPC Process. In respect of the process parameters that influence the quality of components produced by EPC, gating ratios and geometry of

components were investigated in combination with other parameters like the pouring temperature and grain fineness number (GFN) of molding sand [4, 35]. It was observed that geometry of component as a parameter produced significant effect on the mechanical properties and microstructures of the test castings produced.

8. Pouring and pouring equipment

To achieving soundness in metal casting, more importantly in EPC Process that is susceptible to many variables, pouring of liquid metal into the sand mold is carefully done. In pouring, the liquid metal must be clean and free from slag [54]. The pouring is done such that air aspiration and turbulence are excluded. By this, mold erosion is avoided and defect like metal penetration does not occur. Sound castings are then obtained. The pouring equipment which is the ladle should not be too heavy for the foundry man to carry, otherwise, a mechanical system should be used to carry out the pouring to prevent accident which may occur as a result of inability of the foundry man to carry the equipment.

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