Material and technique of Si-Mo heat-resistant vermicular iron exhaust manifold

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Abstract: Si-Mo vermicular iron is an ideal material for exhaust manifold that works in high temperature and thermal cycle conditions because its properties of thermal fatigue resistance and thermal distortion resistance are significantly better than that of gray cast iron and nodular iron. This paper explains that the vermicularity of Si-Mo vermicular iron is better to be controlled approximately to 50% for the applications of exhaust manifold castings, and generalizes the successful experience of vermicularizing technique that uses sandwich (pour over) process combining with cored-wire injection in trough process together, and uses rare earths-magnesium-silicon as vermicularizing alloy in Disa high speed molding line and automatic plug rod air pressure pouring furnace. In addition, this paper also describes the method to solve the shrinkage hole and porosity defects in the exhaust manifold production.

Key words: Si-Mo vermicular cast iron:exhaust manifold;vermicularity:vermicularizing alloy:vermicularizing technique
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Exhaust manifold is an outlet of waste gas with passages from an engine. Because high temperature of waste gas exhausted from engine, this thin wall component with multiple manifold passages is usually made of cast iron type of materials except a quite few of them still fabricated of stainless steel plate. Gray cast iron was applied a long time ago, but it was easily thermal damaged or cracked under the alternative thermal loading conditions of cooling and heating. To solve this problem, vermicular graphite cast iron has successfully replaced gray cast iron in the position of exhaust manifold application. For this reason, it is necessary to do a brief analysis on the material specification and technology for exhaust manifold components applied for engines, in particular for auto engines.

1 Material specification of exhaust manifold and thermal fatigue property of Si-Mo vermicular heat resistant cast iron

1.1 Thermal fatigue property of cast irons and optimal vermicularity range of vermicular cast iron exhaust manifold

As known, an exhaust manifold from engine usually operates under alternative thermal cycles of quick-cooling and quick-heating. Because of restraining of cycling stress produced during alternative thermal expansion and contraction processes, thermal damage usually happens. The heat-resistant capability of gray iron casting against fatigue is lower, owing to that both the precipitation of oxides and carbon from pearlite over 500°C and the austenite phase transformation over 700°C. All of these factors can be enable to cause an exhaust manifold damaged or cracked earlier.

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1.1.1 The factors of influence on thermal fatigue property of casting

In standpoint of materials science, there are so many factors that can affect casting thermal fatigue. These factors can be expressed with the following formula:

$$RST = f\left(\frac{R,\ A,\ M,\ \lambda}{E,\ \Delta T,\ K,\ \alpha}\right) \qquad (1)$$

Where

RTS - Capability against thermal fatigue
E - Modulus of elasticity
R - Tensile strength
ΔT - Temperature drop during thermal cycles
A - Elongation
K - Stress concentration coefficient
λ - Thermal conductivity
α - Thermal expansion coefficient
M - Density

Among them, depending upon variable graphite morphologies in iron castings, the influence factors of the stress concentration coefficient K can be further expressed as:

$$K=f\left\{\sqrt{\frac{l}{d\times\rho}}\right\} \qquad (2)$$

l - Length of graphite

d - Spacing between graphite phases

ρ - Curvature radius at the ends of graphite phase

As seen in the formulae above, the better thermal fatigue property can be achieved if a casting material has higher mechanical properties, higher thermal conductivity, lower thermal expansion, lower modulus of elasticity, and lower stress concentration coefficient.

After comparing the influential factors between gray cast iron, vermicular cast iron and ductile iron, various parameters and coefficients related to thermal fatigue analysis are summarized in Table 1.

1.1.2 The advantage of vermicular iron in the heat resistant capability against thermal fatigue over ones of gray and ductile irons

After analyzing the parameters above, the capability of gray iron against thermal fatigue is the lowest and more easy to be damaged and cracked under thermal cycles because of its lower tensile strength and elongation, higher stress concentration coefficient, and worse capability against oxidation growth, although it has advantages in better thermal conductivity and lower elasticity modulus. Ductile iron, because of its higher strength and ductility, lower stress concentration coefficient, has relatively higher capability against thermal fatigue, but lower capability against thermal deformation because of its higher elasticity modulus and thermal conductivity causing lower creep resistance. Vermicular cast iron has relatively higher capability against thermal fatigue than gray iron because of its higher strength and elongation and lower stress concentration coefficient, and has relatively higher capability against thermal deformation than ductile iron because of its higher thermal conductivity and lower elasticity modulus. Therefore, the application of vermicular iron in exhaust manifold has advantage over both gray iron and ductile under the impact loading conditions with quick-cooling and quick-heating.

The thermal fatigue property of vermicular iron is mainly associated with vermicularity, matrix microstructure, maximum temperature and speeds of heating and cooling in cycles. The influence of vermicularity on thermal fatigue can be drawn from Table 2 [1], Table 3 [1,2] and Table 4 [3].

After analyzing the results in Table 2 through Table 4, the following points can be withdrawn:

Table 1 Various parameters of three cast irons

Materials	Tensile strength MPa	Elongation %	Elasticity modulus $E\times10^4$, MPa	Thermal expansion coefficient $\alpha\times10^{-6}$	Thermal conductivity W/m·k
Gray iron	100-350	<1.0	7.5-15.5	11-12	50-67
Vermicular iron	300-500	1.5-8.0	14-17	12-14	36-48
Ducile iron	350-900	3.0-25	16.5-18.5	11.3-13	25-40

Table 2 Comparisons of thermal fatigue properties among various cast irons

Materials	Chemical composition, wt.%					Pearlite	Cycle#, crack initialized		
	C	Si	S	RE	Ca	%	250-500℃	250-700℃	250-900℃
Gray iron (HT200)	3.30	1.52	0.04			100	7900	340 350 460	80 100 180
Vermicular iron, VG 90%	3.80	2.67	0.018	0.070	0.0013	30	11250	1200 1300 1650	460 640 450
Vermicular iron, VG 50%	3.65	3.72	0.014	0.099	0.0024	50	15760	1250 1900 1800	680 660 640
Ductile iron	3.67	2.51	0.005	0.085	0.034(Mg)	75	18000	1100 1400 1800	620 550 640

Table 3 Comparisons of thermal fatigue properties among various vermicularizing alloys and vermicularities applied

Cast iron specification and types of vermicularizing alloys		Vermicularity %	Temperatures and cycle %, crack initialized		
			250-500℃	250-700℃	250-900℃
Gray irons	HT200		7900	350-460	80-180
	HT250			350	
Vermicular irons	RE-Si-Fe alloy	90		1 000-1 200	
	RE-Si-Ca-Fe alloy	90	11 250	1 200-1 000	450-640
		50	14 500	1 250-1 900	640-680
	Mg-Ti-Si-Fe alloy	90	8 000	280-420	
		50	19 000	900	
	RE-Mg-Ti-Si-Fe alloy	>80		630-920	
		>80		1 300-1 660	
Ductile iron			18 000	1 100-180	620-640

Table 4 Thermal fatigue properties of mid-silicon heat-resistant iron, ductile iron, and gray cast

Materials	Graphite morphology	Ferrite %	Cycle # (initial crack formed)	
			100-800°C	20-900°C
Ductile iron	Nodularity, 90%	95	298	6
	Nodularity, 80%	95	180	6
Si-Mo Vermicular iron	Vermicularity 60%	95	160	14
	Vermicularity 75%	95	150	17
Gray iron	D-type graphite	95	40	3
	A-type graphite	95	42	9

(1) The maximum temperature in thermal cycles has significant influence on thermal fatigue property. The maximum temperature suffered by the iron can significantly cause the cycle number, cracks initialized to be lowered. For instance, concerning with the vermicular iron with vermicularity at 50% under 250-500 °C, the cycle number of initial crack formed is at 15 760 cycles, but, it drops to about 1800 cycles once the maximum temperature reaches 700 °C, i.e., in the 250-700°C range.

(2) Under lower thermal cycle temperatures, e.g., 250-500 °C, the thermal fatigue property of gray iron is the worst, vermicular iron is in the second, and ductile iron is the best. Under higher cycle temperatures, e.g., 250-700 °C, the difference of thermal fatigue properties between gray iron and vermicular iron becomes more significant. As a result, vermicular iron has the property better than gray iron and is similar to one of ductile iron.

(3) Although ductile iron has better thermal fatigue property, it has worse capability against thermal deformation. Under the condition of tendency with larger deformation and restraints, it is enable to induce higher internal stress and promote the initialization and development processes of a crack.

1.1.3 Optimal range of vermicularity in exhaust manifold castings

From Tables 2 through 4, the capability of vermicular iron against thermal fatigue also has strong relationship with vermicularity. With lower vermicularity, both nodularity and thermal fatigue property in vermicular iron increase, and once the vermicularity is at about 50%, the thermal fatigue property reaches the best, even better than that of ductile iron. The main reason is attributable to higher thermal conductivity of vermicular iron with 50% vermicularity than that of vermicular iron with even higher vermicularity and that of ductile iron [1], and also attributable to higher tensile strength at elevated temperature than that in vermicular iron with 70% vermicularity. Therefore, for exhaust manifold under thermal fatigue loading, the vermicular iron with 50% vermicularity is the corrective choice.

On the other hand, it is actually difficult to make vermicular iron in production with higher vermicularity, e.g., higher than 70%. Since typical wall thickness of an exhaust manifold for auto is usually less than 4 mm, it is so easy to suffer flask graphite problem at flange ports if the vermicularity at pipe is over 70%. So, to control the vermicularity in vermicular iron exhaust manifold casting within 50% is also reasonable and feasible in the production.

1.1.4 Variable vermicularity ranges for variable castings

For the applications of engine block and head castings, the situation is quite different. For instance, an engine cyliderly head usually has very complicated structure, variable wall thickness, and even higher temperature and local water cooling applied. If an alloyed gray iron is utilized for the head, because of its lower castability, it might encounter cracking or leaking problem at the gas passage walls nearby oil nozzle area. If a vermicular iron is applied in the case, it can solve the cracking and leaking problems because of its higher strength and improved castability. Engine cylinder block is similar to engine cylinder head, but larger in size and more complicated in structure. To reduce weight from it, higher vermicularity, even 80% or higher, is usually to be required for achieving higher strength and lower sensitivity to wall thickness, as well as higher thermal conductivity and castability.

Because of quite differences in application conditions and the technical requirements of variable castings, the author do not think that the specification of vermicularity, as 50%, in National Standard of our country, regarding to vermicular iron section, is too low. Also, the author disagrees with that higher or lower in vermicularity is not as a criterion to evaluate processing performance level in vermicular iron casting production.

1.2 Ideal material for exhaust manifold: Si-Mo heat-resistant vermicular iron

1.2.1 Improving thermal fatigue property by raising silicon

To improve the thermal fatigue property for exhaust manifold, the silicon content in a mid-silicon heat-resistant vermicular iron has been increased to 4%, comparing with that in a normal vermicular iron. The strength of the mid-silicon vermicular iron at elevated temperature has been achieved 30% higher than that of a normal vermicular iron, which can be attributed to a SiO_2 protection film formed around iron by higher silicon content. This film plays a hindrance against oxygen ions to penetrate into casting, i.e., increasing the capability of oxidation resistance. For instance, the capability of oxidation resistance of mid-silicon vermicular iron is 5 times higher than that of a normal vermicular iron, at 700 °C testing temperature [3].

The high silicon content makes the matrix structure of mid-silicon vermicular iron into ferrite, and with increasing silicon, the critical temperature of phase transformation of ferrite to austenite increases, i.e., A_1, as high as 900 °C, at 4% Si [4]. If the temperature values in a thermal cycle are lower than this temperature, decomposition of pearlite as well as carbon precipitation in the iron will be not happened, as a result, there is no phase transformation leading to volume change in the matrix. On the other hand, higher silicon content can also strengthen ferrite through solid solution, and promote high temperature strength, so as to improve the thermal fatigue property of the vermicular iron significantly, see Table 5 [3].

The silicon content of mid-silicon vermicular iron can be increased to 5% -6%, while increased brittleness. So, in an integral consideration, it is better to control the silicon content at about 4%.

1.2.4 Molybdenum: increasing thermal fatigue property

Molybdenum is the best efficient element for improving heat-resistance. Addition of 0.4% -0.6% Mo into mid-silicon vermicular iron, i.e., the mid-silicon and molybdenum (brief as Si-Mo) heat-resistant vermicular iron, can further improve both capabilities of thermal fatigue and thermal creep at elevated temperature. Its thermal fatigue property can be as high as three times of that in normal vermicular iron, see Table 6. As a consequence, Si-Mo verimicular iron is an ideal material for exhaust manifold and turbine impeller, and can be reliable to work for longer under 800 °C.

Table 5 Influence of matrix structures on thermal fatigue properties of mid-silicon vermicular and ductile irons

Type of cast iron	Nodularity,%	Matrix structure	Cycle temperature,°C	Cycle#, initial crack formed	Relative growth
Heat-resistant iron	25	30% ferrite	100-800	100	50%
vermicular iron	25	95% ferrite	100-800	150	
Heat-resistant iron	90	30% ferrite	100-800	214	39%
ductile iron	90	95% ferrite	100-800	298	

Table 6 Thermal fatigue properties of various irons [5]

Irons	Thermal cycle temperature,°C	Cycle #, failure
Normal vermicular Iron	200—650	80
vermicular iron with 3.6Si,0.5Mo		248
Ductile iron with 3.6Si		173
Ductile iron with 3.6Si,0.4Mo		375

1.3 Technical requirement of Si-Mo heat resistant vermicular iron exhaust manifold

Various irons applied for various exhaust manifolds made by our company include normal ductile iron (ferrite matrix), e.g., those for Chery's Fen Yun and Qi Yun, Si-Mo heat-resistant ductile iron, e.g., those for Shanghai-GM's Buick and SIO, and Si-Mo heat-resistant vermicular iron, e.g., those for Shanghai-Volkswagen's Santana, but those for Passat B5 used with high-Ni austenite ductile iron with even higher heat-resistant property. Considering the property/price ratio, the choice by Santana's exhaust manifold, Si-Mo heat-resistant vermicular iron, is no doubt the best, see the casting in Fig.1.

Fig. 1 An exhaust manifold for Shanghai Volkswagen's Santana

1.3.1 Material and technical specifications of Santana's exhaust manifold

According to the standard TL . Si-Mo45 from Germany Volkswagen, the material and technical specifications of the Santana's exhaust manifold can be seen in Table 7.

Table 7 Technical requirements of Si-Mo heat-resistant iron exhaust manifolds

Analytical items		Technical requirements, range
Compositions	C %	3.0-3.6
	Si%	3.9-4.3
	Mo %	0.4-0.7
	Sc (eutectic)	≤1.25
Microstructures	Graphite	III-type graphite≥50%, 4-8 grade, the rest of VI type, 5-8 grade
	Matrix types	Ferrite≥90%, the rest, pearlite
Mechanical properties	Tensile strength	≥400 MPa
	Elongation	3%-8%
	Hardness	HB(220 ± 25)

1.3.2 A key point of the technical specifications

According to the specification, the samples for microstructure inspection must be taken from a pipe wall location (with thickness 4 mm) and the samples for mechanical testing must be taken from a location at the largest flange (with thickness 13.6 mm). Because of the big difference in the wall thickness between them, the vermicularity of the sample from the flange can be higher than 70% while one from the pipe wall reaches 50% or higher. This is also a difficult key point to ensure both strength and elongation within the specification.

2 Vermicularizing alloys and vermincularity of Si-Mo vermicular iron exhaust manifold

2.1. Choice of vermicularity

The vermicularizing alloys applied in our country and the world can be classified as three categories: rare earth base alloy, Mg-based alloy, Ca-based alloy; the first two categories are more common. Mg-based alloy has stronger modification capability on graphite, self-stirring by boiling in treatment to help distribution of alloy elements in melt more uniformly. But, its disadvantage is that the residual Mg range allowed is so narrow that it has to add some titanium, an anti-nodularization element, to increase the Mg residual range allowable.

The typical vermicularizing alloy in rare earth base category is the rare earth FeSi alloy. It has higher boiling point, so no boiling in the treatment. It is also an alloy with many alloying elements in higher density, so its self-diffusion ability in melt is very low, and requires fully stirring in the treatment for uniform distribution. All of these also bring difficulty in the treatment operation. In addition, it can promote the tendency of more carbide (i.e., white iron) if only rare earth FeSi applied, which is not good for the castings with thin wall. For this reason, a rare earth Mg-FeSi alloy is made by adding Mg into rare earth FeSi alloy.

2.1.1 Comparisons of vermicularizing alloys

During the exhaust manifold sample production, the two vermicularizing alloys were compared, as seen in Table 8. The results from the tests are summarized in Table 9.

From the testing results, it can be seen that both vermicularizing alloys can make the exhaust manifold, in standpoint of vermicularity, to meet the specification. However, the alloy with rare earth as major gives relatively higher sensitivity to the manifold wall thickness, i.e., the vermicularity at the pipe wall, the thinner location, reaches 50% while the graphite at the flange, the thicker location, becomes flake.

2.1.2 Determination of vermicularizing alloys

Table 8 Compositions of vermicularizing alloys

Composition	Mg	RE	Ti	Ca	Al	Si
MgTiRESiFe	4.5-5.5	0.6-1.0	8.5-10.5	4.0-4.5	1.0-1.5	48-52
REMgSiFe	4.0-6.0	9-11		1.0-3.0	1.0-1.5	38-43

After many tests completed, we determined to choose REMgFeSi alloy as the vermicularizing alloy. Afterwards, in the pilot production later, we found that the vermicularizing alloy pre-mixed with Ti can not control the vermicularity very well because of the fluctuation of Ti content from both the returns themselves and the variation of the charging weight of returns. For this reason, we added Ti directly to melt instead of pre-mixed into vermicularizing alloy, as a consequence, we can achieve the stable vermicularity by controlling of Ti in base iron and addition of vermicularizing alloy. In this way, it is unnecessary to make any limitations on the usage of returns. This measure was particularly important to the early stage of the production that was usually accompanying with higher reject rate. It is also necessary to unify the compositions between the vermicularizing alloy and the nodularizer, then, it is enable directly to apply nodularizer into vermicular iron production.

2.2 Vermicularizing process

2.2.1 Pour over / sandwich treatment

The production of exhaust manifold with Si-Mo vermicular iron in our company was on Disa 2013 MK5 molding line, equipped with an Inductotherm's 5 tons of automatic pour furnace. At the beginning stage of the sample production, we utilized the traditional "pour over" method with one 1.5 tons of ladle for the vermicularizing treatment, then poured it into the automatic pouring furnace after deslagged. Nitrogen was applied in the pouring furnace to protect the melt. After kept three ladles of melt, the pouring started, in-stream inoculation applied then. Later on, one ton of treated iron per batch was added in times by times, up to the melt consumption in the furnace. Table 10 gives some of the testing data for exhaust manifold with the "pour over" treatment method.

From the results in Table 10, we can see that the sulfur contents from the auto pouring furnace is as low as 0.002% - 0.004%, although the contents in the base melts are as high as 0.02%. This indicates that at this point, Ti content to be higher and the residual Mg to be lower are needed to achieve for a satisfactory vermicularity.

Based on many testing data, sulfur content usually makes significant influence on the sensitivity to wall thickness. When sulfur content is at 0.004% or lower, the microstructures between thinner and thicker locations are significantly different, and when sulfur is at 0.015% - 0.02%, the sensitivity to wall thickness trends to be tender, at the same time, the difference in the microstructures at thinner and thicker

Table 9 The test results of two vermicularizing alloys

Treatment types	Sample locations on pipe walls			Sample locations from flange		
	Graphite morphology and grade	Vermicularity %	Tensile strength MPa	Graphite morphology and grade	Vermicularity %	Tensile strength MPa
MgTiRESiFe	III VI	60	519	III VI	70	490
REMgSiFe	III VI	50-60	522	IA		219

Table 10 Some of the testing data with "pour over" treatment for exhaust manifold

Chemical composition, wt.%					VG %	Tensile strength MPa	Elongation %
C	Si	Ti	Mg	S			
3.34	4.07	0.105	0.011	0.004	70-80	518.6	3.2
3.21	4.04	0.110	0.011	0.004	75-80	509.6	3.0
3.35	3.90	0.101	0.012	0.002	65-70	510.1	3.2
3.26	3.90	0.097	0.013	0.002	60-70	500.7	3.0
3.40	3.97	0.110	0.013	0.002	70	525	3.3
3,38	4.11	0.107	0.014	0.002	65	530	3.3
3.20	4.04	0.109	0.014	0.003	70	522.3	3.4
3.26	3.99	0.110	0.015	0.003	65	526	3.0
3.33	4.07	0.103	0.015	0.006	75	546.8	3.0
3.34	4.14	0.102	0.016	0.004	75	541.3	3.0
3.26	3.94	0.100	0.016	0.006	65	534.4	3.3
3.32	4.05	0.106	0.017	0.002	55-60	535.2	3.0
3.25	4.01	0.116	0.019	0.005	65	532.2	3.1
3.38	3.90	0.100	0.020	0.002	65	550.0	3.1
3.21	3.94	0.102	0.021	0.004	50-55	536.7	3.6
3.30	3.97	0.102	0.023	0.001	50	525	3.3
3.39	3.90	0.099	0.023	0.002	50-55	555.6	3.7
3.34	3.92	0.099	0.023	0.005	50	535.8	3.3
3.28	4.00	0.112	0.028	0.004	40-50	586.4	5.4
3.20	3.98	0.104	0.030	0.004	35-40	582.9	6.1

locations becomes minor.

When using pour over method for vermicularizing treatment, because of Ti slightly lower and sulfur too low, as a result, the vermicularity at pipe wall area may meet the specification while the elongation values of the samples for mechanical test at the flange area, i.e., thicker area, are relatively lower, close to the lower limit at a risk position.

Under the condition of applying a big capacity of auto pouring furnace, the obvious weakness of using pour over method is at the requirement for production continuity. Once the production has to face a down time for any reasons, the vermicularity in the melt will be fading after a while although the furnace has nitrogen protected.

2.2.2 The treatment of cored-wire injection feeding

We developed this wire injection feeding system for vermicular iron treatment by installing the wire unit at the tap of automatic pouring furnace in 1997. The vermicular wire made of vermicularizing alloy with certain size of grains, covered by thin belt steel, then the wire can be fed into the tap area of the furnace with a feeding rate controllable, then the wire re-molten and dissolved by the overheated melt, through its diffusion, to perform its vermicularizing process. Figure 2 shows its basic operation principle.

Because the treated iron melt can be enable to flow immediately into the mold below through the tap and the nozzle controlled by a stopper rod, this will solve the problem of fading in vermicular iron. Since this system was the first developed by our company, we filed a national patent for it. Table 11 lists some testing data for exhaust manifold production with the wire feeding system.

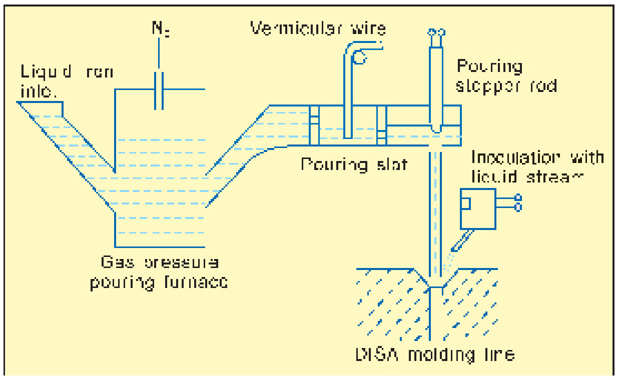

Fig.2 A sketch of showing wire feeding for vermicularizing process

From the results in Table 11, comparing with the pour over method only, the wire feeding method can be enable to allow wider Mg residual range, at the same time, lower Ti content and relatively higher sulfur content. This situation can be beneficial to not only the controlling of vermicularity, but also, less sensitivity to wall thickness, more uniform in microstructure, relatively higher elongation in the mechanical properties. In the first year of the pilot production, we utilized the process and produced about 90 000 pieces of exhaust manifold. For a high volume of production, this process is flexible in its control. Once the production line has to face a down time for any reasons, the vermicularizing treatment can be paused right away, avoiding melt wasted, reversibly, the vermicularizing treatment and pouring operation can be recovered immediately once the production line re-starts. And, this process has also high sensitivity and quick response to the vermicularizing control. Once the treated melt was found to be under or over treated, it can be quickly returnable to normal by adjusting the wire feeding speed.

2.3 Vermicularizing process and its improvement

2.3.1 Disadvantage of wire feeding at the tap

There are disadvantages in the wire feeding for vermicularizing at the tap. One of them is at the shadowed tap of the furnace where flows only a small amount of melt, which results in a lower rate of treatment alloy to be dissolved and absorbed by melt. It is short of a deep reaction reservoir at the area and it is unfavorable to achieve the treated melt homogenous mixed although the alloy added was as much as 1.3%.

Additionally, the strong magnesium light and fume produced in the wire feeding treatment makes the working environment worse, and it is difficult to deslag operation. To solve this problem, it is necessary to build a treatment chamber at the middle of the tap and to take some measures to make the slag removal easily. But, unfortunately, it is not so easy to reach the goal, yet, because of the limitations in equipment and tightened layout at the area.

Table 11 Some testing data of wire injection feeding method for exhaust manifold production

Chemical composition, wt.%					VG	Tensile strength	Elongation
C	Si	Ti	Mg	S	%	MPa	%
3.27	3.80	0.090	0.007	0.017	80-85	498.6	2.8
3.31	3.64	0.087	0.008	0.020	70-80	500.0	3.3
3.32	3.82	0.079	0.013	0.016	75	520.0	3.5
3.36	3.64	0.094	0.013	0.017	75	524.3	5.2
3.31	3.95	0.075	0.013	0.017	65-70	503.0	4.0
3.31	3.82	0.082	0.014	0.018	60-70	513.0	5.0
3.41	4.05	0.093	0.014	0.017	75	524.3	6.4
3.54	3.94	0.116	0.016	0.021	85	501.1	3.2
3.47	4.09	0.095	0.016	0.013	75	515.8	4.5
3.24	3.94	0.089	0.016	0.016	75	512.7	3.8
3.24	3,94	0.08	0.016	0.016	65	526.9	5.9
3.32	4.22	0.087	0.017	0.015	70	526.1	5.5
3.26	3.95	0.077	0.017	0.016	65	512.4	3.7
3.33	3.87	0.081	0.018	0.018	65	523.1	6.0
3.28	3.96	0.078	0.022	0.016	60	526.3	4.3
3.37	4.04	0.087	0.024	0.015	60	561.1	7.2
3.43	4.20	0.106	0.027	0.021	60	559.3	7.0
3.62	4.14	0.101	0.032	0.016	55	571.0	7.0
3.37	4.00	0.088	0.040	0.018	45	615	9.0
3.25	4.05	0.081	0.058	0.016	10-20	623.8	10.6

2.3.2 A combination of pour over and wire feeding methods

Therefore, two years later after the wire feeding unit installed, we modified the vermicularizing operations, i.e., the pour over treatment as a major and the wire feeding as a secondary. We will mainly utilize the pour over method for the treatment when both the equipments in the lines and the production are in normal and stable. When the melt fading in the auto pour furnace happened, we will utilize the wire feeding process to compensate the vermicularizing treatment. This is a combination of the two processes, bringing in their advantages and avoiding their disadvantages. Thus, it makes the operations more flexible and controllable and ensures the stability and efficiency in exhaust manifold production.

2.3.3 The shortness of Mg-Ti vermicularizing alloy

Regarding to vermicularizing alloys, Mg-Ti base alloy had been used for two years. The major problem encountered so far was its bad machinability, because of its higher titanium content, harder phases such as C-Ti and N-Ti carbides formed in the matrix. Particularly, for those castings with thinner wall thickness, if the inoculation was not so good and some of cementite exists at a local (e.g., at an end of pipe), even not so much, the machinability can become even worse. Customer hates to accept the components to machine. To make customer happy, we have to add in an additional rough machining at its finishing operation. One more problem is the charging material management, particularly, the exhaust manifold returns that must be separated carefully from other returns, to avoid them mixed with others to create quality problem.

2.3.4 Improvement of vermicularizing alloy

For the purpose above, we had done lot of experiments on it and decided to use RE-Mg-FeSi alloy as the vermicularizing alloy, and stopped adding Ti into melt. The RE-Mg-FeSi alloy has the composition as shown in Table 12.

For ladle treatment, the alloy added was 0.6% -1.2% , the lower limit for the first three ladles after the auto furnace exchanged from its pouring ductile iron previously, and the upper limit for the three ladles after the auto furnace having stopped pouring for six hours at least or after blasting oxygen operation finished, of course, if everything in normal, the average would be added.

Table 12 Composition of the RE-Mg-FeSi alloy

Grain size	Chemical composition, wt.%					Functions
mm	Mg	RE	Ca	Si	MgO	
8-18	3.5-4.5	7-9	4-6	40-45	<1.0	for ladle
0.43-1.70	5.5-6.5	0.6-1.0	<2	44—48	<1.0	for wire

Note: the diameter of the core- wire is (9±0.5) mm, and its weight is not less than 150 g/m.

Since the improved process was put into operation, the machinability of exhaust manifold had significantly improved, and the rough machining procedure can be no more needed. So far, we have already produced nearly a millions of pieces of exhaust manifolds since then, and the quality of them is stable.

3 Gating/risering system designs of Si-Mo vermicular iron exhaust manifold and its improvement

Because of its larger shrinking tendency of Si-Mo vermicular iron during its solidification, the exhaust manifold casting is easily to encounter shrinkage porosity problem. There exist nine large or small hot spots along the exhaust manifold casting body because of its variable thickness design. And, all locations of these hot spots are close to the machining area and the customer requires defects free on the machining surfaces, which makes the project more difficult.

The exhaust manifold were molded in Disa molding line, vertically parting and pouring, and its internal features were formed by two sand cores. Because of its large amount of gas, air and fume released during the pouring, its gating system design is required to be filled evenly and smoothly, plus the easily escaped vent system and efficient riser system for those hot spots. Usually, it is not so easy to balance all of these concerns, sometimes, to pay an attention to this while causes to ignore others. At the beginning, we applied the bottom filling method to pour the casting at first.

3.1 Bottom filling gating system for exhaust manifold production

Based on the experience and understanding on the vertical parting molding like Disamatic line, for the castings with large size of cavity in height, it is favorite to use bottom filling method in its gating system design, thus liquid metal can be raised in the cavity smoothly and evenly, which is helpful to reduce sand and slag inclusions, but also, to escape air from the mold cavity and the cores. For this reason, we applied the bottom filling gating design for the production, see Fig.3.

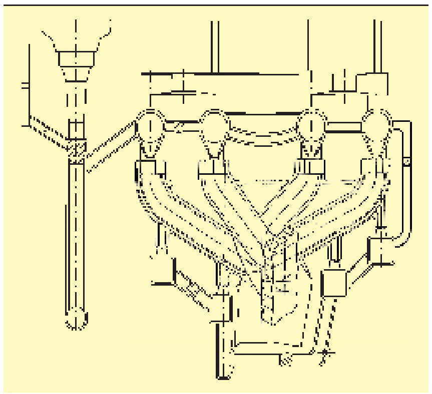

Fig.3 A sketch of the bottom filling gating system

The major problem in the process design is not so favorite to feed, i.e., difficult to solve the shrinkage porosity defects in the castings, as mentioned above, more or less shrinkage porosity existed at the nine hot spots. There are four bosses at the bottom portion of the casting, and multiple ingates located here for liquid metal into the cavity, and porosity also found here after drilling and screwing operations. We revised the gate with flat-thin shape, following solidification rule, but did not work, too. Afterwards, we added a small riser at the runner below the ingate, although its location lower than the boss, it worked, i.e., got the boss fed by sucking liquid metal from the riser newly added.

For the four ports at the flanges located at the upper position of the casting cavity in the mold, at the beginning, we placed four risers for each of them, cold risers, and found shrinkage porosity in them after machining and drilling. Then, we relocated the gating system and let the risers hot by liquid metal through them as well as modified the riser neck into a flat-thin shape, but the results were not as expected yet, and reject rate was still high. So we had to do 100% UT inspection on them piece by piece, cost increased a lot.

As to the largest flange of the casting, because there was no way to place any riser at the hot spot area, the porosity at the location was even more difficult to solve. Again, we had to utilize UT to inspect them one by one, and the reject rate kept high, average at 15%, maximum at 30%. Therefore, we must change and improve this situation. Finally, we determined to adopt the top-filling gating design as described below.

3.2 Top-filling gating system for exhaust manifold

The top-filling gating system design kept the orientation and the location of the exhaust manifold casting in the mold no change, removed the segments of the runner and the gates located at the bottom portion, and let liquid metal fully flowed into the cavity through the top risers at the flange areas on the upper portion of the mold, then placed chilling ribs at the four boss areas, see Fig.4(a) for the sketch of the gating system, and Fig.4(b) for an image of the casting tree.

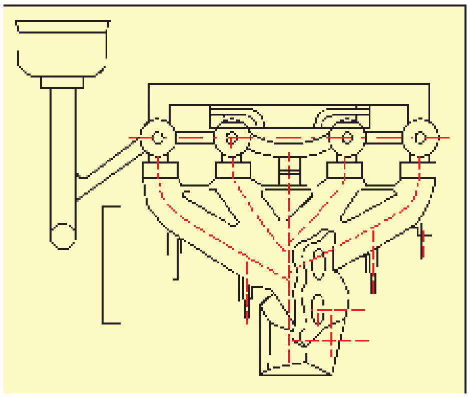

Fig. 4(a) A sketch of the top filling gating system

Fig. 4(b) A photo of the casting tree, showing the top filling gating system

This process design had solved not only the shrinkage porosity problem at the ports of four flanges on the top and at the four bosses at the bottom, but also significantly reduced the size of the shrinkage porosity at the largest flange area and moved the shrinkage location from the critical maching area. Thus, the casting rejects from the shrinkage issue were basically solved. And the weights of the gates and risers were reduced from 9.8 kg to 5.5 kg and the metal yield were increased from 38%, the bottom filling, to 52%.

By improving the gating system, the solution for the shrinkage porosity problem was so successful, but the defects of gas porosity, sand inclusions, slag inclusions were increased a lot. For this reason, we changed the sand core to the shell cores. Then the new problem to come was liquid metal penetration into the shell core. So we modified both the pattern and the core prints and increased ingates on the top and successfully solved the problem. Finally, we achieved the total reject rate, including both internal and external, below 7%.

4 Conclusions

(1) Under the high temperature cycle operation conditions, exhaust manifold castings required to have better properties in both thermal fatigue resistance and thermal deformation resistance. For this requirement, vermicular iron has the advantage, in integral, over those of either gray iron or ductile iron.

(2) To achieve an optimal property of thermal fatigue resistance, it is unnecessary to emphasize only on a higher vermicularity. In practice, ~50% vermicularity is the best choice.

(3) The thermal fatigue property of Si-Mo vermicular iron is double or triple of normal vermicular iron and it is an ideal material for application of exhaust manifolds.

(4) In the production of Si-Mo vermicular iron exhaust manifold, the selection of vermicularizing alloy is very important. Mg-Ti vermicularizing alloy has wider treatment range and better sensitivity to wall thickness, but it can cause worse machinability and higher cost on charging material management. An appropriate selection of Re-Mg vermicularizing alloy can achieve a better balance between vermicularizing control and machinability.

(5) For the production with Disa high speed molding line and automatic pouring furnace, the vermicularizing treatment of combining pour-over method with the wire feeding at the tap of the furnace is a successful process.

(6) The tendency of forming shrinkage cavity and porosity in Si-Mo vermicular iron is significant. It is necessary to apply a process design with top filling and hot riser, at the same time, and to consider multiple ingates and improving vents for sand cores as a plus.

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