Production technique of vermicular graphite iron cylinder head of vehicle diesel engine

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Abstract: The 25 years’ production and application have proved that vermicular graphite iron cylinder heads with vermicularity $\geq 50\%$ satisfy the machinability and performance demand of diesel engine. The method, in which using cupola-induction furnace duplex melting and pour-over process with rare earth-ferrosilicon or rare earth-silicon compound as vermicularizing alloy plus rare earth-magnesium-ferrosilicon as stirring alloy, is an optimal vermicularizing process for obtaining satisfied vermicularity. Using top kiss risers, enlarging kissing areas and expanding covering width and making ingates to freeze earlier are the effective measures to eliminate shrinkage, blowhole and oxide inclusions in the vermicular graphite iron cylinder heads.

Key words: vermicular cast iron; cylinder head; melting and treating process; casting method


In 1983 Wuxi Diesel Engine Works began to produce 6110 model diesel engine for ‘Jiefang’ brand trucks produced by China First Automobile Works. The engine has 6 cylinders with overall dimension of 871 mm × 240 mm × 110 mm, main wall thickness of 5.5 mm and weight of 80 kg (see the photo of Fig.1).

The original design of the cylinder head was chosen alloyed grey iron grade 250 material. However, the early trial application had showed that the areas connecting intake and exhaust valve seats were prone to cracking. Therefore, based on our experience in application of vermicular graphite iron cylinder heads in medium speed, heavy duty diesel engine, it was decided to change the grey iron to vermicular graphite iron for the cylinder head. As a result, the mechanical properties and thermal fatigue properties of the cylinder heads were obviously increased; not only the cracking problem was solved, but the performance of the engine was improved as well. At the same time, the working life of the engine was also prolonged. In addition, with the improved properties, it is possible to further increase the engine power by intensifying measures. For above reason, the vermicular graphite iron head was soon put into large mass production. Over 25 years, the evaluations for the vermicular graphite iron cylinder head from both the engine designer and users have always been very satisfactory. However, for a quite long time, its scrap rate during production process was quite high, 20%–25%. With continuous process improvement, the scrap rate is significantly decreased to 5%–7% in recent 10 years.

This paper describes the production technique of this type of cylinder head.
1 Melting and treating process of vermicular cast iron

1.1 Selection of vermicularity control limit

In the early 1980s, when we began the trial production of 6110 vermicular graphite iron cylinder head, there was no Chinese National Standard of Vermicular Graphite Iron yet. We took vermicularity (the ratio of vermicular graphite area in total graphite area) $\geq 50\%$ (nodularity $0-50\%$) as a control limit of vermicularity, based on the following considerations:

(1) As previous experiences have indicated, the mechanical properties and thermal fatigue properties of cylinder heads with vermicularity $\geq 50\%$ are sufficient, and even exceed the requirement of the engine working conditions.

According to this Standard, we adopted vermicular graphite iron grade 300 as the material for the 6110 cylinder head. The Standard requires the tensile strength at room temperature $\geq 300\text{MPa}$. The actual tensile strength data obtained in production for 6110 cylinder heads is in the range of 350 – 450 MPa. The 25 years’ practical application has proved that there are no cracking or deformation problems happened in the cylinder heads. In addition, in the middle of 1990s, by some power intensifying measures such as extending the piston stroke and changing the working parameters of the engine, the power of the 6110 engine was increased from original 140 hp to 200 hp. The same vermicular graphite iron cylinder head without any structural reinforcement still meets the performance demand for the intensified engine. Based on above facts, the authors agree with the viewpoint of reference [2] that the best mechanical and thermal fatigue properties can be obtained for vermicularity $\geq 50\%$, therefore the control limit of vermicularity specified in Vermicular Graphite Iron Standard of Chines Ministry of Machinery Industry is a proper control limit. For this vermicularity, its machinability and application performance are good and metallurgical control is convenient.

1.2 Vermicularizing processes for cupola melting

Before 1998, the cylinder head was produced in the old foundry of the works. The base iron was melted in two cupolas with fixed spout. The chemical composition of the base iron was as follows (wt.%): 3.5–3.8 C, 1.5–1.8 Si, 0.4–0.7 Mn, $\leq 0.07$ P, $\leq 0.08$ S.

Three types of vermicularizing treatments were utilized successively:

(1) Vermicularizing with adding RESiFe alloy on spout of cupola

From 1961 to 1965, in order to utilize fully the abundant rare earth resources of our country, with the cooperation of The Central Laboratory of Baotou Iron & Steel Co. Ltd., the biggest rare earth alloy producer in China, we carried out a project on utilizing rare earth ferrosilicon (RESiFe) alloy to produce nodular iron. The result revealed that rare earth elements have only a very weak nodularizing effect. In most of the cases, treating iron melt with RESiFe alloy, vermicular graphite is obtained more often than nodular graphite[30]. For this reason, it was quite natural that the RESiFe alloy was used as vermicularizing alloy at first. The composition of the alloy used for the 6110 cylinder head was as follows (wt%): RE: 27–30, Si: 40–50, (Ba+Ca)$\leq 5$, balance Fe. The grain size of the alloy was 2–5 mm. The RESiFe alloy was added uniformly into the iron stream on spout of cupola, the addition was 1.6%–1.7% of the weight of treated iron melt.

As rare earth has relatively weak nodularizing effect on graphite, its content variation has no significant influence on vermicularity; therefore the control range of rare earth content for obtaining a specific vermicularity is relatively wide. However, since the boiling temperature of the rare earth is much higher than the temperature of iron melt, the rare earth in the iron melt will not boil and have no stirring effect itself. Therefore, when using rare earth as vermicularizing alloy, the temperature of iron melt must be high enough, and the alloy must be added into the iron stream on spout of cupola. In addition, it is necessary to stir the iron melt to ensure the alloy thoroughly dissolved to improve recovery of rare earth.

<table>
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<th>Grade</th>
<th>Tensile strength MPa</th>
<th>Yield strength MPa</th>
<th>Elongation %</th>
<th>Hardness BHN</th>
<th>Vermicularity %</th>
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<td>$\geq 335$</td>
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<tr>
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<td>$\geq 0.75$</td>
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<td>$\geq 340$</td>
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<td>170–249</td>
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<td>121–197</td>
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From 1996 to 1998, the cylinder head was produced in the old foundry of the works. The base iron was melted in two cupolas with fixed spout. The chemical composition of the base iron was as follows (wt.%): 3.5–3.8 C, 1.5–1.8 Si, 0.4–0.7 Mn, $\leq 0.07$ P, $\leq 0.08$ S.
Ferrosilicon was used as inoculant, added on spout just after addition of the RESiFe alloy.

In case of vermicularizing treatment failure, following corrective measures could be used:

(a) If the treatment results in certain flake graphite, a proper amount of RESiFe alloy can be re-added into the melt and re-stirring it.

(b) If the treatment results in high nodularity, it is possible to improve the vermicularity by re-tapping proper amount of base iron into the treated melt.

These two corrective measures could be used for all vermicularizing processes described in this paper, as long as the temperature of the treated melt is high enough. However, practical experience showed that the second measure may cause flake graphite formation. For this reason, it is preferred to add as less alloy as possible at first. Then, if it is necessary, re-add a proper amount of the alloy to correct the iron melt.

Statistics showed that, with using this vermicularizing process for cupola melted iron, more than 96% of treatments obtain vermicularity ≥ 50%; the rare earth content for the vermicularity is 0.06%–0.14%.

However, this process has following shortcomings:

(a) The chill tendency of the melt is rather high. The chill tendency can be reduced by using so-called ‘floating ferrosilicon inoculation’, i.e. adding certain lumpy ferrosilicon of 30–50 mm size onto the melt surface in the ladle. The lumpy ferrosilicon will float on the melt surface, gradually, layer by layer be melted and mixed with iron and flow into mould cavity during pouring process, therefore act as instant inoculation. However, this inoculation process often causes too high final silicon leading to graphite floatation. In order to avoid too high final silicon and also reduce chill tendency, stream inoculation was tried. Nevertheless, the graphite count was too high and the shrinkage tendency obviously increased. For this reason, stream inoculation was never been used for both nodular iron and vermicular graphite iron.

(b) Strenuous manual stirring has to be operated during vermicularizing treatment; insufficient stirring will result in vermicularizing failure, i.e. flake graphite will be obtained in the iron.

(c) The addition of the vermicularizing alloy is rather high causing a large amount of slag, temperature drop and low fluidity of the melt.

(d) Since the RESiFe alloy must be added into the iron stream on spout of cupola, this process is not suitable for induction furnace or cupola with rotary forehearth.

(2) Vermicularizing process with adding RE-Si compound on spout of cupola

Compared with the rare earth ferrosilicon alloy produced with traditional silicothermic reduction process, the rare earth–silicon (RE-Si) compound produced with the one-step carbothermic reduction process has relatively higher rare earth content and lower detrimental impurities (wt.%): Ti<0.25, P<0.02, S<0.02. Therefore, it is a better vermicularizing alloy compared to the RESiFe alloy.

The composition of the rare earth-silicon compound we used is (wt.%): RE: 29–33, Si: 49–55, (Ba+Ca)<5, Fe balance.

The vermicularizing process was the same as that for RESiFe alloy. The addition of RE-Si compound was 1.2%–1.4%.

Statistics showed that, when using this vermicularizing process, more than 97% of treatments obtain vermicularity ≥ 50%; the rare earth content for the vermicularity is 0.05%–0.12%, near to that for RESiFe.

The chill tendency of the vermicular graphite iron produced with the RE-Si compound is much lower than that produced with RESiFe alloy due to following reasons:

(a) Among all the rare earth elements, Ce has the strongest nodularizing effect, and La has the best vermicularizing effect. The Ce accounts for 46%–50% of the total RE in the RE-Si compound, which is 2% lower than that in the RESiFe; the La accounts for 35%–38% of the total RE in RE-Si compound, is 10% higher than that in the RESiFe. Therefore, using the RE-Si compound it is possible to obtain better vermicularizing effect. For this reason, the residual RE for obtaining satisfactory vermicularizing effect can be reduced, and the addition of RE-Si compound can be also decreased.

(b) Among all the rare earth elements, La has the lowest chill tendency, Ce has the strongest chill tendency. Since the La content in RE-Si compound is much higher than that in RESiFe alloy, the chill tendency of the iron treated with the RE-Si compound is obviously lower than that of the iron treated with RESiFe alloy.

(c) The silicon content in the RE-Si compound we used is quite high, and moreover, the analysis with electronic probe showed that most of the silicon exists as free phase; therefore the inoculation effect of the RE-Si compound is stronger than that of RESiFe alloy.

However, when using this vermicularizing process, manual stirring the iron melt is still necessary.

(3) Pour-over vermicularizing process with REMgSiFe alloy

During 1995–1996, in order to eliminate strenuous manual stirring operation and reduce the addition of the RE-based vermicularizing alloy, thus reduce chill tendency and eliminate possible graphite floatation, we developed a pour-over vermicularizing process with rare earth magnesium ferrosilicon (REMgSiFe) as vermicularizing alloy. This process was based on the consideration that magnesium has strong stirring effect, and rare earth content range for obtaining satisfied vermicularity is relatively wide. Therefore, by using REMgSiFe as vermicularizing alloy, it would be possible to utilize both the stirring effect of magnesium and the vermicularizing effect of rare earth. Of course, the magnesium content of the alloy should be restricted closely to prevent nodular graphite formation. After a series of experiments, following vermicularizing alloy was chosen (wt.%) 3.0–3.5 Mg, 12–13 RE, 38–45 Si, 2–3 Ca, Fe balance, grain size 10–20 mm. The addition was 1.3%–1.4% for the base iron with 0.05%–0.08% sulphur. The pour-over process was used for vermicularizing treatment. The REMgSiFe alloy was put into a pocket in one side of the bottom of the ladle and covered with 0–0.3% of ferrosilicon powder depending on the temperature of the iron melt.
The application results of this process showed that the chill tendency of the vermicular graphite iron was obviously reduced. Keeping the residual magnesium content less than 0.028%, the proper residual RE content range for obtaining vermicularity \( \geq 50\% \) is of 0.045%–0.082%. As long as magnesium content and RE content are not both at the upper limit or lower limit at the same time, it is always possible to obtain satisfactory vermicularity.

Compared with the former two treatment methods, this vermicularizing process has following advantages:

(a) The fluidity of the vermicular graphite iron is obviously improved, which is very favorable for the thin wall cylinder head;

(b) Manual stirring operation is eliminated, and the influence of stirring operation on the vermicularizing is avoided.

(c) Chill tendency of the treated iron is significantly reduced, thus the inoculation with floating ferrosilicon can be eliminated and graphite flotation is avoided.

However, compared with the former two processes, this process has following disadvantages:

(a) The variation of vermicularity is relatively higher; therefore, the melting and treatment process should be more closely controlled;

(b) Shrinkage tendency of the treated iron is relatively higher, especially when the residual magnesium content is at the upper limit.

1.3 Vermicularizing process with cupola-induction furnace duplex melting

In September of 1998, our new foundry was put into production; all casting production was moved from old foundry to the new foundry. Since then, cupola-induction furnace duplex melting and automatic pouring with MECANA pouring machine have been used for casting production. Considering that the induction furnace has no fixed spout for addition of RESiFe alloy, and vermicularity control by pour-over process using REMgSiFe alloy is rather difficult, all above three vermicularizing processes are not suitable for the new melting and pouring process. In order to take the advantages of above processes and avoid their disadvantages, we decided to use pour-over vermicularizing process with RESiFe alloy (or RE-Si compound) as vermicularing alloy and REMgSiFe alloy (6.5%–7.5%Mg and 2%–3%RE) as stirring alloy. In this process, the REMgSiFe alloy will stir itself, but more importantly stir the RESiFe alloy as well. This is why the REMgSiFe alloy has relatively high magnesium content, compared with REMgSiFe alloy mentioned above, used in the third process.

The addition of the two alloys depends on:

(a) Sulfur content of the base iron;

(b) The residual content range of both RE and Mg needed for obtaining the desired vermicularity;

(c) The stirring force needed to well mix the iron melt and alloys.

The REMgSiFe alloy is added into a pocket in one side of the ladle bottom and covered with the RESiFe alloy (or RE-Si compound). During treatment, the iron melt is poured into the other side of the ladle. Ferrosilicon is used as inoculant and added into ladle after vermicularizing treatment. Then, slag is skimmed off from the treated melt surface.

A wedge specimen is cast after treatment and used to quickly evaluate vermicularity. As the pouring ladle of the MECANA pouring machine cannot be used for vermicularizing treatment, the iron melt must be treated in a special ladle, and then transferred into a pouring ladle. Transfer operation often causes fading of vermicular graphite. Therefore normally, it is safe to re-add a certain amount of RESiFe alloy during metal transferring. The supplemental amount of RESiFe alloy is determined based on the vermicularity of the wedge specimen.

For each ladle, some melt is taken from the pouring cup of the last poured mould and to cast a \( \Phi 25 \times 35 \) mm cylinder specimen used for the fast microstructure inspection for vermicularity. At the same time, a Y block is cast before the last mould. This Y block will be used for the final inspection of microstructure and test of mechanical properties.

This process has been used for about 10 years and will be continuously used in production. Practical application showed that, with this process, it is easier to control the ratio of residual RE to Mg contents, compared with the pour-over process with single REMgSiFe alloy. Statistics indicated that more than 99.5% of treatments obtain vermicularity \( \geq 50\% \).

2 Casting method of the cylinder head

Figure 2 shows the longitudinal section of the 6110 cylinder head casting. It is seen that all the bolt holes, tappet pushrod holes, valve guide holes and screw holes are cast solid, and to be formed during subsequent machining operations. These un-cast holes form a lot of hot spots during casting, especially in the area A, where 4–5 holes are closed together forming a heavy hot spot. As practice experience has showed, all these hot spots might cause shrinkage defect. Even in the early stage of production, when the head casting was made of grey iron, shrinkage defects exist in the cylinder head castings; besides, as for other complicated castings, the blow hole, sand inclusion and oxide inclusion defects also often occur in the grey iron cylinder heads. It could be expected that it would be even more difficult to avoid all these defects after changing the material of the casting into vermicular graphite iron. For this reason, the casting method of the cylinder head has been continuously improved for a long time. Several methods were tried or used in production; finally an optimum method has been developed and used, as described in the following sections.

2.1 Method with two top blind risers

As shown in Fig.3, there are seven ingates on mould parting line and two top risers in the method. Each riser neck is made of a resin sand core fixed onto the cope by nails. This method was conducted on the high pressure moulding line in the old foundry. The result showed that there were severe shrinkage defects in a number of hot spots, including the tappet rod holes, bolt holes and valve guide holes areas.
It is obvious that two top risers in this method act actually as two cold metal collectors. Normally they are called as ‘cold risers and have no much feeding effect; that is the reason that severe shrinkage defects exist in the casting. Also, quite a large volume of iron melt flows through the riser neck and causes it severely overheated. Therefore, the neck area becomes a place where the shrinkage most often occurs.

Later, a method, in which the two top risers were removed and all the ingates were moved to the bottom of the casting, was tried. However, the defects were all the same, not changed.

2.2 Method with one open riser

In order to increase temperature of the top riser to make it work more effectively, a method showed in Fig.4 was used. In this method, only one open riser was used, which was stripped manually during molding. Moulds were made with shockless jolt-squeeze molding machine and poured on the shop-floor. The pouring process was changed as follows: at first, pour the mould cavity through the pouring cup and sprue, after the mould was full, re-pour some hot melt into the open riser to enhance its temperature. As a result, the casting quality was
improved in a certain extent, compared with the first casting method. This method was put into production. The scrap was always in the range of 20%–25% with using RESiFe or RESi compound as vermicularizing alloy. When using single REMgSiFe as vermicularizing alloy, the scrap rate was even higher.

The main defects with using this method were as follows:
(a) Shrinkage in tappet rod holes, bolt holes and valve guide holes (this type of defect accounts for about 70%–80% of the total scrap);
(b) Oxide inclusion on the wall of intake ports or exhaust ports and on the top surface of the casting (accounts for about 10%–20% of the total scrap);
(c) Blowhole on the top surface of the casting (accounts for about 5% – 10% of the total scrap).

In order to eliminate shrinkage defect, tube denseners were used in above holes (see Fig. 5a). The denseners were made of 0.8 mm thick, tin-plated steel sheet. Trial production showed that shrinkage defects were eliminated; however, other new problems occurred:
(a) Cold shut often occurred in the area around the denseners.
(b) Denseners caused water condensation leading to blowholes.
(c) Denseners were not always held in the center of every hot spot; quite often, they were exposed on the surface of hot spots.
(d) The hardness difference between densener and casting caused difficulty for machining.

Then, the tube denseners were changed into spiral denseners made of φ 2 mm tin-plated steel wire (see Fig.5). As a result, problem (a) and (b) were solved in most cases; but problems (c) and (d) were still the same. Therefore, both the denseners were not used in production.

2.3 Method with six side cylindrical risers
Since 1998, all castings have been produced on HWS SEIATSU molding line (air flow pre-compact-high pressure squeeze molding line). It is obvious that the method showed in Fig.4 is not suitable for the HWS line: the open riser can not be striped manually and it is not possible to re-pour melt into the open riser after the mould cavity is full on the new molding line.

The reason that the method in Fig.4 has high scrap can be explained as follows:
(a) The top open riser is still relatively cool. Although some supplemental hot melt is poured into the riser after the mould cavity is full, the supplemental amount is very limited, so the temperature increase of the riser is also very little; its feeding effect is still insufficient.
(b) As all the hot spots are isolated by several thin walls of 5.5 mm, but there is only one riser in the casting, it is impossible for the only one riser to feeding every hot spot.
(c) Since the casting is gated on parting line, the temperature at the top surface of the casting is relatively low that promotes formation of iron oxide film which causes slag inclusion or blowhole.

Based on above analysis, it was decided to utilize a improved method showed in Fig. 6. In this method, six cylindrical risers with dimension of φ80×200 mm were placed near to the exhaust ports of each cylinder head. Each riser neck was positioned at the top edge of the casting and in contact with the hot spot of area A showed in Fig.2. The section dimension of each neck was of 60 mm × 12 mm, and the section of the ingate also was of 38 mm × 8 mm.

However, the result with this method was disappointed:
(a) There were still severe shrinkage defects in a number of tappet rod holes and bolt holes;
(b) There were obvious surface depression defects around every riser neck;
(c) It was very difficult to remove the risers, breakage of casting during removing riser often occurred in the neck area.

2.4 Method with six cylindrical kiss risers
Base on the above method, another method was tried, in which all side risers were changed into kiss risers, riser overlaps the casting at top surface, as showed in Fig.7. The dimension of every riser was the same as in Fig 6. The risers were placed on area A as shown in Fig.2, the kising area, connection area of riser with casting, was of 60 mm × 8 mm; the section dimension of every ingate also was of 38 mm × 8 mm.

The first casting test with this method showed that the
surface depression defect and breakage of casting during removing risers were solved and shrinkage defects were also improved to a certain degree, compared with using side risers showed in Fig. 6. Therefore the method was put into trial production. However, the result showed that the scrap was as high as 30% - 40%; the shrinkage in the tappet rod holes and bolt holes was still the main defects causing scrap.

In this method, despite of that all risers are hot risers, their temperature must be higher than the temperature of the casting, the shrinkage-related scrap was not reduced but even increased, compared with that of the method with one cold riser showed in Fig.4. The reason for this unexpected situation may be explained as follows:

(a) Both RESiFe alloy and REMgSiFe alloy are used for vermicularizing treatment that may cause increased shrinkage tendency of the treated iron melt due to the residual magnesium in the iron.

(b) As mentioned above, the treated melt must be transferred from the treatment ladle into the ladle on the pouring machine. As this transfer operation may cause vermicular graphite fade, it is necessary to re-add some RESiFe alloy during transfer. Considering that the loss of both RE and Mg content during transfer is variable depending operation process, the supplemental amount of alloy is normally more than that needed to compensate for the actual loss. This may also increase residual RE, thus increase the shrinkage tendency of the iron melt.

Nevertheless, it is impossible to change both the vermicularizing process and the pouring process for new molding line. Improving casting method is the only way to eliminate shrinkage defect.

Based on the design principle of the pressure-control risering\[4,5\], the kissing area of every riser was reduced from 60 mm × 8 mm to 60 mm × 6 mm. It was hopped that the
reduced kissing area may cause the neck area solidify earlier, thus the feeding effect due to graphitization expansion could be improved. This measure was tried in production for one month. However, the shrinkage scrap rose up to 62.5%.

This disastrous failure, however, told us that too small kissing area (neck area) is the exact reason causing shrinkage defect; this helped us to find a correct casting method.

2.5 Method with three rectangular kiss risers
In order to enlarge the kissing area of risers, three rectangular kiss risers with dimension of 200 mm (L) × 55 mm (W) × 90 mm (H) were used and kissing area of each riser was enlarged to 200 mm × 10 mm. At the same time, the section of every ingate was reduced to 20 mm × 5 mm to make them freeze rapidly after pouring was finished with the purpose to shift the blocking point from neck area to the ingate [6], as shown in Fig. 8.

With using this method, trial production showed that the scrap rate was reduced to 5% sharply; and the total weight of risers per casting was reduced to 16.8 kg compared to 31.2 kg with six cylindrical kiss risers (mould yield was increased from 60% to 70%). Hence, this method was put into mass production, and there was no any trouble happened for the first six months. And then sometimes it was found that there was shrinkage occurred in one or two valve guide hole areas; this may due to the fluctuation of raw materials quality and process operation. A small chill was used at the place where shrinkage may occur, as shown in Fig. 9. As a result, shrinkage problem was eliminated completely.

This casting method has been used in mass production for about ten years and the total scrap rate of cylinder head is steadily in the range of 5% –7%. Compared to the method with six cylindrical kiss risers showed in Fig.7, the reason of success for this method can be explained as follows:
(a) Since the kissing area is largely increased, the effective feeding time of risers is extended and their feeding effect is improved.
(b) In the casting method of Fig. 7, the iron melt flows into the mould cavity wholly through six risers then six hot spots (i.e. areas A showed in Fig.2). This makes hot spots severely overheated. However, these hot spots could not receive sufficient feeding due to too small kissing area. Therefore, these hot spots often have shrinkage defects.

The situation with rectangular kiss risers is different. The covering width of risers is largely expanded and the metal flows into casting not only through six hot spot areas, and but also through non-hot spot areas, which is favorable to reduce overheating of hot spots and thereby to prevent them from shrinkage. In addition, the expanded covering width of risers increases the temperature of the whole top surface of the casting, which is favorable to prevent the blowhole and oxide inclusions, which often occur on the top surface when using bottom or parting line gating.
(c) The blocking point of metal in the mould cavity is shifted from kissing areas to ingates that is favorable to fully utilize the feeding effect of graphitization expansion [6], and furthermore, early freezing of ingates is also favorable to promote the iron melt moving from risers into casting, thereby improve the early liquid feeding [7].

3 Conclusions
(1) The vermicularity requirement for a specific casting should be determined by considering the working property
demand and machinability requirement and metallurgical control convenience. The 25 years production and application have indicated that 6110 vermicular graphite iron cylinder heads with vermicularity $\geq 50\%$ satisfy thermal fatigue properties, dimension stability and machinability requirements for 6110 cylinder heads.

(2) With using cupola-induction furnace duplex melting, the pour-over process with rare earth-ferrosilicon or rare earth-silicon compound as vermicularizing alloy plus rare earth-magnesium-ferrosilicon as stirring alloy is an optimal vermicularizing process to obtain satisfactory vermicularizing effect.

(3) Using top rectangular kiss risers with enlarged kissing areas and reduced section area of ingates is an optimal casting method for the 6110 vermicular graphite iron cylinder head to effectively eliminate shrinkage, blowhole and oxide inclusions defects.

References