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Effects of Quenching Medium on Microstructure and Mechanical Properties of High Chromium Cast Iron

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Abstract: The cooling properties of different cooling mediums were studied and heat treatment of high chromium cast iron was carried out by different cooling mediums. The results showed that the maximum cooling rate, cooling rate at 300 °C and the quenching liquid cooling capacity of water at 20 °C was 193.6 °C/s, 88.6 °C/s and 2431.1, respectively. With the increase in PAG concentration, the maximum cooling rate and the cooling rate at 300 °C of the coolant decreased. The microstructure of high chromium cast iron treated by water cooling, 10% PAG coolant and 20% coolant was white carbide + tempered martensite + retained austenite, and its impact toughness and fracture toughness were gradually improved. The water-cooled high chromium cast iron had the highest Rockwell hardness of 66.2 HRC, good wear resistance of 0.6103 g and the greatest friction coefficient of 0.4233, the high chromium cast iron treated with 10% PAG had the best wear resistance of 0.5715 and the lowest friction coefficient 0.4182, the high chromium cast iron treated with 20% PAG had the lowest Rockwell hardness 58.1 HRC and the worst wear resistance 0.8213 g.

Keywords: high chromium cast iron; PAG; mechanical properties; friction and wear

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1. Introduction

High chromium cast iron had the advantages of high hardness, high wear resistance and good corrosion resistance [1–3]. It was widely used in lining plates, blades, hammers and other vulnerable parts, but used in grinding, crushing and other harsh conditions, its service life could not meet the design requirements. Now, the way to improve the performance of high chromium cast iron is mainly through changing the alloy composition and heat treatment process [4]. J.P. Lai [5] studied the effect of the Si element on the microstructure and mechanical properties of high chromium cast iron. The density of secondary carbides precipitated from the matrix increases greatly with the addition of Si from 0.5 to 1.5 wt%. The mechanical properties were improved with a 7% increase in tensile strength from 586 MPa to 626 MPa and impact toughness from 5.8 to 7.3 J/cm^2. Researchers have tried different carbide-forming elements, such as titanium [6,7], niobium [8] and tungsten [9] to improve the microstructure and wear resistance of high-chromium cast iron. The addition of niobium or titanium to high-chromium cast iron resulted in the preferential formation of NbC or TiC, which was appreciably harder than other carbides (M_7C_3). Through the application of a Design of Experiment technique (DOE), González-Pociño [10] analysed different factors related to thermal industrial treatments with regard to resistance to abrasive wear and impact response. Fortini [11] investigated the microstructural and erosive wear characteristics of a hypereutectic high-chromium cast iron, considering the erosion resistance, resulting from the impact of micro-sized particles, of both as-received and heat-treated conditions. Tabrett [12], Vasily Efremenko [13] and Karantzalis [14] studied the effect of quenching on the microstructure of high chromium cast iron. It was found that the microstructure of high chromium cast iron after quenching was eutectic carbide and martensite matrix. The quantity and size of the two carbides precipitated were related to the holding temperature and time of quenching. However, the effect of the cooling medium on the microstructure and properties of high chromium cast iron had not been studied. In this paper, through the heat treatment of high chromium cast iron with different cooling mediums, the influence of the cooling medium on the structure and properties of high chromium cast iron was studied, so as to select the best quenching cooling medium and provide guidance for the improvement of the properties of high chromium cast iron.

2. Materials and Methods

According to the ISO 9550 Industrial quenching oils-Determination of cooling characteristics-Nickel-alloy probe test method, the cooling performance of the cooling medium was tested by the KR-SQT II cooling characteristic tester, which was manufactured by Nanjing Kerun Industrial Media Co., Ltd in china. The nickel-based probe was heated to 850 °C and then cooled in different quenching mediums. The high chromium cast iron was prepared by lost foam casting in a medium-frequency induction furnace. Its chemical composition was shown in Table 1. The high chromium cast iron was placed in a muffle furnace. The heat treatment process was shown in Table 2. After heat treatment, the specimens were cut into $(10 \times 10 \times 20)$ mm^3 metallographic specimens, $(55 \times 10 \times 10)$ mm^3 unnotched impact specimens, $(12 \times 12 \times 140)$ mm^3 fracture toughness specimens and $(25 \times 10 \times 10)$ mm^3 wear specimens. Then, the performance testing was carried out by Leica DMI5000M metallographic microscope, THRP-150D Rockwell hardness tester, KB-30S micro-Vickers hardness tester, PTM2200 low-temperature pendulum impact tester and INSTRON 8802 universal tester. Impact toughness and fracture toughness were tested according to ISO 148-1 Metallic materials-Charpy pendulum impact test-part 1: Test method and ISO 12135 Metallic materials-Unified method of test for the determination of quasistatic fracture toughness. The wear testing was carried out by the vertical universal friction and wear tester. The loading force, the pin-disk speed and the loading time were 300 N, 180 r/min, and 3600 s, respectively. The original mass W_1 was weighed with an electronic balance before the test, and then the mass W_2 was measured after wearing. The abrasion loss $\Delta G = (W_1 - W_2)$. Finally, the impact fracture and wear morphology were observed by Inspect S50 scanning electron microscope.

Table 1. The chemical composition of high chromium cast iron.

Elements	C	Mn	Si	P	S	Ni	Cr	V	Mo
Wt%	2.142	0.928	0.301	0.024	0.014	0.088	14.682	0.053	0.004

Table 2. Heat treatment parameters of high chromium cast iron.

Quenching Temperature/°C	Holding Time/h	Quenching Medium	Tempering Temperature/°C	Holding Time/h
950	2	Water	250	3
950	2	10% PAG	250	3
950	2	20% PAG	250	3

3. Results

3.1. The Cooling Properties of Different Quenching Medium

As can be seen from Figure 1 and Table 3, the maximum cooling rate and cooling rate at 300 °C of water, 10% PAG and 20% PAG decreased gradually. PAG was reversibly soluble and could precipitate polymer wrapped on the surface of the workpiece at high temperatures so that water cannot form a steam film on its surface. As the temperature decreased, the precipitated polymer was re-dissolved into the water, thus increasing the viscosity of the PAG solution. In addition, with the increasing concentration, the viscosity of the PAG medium also increased, which made it difficult to gasify, leading to a decrease in cooling rate. It indicated that the concentration of PAG was the main factor affecting the cooling rate in the quenching process.

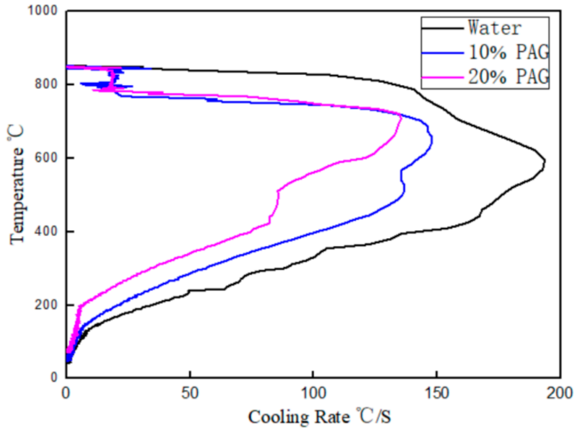


Figure 1. Cooling curves of different quenching mediums during quenching at 20 °C.

Table 3. The cooling characteristics of different quenching mediums at 20 °C.

Quenching Medium	Maximum Cooling Rate V_{Max}/°C/s	Temperature at Maximum Cooling Rate T_{VMax}/°C	Cooling Rate at 300 °C V 300/°C/s
Water	193.6	596.4	88.6
10% PAG	148.0	655.7	56.4
20% PAG	135.4	707.3	33.7

According to the ISO 9550 Industrial quenching oils-Determination of cooling characteristics-Nickel-alloy probe test method and the formula CP = 300 + 0.9 × Tvp + 9 × CR − 40 t [15], the CP, Tvp, CR and t was the quenching liquid cooling capacity, the quenching characteristic temperature, the average cooling rate from 800 °C to 400 °C, and the cooling time from 400 °C to 150 °C, respectively. The CP of different quenching mediums was shown in Table 4.

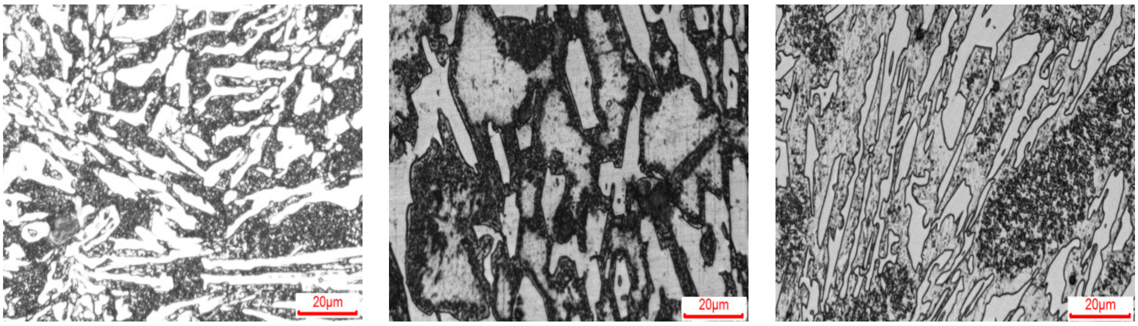
Table 4. The CP of different quenching mediums at 20 °C.

Quenching Medium	Characteristic Temperature Tvp/°C	Average Cooling Rate from 800 °C to 400 °C CR/°C/s	Cooling Time from 400 °C to 150 °C t/s	Quenching Liquid Cooling Capacity CP
Water	842	167.7	3.4	2431.1
10% PAG	803	87.3	7.8	1496.4
20% PAG	785	79.3	17.9	1004.2

3.2. Effect of Quenching Medium on Microstructure of High Chromium Cast Iron

From Figure 2, the microstructure was white carbide + tempered martensite. The white bulk carbide was the primary alloy carbide, the eutectic carbide was a white stripe, and the gray structure was tempered martensite. The retained austenite was in the margin of carbide and the dot-like secondary carbide was dispersed in martensite and austenite [16].

The quenching temperature provided a driving force for the diffusion of alloying elements. The alloying elements in the carbide diffused into the austenite matrix. The interface between the austenite and carbide was constantly moving towards the carbide, so the carbide was continuously dissolved and transformed into austenite [17]. After austenitizing at 950 °C, the matrix was supersaturated due to the diffusion of carbon and other elements into the matrix, so the matrix was in an unstable state with high distortion energy. When the high chromium cast iron was cooled, the matrix precipitated carbon and other alloy elements in the form of secondary carbide to reduce self-absorption. The distortion of the body can achieve a stable station. The high chromium cast iron was cooled in water, 10% PAG and 20% PAG. The quenching liquid cooling capacity of the water was 2431.1. The cooling capacity of the surface water was strong, and the cooling time was very short, so the element diffusion time was short. Therefore, the martensite and the original austenite had the same chemical composition. With the increase in PAG concentration, the quenching liquid cooling capacity and the cooling capacity decreased gradually, which resulted in the diffusion of alloy elements. When the temperature was lower than Mf, the austenite cannot completely transform into martensite and retained austenite existed. It was mainly because the specific volume of austenite was smaller than martensite. When the austenite was transformed into martensite, the volume expansion of the metal could be caused, the internal stress of the metal structure increased, and then the austenite was inhibited to continue to martensite transformation [18]. After low-temperature tempering, the segregation of alloy elements, especially carbon atoms, enriched in martensite which decreased the distortion energy of quenched martensite, and no new phase was formed [19].



(**a**) Water (**b**) 10% PAG (**c**) 20% PAG

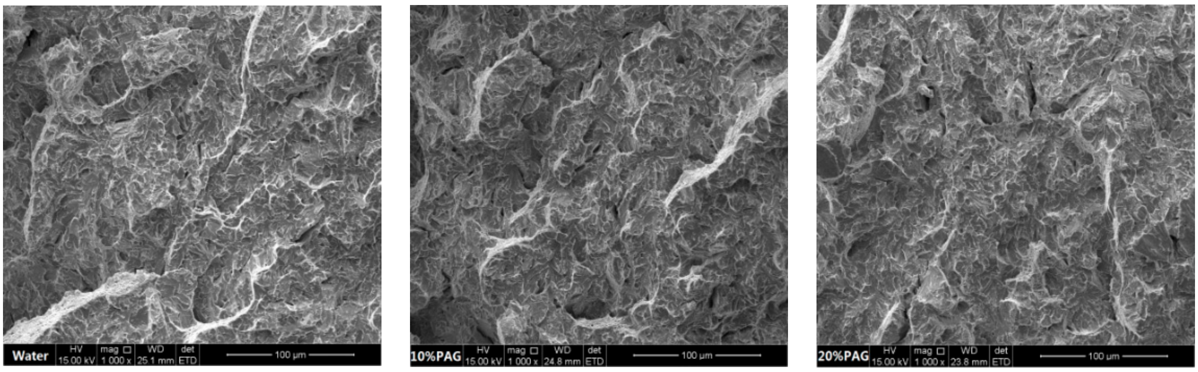
Figure 2. Microstructure of high chromium cast iron with different quenching mediums.

3.3. *Effect of Quenching Medium on the Toughness of High Chromium Cast Iron*

The results of impact toughness and fracture toughness were the averages of five samples. It could be seen from Table 5 that the toughness of high chromium cast iron cooled by 20% PAG was the best, A_k was 5.98 J/cm^2, and K_{IC} was 23.68 MN $\times$ m$^{-3/2}$. For quenched and tempered steels, the toughness was closely related to the content of retained austenite and the shape of carbide. The higher the content of retained austenite was, the less the carbide tip angle was, and the higher the impact toughness and fracture toughness was. After water cooling, high chromium cast iron had less retained austenite because alloy elements have been fully diffused during austenitizing. The carbides were white and thin, with more sharp corners and less dispersed carbides. The subsequent tempering treatment does not change the structure of high chromium cast iron. The distortion energy of martensite leads to low toughness of high chromium cast iron after water cooling. After cooling by 10% PAG and 20% PAG, the retained austenite content of high chromium cast iron was more than that of water-cooled high chromium cast iron, and the sharp angle of carbide disappeared basically, and the dispersed carbide appeared after being treated by 20% PAG, which greatly improved the toughness of high chromium cast iron. It can be seen from Figure 3 that the impact fracture of three kinds of heat-treated high chromium cast iron was a cleavage fracture. Microcracks were observed in the high chromium cast iron impact fracture after water cooling and 10% PAG. After 20% PAG cooling, there is a slight tear edge on the high chromium cast iron impact fracture which indicated its toughness was best.

Table 5. Influence of quenching medium on the toughness of high chromium cast iron.

Quenching Medium	**Ak/J/cm^2**	**K_{Ic}/(MN $\times$ m$^{-3/2}$)**
Water	3.20 ± 0.15	16.62 ± 0.55
10% PAG	4.32 ± 0.18	20.16 ± 0.72
20% PAG	5.98 ± 0.20	23.68 ± 0.81

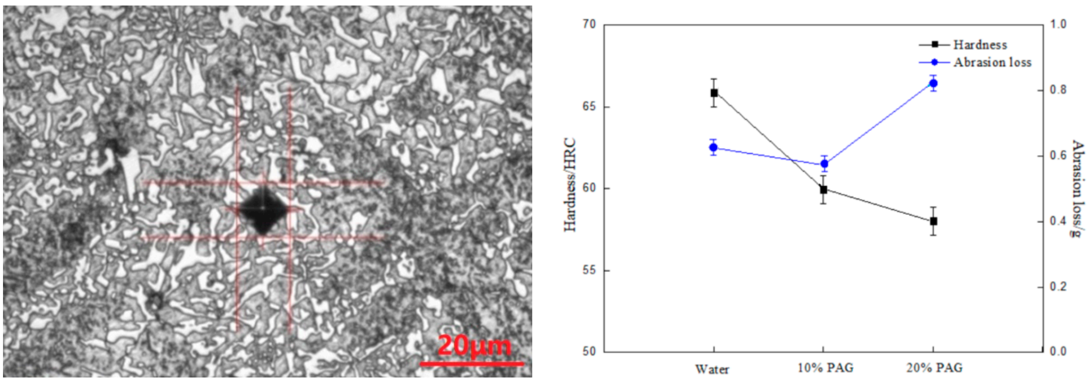


(**a**) Water (**b**) 10% PAG (**c**) 20% PAG

Figure 3. Impact fracture morphology of high chromium cast iron with different quenching mediums.

3.4. Effect of Quenching Medium on Wear Resistance of High Chromium Cast Iron

The relationship between hardness and wear volume of high chromium cast iron treated by different cooling mediums was shown in Figure 4. The high chromium cast iron treated with 10% PAG had the best wear resistance, and the high chromium cast iron treated by water cooling had the highest Rockwell hardness. It was known from the literature that the wear resistance of high chromium cast iron was mainly determined by eutectic carbides in the microstructure [20]. Rockwell hardness had a large indentation, and the measured results reflected the matrix hardness, not the eutectic carbide hardness. The eutectic carbide of high chromium cast iron was tested by a micro-Vickers hardness tester. It could be seen from Table 6 that the eutectic carbide of high chromium cast iron treated with 10% PAG coolant had the highest hardness, so it had the best wear resistance.



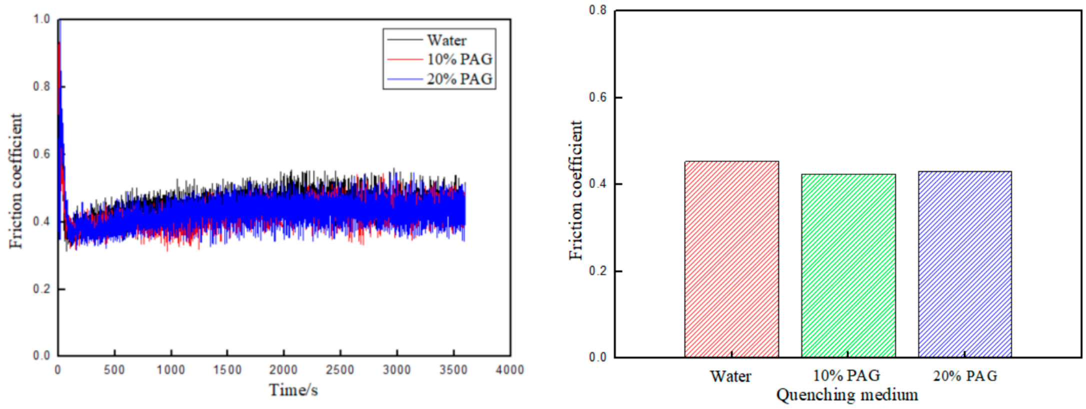
(**a**) Vickers hardness test diagram (**b**) Diagram of hardness and wear change

Figure 4. Relationship between hardness and abrasion loss of high chromium cast iron with different quenching mediums.

Table 6. The HV0.1 of the eutectic carbide of high chromium cast.

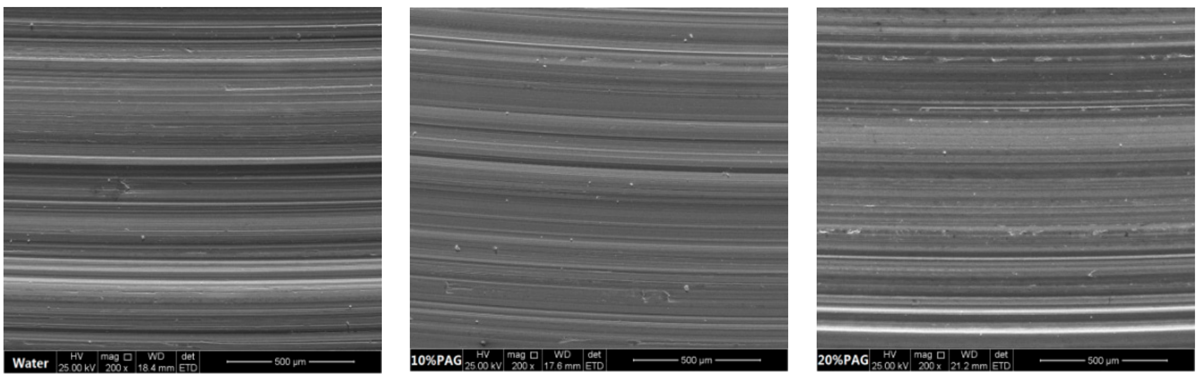
Quenching Medium	HV0.1			
Water	1185	1268	1252	1235
10% PAG	1276	1195	1343	1271
20% PAG	1108	962	1083	1051

As can be seen from Figure 5, the friction coefficient of high chromium cast iron treated by water cooling was the largest, which was due to the high hardness of the matrix during wear, resulting in greater resistance during friction with the grinding sample. It could be seen from Figure 6 that there were furrow grooves in the three kinds of wear patterns, and there are ridges on both sides of the furrow [21]. In the process of resisting abrasive wear, the main function is (Fe, Cr)$_7$C$_3$ carbide and the matrix mainly acted as a supporting carbide. For the high chromium cast iron with water cooling, the hardness of the matrix was higher, and it can resist abrasion better. For high chromium cast iron treated with 10% PAG, the hardness of the matrix decreased slightly. The precipitation of carbide protected the matrix from wear and reduced the chance of abrasive particles contacting the matrix and the depth of the plough [22–24] so that the overall wear resistance of high chromium cast iron was improved [25]. For high chromium cast iron treated with 20% PAG, due to its relatively low hardness, plastic deformation occurred on the surface of specimens under shear and tensile and compressive stresses. With the increase in friction time and temperature, the surface hardness decreased and the occurrence of plastic deformation was aggravated. As a result, the surface furrows were deepened, the ridges on both sides of the furrows were widened, and a few lumps appeared, which showed the characteristics of abrasive wear and adhesive wear.



(**a**) Friction coefficient comparison diagram (**b**) Comparison Chart of Wear Amount

Figure 5. Relationship between friction coefficient and time of high chromium cast iron with different quenching mediums.



(**a**) Water (**b**) 10%PAG (**c**) 20%PAG

Figure 6. The morphology of the worn surface of high chromium cast iron with different quenching mediums.

4. Conclusions

(1) The maximum cooling rate, cooling rate at 300 °C and the quenching liquid cooling capacity of water at 20 °C was 193.6 °C/s, 88.6 °C/s and 2431.1, respectively. With the increase in PAG concentration, the maximum cooling rate and the cooling rate at 300 °C of the coolant decreased.

(2) The microstructure of high chromium cast iron treated by water cooling, 10% PAG and 20% PAG was white carbide + tempered martensite + retained austenite, and its impact toughness and fracture toughness were gradually improved.

(3) The water-cooled high chromium cast iron had the highest Rockwell hardness 66.2 HRC, good wear resistance of 0.6103 g and the greatest friction coefficient of 0.4233, the high chromium cast iron treated with 10% PAG had the best wear resistance of 0.5715 and the lowest friction coefficient of 0.4182, the high chromium cast iron treated with 20% PAG had the lowest Rockwell hardness of 58.1 HRC and the worst wear resistance of 0.8213 g.

(4) The optimal quenching cooling medium for high chromium cast iron was obtained through research. The effect of the strengthening process on the properties of high chromium cast iron will be studied later, so as to obtain different preparation processes and properties of high chromium cast iron and guide its use under different working conditions.

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