

Experimental Analysis of Porosity in Gray Iron Castings

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Abstract- This paper presents the experimental analysis of porosity in gray iron castings poured with cores prepared with Phenolic urethane no-bake binders. The data for analysis were obtained by altering the casting parameters such as binder ratio, binder level, casting temperature, section size, mixing effect, metal composition, addition of Titanium, Zirconium, Iron oxide, core washes and core post-baking on porosity formation in gray iron castings. Results obtained showed that pouring temperature above 1482°C, poor binder dispersion and use of binder ratio favouring higher level of poly-isocyanate component of the binder promotes porosity. However the additions of 0.25% red iron oxide (Fe_2O_3), 0.025% Titanium and 0.05% Zirconium were also effective in eliminating porosity just as core post-baking and the use of core coating modified with red iron oxide. This result will help metal casters to reduce porosity defects in gray iron castings when they are poured with cores prepared with Phenolic urethane no-bake binders.

Keywords: Porosity, Castings, Gray iron, Phenolic urethane no-bake binders.

I. INTRODUCTION

Monroe (2005) in his work described porosity as the most persistent and common complaint of casting users. Forgings, machined parts and fabrications are able to avoid porosity with ingot cast feedstock, mechanical processing and automated inspection of simple shapes. Controlling porosity depends on understanding its sources and causes. Significant improvements in product quality, component performance, and design reliability can be achieved if porosity in castings can be controlled or eliminated. Porosity in castings is due to bubbles or gases being trapped during solidification. Porosity sources include entrapped air during filling, centerline shrinkage that occurs during the final solidification, blowholes from unvented cores, reactions at the mould wall, dissolved gases from melting and dross or slag containing gas porosity (Bates et al, 1980). In addition, due to a decrease in the solubility of gases during solidification, gases dissolved in a molten alloy are rejected from the solid to the liquid, resulting in an increase in the gas concentration in the remaining liquid. As a result, the last liquid to solidify can have relatively high dissolved gas content and exceed the limit of solubility. Dissolved gases in molten irons may come from various sources, but charge materials containing high amounts of nitrogen, oxygen, and hydrogen, and decomposing organic mould binders during pouring are the most common

sources. Volume contraction during solidification creates shrinkage in castings. Some of the factors contributing to shrinkage are the density differences of liquid and solid, the viscosity of the liquid, the solidification range, the solidification rate, and the permeability of the mushy zone (Coble, 1971). Since the pioneering work of Pellini (1953) on solidification shrinkage, there have been a number of studies to understand the mechanisms of gas and shrinkage porosity formation and to develop models to predict porosity formation, particularly in Al alloys. Using hydrodynamic principles, several workers such as Fang and Granger (1989) developed models to predict shrinkage which correlated well with experimental data in some cases. The relationship between porosity and surface tension in ductile irons was presented in Henych (1998). Niyama et al (1982) investigated the effect of casting size and temperature gradient in castings on shrinkage porosity. There has also been a thermodynamic approach to the porosity problem. Authors such as Poirier et al (1987) calculated the effect of the segregation of gases in the liquid on porosity formation. These studies have yielded useful information on topics such as the level of gas pressure required to form gas porosity in a few alloys under various conditions. The above works describes porosity defects and the metallurgical practices that promote the occurrence and treatment of such defects, relatively little experimental work had been conducted in the area of effect of chemical binder induced porosity defects especially with Phenolic urethane no-bake binders. This work investigates the influences of casting variables on porosity formation in gray iron castings poured with cores prepared with Phenolic urethane no-bake binders. In a bid to achieve these objectives there was the need to design a well balanced experiment that promotes and prevent porosity formation in gray iron.

II. MATERIALS AND EXPERIMENTAL PROCEDURE

The materials and equipment used for this investigation were sourced and provided by the foundry department of Delta steel company. These includes; No-bake furan binder, Phenolic urethane no-bake binder, washed and dried silica (W/D) sand, Cast iron of varying grade, Assorted inoculants, Pt-Pt pyrometer, Strip chart recorder, Electronic weighing scale, Magnifying glass, Strip chart recorder, Gas furnace, Ladle, Patterns, Core and mould boxes, Mould boards, Crucible, Wooden rammer, Electric saw, Emery cloths, Vice, Ingot mould. The experimental program used in this investigation was divided into two phases. First phase was devoted to the development of suitable tests having the capability to produce porosity defects. The

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cylindrical test casting shown in Figures 1 was developed for these tests to observe the extent of porosity formation under various test conditions. This "stepped cone" configuration was selected because its design was such that core decomposition gases would be generated rapidly while the casting was still in the molten state and for the study of how section size affect porosity formation.

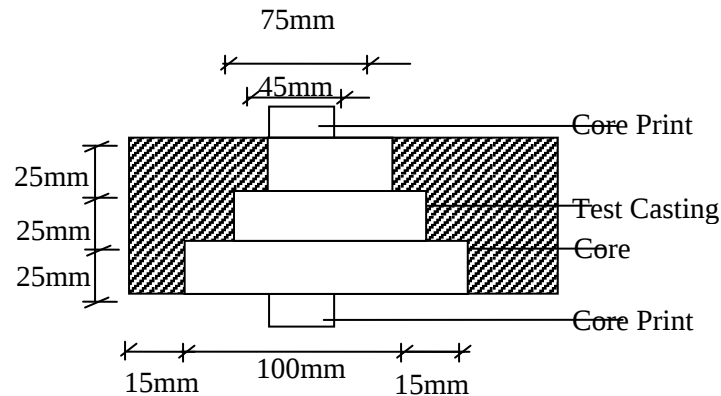


Figure 1: Schematics of cylindrical test casting showing the core and core print

The moulds used for the production of test castings were made with a zero nitrogen no-bake furan binder. The base core sand mix used for the experimental work consisted of the phenolic urethane no-bake binder (PUN) mixed with a high purity, washed and dried, round grained, silica (W/D) sand. The core making procedure used throughout this work consisted of adding the phenolic polyol resin component (Part I)** to 4.0x10⁻⁴m³ of the core sand and mixing for two minutes, followed by the addition of the polyisocyanate component (Part II)** and mixing for an additional two minutes. The mix was immediately hand rammed into the core box and the stepped cone cores were stripped after five minutes. The melts were poured at selected temperatures as measured with a Pt-Pt 10% Rd immersion pyrometer and a high speed, strip chart recorder. Variables investigated in this phase includes binder ratio, binder level, pouring temperature, sand type, mixing effects, metal composition and core age. Within each series of tests, the conditions were controlled as carefully as possible and individual variables altered to determine their effect on porosity. The second phase depends upon the first phase of the work in that conditions that were found to promote porosity were used exclusively to developing remedial techniques to prevent porosity. The same melting and core making procedures previously described were likewise used at this time. Techniques studied in attempt to eliminate defects included; use of various grades of iron oxide, additions of ferrotitanium, as well as titanium and zirconium based ferroalloy inoculants, use of core sand additives, core baking, and a study of experimental core coatings. The extents of porosity formation in all the castings were determined by careful sectioning at several locations. The

porosity extent was rated 1 Nil-6 Very severe. i.e (1-Nil, 2- Nil-Trace, 3-Trace, 4-Moderate, 5-Servere and 6-Very severe.

III. RESULTS AND DISCUSSION

Below are the results obtained from tests carried out to determine the effects of casting parameter in the formation of porosity in test castings poured with cores prepared with Phenolic urethane no-bake binder. Figure 1 below shows the effect of binder ratio on porosity propensity. The ratio of Part I to Part II resin components for PUN binders was varied at constant binder level of 1.5%. Test castings made with binder ratio of 60:40 (Part I: Part II) were without porosity defects. As this ratio became balanced (50:50), trace amounts of porosity were found in a few test castings. As the binder ratio was unbalanced again in favour of excess Part II (40:60 and 35:65), greater amounts of subsurface porosity formed in the test casting. The types of defects observed varying in intensity from nil to very severe. The severity of the porosity defects increases as the binder level was increased at constant Pt I: Pt II ratio, as shown in table 1. These results show that if sufficient amounts of evolved hydrogen and / or nitrogen decomposition gases are made available to the solidifying irons, porosity will generally occur even with favourable binder ratios of 60:40 (Part I: Part II) and using relatively high pouring temperatures. The result also demonstrated the temperature dependency of porosity formation with PUN binders. The test Castings poured at temperatures of 1482°C and higher produces severe subsurface defects when unbalanced binder ratios in favour of Part II were used. However, test castings poured at temperatures between 1371°C and 1400°C show little or no trace of porosity.

Table 1: Effect of Binder Level on Porosity Formation

BINDER LEVEL (%)	RATIO PT. I : PT II	POROSITY EXTENT
3.0	60 : 40	Nil to Trace
3.0	50 : 50	Moderate
3.0	40 : 60	Severe
3.0	35 : 65	Very Severe
1.8	60 : 40	None
1.8	50 : 50	Trace
1.8	35 : 65	Severe
1.5	60 : 40	None
1.5	50 : 50	None to Trace
1.5	35 : 65	Severe
1.25	50 : 50	None
1.25	35 : 65	Moderate

TEST CONDITIONS:
PUN on W/D silica sand.
Iron Chemistry: 4.3 C.E. Gray Iron
Binder Ratio: Part I: Part II ratio varied.
Pouring Temperature: 1482°C

Porosity occurred in section thickness ranging between 10mm-24mm in the test castings containing porosity. It occurred in preferential locations. Deep seated, subsurface porosity was usually located adjacent to the 90° re-entrant angle or step. These locations act as localized hot spots since a small volume of the core is heated from both sides by the solidifying iron. In thinner sections, varying degrees of surface porosity were often found. Results obtained with typical lake sand and washed and dried silica sand incorporating unbalanced binder with Part I : Part II ratio held constant at 35:65 and pouring temperature of 1482°C shows that sand type has significant effect on porosity formation. Severe subsurface porosity was very prevalent with washed and dried silica sand cores while castings made with Lake Sand cores were entirely sound. The behaviour of lake sand in eliminating gas defects may possibly be attributed to either its significantly larger quantity of surface impurities, bulk impurities or greater permeability. Comparisons of casting results obtained with acid-treated versus untreated Lake Sands showed that the removal of surface impurities by acid leaching was not effective in promoting porosity and no porosity was observed in the test castings.

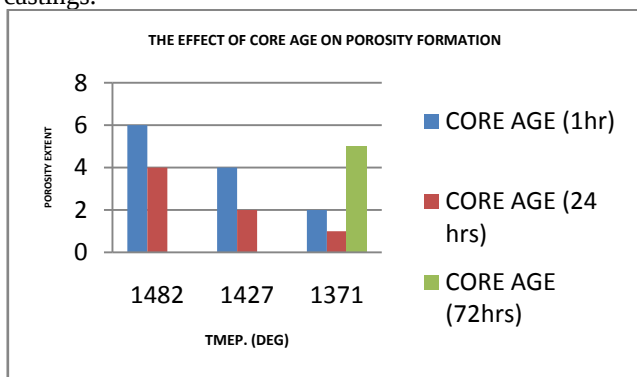


Figure 2. The effect of core age on Porosity Propensity in test casting poured at three different temperature regimes

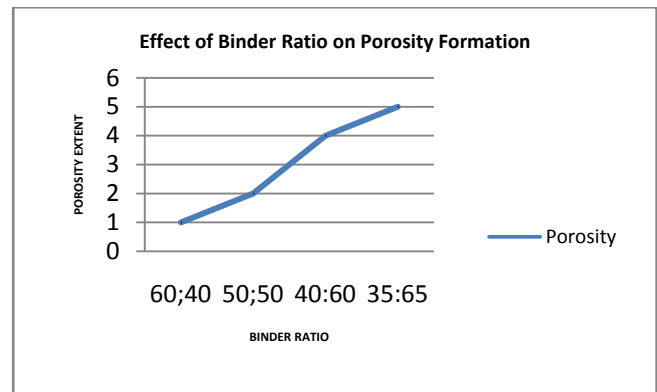


Figure 3. Effect of Binder Ratio on porosity formation in test castings poured at four different Binder Ratio

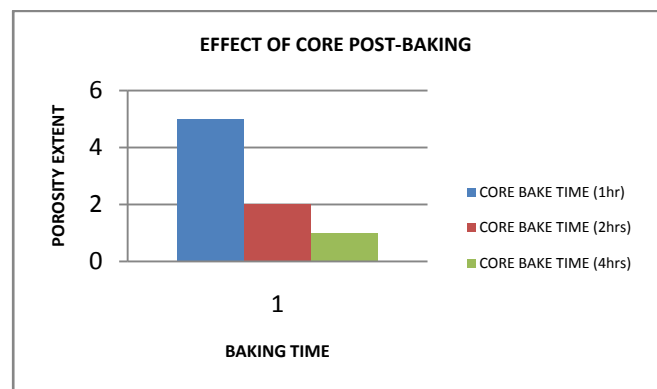


Figure 4. Effect of core post-baking at 1, 2 and 4hrs on porosity formation in test castings

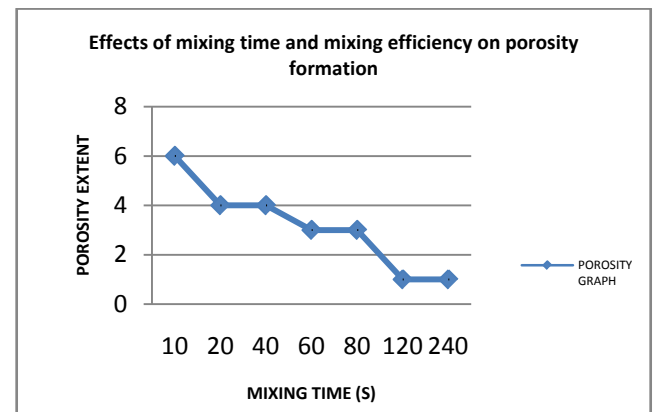


Figure 5. Effect of binder dispersion on porosity formation

Experimental test cores were made using mixing times of 5, 10, 20, 30 and 60(s) for each component (double for actual total mix cycle). The result as shown in Figure 5 demonstrated that, short mix cycles of 10 to 40 (s) total times tended to promote the formation of both surface and subsurface porosity. Only trace amounts of subsurface porosity were found in the remaining castings made with cores mixed for intermediate times of 60 to 80(s). Sound castings were obtained when total mixing times ranged from

120 to 240(s). Results obtained from core age tests poured at three pouring temperatures of 1371oC, 1427oC and 1482oC incorporating unbalanced binder with Part I : Part II ratio held constant at 35:65 is as shown in Figure 2. The cores were allowed to age for 1, 24 and 72hours after stripping. The effect of test core age within the first 24 hours after strip had no effect on porosity formation. Test castings poured with cores used immediately after strip or after overnight aging performed in a similar manner. Susceptibility to porosity formation reduces with the core age within 24hours after stripping. However, with test cores aged over three days under ambient conditions, the severity of the defects increased slightly. This phenomenon appears to be related to moisture from atmospheric humidity combining with unreacted 'NCO' groups in the Polyisocyanate and forming urea structures. Dawson et al (1962) reported in their work that the porosity forming tendencies of this latter group of substances is well known. They are reported to readily break down into ammonia derivatives at high temperatures that later dissociate into nascent hydrogen and nitrogen, both of which are highly soluble and dissolve very readily in molten irons. Metal composition of the castings poured had a significant effect on porosity formation as shown by result obtained. The tests results indicate that the porosity forming tendencies seemed to be greatest for the low carbon

equivalent iron followed by High carbon equivalent iron and least for ductile iron. Ductile iron castings seemed to be far less susceptible to defect formation than either composition of gray iron. Further tests incorporating the use of proprietary inoculants containing carefully controlled additions of surface active elements as well as elements that neutralize nitrogen were examined and are reported herein. Titanium (Ti) and zirconium (Zr) were added to the molten metal prior to pouring. The results obtained from these tests showed that in almost all cases, the addition of small amounts of titanium was effective in eliminating subsurface porosity in castings made with cores bonded with excessive (Part II) polyisocyanate levels. In the case of 70% ferrotitanium additions, titanium additions of 0.05% as were effective in removing subsurface porosity defects. No porosity was found when titanium addition levels of 0.025% were employed with Inoculant B (- 75% Si, 11% Ti, 5.5% Ba, 3.5% Mn, 1.25% Ca, 1.0% Al, Bal - Fe). Ferrosilicon zirconium was almost as effective in eliminating porosity but somewhat higher levels of 0.05% zirconium had to be added. With zirconium additions of 0.025%, trace to no subsurface porosity was found. The effect of controlled addition of zirconium and selenium in mould are listed in Table 3.

Table 2: Effect of Selenium and Zirconium Additions on Porosity Formation

% ADDITION	BINDER LEVEL (%)	RATIO PT. I TO PT. II	POROSITY EXTENT
None – Standard 75% FeSi	1.5%	35 : 65	Very Severe
Inoculant Tablet D. 0.0048% Zr	1.5%	35 : 65	Severe
Inoculant Tablet E. 0.0048% Zr and 0.0019% Se	1.5%	35 : 65	Severe
TEST CONDITIONS: PUN Binders applied to Washed and Dried Silica sand, Iron Chemistry: 4.3 C.E. Gray Iron, Pouring Temperature: 1482°C Standard Inoculant - Foundry grade 75% FeSi with 0.75% Calcium, 0.33% addition rate INOCULANT D - 9 gram inoculant tablet containing 27.7% Si, 28.41 oxy-sulfide forming elements plus 8.0%Zr, Bal - Fe INOCULANT E - 9 gram inoculant tablet containing 25.6% Si, 26.88% oxy-sulfide forming elements plus 8.0%Zr and 3.3% Se, Bal - Fe			

The result shows that castings made with either zirconium by itself or with both selenium and zirconium contained subsurface porosity. The of additions of varying amounts of red iron oxide (Fe₂O₃ or hematite) to PUN core sand mixes showed that the additions of as little as 0.25% red (hematite) iron oxide were sufficient to inhibit the formation of all traces of porosity in test castings poured under adverse testing conditions. Furthermore, the casting tests run comparing hematite (Fe₂O₃ -red) to magnetite (Fe₃O₄ - black) shows clearly the effects of iron oxide mineralogy

and chemistry. The red iron oxide (hematite) clearly outperformed the black iron oxide (magnetite) in preventing porosity in gray iron castings. Proprietary red iron oxide (Fe₂O₃) bearing core washes provided very slight or no reduction in porosity defects. Experimental washes composed of aluminum powder and titanium powder provided similar performance. However, a 100% red iron oxide (Fe₂O₃) wash, and another prepared with sodium silicate and iron oxide (Fe₂O₃) completely prevented the formation of porosity.

To determine the effect of core baking on porosity elimination, several test scores were subjected to post-baking or curing for three different times. The result in Figure 4 indicates that castings made with test cores baked at 232°C but for only 1 hour contained severe porosity defects. Intermediate times of 2 hours significantly reduced the extent of porosity. Baking for 4 hours at 232°C produced a distinctive core colour change to chocolate brown and had a significant effect on porosity elimination. Baking might be effective in reducing overall binder level in the core surface layers and demonstrates that some free hydrocarbons are undoubtedly volatilized and nitrogen components from the Part II resin may undergo further reactions to form more stable compounds. Although several variables have been identified that either exaggerate or promote the formation of porosity defects in PUN binders, these variables are in one way or another related to the gaseous decomposition products generated by the resin during casting. Decomposition gases consisting of both hydrogen and nitrogen are readily liberated during casting pouring and during subsequent solidification. High pouring temperatures further enhance both the breakdown rate and amount as well as favour increased gas solubility in the liquid metal. High pouring temperatures also have a significant effect on liquid metal surface tension, which is known to have a significant effect on porosity formation. Because both hydrogen and nitrogen are readily available and extremely soluble at the casting temperatures employed, their effect on potential porosity defects is often additive. From the results obtained during this investigation it is believed that considerable pickup of both hydrogen and nitrogen occurred in the immediate subsurface layers when conditions favouring porosity were employed. At depths of 6mm and more below the cored surface, hydrogen and nitrogen levels tended to be quite low and representative of the base metal. It is probable that just before solidification, momentary super saturation of both hydrogen and nitrogen exist just under the casting surface. Furthermore, if a considerable amount of nascent nitrogen is dissolved in a casting from unbalanced binder ratios favouring excessive polyisocyanate components, the presence of even a small amount of hydrogen will serve to lower the overall solubility of nitrogen. Stated another way, hydrogen may be exerting a catalytic effect on nitrogen to enhance porosity formation. The same effect of alloying elements on gas solubility is well known and acts in a similar manner. To further aggravate conditions, if the melt initially has a high gas content resulting from the use of poor charge metallics or carbon additives, then the tolerance for additional solution of nascent mould or core gases is reduced considerably and porosity formation becomes extremely favourable. Gas holes formed were located just underneath the surface, and most extended no more than 6mm into the casting, a few castings contained gas fissures almost 12.6mm long. Incorporation of proprietary nitrogen stabilizing elements or "scavengers," which include both titanium and zirconium based ferroalloys, offered additional

possibilities for treating binder induced porosity defects. Likewise, in-mould inoculating tablets incorporating zirconium for nitrogen control and small amounts of selenium for hydrogen control also offer promise for defect elimination. It is not well understood how small amounts of red iron oxide (0.25% addition rates) were so effective in eliminating subsurface porosity in the test castings. It has been suggested that the red iron oxide is exerting some type of "catalytic effect" on binder decomposition products that minimize or alter the generation of nitrogen and hydrogen gases. One such theory is that when exposed to the sudden high temperatures of iron casting, red iron oxide (Fe_2O_3) readily releases oxygen. This released oxygen immediately reacts with nitrogen decomposition products from the binder to form stable NO_x compounds. Since hematite (red iron oxide) has a much higher concentration of oxygen compared to magnetite (black iron oxide), and based on the improved performance of red iron oxide compared to black, this mechanism certainly appears to be very feasible.

IV. CONCLUSIONS

This work has successfully showed the causes and the prevention of porosity defects in gray iron castings poured with cores prepared with Phenolic urethane no-bake binders. The results of this investigation lead to the following conclusions: Unbalanced PUN systems favouring excess Part II or polyisocyanate promote the occurrence of both surface and subsurface gas defects. High binder levels also tended to slightly increase defect propensity even when balanced ratios were employed. Inadequate mixing that result in poor distribution of the binder components in the mix was also found to promote porosity formation. The temperature of the molten iron as it contacts the core surface was found to have a significant effect on porosity formation when castings were poured under conditions favouring their formation. Severe porosity defects were formed at 1482°C and higher. As the temperature was gradually reduced, these defects became fewer in number and intensity until none formed at 1399°C. Porosity formation was found to be very sensitive to core sand type. Lake sands were relatively insensitive to defect formation while high purity, round grained white silica sands were found to be very sensitive. Cast iron composition had an effect on porosity formation. Ductile iron was least susceptible to defect formation while low carbon equivalent irons were most susceptible. Addition of Titanium and Zirconium was effective in eliminating porosity defects. Incorporation of ferrosilicon zirconium into proprietary inoculants was also found to reduce the incidence of defects. The addition of small amounts of red iron (Fe_2O_3) oxide (82% minimum purity) to silica sand mixes was extremely effective in eliminating porosity. Sound castings were obtained with additions as small as 0.25% red iron oxide. Black iron oxides were not anywhere as effective as red iron oxide. Porosity defects tended to form in geometric hot spots or re-entrant angles on the test casting. The location seems to indicate that localized heating of the core re-

entrant angles creates a condition that results in a momentary super saturation of the surface layers. The table below gives the summary of conclusions and

recommendation for producing sound castings poured with cores prepared with Phenolic Urethane no-bake binder.

Casting Variables	Recommendation for Sound Castings Poured with PUN-B		
Binder Ratio (Pt I : Pt II)	60:40	50:50	40:60
Binder Level (%)	1.25-1.8	1.25	1.5
Pouring Temperature (° C)	1371-1400	1371-1400	1371
Sand Type	W/D silica Sand, Lake Sand	W/D silica Sand, Lake Sand	W/D silica Sand, Lake Sand
Binder Dispersion (Sec)	120-240	120-240	120-240
Metal Composition	High Carbon Equivalent Iron/Ductile Iron	Ductile Iron	Low carbon Equivalent Iron/ Ductile Iron
Core Age (Hours)	< 24	< 24	< 24
Titanium and Zirconium Addition (%)	0.025-0.50	0.025-0.50	0.025-0.50
Zirconium & Selenium In Mould Addition	-----	-----	-----
Iron Oxide Addition	0.25 and Above	0.25 And Above	0.25 And Above
Core Wash application	100% Fe ₂ O ₃ wash /With Sodium Silicate and Fe ₂ O ₃	100% Fe ₂ O ₃ wash /With Sodium Silicate and Fe ₂ O ₃	100% Fe ₂ O ₃ wash /With Sodium Silicate and Fe ₂ O ₃
Core Post-Baking (H@ ° C)	2-4 @ 232 ° C	2-4@ 232 ° C	2-4 @232 ° C

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