Application of complex inoculants in improving the process-ability of grey cast iron for cylinder blocks

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Abstract: Effect of several complex inoculants on mechanical properties, process-ability and sensibility of grey cast iron used in cylinder block were investigated. The experimental results showed that the grey cast iron treated with 60% FeSi75+40%RE complex inoculants has tensile strength consistently at about 295 MPa along with good hardness and improved metallurgy quality. While the grey cast iron inoculated with 20%FeSi75+80%Sr compound inoculants has the best process-ability, the lowest cross-section sensibility and the least microhardness difference. The wear amount of the drill increases correspondingly with the increase of the microhardness difference of matrix structure, indicating the great effect of homogeneousness of matrix structure in the grey cast iron on the machinability of the grey cast iron.

Key words: cylinder block; process-ability; grey cast iron; compound inoculants

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The automobile engine cylinder block made of gray cast iron has complicated shape and requires high performance, which has been drawing significant attention to producers and investigators for many years. Due to the conventional conception that gray cast iron had ideal process-ability in comparison to other cast irons, the research related to the process-ability of the gray cast iron was very limited. With the strengthening corporation between China and foreign countries in the recent years, the problems have shown that the cutting tool wear for the gray iron castings was much severer than that for the imported castings. This problem precluded the replacement of imported castings with homemade products. For example, tests conducted at an auto-maker foundry showed that under identical processing/ machining conditions the homemade cylinder block castings had 10 times as much wear on drill-bit as that of foreign castings [1]. Investigators in the state studied this subject and found that inoculation technique was an effective method to improve the properties of gray cast iron parts[2]. Inoculation treatment could not only minimize the chill tendency at thin sections, improve microstructure and properties and refine grains, but also increase the strength of the gray cast iron[3]. Therefore, inoculation is a feasible approach to improve the process-ability of the gray cast iron used in cylinder block.

The present research investigated the effect of several complex inoculants with different composition ratio on the machinability of the gray cast iron for cylinder block.

1 Experimental details

Test samples were melted in an 100 kg induction furnace of acid lining, and the melting temperature was controlled at around 1 510℃. Based on the type of selected inoculants, samples were separated into 11 groups. Each group included three standard tensile bars with dimension of Φ30 mm×330 mm, one disc sample (as shown in Fig.1a) and a step sample (Fig.1 b). Samples in all groups were tested for tensile strength, hardness, microhardness and the wear generated on the drill. At the fracture of the tested tensile samples, the microstructures of the gray castings were analyzed to evaluate graphite morphology and length, primary austenite in the matrix, lamellar spacing of pearlite and the distribution and size of eutectic cells. The section sensitivity was measured by using of the step sample, which was dissected in the middle along the longitudinal direction. Brinell hardness readings were measured along the diagonal line at each step cross section to calculate the maximum difference in average hardness for different section thickness. The homogeneity of matrix structure was measured by the difference value

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ΔHB in microhardness at the fracture of the tested tensile samples. The machinability was measured by the wear size (width) on drill bit under the same condition after the tool drilled one of the disc samples treated with different inoculants. Specifically, it was to drill 15, 20 and 35 holes along the circle respectively at the diameter of 50 mm, 100 mm, and 150 mm on the disc. The wear surface of the drills was evaluated with an universal tool microscope. Through comparisons of microhardness differences in a sample and the wear of the corresponding drill, the relationship between the microstructure homogeneity and machinability of grey iron castings/samples can be established.

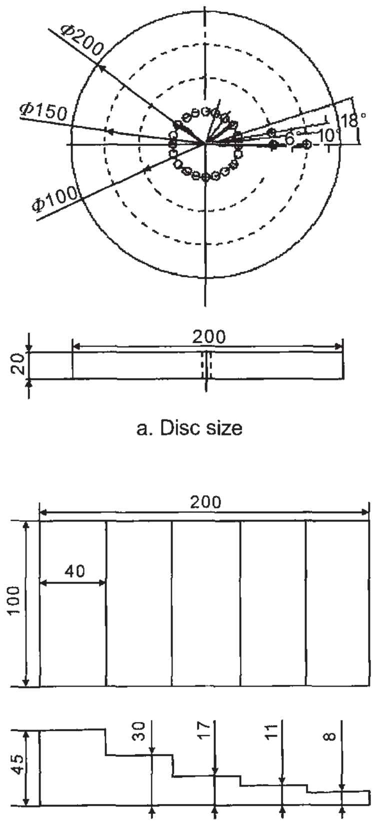

Fig.1 The sample of experiment

The inoculation approach was an in-ladle treatment in front of the furnace. The selected inoculants were FeSi75 inoculant, Sr inoculant and RE (rare earth) inoculant. The compositions of the inoculants are given in Table 1. The effect of the Sr inoculant was better than that of the FeSi75 inoculant, showing twice as much chill reduction ability as that of the FeSi75 inoculant and leading to uniform microstructure at the fracture. The RE inoculant had very strong inoculation effect. The RE inoculant is an excellent desulfurization agent and deoxidant, and the formed RE-sulfates are very likely to serve as the substrate for graphite nucleation, promoting unspontaneous nucleation and improving the mechanical properties of the grey iron castings. Complex inoculants were made by blending the FeSi75 inoculant with either the RE inoculant or the Sr inoculant at different ratios (Table 2), which were added into molten iron at the amount of 0.4%. The tapping and inoculation temperatures were respectively 1 510℃ and 1 480℃. The test samples were poured after the molten iron stirred and held for five minutes.

The raw test material was made of pig iron, returned material and steel scrap at the ratio of 50:30:20. The minute alloying materials were ferrochromium, pure copper, ferrosilicon and ferrous sulfide. Generally speaking, the higher the graphite content, the better the machinability of the casting. But too high graphite content would result in coarser graphite structure and lower mechanical properties. When all factors were considered, the following composition was chosen: Sc: 0.94-0.97%, C 3.2%-3.4%, Si 1.8%-2.0%, Mn 0.8%-1.0%, P≤0.08%, S<0.1%, Cr 0.2%-0.3%, Cu 0.6%-0.8%. The eutectic degree Sc is equal to C(actual measurement)/(4.26 -0.31Si -0.27P).

The addition of alloy elements in the experiment was to increase the pearlite content, to improve the homogeneity of cross sections and to refine the graphite in grey iron castings [4]. Under the present experiment condition, the effectiveness of various tested inoculants was preliminarily evaluated by the result of chill elimination ability, cross-section homogeneity increase, cross-section sensitivity reduction, strength and hardness improvement. However, at the same time, the effect of the carbon equivalent on mechanical properties of grey iron castings should also be considered. Therefore, in this study, three other parameters were also taken into account for comparison, including the maturity (normality) level (RG), the hardening index (HG) and the quality coefficient (Qi) of grey iron [5]. Here, the maturity level RG= σ_b (actual measurement)/(981-785Sc), the hardening index HG= HB (actual measurement)/ (530-344Sc), and the quality coefficient Qi=RG / HG.

Table 1 Compositions of compound inoculants (Wt. %)

Inoculants	Si	Al	Ca	Ce	Mn	Sr	P	Ti	Fe
FeSi75	74.6	1.3							bal.
RE inoculant	41.1	0.35	0.96	9.08	0.33	0.08	0.44	0.08	bal.
Sr inoculant	46.59	0.36	0.014		0.41	0.99	0.028		bal.

2 Results and analysis

2.1 Comparison on the effectiveness of inoculants

FeSi75 is the most common inoculant, while Sr inoculant and RE inoculant also provide very good inoculation results. In order to discover the optimal compositional ratios for the complex inoculants (FeSi75+Sr inoculant and FeSi75+RE inoculant) to achieve best result, experiments were carried out by changing percentage concentration (or ratio) between the components in each type of complex inoculants. The experiment was divided into two groups, the FeSi75-Sr complex inoculant group, and the FeSi75-RE complex inoculant group. The best results of the inoculants are shown in Table 2. It is obvious that the grey iron treated with the FeSi75-Sr complex inoculants had smaller variations of strength and hardness than that treated with the FeSi75-RE complex inoculants with the variations of compositions, indicating that the FeSi75-Sr complex inoculant was the least sensitive to compositions. Grey iron castings treated with complex inoculants had superior mechanical properties to those treated with sole FeSi75 inoculant. Among all grey iron castings treated with FeSi75-Sr complex inoculants, the one treated with the 40% FeSi75-60% Sr complex inoculant had the best strength, the appropriate hardness and good quality coefficient. Among the castings treated with FeSi75-RE complex inoculants, the one inoculated with sole RE had the highest strength, hardness and quality coefficient, while casting treated with 40% FeSi75-60% RE had the highest maturity level, suitable hardness and the ideal quality coefficient.

2.2 Complex inoculants and cross-section sensitivity

The average hardness readings of the step samples are shown in Table 3. It can be seen that the castings treated with FeSi75-Sr complex inoculants had less cross-section sensitivity than the castings treated with FeSi75-RE complex inoculants, suggesting that the castings treated with the FeSi75-Sr complex inoculants received little influence by section size. Among all castings, the one treated with 20% FeSi75-80% Sr complex inoculant had the least section sensitivity, while the casting treated with RE inoculant had the highest sectional sensitivity.

Table.2 Experimental results of RE+FeSi75 and Sr+FeSi75 compound inoculants

Contents of the compound inoculants	Tensile strength, MPa	Hardness, HB	Maturity	Degree of cure	Factor of merit
100 %Re	319	235	1.04	1.17	1.20
20% FeSi75+80% RE	270	232	1.19	1.16	1.03
40% FeSi75 +60% RE	276	229	1.21	1.15	1.05
60% FeSi75 +40% RE	295	222	1.30	1.11	1.17
80%FeSi75 +20% RE	267	226	1.17	1.13	1.04
100 %FeSi75	264	223	1.16	1.12	1.04
80%FeSi75 + 20% Sr	281	225	1.04	1.03	1.01
60%FeSi75 + 40% Sr	278	224	1.02	1.02	1.00
40% FeSi75+ 60% Sr	285	228	1.05	1.04	1.01
20%FeSi75 + 80% Sr	280	229	1.03	1.05	0.98
100 %Sr	268	220	0.98	1.00	0.98

Table 3 Hardness data of step -bars

Contents of the compound inoculants	The average hardness of the different wall thickness, HB					
	45 mm	30 mm	17 mm	11 mm	8 mm	△HB max.
100 % RE	222	224	230	240	260	38
20%FeSi75 + 80%RE	209	216	227	235	244	35
40%FeSi75 + 60%RE	206	218	233	227	236	30
60%FeSi75 + 40%RE	206	218	223	236	240	21
80%FeSi75 + 20%RE	224	226	233	237	238	19
100 % FeSi75	209	214	225	232	234	25
80%FeSi75 + 20%Sr	215	216	227	233	235	20
60%FeSi75 + 40%Sr	212	214	227	233	239	27
40%FeSi75 + 60%Sr	219	220	233	235	238	19
20%FeSi75 + 80%Sr	220	229	231	233	237	17
100 %Sr	214	218	220	228	235	21

2.3 The test results of the machinability

At present, there is no effective method that could accurately measure the wear of the drill, although there exist some measurement approaches such as qualitative description using SEM pictures and the weight loss method [6] using the amount of weight loss of the drill during machining process as the measure to evaluate machinability. Since the weight loss and other methods have relatively large measurement errors, these methods can only provide rough description on the level of machinability of castings. The universal tool microscope was applied in this experiment to measure the wear band/width of the back blade of the drill, which could accurately measure the wear level of the drills. The measuring results are shown in Fig.2. It is apparent that the castings treated with complex inoculants generated less wear on the drill than the castings treated with individual inoculant, and the castings treated with FeSi75-Sr complex inoculants resulted in less wear on the drill than the castings treated with 75FeSi-RE complex inoculants, showing that the castings treated with FeSi75-Sr inoculants have excellent machinability. Among all test castings, the one treated with 20% FeSi75+80%Sr complex inoculant had the lowest wear on the drill, while the one treated with sole RE inoculant generated the highest wear on the drill. Through investigation, it was found that the homogeneity of casting microstructure had a great effect on the process-ability of the castings [7]. Therefore, the relationship between the homogeneity of casting microstructure and casting process-ability was discussed in this research. Figure 3 shows that the castings inoculated with the FeSi75-RE complex had bigger microhardness difference than the castings treated with the FeSi75-Sr complex inoculants, indicating the castings with the FeSi75-Sr inoculation treatment had excellent microstructure uniformity. In all inoculated castings, the castings treated with 20% FeSi75-80% Sr complex inoculants had the least microhardness difference. In comparison of Fig.2 with Fig.3, it can be drawn that, for the castings treated with the FeSi75-RE complex inoculants, both the wear of the drill and the casting microhardness difference varied in decreasing trend with the decrease of the RE concentration. For castings treated with the FeSi75-Sr complex inoculants, the wear of the drill and casting microhardness showed increasing tendency with the decrease of Sr content. There existed good agreement between the changing trends of the drill wear and the microhardness difference, suggesting the great effect of microstructure homogeneity on process-ability of grey iron castings.

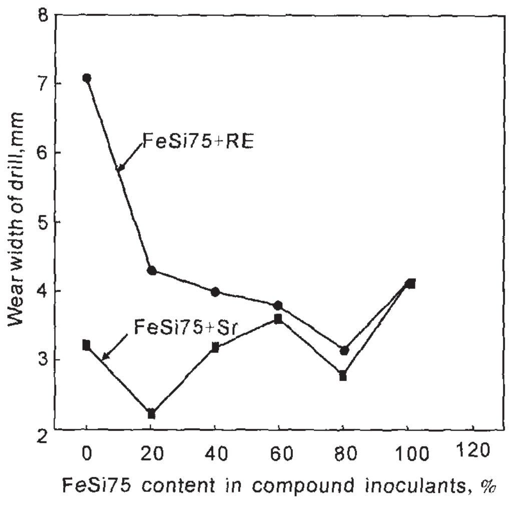

Fig.2 Relation between wear of the drill and FeSi75 content in every kind of the compound inoculants

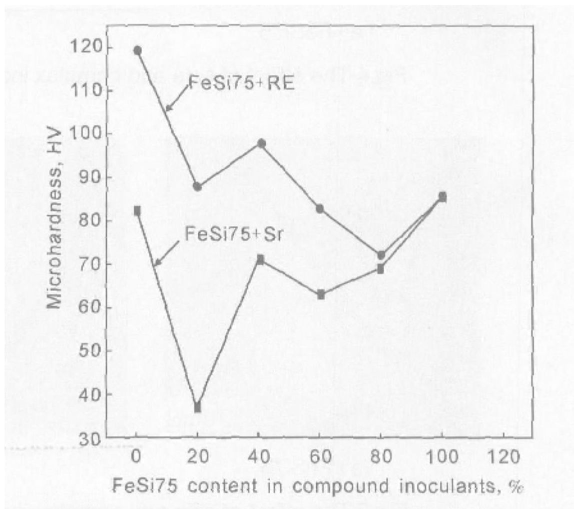

Fig.3 Relation between microhardness difference and FeSi75 content in every kind of the compound inoculants

2.4 Effect of inoculants on microstructure of grey cast iron

Inoculants reduce chill tendency, promote graphitization, affect the solidification process, and consequently, affect the as-cast microstructrue of grey cast iron. For grey iron castings, the purpose of inoculation treatment is to promote the formation of type A graphite during solidification, refine pearlite and so as to improve the properties of the castings. In all inoculated castings, those treated with the FeSi75-Sr complex inoculants are chosen as example due to their good results. The relationship between the wear of the drill and the microstructure of the matrix was studied. The graphite morphology of the inoculated grey iron castings is shown in Fig.4. It can be seen that after treatment with the complex inoculants, the amount of graphite was evidently increased, the form of the graphite became preferable with shorter length and rounded tip, which is beneficial to the improvement of casting mechanical properties. The increased quantity of the graphite helped lubricating the drill and fracturing the machining chips, and therefore reduced the wear of the drill. It is obvious from the matrix microstructure shown in Fig. 5 that the castings treated with complex inoculants have not only better matrix homogeneity but also smaller lamellar spacing than the castings treated with single or simple inoculants. As a result, the castings treated with the complex inoculants have ideal mechanical properties and machinability. When the FeSi75-Sr complex inoculants were added into the melt, the FeSi75 inoculant component formed micro carbon-rich and silicon-rich zones, generated concentration fluctuation (gradient), and provided the condition for the nucleation. At the same time, silicon could increase the number of the heterogeneity nucleation sites by converting into the silicate. On the other hand, the Sr inoculant component delayed the diffusion of silicon and carbon, and strengthened the role of the silicon. Therefore the Sr inoculants had strong anti-fading ability and some nucleation ability. Besides, the addition of the sole Sr inoculant did not increase the number of the eutectic cells, but reduced the number of the shrinkage cavities and shrinkage porosities. When the mixtures of the Sr inoculant and the FeSi75 inoculant were added in the molten iron, the number of graphite was increased, and the structure of the matrix was significantly homogenized and refined. Thus, the castings treated with the FeSi75-Sr complex inoculants have better machinability than those treated with the sole inoculant. The microstructure analysis indicates that the more the type A graphite in the microstructure, the more uniform the matrix, and the better the machinability of the grey iron castings.

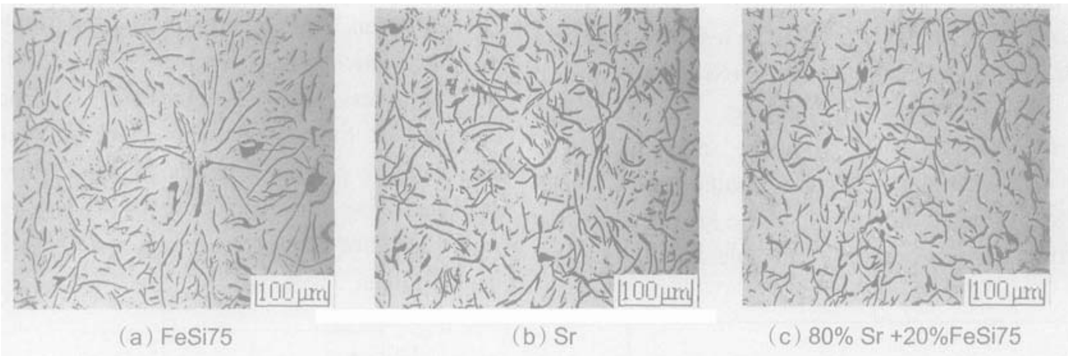

Fig.4 The effect of sole and complex inoculants on graphite morphology of grey cast iron

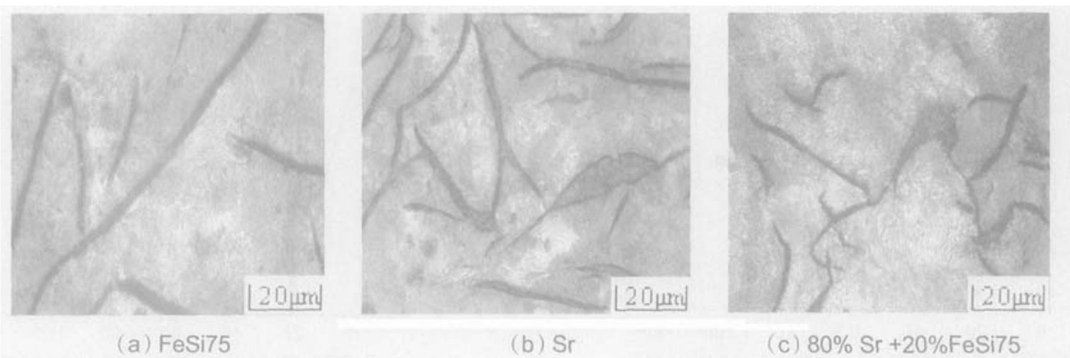

Fig.5 The effect of sole and complex inoculants on the matrix structure of grey cast iron

3 Conclusions

(1) Based on the obtained results on casting mechanical properties, the grey iron castings treated with the RE inoculant have the highest strength, hardness and quality coefficient. In all inoculated castings, those treated with the 60% FeSi75 + 40% RE compound inoculants have very high strength, suitable hardness and ideal quality coefficient. The castings treated with the 20% FeSi75 + 80% Sr complex inoculants have the least sectional sensitivity.

(2) The results on the casting machinability showed that the castings treated with the 20% FeSi75 + 80% Sr complex inoculant have the least wear on the drills. Castings treated with this complex inoculant have the smallest microhardness difference. By comparing the results of microhardness difference with the wear of the drills, there seem to be a strong correlation between the two, suggesting that the homogeneity of the microstructure has a great effect on the machinability of the castings.

(3) From the view of microstructure, the castings treated

with the complex inoculants have higher graphite content and better matrix homogeneity and machinability than the castings treated with the sole inoculants. High graphite content and good homogeneity of the microstructure can help improving the machinability of the grey iron castings.

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