



ARCHIVES
of
FOUNDRY ENGINEERING

ISSN (2299-2944)
Volume 21
Issue 3/2021

5 – 10

10.24425/afe.2021.136106

1/3



Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

A Process of As-Cast Ferritic Gray Cast Iron Production

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Received 19.04.2021; accepted in revised form 10.06.2021

Abstract

Though normal air cooling and green sand mold-casted gray iron convey an essentially pearlitic matrix, ferritic gray iron is used in some electro-mechanical applications to have better magnetic properties, ductility, and low hardness. Conventionally, to produce ferritic gray iron, foundryman initially produces pearlitic gray iron, then it is carried through a long annealing cycle process for ferritic transformation. This experiment is conducted to eliminate the long annealing cycle from the conventional process. A process is developed to produce as-cast ferritic gray cast iron by air cooling in the green sand mold. In this experiment, Si content is kept high, but Mn content is kept low based on sulfur content; a unique thermodynamic process is established for decreasing the Mn content from the melt. After a successful preconditioning and optimum foundry return charging, the melt is specially inoculated, and metal is poured into the green sand mold. An extra feeder is added for slowing down the cooling rate where casting thickness is around 15mm. Finally, hardness and metallographic images are observed for final confirmation of the ferritic matrix.

Keywords: Ferrite, Pearlite, Metallography, Pre-conditioner, Inoculant

1. Introduction

In some special engineering applications where heavy machining, heat management, noise absorption, and compressive strength are the vital issues, gray cast iron is the first choice. Because free graphite is inherently distributed in the gray iron matrix, this free graphite act as a lubricant during machining hence increase machinability as well as heat conductivity, damping properties and compressive strength of the base iron [1]. The matrix of the gray iron is not very much a focusing factor for normal engineering uses as graphite distribution and size. However, in some electro-mechanical engineering applications, low hardness, ductility, and magnetic properties are also expected with other properties of gray cast iron. For example, in the refrigerator's compressor, four casted parts are generally used to make a compressor (Crankcase, Crankshaft, Flange bearing, and Cylinder

head). During the operation of a compressor, torque is applied on the Crankshaft and some external force on Flange Bearing. For this reason, these blocks are needed to be robust under high tensile stress [2]. So pearlitic structure is the best option here. In the Crankcase case, essential properties are machinability and damping properties because it absorbs the vibration created by the rotational Crankshaft, and the coolant is delivered through it (Tensile strength is not a focusing point). As ferrite is softer than perlite, the life of the machining tools is increased by replacing the pearlitic structure with ferrite. Again, the damping property of the ferritic structure is better than the pearlitic structure [3]. So, ferritic gray iron is an intelligent choice for the crankcase that can make a silent compressor. Figure.1 represents the internal view of a typical compressor.

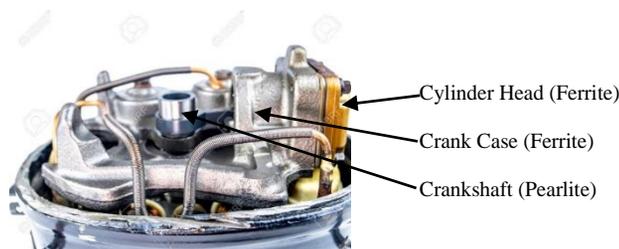


Fig. 1. Internal view of a compressor

Again, the ferritic structure is a soft magnetic material; this structure quickly magnetizes by cutting the external magnetic flux. It has a narrow hysteresis loop hence losses small energy in every magnetization cycle [4].

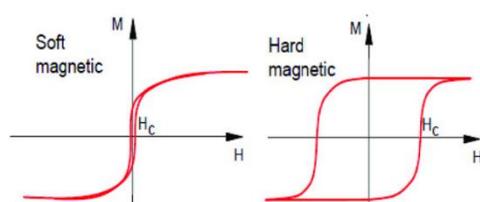


Fig. 2. Hysteresis loop of Soft magnetic material vs. Hard magnetic material

Soft magnetic materials are used in the magnetic core of electric motors, alternators, DC generators, electrical transformers, protective relays, inductors, etc., where changing magnetic flux is associated. Though conventionally, unalloyed iron, silicon-iron, aluminum-iron, nickel-iron, etc., are known as soft magnetic materials, modern researchers have found that ferritic cast iron can also be successfully used in many electromagnetic applications [5]. Ferrite gray iron is also used in many other industrial applications, having unique thermal properties (thermal shock and thermal fatigue resistance). Ferritic iron is used as a mold in the glass-making industry instead of pearlitic iron [6]. So, for all the engineering applications explained above, the ferritic matrix and A-type graphite distribution are considered. As two factors (graphite morphology and matrix) of the gray iron are now the focusing point of a foundryman, particular directions are needed to follow. It is much more challenging to maintain the melting environment that upholds both properties during the solidification of the gray iron. Thousands of parameters are involved in foundry practice; some ease the graphite morphology, some the matrix. Again, some contradict the formation of both properties simultaneously during solidification.

For this reason, foundrymen keep a target on the graphite morphology during solidification in normal air-cooling conditions. After that, a long-time annealing cycle is followed to transfer the pearlitic structure to a ferritic one. The problems are, it needs extra time, cost as well as extra process and human resources. So, from the industrial point of view, "As Cast" ferritic gray iron production is always a welcoming practice. Many researchers establish various processes to cast the ferritic nodular cast iron [7-9]. This process, unfortunately, cannot directly apply to produce "As Cast" ferritic gray iron. Basic knowledge of the graphite nucleation mechanism may be sufficient to explain the failure of these processes to cast ferritic gray iron. The main concept of these processes is to create

proper nucleation sites for graphite precipitation. It decreases the undercooling temperature; hence solidification temperature is raised over the cementite eutectic. Finally, it touches the graphite eutectic temperature, which indicates the precipitation of eutectic graphite [10]. Typically in base iron-sulfur and Mn form MnS, itself MnS, various oxides, nitrides, and other nonmetallic inclusion create core and (Mn, X)S compounds (X = Fe, Al, O, Si, Ca, Sr, Ti, etc.) create the shell of the nucleus sites. But these are not in a hexagonal structure that graphite lattice structure conveys. This is the reason why Ca, Sr, Ba, or Zr, etc. carrying FeSi is used as an inoculant that formed the hexagonal structure of very complex compound $XSiO_2$ or $XO Al_2O_3 2SiO_2$ where (X = Ca, Sr, or Ba) and these hexagonal structure cover the nucleus sites [11-12]. Now hexagonal graphite can easily precipitate on these complex hexagonal silicate compounds. This is the normal mechanism for graphite precipitation; here, MnS is the vital compound for graphite precipitation, enough Mn is needed to neutralize the existing sulfur content and fruitful graphite precipitation, but Mn is strong pearlite former [13]. Unfortunately, a trace amount of Mn suppresses the ferrite formation; hence pearlitic gray iron is produced. In the case of nodular cast iron, Mg treatment is done. For this reason, enough Mg is present in the melt. Therefore, the absence of Mn or trace amount of its presence does not hamper graphite precipitation, Because Mg forms MgS and permits the same mechanism explained above for nodular iron replacing the MnS core by MgS [14]. As Mn content is low now (in the case of nodular cast iron), the environment eases the ferrite formation. However, in the case of gray cast iron, not enough Mg is present in the melt, so complete elimination of the Mn from the gray iron melt is not permitted by metallurgy to produce quality gray iron. Again, a trace amount of Mn suppresses the ferrite formation. Therefore "As Cast" ferritic quality gray cast iron production is more challenging compared to "As Cast" nodular iron production. In this experiment, some exceptional melting and solidification processes are established to overcome the challenges.

Background of the process

1.1. Rational Content of S, Mn & Si

Foundryman has no choice to change the carbon content in a larger amount because carbon content directly alters the CE value, hence the cast iron's mechanical properties. Again, when cast iron is produced from the mild steel scraps, the final S content of the cast iron remains around 0.01%. A certain amount of Mn is needed to neutralize the existing S content to avoid the chilling effect. To promote the maximum amount of ferrite, the amount of Mn content can be calculated by the following formula. [15]

$$\% S \times 1.7 + 0.15 = \% Mn \quad (1)$$

We calculate the required Mn amount 0.167 and target to keep the Mn amount around 0.2%. The roles of Si are more positive than any other elements to produce quality ferritic gray cast iron, So, it is beneficial to keep a significant amount of it in the gray iron melt. In our experiment, we keep Si content around 3% for industrial consideration: In the crankcase case, our main focusing points are machinability, low hardness, and damping property but not tensile

properties. So, a specific (low) hardness, better graphite morphology with ferritic structure is our main target. We know that mechanical properties (hardness or tensile strength) of gray cast iron are closely related to the CE value [16]. So very first, we have to calculate a fixed CE value (high) so that it helps to achieve the target hardness (low). Carbon directly alters the CE values, hence mechanical properties, so it is not wise to change the carbon value drastically. On the other hand, the addition of Silicon slowly changes the CE value, and it promotes ferritic matrix as well as A-type graphite. For this reason, we have increased the Silicon content by 3%, keeping the carbon content fixed (3.4%), and finally confirmed the hypo eutectic gray cast iron. The reader may be puzzled to think that the current grade is a hyper eutectic gray iron but, $CE = [\%C] + \frac{1}{3}[\%Si]$ is a theoretical value derived from the carbon solubility. In the viewpoint of the cooling curve, carbon flotation, and internal shrinkage, conventional CE equations do not give accurate results. Researchers analyzed the liquidus temperature of a cooling curve using thermal analysis of the cast iron and derived a new Carbon equivalent equation CE_L that closely meets the practical findings. Here coefficient of the silicon varies 0.22 to 0.25, $CE_L = [\%C] + 0.23[\%Si]$ is the recommended Carbon equivalent equation [17]. For this reason, it is needed to define an actual carbon equivalent by using a proper thermal analysis system to determine the type of gray cast iron) [16]. We have used a

thermal analysis system, and the described melting condition gives the CE_L value slightly less than 4.30%; that is our target because a high CE value promotes the ferrite formation [18] and decreases the hardness [16]. As MnS is the vital compound for graphite nucleation, 0.2% Mn is not sufficient to produce quality gray cast iron. Because the worldwide recommendation is to neutralize the 0.1% or less amount of sulfur, the cast iron melt needs to have more than 0.2% Mn [19]. Again, 0.2% Mn cannot avoid intercellular carbides formation [20]. Therefore, we introduce preconditioning and double inoculation to compensate for the Mn deficiency in the gray iron melt.

1.2. Preconditioning and Double inoculation

This technique is adopted to compensate for the Mn deficiency of the cast iron melt as well as to produce quality ferritic gray cast iron. We add 0.1% Zr bearing FeSi as a preconditioner after removal of the slag in the furnace, then 0.1% Ba bearing FeSi is used after tapping the liquid metal in the ladle. Finally, 0.1% Ba bearing smaller grain FeSi is used again as an inoculant in stream condition of the casting. The summary of the preconditioning and double inoculation technique is presented in Table 1.

Table 1.

Summary of the Preconditioning and double Inoculation technique:

Sl no	Additive Name	Proprietary Elements	Main element	Application stage	Grain size (mm)
01	Pre-conditioner	Zirconium	FeSi	Furnace	2-10
02	Inoculant	Barium	FeSi	Ladle	2-7
03	Inoculant	Barium	FeSi	Instream condition	0.2-0.7

The chemical composition of the Preconditioner and Inoculant is described in table 2.

Table 2.

Specifications of Preconditioner and Inoculant

Preconditioner	Inoculant
Silicon 62-69%	Silicon 64-70%
Zirconium 3-9%	Barium 2-3%
Calcium 0.6-1.9%	Calcium 1-2%
Aluminum 3-5%	Aluminum 0.8-1.5%
Iron balance	Iron balance

1.3. Thermodynamic Consideration for removal of Mn

There is no blast furnace in Bangladesh, so the availability of pig iron is very rare here. Therefore, the production of gray cast iron from pig iron is not industrially viable. Fortunately, there are many mild steel manufacturing plants here, and these scraps are cheaper than pig iron. So, the production of cast iron from mild steel scrap is more profitable than pig iron. Nevertheless, the problem is to produce as cast ferritic gray iron from the mild steel scraps. As mild

steel scraps contain around 1% Mn, a special melting technique is established to decrease the Mn content from the melt to produce as-cast quality ferritic gray iron. We use the Ellingham diagram for creating the convenient thermodynamic condition that saves the Si content and, at the same time, decreases the maximum amount of Mn from the melt.

Special melting technique

The Ellingham diagram is explained in figure 1. As both Si and Mn oxidation lines are laid below the carbon oxidation line at the furnace operating temperature (1300-1550°C), Si and Mn oxidize before carbon and go to the slag. Again, the Si line is below the Mn oxidation line, so, during the oxidation of Mn, Si will go to the slag before Mn. However, we will not want to do that because Si is beneficial for both graphite morphology and ferritic matrix. For this reason, we approach to decrease the Mn first. After removing the Mn carrying slag, Si additives are used. We set the furnace temperature at 1300°C by analyzing the Ellingham diagram and performing some trial and error to remove the maximum amount of Mn from the melt. At the described thermodynamic condition, the partial pressure of the oxygen is 10^{-18} atmosphere. It indicates the spontaneity of the Mn oxidation reaction on normal atmospheric pressure. We perform this reaction in open conditions very successfully by blowing some air over the furnace as the source of oxygen. The base equation is given below.

$$\Delta G = \Delta H - T\Delta S$$

(2)

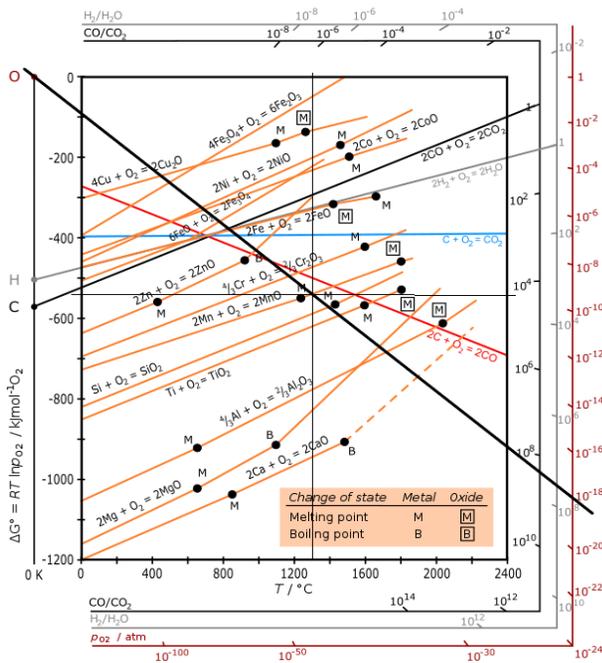


Fig. 3. Ellingham Diagram

1.4. Extra Feeder

Our main goal is to produce essentially ferritic structure throughout the casting, but the problem is the faster cooling rate on

Table 3.

Details of Charge Recipe

Materials	% Charge	%C	%Si	%Mn	%S	%P	%Cr	%Cu	%Al
Foundry Return	30%	3.3	2.3	0.45	0.01	0.04	0.04	0.04	0.002
MS scrap	70%	0.17	0.058	0.872	0.0117	0.0159	0.0180	0.070	0.0276

The amount of the specific additives are calculated individually based on charge recipe and target chemical composition. Before starting the furnace, the furnace lining is cleaned, and some limes are spread out the furnace. The furnace is loaded with steel scraps, and 3% of the calculated carbon is added to the furnace. Air is blown over the furnace as a source of oxygen, and when the furnace temperature is around 1300°C, it is kept in holding condition, and high Mn content slag is removed. As oxidation reaction has happened on the furnace, therefore the temperature of the furnace is increased automatically. At a temperature of 1400°C (around), melt contains a low amount of Mn. One coin sample is prepared for Spectro analysis to check the final Mn content of the castings ($\leq 0.02\%$). The process is repeated until the Mn content comes to the target range. As discussed earlier that Mn oxidation has happened spontaneously at normal pressure and around 1300°C, the reaction rate is increased by air blowing. So, removal of Mn can quickly be

the thinnest portion of the casting. Faster cooling promotes the pearlitic structure [21], especially the casting thickness less or equal to 15 mm is an extremely critical value. For this reason, we add an extra feeder where the casting thickness is around or less than 15 mm. Though the main feeder is calculated based on modulus and volume criteria to cast a sound casting, we only consider the modulus criterion during the calculation of the extra feeder as heat transfer rate is our main focusing point here. We consider the modulus of the feeder to be 1.2 times greater than the casting modulus, and the feeder neck modulus is 1/3 of the feeder modulus during feeder calculation. It may be thought that an extra feeder will increase the production cost, but conventional technology follows two stages (casting then 30hrs annealing cycle) process to produce ferritic gray iron. Implementation of this process drastically reduces the production cost and, more importantly, increases production quantity.

1.5. Optimum Foundry Return Charging

Foundry returns are the gating-feeding parts or defective casting of the previous production lots. Using the repeated additives, inoculant, and molding constituents make this foundry returns rich in nonmetallic inclusion. Usually, nonmetallic inclusion acts as nucleus sites for eutectic graphite, but high concentrated nonmetallic inclusion increased the graphite nucleation density; hence gray cast iron loses its quality. So, during the production of as-cast ferritic gray iron, foundry return charging should be checked based on its chemical composition. In this experiment, the amount of the foundry return is kept 30% of the total raw materials

2. Summary of the Established Process

The first step of this process is setting an appropriate charge recipe to achieve the target chemical composition. The charge recipe explained in table 5 is used to produce as-cast ferritic gray iron.

done to follow the discussed method. We consider the furnace stage is 2 after Mn removal. Now 0.1% preconditioner, required FeSi, and rest of the calculated carbons are added to achieve the target chemical composition. Metal is tapped on a preheated ladle at the temperature of 1450°C, and 0.1% ladle inoculant is added, and the entire metal is transferred on a holding furnace. Metal is kept on the holding furnace for around 5 mins for a homogenous mixture of the melt. At 1380°C to 1400°C temperature, metal is poured (by 0.1% instream inoculated) into the green sand mold (around 2% new sand, 1% bentonite, 0.6% coal dust balanced is old sand). The physical properties of the green sand are moisture content 3.5-4%, compactibility 40±2, active clay 10%, AFS clay 14%, wet tensile strength is 0.20 N/cm², bunch weight is 14 kg, pouring time is 6 sec and every crankcase (casting) weight is 1.6 kg which thickest and thinnest portions thickness are 45 mm and 15 mm. The process Layout is explained schematically in fig 2.

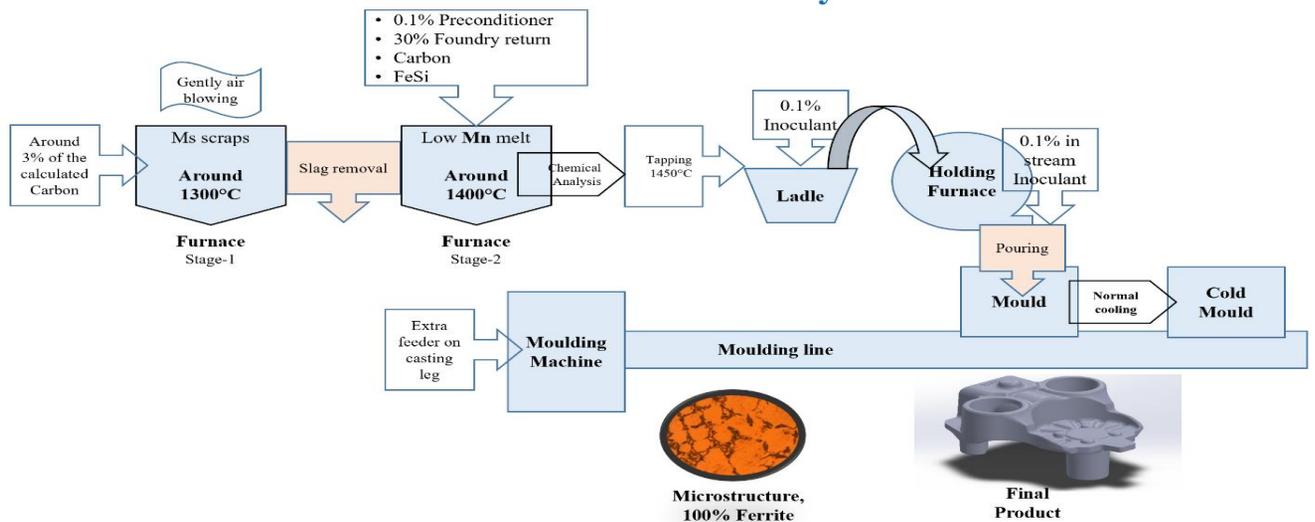


Fig. 4. Established Process Lay-Out of As-Cast Ferritic Gray Iron Production

3. Result and discussion

3.1. Chemical Composition

Before pouring the metal, the coin sample is cast in a copper block, then melt composition is analyzed by "Spark Analyzer Pro LAB Version 1.04.0000 from SPECTRO Analytical Instruments GmbH" The final composition of the casting is as follows:

Table 4.

Chemical composition of the final product

Elements Name	Weight percent
%C	3.4
%Si	3.1
%Mn	0.19
%S	0.01
%P	0.04
%Cr	0.04
%Cu	0.04
%Al	0.002

3.2. Brinell Hardness and Microstructure

After the casting, crankcases are cooled naturally, and the cool drum breaks down the mold. The castings are separated from the sand and shot blasted for final cleaning. Then hardness test specimens are prepared by Metkon METACUT 251 cutter in normal condition. After that Brinell hardness number on the thinnest portion of the crankcase is measured by Affri Integral Hardness Tester following the ISO 6506 standard.

Table 5.

Hardness on the thinnest portion (around 14 mm)

Sample Name	HBW 5/750/10	
	HBW	Avg HBW
Sample:1	141	146
Sample:2	146	
Sample:3	151	

Here randomly, three samples are collected, and finally, the average Brinell Hardness is calculated. The hardness result is displayed in table 5. The average hardness is very consistent. For microstructure observation on the same points, the metallographic samples are prepared by the Metkon FORCIMAT grinding and polishing machine.

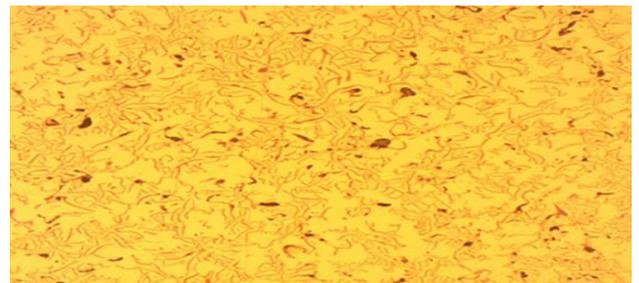


Fig. 5. Microstructure of the thinnest portion of the sample:1 (Mag.100X, unetched)

CLEMEX VISION PE software following DIN EN ISO 945 standards. The room temperature is 24°C, and the average humidity is 40-50%. Fig 5 displays the graphite morphology, which is found more than 90% A-type graphite, and the rest are B. Finally, fig 6. Confirms the 100% ferritic matrix of the cast iron sample. As no significant changes are found on the exact position of the three samples, only the microstructure of the sample:1 is presented.

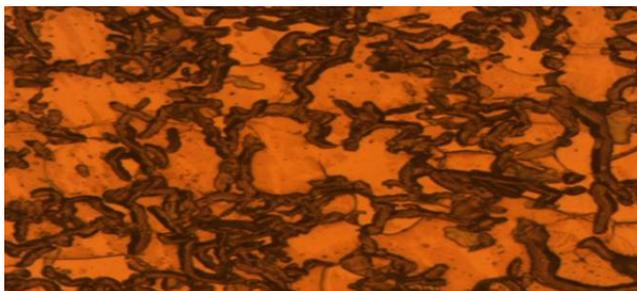


Fig. 6. Matrix of the thinnest portion of the sample:1(Mag. 200X, 2% nital etched)

4. Conclusion

This experiment is done to produce As cast ferritic gray iron from high Mn content MS scraps. Though Mn promotes graphite nucleation, It hinders ferrite formation. Here we keep the Mn, Si, and S content rationally (around 3% Si and 0.2% Mn). A unique melting technique is established to decrease the maximum amount of Mn from the melt. Then, double inoculation and preconditioning techniques are introduced to compensate for the absence of Mn for graphite nucleation. The extra feeder is added on the thinnest portion of the casting for decreasing cooling rate; a slow cooling rate facilitates the ferritic matrix on that portion. The establishment of this technique drastically reduces the production cost of ferritic gray iron on the foundry where the conventional two-stage process (casting then annealing) is followed. Further investigation may be carried out to observe the effect of CE values on the ferritic matrix produced by this established method.

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