Some problems in the production of ductile irons by investment casting

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Abstract: Because of the excellent performance of ductile irons and the unique superiority of investment casting, the preparation of complicated and thin-wall ductile iron castings by investment casting shows a good development prospect. In this present work, combined with the actual product experiments, the characteristics of shell making, spheroidization, inoculation and defect prevention are presented, and some suggestions are given for investment casting of ductile iron.

Key Words: ductile iron; investment casting
CLC number: TG249.5                           Document Code: A                            Article ID: 1672-6421(2008)01-007-05

1 Investment casting of ductile iron

With the characteristics of high dimensional accuracy, good surface finish and being able to produce complex shape and ultra-thin wall castings, investment casting has already become an important preparation means of ductile iron parts. Since the 1960s, the investment casting technology of ductile irons has rapidly developed abroad, and it also has developed rapidly in China in the recent years. The production and complexity of ductile iron castings produced by investment casting are all significantly increased [1-3].

There are characteristic differences exist between investment casting and sand casting, as shown in Table 1. The main differences are as following: (1) the poor ability of slag-off and difficulties in feeding presented in investment casting process because a complete gating and feeding system can not easily to set up; (2) microstructures and properties of ductile irons are affected by slow solidification rate which generates in the heated mould shell casting; (3) high soundness of mould shell causes the difficulties in exhaust and the increase of casting pinhole, which will bring great impact on the internal and external quality of castings, and result in an increase of rejection rate.

In this present work, the process characteristics of shell making, spheroidization, inoculation and defect prevention are presented, and the results are hoped to give some useful information to the study of investment casting of ductile irons.

Table 1 Comparison between sand casting and investment casting on process characteristics [4]

<table>
<thead>
<tr>
<th>Casting process</th>
<th>Green sand casting</th>
<th>Investment casting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear contraction</td>
<td>0.8%—1.5%</td>
<td>Wax mould shrinking 0.8%—1.2%</td>
</tr>
<tr>
<td>Gating system</td>
<td>Considerable ability in slag removal</td>
<td>Poor ability in slag removal</td>
</tr>
<tr>
<td>Mould stiffness</td>
<td>Higher in dry-sand mould, lower in green sand mould</td>
<td>Higher</td>
</tr>
<tr>
<td>Atmosphere during pouring</td>
<td>Reducing atmosphere</td>
<td>Weak oxide atmosphere</td>
</tr>
<tr>
<td>Venting effect</td>
<td>Good</td>
<td>Poor</td>
</tr>
<tr>
<td>Dimensional accuracy</td>
<td>T8—13</td>
<td>T4—6</td>
</tr>
<tr>
<td>Surface roughness</td>
<td>Ra 12.5</td>
<td>Ra 0.8—6.3</td>
</tr>
</tbody>
</table>

2 Shell mould-making

2.1 The determination of linear contraction

The total contraction (ε) of traditional investment casting consists of three parts, i.e. ε = ε₁ + ε₂ + ε₃, where, ε₁ is the contraction of the low-temperature waxes, ε₂ is the shell bulging after firing, and ε₃ is the contraction of liquid metal for casting steel and other non-ferrous alloy. For ductile iron, in addition to the above three factors, solidification shrinkage and graphitization expansion also should be considered.

In the process of investment casting, research results have showed that the total contraction of ductile irons is much smaller than that of low carbon steels or other alloys [5]. This is because element carbon in steel exists in the form of carbide, but in the ductile iron exists mainly in the form of free carbon, graphite. Therefore the contraction is smaller due to the volume expansion

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Received: 2008-12-20; Accepted: 2008-02-02
by graphite precipitation. With increasing of casting wall section thickness, the total contraction is also increased. For low carbon steel casting with wall section thickness 3 to 10 mm, if sodium silicate shell mould is used and under the condition of partial hindered contraction, the empirical value of total contraction is 1.2% to 1.8%; however, if the wall section thickness is 10 mm to 20 mm, the total shrinkage rate is 1.4% to 2.0% [8]. Yang Qingle et al of Dongfeng Precision Casting Co. Ltd. found that using $\varepsilon_1 = 0.6\% - 0.8\%$, $\varepsilon_2 = 0.6\% - 0.8\%$, $\varepsilon_3 = 0.7\% - 0.9\%$, the total contraction is 0.7% to 0.9% which is more suitable for practical production of ductile iron bracket. Moreover, the total contraction can vary between 0.5% and 1.2% for different ductile iron castings [7]. In the actual production, the total contraction for a specific component should be determined according to its casting structure, size and shape and verified experiments.

### 2.2 Shell mould- making

Three types of binders, ethyl silica, colloidal silica and sodium silicate, are commonly used in investment casting production. Ethyl silica and colloidal silica are very good as investment casting binder and can produce high dimension accuracy and high surface quality castings. From the point of view of an environmental and sustainable development, the use of ethyl silica is gradually decreased recently. Various new fast-drying colloidal silica sells are being gradually increased. Sodium silicate binder is cheap, but has poor performance leading to low high-temperature shell strength, poor ability of anti-deformation therefore poor casting surface quality. For the surface coats of the shell mould, refractory ceramics mainly are zirconia sand, fused alumina, fused silica etc., for the back-up coats usually the aluminum-silica refractory is chosen [8-11].

The ductile iron castings produced by hybrid shell mould in Dongfeng Precision Casting Co. Ltd. have obtained good results. The shell mould consists of 5.5 layers. For the primary (1—2) layers 270 mesh and 200 mesh zirconia powder are used as refractory ceramics and the silica sol is used as the bonding agent. For the back-up (3—5) layers mullite sand is used as the material of reinforcement layer and sodium silicate is used as the bonding agent. The sodium silicate coating is used as the bonding agent to reinforce the outer (0.5) layer. This type of shell mould can guarantee good surface quality and also reduce production costs. After each primary coats, the shell needs to dry 6 h at a constant temperature and humidity environment; after each of back-up coats, the shell needs to be hardened in aluminum chloride solution and then naturally dry 6 h respectively for further hardening [7]. After being hardened, de-waxed and fired, then the shell mould can be used to pour. Changsha Peace Investment Casting Plant using colloidal silica shell technology in the surface and transit layers and sodium silicate shell technology in the reinforcement layers in the shell mould system has achieved excellent results [8]. Luo Souxin et al of Wuhan Machine Craft Research Co., Ltd. use the ethyl silica solution, colloidal silica and active alcohol to prepare the binder and use this binder for the first 1—3 coats, sodium silicate for rest back-up coats [13]. This process has achieved good results. Considering casting quality and production costs, the method of using the colloidal silica and sodium silicate hybrid shell mould is a good process for investment casting ductile iron.

### 3 Production process of ductile iron

#### 3.1 Chemical composition

In comparison, the chemical composition of ductile irons produced by investment casting and sand casting is almost identical. Both of the production process needs to be controlled closely. Normally high C, Si content and low Mn, S, P content are used. The content of Mg and RE needs to be kept low to ensure good nodularity and eliminate pinhole of castings.

Anhui Pumps Choke Production Plant produces ductile iron 600-3 camshaft by investment casting. They obtain 1—4 grades graphite nodules and more than 85% pearlite [14]. Their chemical composition is listed in Table 2, the carbon equivalent is about 4.5%.

**Table 2 Chemical composition of ductile iron 600-3 molten iron and castings, wt. %**

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bath</td>
<td>3.6-3.8</td>
<td>1.3-1.5</td>
<td>0.3-0.6</td>
<td>≤ 0.03</td>
<td>≤ 0.05</td>
</tr>
<tr>
<td>Final</td>
<td>3.6-3.8</td>
<td>2.5-2.7</td>
<td>0.3-0.6</td>
<td>≤ 0.03</td>
<td>≤ 0.05</td>
</tr>
</tbody>
</table>

Shanxi Light Machinery Factory produces small tractor components of ductile iron 450-10. The chemical composition of the ductile iron is listed in Table 3 [15].

**Table 3 Chemical composition of ductile iron 450-10 castings, wt.%**

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>S</th>
<th>P</th>
<th>Mg</th>
<th>RE</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4-3.7</td>
<td>2.4-2.7</td>
<td>&lt;0.03</td>
<td>&lt;0.08</td>
<td>0.035-0.05</td>
<td>0.03-0.045</td>
</tr>
</tbody>
</table>

Alloy elements have strong effects on spheroidization and microstructure of ductile iron. Authors used pig iron containing V and Ti to produce ductile iron components by investment casting, the chemical composition of the pig iron and the ductile iron castings which were prepared using new pig iron are listed in Table 4. It was found that when the content of V, Ti elements is high, the spheroidization is poor. There is a large amount of distorted graphite nodules in the microstructure, see Fig.1a. The graphite form is grade 3 to 4 in Chinese graphite nodule standard; also there is lot of carbides in the metal matrix.

Because the content of V, Ti is high, the phenomena of spheroidization fade and high content of carbide appear. The existence of V, Ti leads to high chilling tendency and intensive formation tendency of carbide. Ti is adverse to graphitization and spheroidization, and interferes the spheroidization effect of Mg [16, 17]. After the replacement by new pig iron, the nodularity is significantly improved, the spheroidization of castings reaches to grade 1 to 2 under the same process, see Fig.1b.

#### 3.2 Inoculation

Unlike sand casting which must have scum riser, the gating system of investment casting is relatively simple, so the stream inoculation is different from that usually used in sand casting. In order to avoid inoculation fade, the inoculant is generally added...
to molten iron at different stages. Firstly, it is added partly in the periods of metal-tapping and then it is added when the molten iron is transferred to another ladle. Confirmed by the author in the actual experiments, this method can guarantee good inoculation. Moreover, adopting multiple-element long-acting inoculants is also effective, such as SRCB type inoculant.

### 3.3 Spheroidizing and casting process

In the process of investment casting ductile iron, the castings were generally small and the molten irons were not so many, so the treatment of speroidization was very important. Some literatures indicated that, for the ladle under 250 kg, the ratio of height to diameter should be not less than 1.6 and the package of spheroidization should be more than 35 mm\(^4\). The authors used one 1.5 kg package of spheroidization in the production which has the height of 430 mm, the top diameter of 260 mm and the height-diameter ratio of 1.65, so it can guarantee the spheroidization quality of liquid iron. In addition, during the spheroidization, if increased the cover over the ladle of spheroidization, it will have better effect on assuring the spheroidization and reducing environmental pollution.

### 3.4 The effect of shell temperature on the microstructure and properties

Shell temperature has strong influence on the microstructure and properties of ductile iron castings produced by investment casting, but no much research work has been performed. The authors studied the effect of shell temperature. In the experiment, liquid iron was melted and poured into cold shell mould (at temperature 23\(^\circ\)C) and hot shell mould (at temperature 330\(^\circ\)C) to make ductile iron 500-7 upper cover casting; at the same time the temperature field of the castings was measured, see Fig. 2. It is seen from Fig. 2 that compared with the casting made from cold shell, the casting made by the hot shell has higher eutectic temperature, longer eutectic reaction time and the eutectic platform is more stable. The casting made from the cold shell has a large amount of distorted graphite nodules in the microstructure see Fig. 3a; while the casting made from hot shell has relatively larger amount and good shape of graphite nodules, see Fig. 3b. The etched microstructures show that the ferrite in the hot shell castings is significantly more and the carbide is much less than that in the cold shell castings, see Fig.3.

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>S</th>
<th>Ti</th>
<th>V</th>
<th>P</th>
<th>Mn</th>
<th>Mg</th>
<th>RE</th>
</tr>
</thead>
<tbody>
<tr>
<td>old pig iron</td>
<td>&gt;3.3</td>
<td>0.80</td>
<td>&lt;0.05</td>
<td>0.27</td>
<td>0.39</td>
<td>&lt;0.06</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>new pig iron</td>
<td>&gt;3.3</td>
<td>1.2–1.6</td>
<td>&lt;0.04</td>
<td>–</td>
<td>–</td>
<td>&lt;0.06</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>castings</td>
<td>3.8</td>
<td>2.3</td>
<td>&lt;0.03</td>
<td>–</td>
<td>–</td>
<td>&lt;0.05</td>
<td>0.3–0.6</td>
<td>0.03–0.05</td>
<td>0.03–0.05</td>
</tr>
</tbody>
</table>

Fig. 1 Graphite form

(a) Using pig iron containing V and Ti, the graphite form is grade 3 to 4 in Chinese graphite standard;
(b) Using pig iron without V and Ti, the graphite form is grade 2 in Chinese graphite standard (there are 6 grades in the Chinese Standard)

(a) Graphite form made by cold shell; (b) Graphite form made by hot shell; (c) Microstructure made by cold shell; (d) Microstructure made by hot shell (× 100)

Fig. 3 The effect of shell temperature on microstructure and performance of castings

In the other hand, there is much more blowhole in castings made by cold shell, and the surface quality of cold shell castings is poorer compared to that of the hot shell made castings, see Fig. 4.
4 Defects of the investment casting ductile iron

4.1 Shell crack and burst

Graphitizing expansion usually appeared in the solidification process of ductile iron, so bulging shell was common in the production of the investment casting ductile irons. It most likely occurred in the casting with special structure, heavy and inhomogeneous thickness. Wang Wensan [14] found that, in the process of hardening sodium silicate — shell mold, there were the precipitates of undefined SiO$_2$ and a little Na$_2$O, which produced sodium silicate. Sodium silicate and silica gel would form the lowest melting point at 793°C, and made the shell mold soften and deform in the process of sinter. Serious rupture could take place in the shell mold in the process of pouring, with the maximum rupture rate of 25 percent. Han Yulin [18] also found that the rejection rate caused by bulging shell in the production of ductile iron casting was as high as 80 percent.

To solve the problem of the bulging shell, Light Industry Machinery Plant in Shanxi Province [15] carried out experiments using aluminum chloride-bauxite high-strength shell. As the small blanching and the high shell-density, it generated mullite phase and a small amount of sodium silicate phase after high-temperature roasting. Compared with the original quartz powder — ammonium chloride shell, the shell has smaller thickness, lighter weight, better thermal stability, higher modulus shell strength, smooth inner cavity, and the high-temperature liquid retention time was also reduced.

Dongtai Precision Casting Plant made the strength of castings improved by reducing the modulus of sodium silicate [15]. The process was as following: using the bimodal graded powder on the surface, raising the powder and liquid ratio of coating, choosing the Al-Si refractory material in the reinforced layer and using crystallization aluminum chloride to harden, drying each coating layer before hardening, for the shells with special shape, using wire tied to improve the high temperature strength of the special shells. In order to effectively guarantee the strength of shell, Qinhuangdao Shougang Machinery Plant strictly checked the process of the waxes ingredients, pattern die, the welding position of ingate, dried paint hardening and pattern assembly air drying; removed wax rods before dewaxing, using the method of combined melting to make wax melt at the same time; strictly controlled the pouring temperature, the pouring speed and the pouring liquid height of the liquid iron, to achieve the goal of “the medium temperature steady flow and low pressure head,” which could reduce effectively the destruction of iron liquid on shell mold in the process of pouring [18].

4.2 Blowholes

In the experiment, the authors found that the blowholes occur from time to time in the production of thin-wall parts. The reasons were mainly as following:

- In the melting process, gas in the absorption of the liquid iron in contact with the furnace and gas in the metal of charge will lead to the formation of blowholes;
- The residual NaCl in the shell after incompletely dewaxing and carburating in the process of pouring causes blowhole;
- Lower pouring temperature or mould shell sinter temperature;
- The carbon equivalent was far from eutectic point;
- Excessive residual Mg. When the residual content of Mg was more than 0.03 percent, the risk of the formation of surface blowhole rapidly raised; when it was more than 0.05 percent, it will be very difficult to eliminate the surface blowhole [19].

Therefore, we should carefully analyze various technological processes, find out the reasons of blowhole generation, and then act appropriately to situation. Apart from the above reasons, in the process design, choosing the bottom gating system is beneficial to gas emission [20, 21].

4.3 Slag inclusion

The situation of slag inclusion occurred frequently in the production of investment casting ductile irons. Among which, the first slag inclusion was the most serious. The author in references [22–24] propose using the method of bottom pouring and the teapot packet filtering technology that will effectively prevent castings from slag inclusion.

5 Conclusions

Because of the unique superiority of investment casting, the preparation of complicated and thin-wall ductile iron castings by investment casting shows a good development prospect. Unlike sand casting which had scum riser and good exhaust system, the gating system of investment casting was relatively simple, so the tendency of blowhole and slag inclusion were much more in the investment casting. Therefore, the following questions are very important to preparation of ductile iron castings by investment casting.

1. In order to make full utilization of graphitizing expansion to decrease the tendency of shrinkage of ductile iron, the strength of shell should be high;
2. Accepting higher temperature of the shell in the pouring process to reduce the amount of gas forming and formation of surface blowhole;
3. Choose a suitable pouring temperature. Higher pouring
temperature will cause serious burning of the nodulizer and inoculant; lower pouring temperature will produce misrun in thin-walled casting;

4 As far as possible to reduce all factors of the production of gas blow in the period of dewaxing, melting, spheroidizing, inoculation, shell baking;

5 Using of CAE simulation to determine the process parameters and to validate them in practice if needed.

References


