The Microstructure and Mechanical Properties of Novel MQ-P-T Processes Proposed to Ductile Iron Casting Ball with Different Composition

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Abstract. Based on microstructure desired, ductile iron casting balls are treated by a multi-cycle quenching-partitioning-tempering (MQ-P-T) process and such a complex process is performed by alternating water quenching and air cooling. The resultant microstructure is characterized and the effect of the heat treatments on the mechanical properties is evaluated. Compared to ductile iron casting iron samples, the hardness of MQ-P-T ductile iron balls has been significantly enhanced. After treated by MQ-P-T process, the impact performance of sample 1# reduces, while the impact performance of 2# and 3# increases. With the purpose of studying the root causes of the mechanical performance enhancement, this paper will further investigate the strengthening and toughening mechanism of MQ-P-T ductile iron casting balls by means of microscopic characterization technique, such as OM and XRD methods.

1. Introduction
Ductile iron is a high-strength material developed in 1950s. It has the excellent mechanical performance which satisfies the extreme usage conditions and complex geometrical requirements [1, 2]. Therefore, this material is extensively used for casting some vital components in various industrial applications, such as the motor industries and mining [3, 4, 5]. In order to further improve the mechanical properties of ductile iron, numbers of dedicated heat treatments are applied based on the characteristics of microstructure of ductile iron. As a result, the overall mechanical performance of ductile iron is enhanced by optimizing the microstructure [6].

Common heat treatment processes consist of quenching and annealing process [7], isothermal quenching and etc [8]. The Quenching-Partitioning treatment proposed by Peer [9] can improve the overall mechanical properties of steel significantly [10, 11]. Another heat treatment method called Quenching-Partitioning-Tempering(Q-P-T) is developed by Academician Hsu T Y based on the former Q-P method in 2007 [12]. The Q-P-T process can further improve steel strength by adding carbides alloys. The results show that the strength of Q-P-T martensitic steel is much higher than that of Q&P martensitic steel[12, 13]. Although the Q-P-T process can improve the mechanical properties of steel in an all-round way, the Q-P-T process is significantly affected by the size of the workpiece. Therefore, a multi-cycle Q-P-T (MQ-P-T) process is developed based on the above facts.

In this paper, water and air are used as quenching medium. The multi-cycle quenching-partitioning-tempering (MQ-P-T) process is performed on the 100mm diameter ductile iron balls. The mechanical properties and microstructure of MQ-P-T ductile iron are compared with as-cast ductile iron. the optimal composition ratio of ductile iron ball is developed by using the microstructure characterization
technology.

2. Experimental materials and methods
Three different compositions of ductile iron casting balls are used as experimental materials, and the diameter is 100 mm. The composition is shown in Table 1.

| No. | Elements (wt%) | C  | Si  | Mn  | P   | S   | B   | Cr  | CE  |
|-----|----------------|----|-----|-----|-----|-----|-----|-----|-----|
| 1#  |                | 3.7| 2.2 | 1.94| 0.030| 0.023| 4.43|
| 2#  |                | 3.57| 3.5 | 1.87| 0.036| 0.022| 0.015| 4.55|
| 3#  |                | 3.86| 2.1 | 0.97| 0.032| 0.022| 0.77| 4.784|

The mechanical properties of the ductile casting balls are measured after treated by MQ-P-T process. The samples 10x10x100(mm) with the hardness measurement purpose have been taken along radial direction. The hardness is measured by Model 500RA Rockwell hardness. The samples 10x10x55(mm) with the standard impact measurement purpose are taken in the radial direction and conducted the impact test on PTM2200-D1 automatic impact testing machine. The microstructure of the samples is observed by using a Nikon ECLIPSEMA200 optical microscope (OM). The content of the tissue of the samples is measured by a Rigaku / max2550VB / PC X-ray diffraction (XRD).

3. Test results and analysis
In the process of MQ-P-T method, immersion is aimed to get rapid cooling. The use of air-cooling is aimed to achieve carbon precipitation and distribution. At the meantime, self-tempering process is accomplished. Thus, the desired temperature and timing of ductile iron casting balls are controlled by the duration of immersion and out of water. Mechanical properties and microstructure carried out on the basis of the ductile iron casting balls with diameter of 100mm are subjected to multi-cycle quenching-partitioning-tempering (MQ-P-T) process.

3.1. Hardness
Making exploration of three components ductile iron casting balls which are treated by air-water treatment process. In order to distinguish the as-cast ductile iron balls and ductile iron balls which are treated by MQ-P-T process, the ductile iron casting balls of the corresponding components after treated by MQ-P-T process are labeled respectively: labeled 1#-1, 2#-1, 3#-1, 3#-2, of which X# is the sample of as-cast ductile iron and -X is the sample number of ductile iron balls which are treated by MQ-P-T process. The hardness bar is cut in a radial direction of 10x10x100(mm). The specific results are as follows:

![Figure 1](image1.png)  ![Figure 2](image2.png)

**Figure 1.** Radial hardness of As-cast ductile iron balls. **Figure 2.** Radial hardness of ductile casting balls treated by MQ-P-T process.
As shown in the Figure 1, the radial hardness ranges from 26.6HRC to 29.8HRC for sample 1#. According to Figure 2, the hardness of samples which treated by MQ-P-T process has been significantly increased to a range from 48.1HRC to 50.2HRC. The improvement of hardness performance can be seen for all the samples which are treated by MQ-P-T process.

According to the following results, the difference of hardness is determined by the ferrite content in the as-cast microstructure of each component. The sample 1# contains about 10% bovine ferrite and massive ferrite. Sample 2# contains about 50% bovine eye ferrite. Sample 3# contains about 8% free ferrite. The amount of ferrite depends on alloy elements, especially the element Si which plays a dominant role. After treated by MQ-P-T process, the hardness of sample 1#-1 and 2#-1 is about 50 HRC with uniform hardness inside and outside. The hardness of 3#-1 and 3#-2 is about 52 HRC in the surface hardness (3 mm under from the surface), and 43 HRC in the center.

3.2. Impact toughness
Impact results are shown in Table 2; sample 1# has the highest impact values, while sample 3# has the lowest impact properties. After treated by MQ-P-T process, the impact properties of sample 1# decreases, while the impact properties of sample 2# and 3# increases. From the analysis of subsequent metallography, sample 1# and 2# have a lot of bovine matrix graphite and ferrite which make the 1# and 2# have high impact toughness.

| Impact sample number: | 1# | 2# | 3# | 1#-1 | 2#-1 | 3#-1 |
|-----------------------|----|----|----|------|------|------|
| Sample1 J/cm²         |    |    |    |      |      |      |
| Sample2 J/cm²         |    |    |    |      |      |      |
| 31.65                 | 21.17 | 12.48 | 21.17 | 29.91 | 15.28 |
| 31.65                 | 22.69 | 10.99 | 21.40 | 26.53 | 11.63 |

4. Microstructure analysis

The samples are cut at the surface, 0.5 radius and the center of the ball, then observed under microscope after polishing and etching. XRD is performed on 0.5R samples. On this basis, the ball is analyzed on different processing organizations and the graphite size and spheroidizing effect are rated according to GB/T9441-2009.

4.1. Microstructure of sample 1#

Figure 3. The microstructure of sample 1# at different locations.
The effect of sample 1# is good. The level of the ductile casting ball is above 3 and graphite size level is above 6. The calculated results show that the microstructure of sample 1# is non-uniform from the surface to the center. The total ferrite content of sample 1# is 5.37% at surface, 0.5R is 7.48% and center is 13.04%. The morphological distribution of the structure is related to the segregation of components during casting cooling.

After treated by MQ-P-T process, the microstructure of sample 1#-1 shows in Figure 3 and Figure 4. The ferrite of as-cast casting ball has been transformed into martensite after treated by MQ-P-T process. Sample 1#-1 mainly made up of spheroidal graphite, maintensite, retained austenite and small amount of carbides. The analysis of XRD results in Figure 5 and Figure 6 shows that the content of retained austenite reaches 17.83% and the martensite reaches about 75% in the matrix. The hardness of the matrix is about 50 HRC and the impact toughness is above 15 J. The result shows that the ductile iron casting ball which is treated by MQ-P-T process has an excellent performance.
4.2. Microstructure of sample 2#

Figure 7. The microstructure of 2# at different locations.

Figure 8. The microstructure of sample 2#-1 at different locations.
The effect of sample 2# is good. The level of the ductile casting ball is above 5 and graphite size level is above 5. The graphite state of 1# is poor. The structure of sample 2# is relatively uniform from face to the center. The ferrite of sample 2# is 47.05% at surface, the 0.5R is 45.46% and the center is 51.68%, which further confirms the low hardness of the as-cast state. It is worth noting that the ductile iron casting ball has a large number of flocculent graphite, which will affect the performance of the product.

After the altering water-air quenching treatment, the microstructure of each part of sample 2#-1 is shown in Figure 8. From the microstructure of as-cast casting ball, we can see that most of bovine ferrite is transformed into lath martensite. The main microstructure of 2#-1 matrix is nodular graphite, martensite(lath martensite+twin martensite), retained austenite and a small amount of phosphorus eutectic and carbides. According to the analysis of Figure 9 and Figure 10, the content of retained austenite in 0.5R reaches 8.49% and martensite reaches 85%. The hardness of the matrix is about 50HRC, the impact property is above 20J. In ductile iron, B is a serious anti-nodular element. B can increase the hardenability of the product. Si element to further promote the formation of graphite.

4.3. Microstructure of sample 3#

![Figure 9. XRD spectra of sample 2# at 0.5R.](image)

![Figure 10. XRD spectra of sample 2#-1 at 0.5R.](image)

Figure 11. The microstructure of 3# at different locations.
The effect of sample 3# is good. The level of the ductile casting ball is above 3 and graphite size level is above 5. Compared with sample 1# and 2#, the hardness of sample 3# is the highest and the hardness is about 30HRC. The chromium eutectic carbide exists around the grain boundary in sample 3# which affects the hardness and wear resistance of the ductile iron casting ball. The total content of carbide and ferrite in sample 3# is 5.25%, the 0.5R is 6.23% and the center is 11.93%. It can be inferred that the element segregation phenomenon exists in the casting cooling process.

After treated by MQ-P-T process, the metallographic structure of sample 3#-1 is shown in Figure 11 and Figure 12. According to the result of XRD diffraction analysis, the content of retained austenite in the matrix is 8.49%, martensite content is 85%, and the content of carbide and phosphor eutectic is about 7.15% at 0.5R. It is worth noting that the hardness of surface is above 50HRC. The hardness of center is reduced. Preliminary tests show that the content of austenite in center increases to 18.26%. Due to segregation, the content of austenitic carbon and austenite stability increase. The existence of excessive retained austenite makes the hardness of the material reduce. At the same time, the eutectic carbides presents a shape of fishbone, which reduces the impact performance of sample 3# to about 9J. For sample 3#, it is appropriate to reduce the carbon content in order to improve the hardenability of products. While a slight reduction of chromium content to further reduce the formation of eutectic
carbides to improve product impact toughness.

5. Conclusion
In this paper, three different kinds of spheroidal graphite cast balls are studied:

(1) After MQ-P-T heat treatment process, the hardness distribution of sample 1#-1, 2#-1 is more uniform, the hardness of surface (within 3cm from the surface) is significantly higher than the center. It is obviously seen that MQ-P-T process can effectively improve the hardness of three different composition ductile iron casting balls. For the impact toughness performance, sample 1#-1 has decreased toughness after treated by MQ-P-T process, while the impact performance of sample 2#-1 and 3#-1 increase. The hardness and the impact of sample 3#-1 is rather low, and the mechanical properties of 1#-1 are the best.

(2) Si can promote the formation of graphite and refine the graphite ball. Manganese ductile cast iron ductile contribution is more obvious, but also enhances the stability of austenite. Mn contributes significantly to the hardenability of ductile iron, but also enhances the stability of austenite. Si-Mn alloy can replace chromium, molybdenum and other alloying elements which have a very high price, thus reducing the cost of ductile iron casting balls.

(3) Compared with the traditional oil quenching and other traditional heat treatment methods, MQ-P-T heat treatment method has the advantages of energy saving and environmental protection.

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