CASTING PROCESS DESIGN AND WEAR PROPERTIES OF A HIGH CHROMIUM CAST IRON HAMMER

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Abstract:

In this article, both chemical composition and structure of a high chromium iron hammer head were designed and analyzed respectively. Also, the casting process was investigated and optimized through numerical simulation using commercial software View Cast. On the basis of numerical simulation and optimization, several hammer heads with fine surface quality and no internal defects were cast into one mold through shell molding and string casting process. In addition, heat treatment of the as-cast hammer head was carried out. Consequently, the microstructure was observed, and wear resistance was tested. After being quenched at the temperature of 950℃ and tempered at the temperature in the range of 230-260℃, the microstructure of the hammer is made up from tempered martensite, retained austenite and network eutectic carbides. The hardness is 60 HRC. Experimental result shows that the wear loss is slowly increased with an increase in load and rotating speed.

1 Introduction

Hammer is used to break hard and brittle objects, such as ores, rocks and chamottes. The working conditions require both good wear resistance and toughness of the hammer. With good wear resistance and toughness, the hammer can have long life time, the production cost can be reduced and economic benefit improved. At present, a solid-liquid melt cast composite hammer head is generally used, with the upper part and the handle respectively made of high chromium cast iron and carbon steel [1, 2].

The high chromium cast iron is of eutectic composition. The fine eutectic carbide in iron makes the hammer head not easy to get broken when being impacted. Especially the wear resistance of the high chromium hammer head will be improved when the appropriate microstructure is gained after being suitably heat treated. However, there are some defects formed in the cast iron if the process is not optimized. The defects often appear in the form of shrinkage cavity and shrinkage porosity in the hammer head where consequently fracture initiates.

In order to prolong life time of the hammer head, the casting process was simulated and heat treatment carried out to eliminate the defects and to gain the appropriate microstructure. Therefore, friction and wear properties were also investigated.

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2 Casting simulation of high chromium cast iron hammer head

2.1 Chemical composition design

The hammer head is anticipated to be quenched and tempered at low temperature to gain the microstructure composed of residual austenite, tempering martensite and carbide. Generally, the harder the hammer head is, the better its wear resistance is. As the carbide with the type of M_7C_3 owns the highest hardness with the value of 1300 HV-1800 HV, rationally, a higher content of it is expected [3, 4] during chemical composition design process. An analysis of the chemical composition of a high chromium alloy hammer head is shown in Table 1.

2.2 Casting process design of the hammer head

Because of the low impact resistance of high chromium cast iron, the hammer head was designed as a composite one while being used under conditions with high impact. The hammer handle was previously made of carbon steel or low alloyed steel. Then the upper part of the hammer head was cast and combined with the handle. The upper part was made of high chromium cast iron. This kind of the hammer head was able to take advantage of high wear resistance of high chromium cast iron.
Figure 1 shows the hammer handle structure used in composite. Figure 1 (a) illustrates the common structure which cannot provide firm combination with the cast upper head. It will lead to the separation of the hammer head when it has been used for a long time. In order to promote the combination, the structure of the handle was redesigned, as shown in Figure 1 (b). The hammer handle was designed as a special card slot shape cross-section, which might improve the combination even though it is still mechanically and not metallurgically designed.
In addition, the cast steel hammer handle was preset within the cavity, which can be used as internal chill iron. This can reduce the amount of melted high chromium cast iron, increase the rate of process production and reduce the production cost.

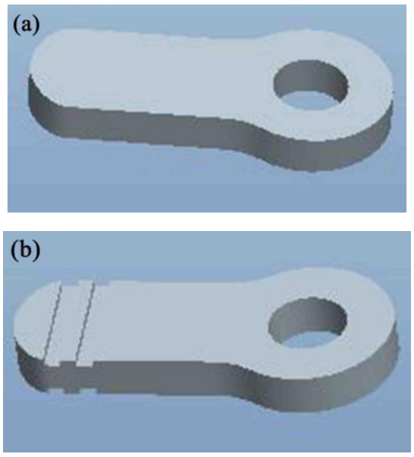


Figure 1. Part drawing of (a) the common-used and (b) the revised hammer handle.

Table 1. Chemical composition of high chromium cast iron

Element	C	Cr	Mo	Cu	Mn	Si	S	p
Content (wt. %)	2.6 - 3.1	18 - 22	1.7 - 2.1	0.7 - 1.2	0.5 - 0.7	0.4 - 0.9	< 0.05	< 0.06

2.3 Casting process of hammerhead

The high chromium cast iron hammer is of small size, so that shell mold casting process can be used. To improve the production rate, the process of more than a bunch of castings was adopted for this case as shown in Figure 2. Because of high melting point, poor liquidity, big shrinkage and easy oxidation of casting, for a smooth filling, the gating system was required to be of simple structure and large sectional area. Taking small batch production and the reduction of material waste into consideration, the runner was not set. Additionally, the ingate was connected with sprue directly so that the sprue can provide feeding of castings more easily.

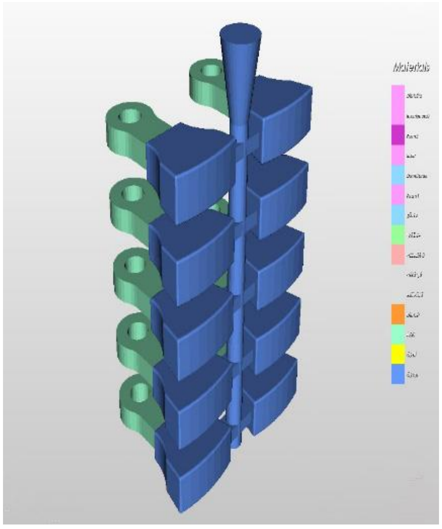


Figure 2. 3 D model of casting project with gating system.

(1) The original process

During the original process, the sprue with the diameter of 32 mm was settled at the profile of the casting. Defects were predicted by simulation using View-Cast software [5]. Figure 3 illustrates defects formed in the casting when 97% solidification is reached. It is observed that there are many shrinkage cavities and shrinkage porosities in the casting because solidification occurs so fast that the sprue cannot feed the casting.

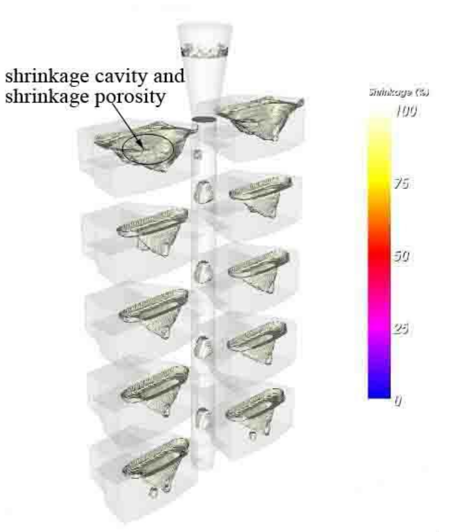


Figure 3. Simulation of the casting in the original process when 97% solidification is reached.

(2) The optimized process

Analysis shows that defects are not caused by the shortage of molten metal in sprue cup. During the original process, solidification of molten metal in sprue cup is in front of that at the top of the casting. Thus, the sprue cannot feed the mold top of the casting. In order to reduce or illuminate defects, the sprue cup was considered to be encapsulated by thermal insulation material. Furthermore, diameters of the upper and the lower pouring are increased from 40 to 80 mm respectively.
Simulation of the defects formed in the optimized process is shown in Figure 4. The result shows that the molten metal in the sprue cup solidified slowly and the casting can be fed effectively with the encapsulation of thermal insulation sleeve and with an increase in the diameter of the pouring cup. There are only little defects formed in the area at the contact of the runner and the casting, which proves the effect of improvement measures.

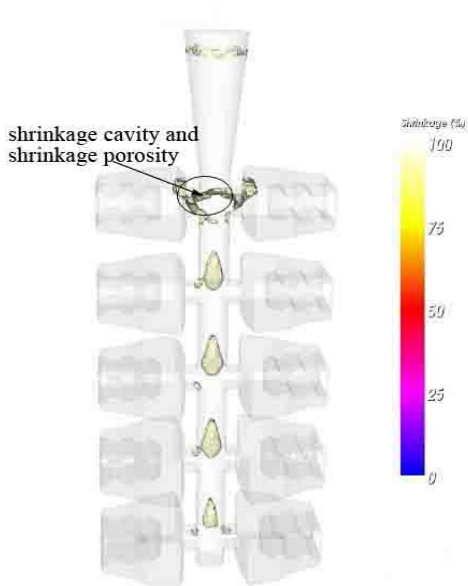


Figure 4. Simulation of the casting in the optimized process when 95% solidification is reached.

Figure 5 shows the hammer head cast with an optimized process. It can be observed that the casting has high surface quality. And investigation into the microstructure indicates that no big shrinkage cavity and shrinkage porosity exist in the casting.

Figure 5. The hammer casted by optimized process.

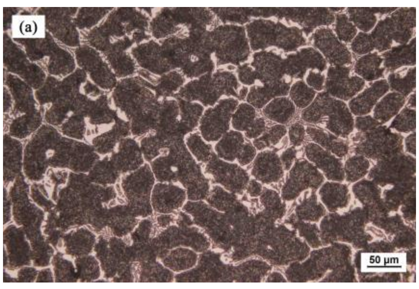
3 Analysis of microstructure and properties

3.1 Heat treatment of the hammer head

The as-cast composite hammer head by optimized process was heated inside the furnace to 950℃. After being kept at 950℃ for 3 h, the furnace was cooled to about 400℃, and then cooled to below 300℃ for annealing by opening the furnace door.
When the casting was cooled to room temperature, it was machined to obtain the precise dimensions.
The machined hammer head was reheated to 600℃ inside the furnace with the rate of 80℃/h, and hold for 1 h. Then the furnace temperature was raised to 950 - 980℃. After being kept from 2 to 4 hours at this temperature, the machined hammer head was taken out and air cooled to room temperature. Subsequently, it was tempered at 230-260℃ for 3 – 6 h.

3.2 Microstructure investigation of the upper part of the hammer head

The sample was cut off from the upper part of the heat treated hammer head. It was ground and polished, and etched with a solution of 4% nitric acid and alcohol. Microstructure was investigated through OLYMPUS GX51 microscope, as shown in Fig. 6.



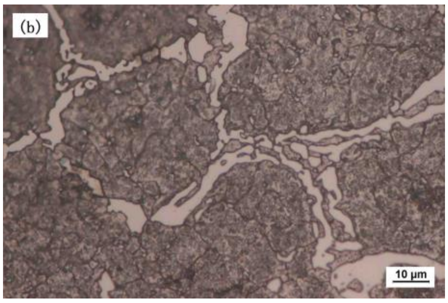


Figure 6. Microscopy of the upper part of heat treated hammer head under light microscope of (a) 200 times and (b) 1000 times.

It can be observed from Figure 6, that the microstructure of the sample is similar to that in reference [6, 7]. Network eutectic carbides and secondary carbides are distributed in the black matrix. It is worth mentioning that (Fe, Cr)$_7$C$_3$ is the main kind of carbide in the casting, whose content of Cr is higher than 11% and ratio of Cr to C is higher than 3.5 [8]. And the carbide of (Fe, Cr)$_7$C3 is considered to be beneficial for hardness and impact toughness of high chromium cast iron [8]. In the experimental alloy, the content of Cr is higher than 18% and the ratio of Cr to C is about 7. It is considered that the main structure/composition of the carbide in the alloy is (Fe, Cr)$_7$C$_3$.

3.3 Hardness of the heat treated hammer head

Table 2 shows four hardness values tested at half thickness and across the width of the upper part of the heat treated high chromium iron hammer head. After the hammer head was heat treated with the above process, the high chromium part can be hardened to be in the range of 58 HRC to 60 HRC.

Table 2. Hardness of a high chromium iron part of the heat treated hammer head

Sample	Hardness value (HRC)			
	Test 1	Test 2	Test 3	Mean
1 #	58.8	58.8	58.9	58.8
2 #	59.1	58.8	59.1	59.0
3 #	59.6	59.2	58.9	59.2
4 #	58.8	58.6	59.8	59.1

Generally, wear resistance is proportional to hardness. For this purpose, the cast high chromium iron hammer is usually treated to obtain the hardness of 60 to 65 HRC. But when impact abrasion is bore, it tends to break easily with too high hardness.

Hardness of high chromium iron cast hammer is therefore determined by volume fraction, hardness of carbide, and the type of matrix microstructure [10]. In order to obtain appropriate hardness, the ratio of chromium to carbon is controlled in the experimental alloy. During designing a chemical component, to acquire carbide of type of $(Fe, Cr)_7C_3$ with high hardness, the ratio is to be increased. By contrast, it is also to be properly low, because the amount of residual austenite may be increased with a decrease in the ratio, which results in an increase in the content of carbon. Residual austenite is benefit for toughness and resistance of impact abrasion [11].

4 Friction and wear properties

After being heat treated, a pin-on-disk wear test was adopted to evaluate the friction and wear properties of the experimental hammer head. The pin disk material is made up of 45 carbon steel (S45C), so that carbon steel 45 (S45C) was used for the comparative test. During the test, a pin with the diameter of 4.8 mm was used.

The test was done with different loads and rotation speeds, as shown in Table 3.

Table 3. Test parameters and results

Load	Rotation speed	Weight loss
N	r/min	g
50	200	0.00046
80	100	0.00041
80	200	0.00053
80	300	0.00154
100	200	0.00189
200	200	0.00371

4.1 Influence of test load on wear property

After performing the test for 30 min at the rotation speed of 200 r/min, the pin of the hammer head was cleaned up and dried. Then it was weighed using an analytical balance with the accuracy of 0.0001 g. Test results shows some weight loss after testing the pin. When the test load is 50 N, the weight wear loss is 0.00046 g. By increasing the load to 80 N, the weight wear loss is slightly increased to 0.00053 g. But the weight wear loss is sharply increased to 0.00189 g with an increase in load to 100 N. By increasing the load, the rate of an increase weight loss is reduced, which is shown in Figure 7. The stress exhibited on contact points may just reach compression yield limit, which caused some small plastic deformation. So the weight loss was small at load of 50 N and 80 N.

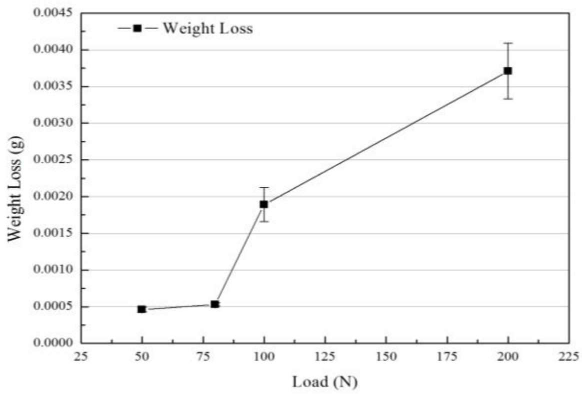


Figure 7. Influence of test load on the weight wear loss during the wear test.

Investigation was carried out into surface morphologies of samples after being tested, as shown in Figure 8. It is obvious from Fig. 8 that adhesive wear and abrasive wear happen on the surfaces of the samples tested at different loads. After being worn at loads of 50 N for 30 min, surface failure occurred caused by slight adhesive wear and abrasive wear. Because the load was low, small plastic deformation formed on the sample surface, which led to slight adhesive wear and bright zone in Figure 8 (a). And the adhesive wear accounts for shallow scratches. As the pressure rose, severe surface plastic deformation was observed, which resulted in more severe adhesive wear and greater wear weight loss, shown in Fig. 8. The surface of material has first got scratched and abraised and then severe crack propagation has been developed as seen in Fig. 8 (c).

4.2 Effect of rotation speed on wear property

At the pressure of 80 N, samples were respectively wear tested at the rotation speed of 100 r/min, 200 r/min and 300 r/min. After being tested for 30 min, wear weight loss of sample was weighed. And the effect of rotation speed on the weight loss is illustrated in Figure 9.

Fig. 10 shows the surface morphology of sample worn at different rotation speeds. Since the test time is stable, variation caused by different rotation speeds is firstly manifested as different wear distance. Furthermore, an increase in speed will probably lead to temperature rise at the contact surface between sample and friction pair.

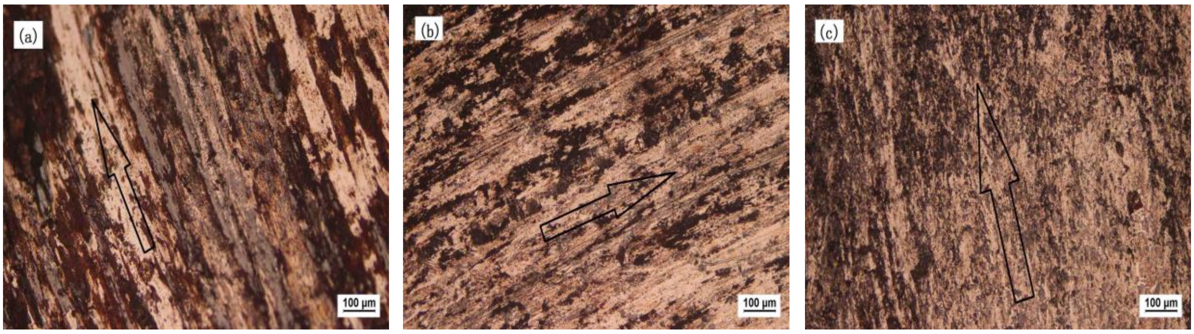


Figure 8. Surface morphology of sample after being respectively worn at (a) 50 N, (b) 100 N and (c) 200 N.

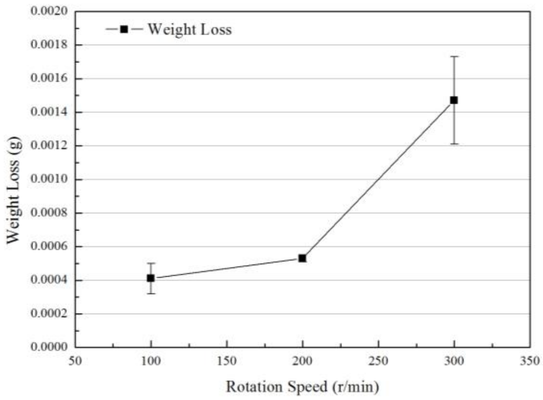


Figure 9. Average weight wear losses of samples respectively tested at different rotation speeds.

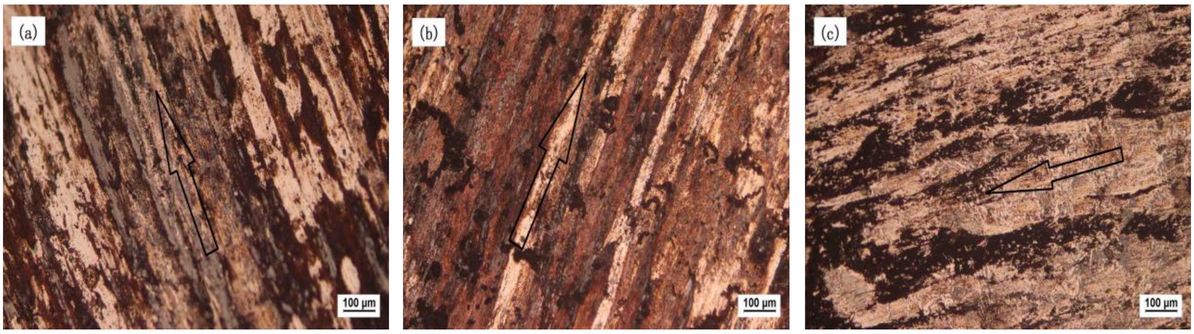


Figure 10. Surface morphology of samples after being respectively worn at rotation speed of (a) 100 r/min, (b) 200 r/min and (c) 300 r/min.

It is observed that slight scratches formed on the surface of the sample that was short-distance worn is shown in Fig. 10 (a). With an increasing rotation speed to 200 r/min, the wear distance is increased and temperature is raised at contact surface. The wear trace becomes deeper and slight deformation forms appear on the sample surface in Fig. 10 (b). By increasing the speed, the temperature is increased, which may cause severe deformation on the sample surface. Severe adhesive wear and wear spall were affected with deformation, so that the wear rate and wear weight loss were promptly increased. Therefore basic wear mechanisms could be the impacts of micromachining and ploughing.

4.3 Comparison with wear weight loss of 45 steel

Figure 11 illustrates the wear weight losses of 45 carbon steels and the heat treated high chromium iron after being wear tested at the rotation speed of 200 r/min for 30 min with a load of 50 N and 80 N.

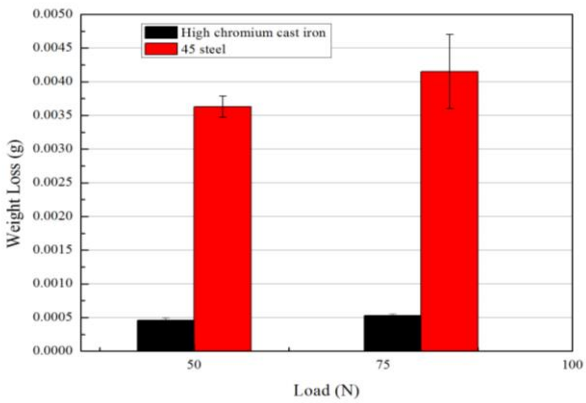


Figure 11. Average wear weight loss of 45 steel and the heat treated cast iron after being worn.

It can be seen that the weight loss of 45 carbon steel is greater than the one of high chromium iron, during the same test conditions. This test shows clearly that the heat treated high chromium iron has excellent wear resistance.

5 Conclusions

Based on the analysis of the working conditions, not only chemical composition and structure were designed for a high chromium iron cast hammer head, but also the casting process was designed and optimized. Then the cast hammer head was heat treated, and the microstructure and wear property were investigated. The main results are shown as follows:

(1) Chemical composition of the hammer head is designed as: 2.6 - 3.1% carbon, 18 – 22% chromium, 1.7 - 2.1% molybdenum, 0.7 - 1.2% copper, 0.5 - 0.7% manganese, 0.4 - 0.9% silicon and balance of ferrum.

(2) Simulation result shows that shell casting process can satisfy the requirement of a high chromium alloy hammer, with the runner size of φ 30 mm × 23 mm, the sprue diameter of 40 mm and 5 × 2 string cast mode.

(3) The appropriate heat treatment process is that the hammer head is quenched at 950℃ after being kept for 6 hours at this temperature, and tempered at 230 - 260℃ for 5 h. The microstructure consists of tempered martensite and the hardness is in the range of 58 to 60 HRC.

(4) At the same friction condition, wear weight loss of the heat treated high chromium cast iron increases with an increase in wear load. To increase the rotation speed, wear rate is to be first decreased and then promptly increased. Moreover, wear resistance of the heat treated high chromium cast iron is much better than that of 45 carbon steel.

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