Microstructure and properties of ductile iron bars for plunger pump prepared by horizontal continuous casting process

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Abstract: Ductile iron bars (DIBs) with a diameter of 145 mm, used for plunger pump production, were made by the horizontal continuous casting (HCC). The microstructure of the samples cut at three locations with different distances away from the surface (~20 mm from the surface, half of the radius and the center of the HCCDIBs) were investigated. The mechanical properties were measured by tensile and torsion tests. Results show that after the spheroidization of graphite, the iron matrix incorporates the nodules of Format I, Size 8 close to the surface, Format I, Size 7 at the half of the radius from the surface, and Format II, Size 6 in the centre of the bar, according to the ASTM A247 standard. The content of pearlite in the matrix changes from 55% (~20 mm from the surface) to 70% (half of the radius) and 80% (the center of the HCCDIBs). The strengths in tension are 552, 607 and 486 MPa with the elongations of 12.5%, 10.5% and 5.8% in samples cut at these three locations from the surface to the centre, respectively. The strength in torsion is equal to 558, 551 and 471 MPa at corresponding torsion angles of 418°, 384° and 144° respectively to the same distance from the bar surface. Fracture in tension is manifested via crack propagation through the interface between graphite nodules and matrix (Mode I), while in torsion the fracture is caused by the shear of graphite nodules (Mode II). It is shown that the transition between two fracture modes is also dependent on the size of graphite nodule. Typically, fracture Mode I was observed for nodules of smaller diameter (less than 22.7 μm) and fracture Mode II was seen for nodules of greater diameter (more than 24.8 μm).

Key words: horizontal continuous casting; ductile iron bars; plunger pump; tension and torsion properties; microstructure

CLC numbers: TG143.5

Document code: A

Article ID: 1672-6421(2019)02-118-08

In recent years, with the development of the hydraulic industry to the high speed, high precision and high efficiency, the higher requirements are put forward for hydraulic pumps^[1-3]. During the operation of a plunger pump, the cylinder body rotates at a high speed, it requires the body to bear great torsion torque and tensile stress to complete the oil absorption and draining process. Due to the defects of sand holes,

inclusions and shrinkage, traditional sand cast ductile iron has problems of insufficient pressure resistance and leakage resistance, which cannot meet the requirements of high performance hydraulic pumps such as plunger pumps.

The horizontal continuous casting iron bars (HCCIBs) are homogeneous and compact in structure, free from defects such as slag inclusion, sand inclusion and gas holes of sand mold casting, and have excellent mechanical properties, good cutting and processing performance, and especially excellent toughness and pressure resistance. As a result, the HCCIBs have been widely used in machinery, hydraulics and other industries and fields^[4-11]. In addition, the HCCIBs have an excellent anti-leakage performance and can

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Received: 2018-08-15; Accepted: 2018-11-16

meet the special requirements of ultra-high pressure hydraulic components^[4]. Therefore, in recent years, the HCCDIBs are widely used to process cylinders for the plunger pump. However, there is deformation of the cylinders of the plunger pump will be holding and clamping, and this failure is mainly caused by the nonuniformity of microstructure and mechanical properties of different parts of HCCIBs.

The objective of the present work is to study the microstructure, tensile and torsion properties, and fracture failure mechanism of different parts of HCCDIBs with a diameter of 145 mm. This work can provide basic data for improving horizontal continuous casting process, and reducing the section sensitivity of HCCDIBs, to expand the application of HCCDIBs in the field of high pressure and power plunger pump cylinder.

1 Experimental procedure

The HCCDIBs with 145 mm in diameter were prepared in a ZSL-02 horizontal continuous casting (HCC) production line. The duplex melting process was carried out in a 3 t medium-frequency induction furnace, and the tapping temperature was from 1,480 to 1,520 °C. 1.70% RE (8–3) nodularizer was added, and the nodularizing treatment was completed in a 1,000 kg dam-type ladle. The metal-stream inoculation method was used with 0.6% 75Si-Fe inoculant. The temperature of melted iron transferred into the holding furnace ranged from 1,360 to 1,400 °C.

The experiment was carried out using the HCCDIBs with 145 mm in diameter as the material of a plunger pump cylinder. The measured chemical composition was 3.02% C, 2.41% Si, 0.27% Mn, 0.04% P and 0.01% S and the balance Fe. According to the Machinery Industry Standard of China (" MISC ") (JB/T 10854-2008), the designation is LZQT500-7. Image J analysis software was used to quantitatively measure the microstructural features of the number and diameter distribution of graphite spheres in different parts, and a shape factor F is defined as follows:

$$F = 4\pi A/p^2 \quad (1)$$

where F is defined to characterize the shape variation of the graphite nodules. A and p are the area and the perimeter of the nodules, respectively. A value of $F=1$ corresponds to a perfectly round particle and the shape becomes more irregular

with the decreasing F . Tensile and torsion specimens cut at three points with different distances away from the surface (~20 mm from the surface, half of the radius and the centre of the HCCDIBs), effective cross section size is 10 mm in diameter, as shown in Fig. 1. The tensile tests were carried out using HT-2402 test machine at a strain rate of $8.33 \times 10^{-4} \text{ s}^{-1}$ at the room temperature, and the torsion tests were evaluated on HT-9726 torsion testing machine at an active clamp head rotation speed of $30^\circ \cdot \text{min}^{-1}$ at the room temperature. Specimens for microstructural analysis were characterized by GX71 optical microscope, the fracture morphology was investigated by SM-6700F scanning electron microscope.

Fig. 1: Schematic diagram and dimensions of tensile and torsion test specimens (unit: mm)

2 Results and discussion

2.1 Microstructure characterization

The graphite morphology from different parts of HCCDIBs with 145 mm in diameter can be seen in Fig. 2. The number of graphite nodules is greater, and the graphite nodules diameter is smaller on the surface layer compared with that at the 1/2 R and in the center. Among them, the individual graphite nodules at 1/2 R and in the center of HCCDIBs are not round enough. According to the American Society for Testing and Materials (ASTM) A247 International Standard, after the spheroidization of graphite, the iron matrix incorporates the nodules of Format I, Size 8 close to the surface; Format I, size 7 at the half of the radius from the surface; and Format II, Size 6 in the centre of the HCCDIBs. From Fig. 3, it can be seen that the graphite nodules density at 20 mm from the bar surface, 1/2 R and in the center are 306, 238 and 209 nodules·mm⁻², respectively. The diameter distribution and shape factor F of graphite spheres in different parts are shown in Fig. 4. It can be seen that the diameter and shape factor F of the surface graphite sphere at 20 mm from the bar surface are mainly in the range of 3–42 μm

Fig. 2: Graphite morphology of HCCDIBs with diameter of 145 mm: (a) 20 mm from surface; (b) 1/2 R; (c) center

Fig. 3: Number of graphite sphere per unit area in different parts

and 0.8–1, respectively. The average diameters of graphite spheres at 20 mm from the bar surface, 1/2 R and in the center are 22.7, 24.8, and 26.0 μm , and the shape factors F are 0.860, 0.793, and 0.747, respectively. Furthermore, since the average grain size (λ) of different parts of the casting has a certain relationship with the cooling rate of the part (V), according

to the fitting relationship $\lambda = 85.1 V^{-0.35}$ [12], the cooling rates of different parts are 43.48, 33.70 and 29.48 $^{\circ}\text{C}\cdot\text{s}^{-1}$, respectively.

The matrix microstructure etched by 4% nitric acid alcohol is shown in Fig. 5. According to the ASTM A247 standard, the content of pearlite in the matrix changes from 55% (~20 mm from the surface) to 70% (half of the radius) and 80% (the center of the HCCDIBs). These differences are determined by the inherent characteristics of horizontal continuous casting. In the process of HCC, due to the quenching effect of water-cooled graphite crystallizer of the molten iron, the surface microstructure crystallized at a high degree of supercooling, the cooling rate was relatively fast. After a certain intensity of solidification, the HCCDIBs were pulled out of the water-cooled crystallizer, and then cooled by the air convection or secondary spray mist outside the crystallizer. At this time, the molten iron at the 1/2 R and in the center was not solidified, and these parts of molten iron can only solidify by the heat transfer through the solidification shell with a low cooling speed. As a result, the surface microstructure nucleation rate is greater than that at the 1/2 R and in the center, the number of

Fig. 4: Diameter distribution and shape factor of graphite spheres: (a₁) and (a₂) 20 mm from surface; (b₁) and (b₂) 1/2R; (c₁) and (c₂) center

Fig. 5: Microstructures of HCCDIBs with diameter of 145 mm: (a) 20 mm from surface; (b) 1/2 R; (c) center

graphite nodules is greater, the sphere diameter is smaller, and the grain is finer, as shows in Fig. 5(a).

The cooling rates of the molten iron at the 1/2 R and in the center of HCCDIBs are relatively low, the crystallization nucleation rate greatly decreases. When the HCCDIBs are pulled out of the water-cooled crystallizer, the molten iron in the solidified shell (the length of liquid cavity) can remain about 1 meter, and the holding time is about 1.5–2 min, providing conditions for the further growth of the graphite nodules. Therefore, the number of graphite nodules decreases, diameter of the spheres increases, the structure is relatively coarse and the pearlite increases, as shown in Fig. 5(b) and Fig. 5(c).

In addition, due to the different cooling rates at different locations, the diffusions of solute atoms such as C and Si are different. In the surface layer, the solute atoms in the matrix distribute relatively uniformly and the content is high because the high cooling rate is not conducive to the diffusion of atoms; and the cooling rates at 1/2 R and in the center are slow, so there is enough time to make sure that the C atoms to diffuse into the graphite nodules, which is favorable for the graphite nodule growth. As a result, the distribution of solute atoms in the matrix is relatively inhomogeneous, and a microsegregation occurs. There is even a carbon-poor tendency in ferrite near graphite nodules, which is not conducive to pearlite formation. However, the pearlite can be easily obtained by the austenite far away from the graphite nodules at the eutectoid transition temperature^[2].

2.2 Mechanical properties

The tensile properties and torsional properties from different parts of HCCDIBs with 145 mm in diameter are shown in Fig. 6. The tensile strength at three points with different distances away from the surface (~20 mm from the surface, half of the radius and in the centre of the HCCDIBs) are 551.6, 607.0 and 485.7 MPa, the torsion resistance strength is 557.7, 551.2 and 470.5 MPa, respectively. The maximum torsion angle of the specimen at the point 20 mm away from the surface is 417.5°. The diameter of the graphite nodules gradually increases from the surface layer to the center of

HCCDIBs [Fig. 4(a₁), (b₁) and (c₁)], the spheroidization effect becomes poor [Fig. 4(a₂), (b₂) and (c₂)], the number of graphite nodules gradually decreases (Fig. 3), and the grains become coarse (Fig. 5). According to the principle of Hall-Petch formula and the strengthening mechanism of fine crystals, the cooling speed of the surface layer and 1/2 R layer is high, and the graphite nodules and matrix grain is fine, so the tensile properties are better than that in the center. In addition, the graphite nodules in HCCDIBs are regarded as holes or defects, which are easy to generate stress concentration and crack sources during tensile or torsional deformation. However, more microcracks have less impact than a large one on the performance^[13], which is another reason why the surface layer and 1/2 R have better strengthening and toughness than the center.

2.3 Fracture morphology

The tensile fracture SEM images from different parts of HCCDIBs with 145 mm in diameter are shown in Fig. 7. It can be seen that the macroscopic fractures surface are relatively flat, as show in Fig. 7(a₂), Fig. 7(b₂) and Fig. 7(c₂), without obviously necking and plastic deformation, because there is no obvious yield point during the tensile processing. As shown in Fig. 6(a), the sample is basically uniformly deformed before the fracture.

It can be seen from the local amplification of the tensile fracture that fractures are distributed with equiaxial dimples of similar size, as shown in Fig. 7(a₁), (a₃), (b₁), (b₃), (c₁) and (c₃). These dimples are all centered on the graphite nodules, that is, the crack source generates from the graphite nodules.

Due to each graphite nodule acting as a hole in the tensile process, it increases with the increase of strain, and the merging of adjacent holes will lead to the formation of a ridged profile of the equiaxial dimple. Figures 7 (a₁), (a₃), (b₁), (b₃) (c₁) and (c₃) show the traces of aggregation between the pores formed by adjacent graphite nodules under tensile stress, i.e., equiaxial dimples formed by the hole connection^[14]. The samples all produced large plastic deformation as a whole before the fracture, which belongs to the ductile fracture. At the same time, in a small number of dimples, it can be clearly

Fig. 6: Properties curves of HCCDIBs with diameter of 145 mm: (a) tension properties; (b) torsion properties

Fig. 7: SEM morphology of tensile fracture of HCCDIBs with diameter of 145 mm: (a₁–a₃) 20 mm away from surface; (b₁–b₃) 1/2 R; (c₁–c₅) center

observed that the tearing edge left after the plastic deformation of the ferrite around the graphite sphere due to its good plastic deformation ability during stretching to fracture, and the graphite nodules are removed, broken, or left in the hole formed at the tearing edge, the surface and 1/2R as shown in Fig. 7(a₁–a₃) and Fig. 7(b₁–b₃), respectively. It can be seen from the macroscopic morphology of the center fracture that the fracture surface is quite different and there are obvious boundaries, as shown the line in Fig. 7(c₂). There are a large number of ferrite fracture dimples around the tear pit formed by graphite nodules, as well as obvious lamellar pearlite (P) tearing and some ferrite (F) cleavage edges, as shown in

Fig.7(c₄), and the aggregation process of adjacent holes also occurs here ^[15]. At the same time, cleavage facets typical of ferrous alloys are also present on the fracture surface, as shown in Fig. 7(c₅). The topology of the facets hints at a transgranular mode of fracture. During the crack propagation, cleavage brittle fracture is rapidly formed under tensile stress, which will lead to materials normal fracture ^[16].

Figure 8 shows the torsional fracture SEM images of HCCDIBs with 145 mm in diameter. The fracture traces in the samples torsion process can be clearly seen from the macroscopic fracture morphology, as shown in Figs. 8(a₂), (b₂) and (c₂). The macroscopic fracture surface of the point away

Fig. 8: SEM images of torsion fracture of HCCDIBs with diameter of 145 mm: (a) 20 mm away from surface; (b) 1/2 R; (c) center

from surface layer and 1/2 R of HCCDIBs is relatively flat and neat, while the broken steps appear at the center fracture, as shown in the dotted rectangle in Fig. 8(c₂). It can be seen from the fracture microscopic morphology that the interface fracture occurs between the graphite nodules and the matrix on the surface of each fracture. This interface fracture ratio is reduced compared to unidirectional stretching, forming a shear paraboloid dimples along the torsion direction, as shown in locations D and E of Fig. 8(a₃). A part of the graphite nodules is cut off from the middle under shear stress, as shown in locations F and G of Fig. 8(b₃) and locations H and I of Fig. 8(c₁). It can be seen that the fracture between the graphite nodules and the matrix is related to the size of the graphite nodules. The smaller the size of graphite nodules, the greater the fracture tendency from the interface between graphite nodules and matrix, as shown in Fig. 8(a₃). On the contrary, the cutting tendency from the graphite nodules is greater, as shown in Figs. 8(b₃) and (c₁). Furthermore, large numbers of paraboloid dimples can be observed on the transgranular

fracture surface of the matrix due to shear stress. Paraboloid dimples formed by holes under shear stress are the traces left by this fracture mode^[16].

Figure 9 shows the longitudinal section lateral surface microstructure of fracture of tensile and torsion samples. It can be seen that the crack propagation paths of both fracture openings are two types. One is along the ferrite boundary surrounding the graphite nodules, and the graphite nodules are well preserved, that is, the tensile or torsional fracture of the surface materials of the HCCDIBs, as shown in Figs. 9(a₁) and (b₁). The other mode is the transverse crack extending through the graphite nodules, as that at the 1/2 R and in the center of HCCDIBs shown in Figs. 9(a₂), (a₃), (b₂) and (b₃). It is obvious that the graphite nodules at the fracture are cut or pulled out, leaving a semi-closed ferrite ring of bull's eye graphite. These two types of cracks originate from the holes formed by the graphite nodules are debonding from the matrix, both of them can lead to material fracture^[14]. Under the action of a shear force, tiny pores in the necking zone develop into cracks. This

Fig. 9: Lateral surface microstructure of fracture of HCCDIBs with diameter of 145 mm: (a₁) and (b₁) 20 mm away from surface; (a₂) and (b₂) 1/2 R; (a₃) and (b₃) center

Table 1: Shape factor change in different parts

Location	Original	Tension	Torsion
20 mm away from surface	0.860	0.709	0.708
1/2 R	0.793	0.713	0.732
Center	0.747	0.663	0.695

type of expansion occurring at the graphite-ferrite interface usually requires less energy and the crack propagation in the necking zone is relatively easy^[17]. When the crack propagates across the cut graphite spheres, it easily forms a large crack because the graphite spheres are close to each other. In addition, it can be seen from Fig. 9 that some graphite spheres near the edge of the fracture appear oval in the tensile direction or torsional shear direction due to the great hydrostatic pressure^[18]. A slight decrease in the average shape factor F can be seen as in Table 1. This is mainly because there are many crystal defects in graphite nodules in ductile iron, mainly the small-angle tilted grain boundary, and the grain boundary is movable and is rarely restricted in movement^[17]. Therefore, when the load exceeds the elastic limit, graphite nodules will undergo obvious deformation with the increase of the load. In addition, due to the graphite nodules being surrounded by ferrite, the ferrite space surrounding the graphite nodules is spherical, and the BCC structure α -Fe can easily undergo a plastic deformation along the direction of deformation under

tensile stress or torsional shear stress, so the α -Fe wrapped graphite nodules can also undergo a collaborative deformation without cracking.

3 Conclusions

(1) The spheroidization of graphite in the iron matrix of HCCDIBs with 145 mm in diameter incorporates the nodules of Format I, Size 8 close to the surface; Format I, Size 7 at the half of the radius from the surface; and Format II, Size 6 in the center of the HCCDIBs. The content of pearlite in the matrix is 55%, 70% and 80% from the surface to the center, respectively.

(2) The graphite nodule density at 20 mm away from the bar surface, 1/2 R and in the center are 306, 238, and 209 nodules·mm⁻², average diameters are 22.7, 24.8, and 26.0 μ m, and the shape factors F are 0.860, 0.793, and 0.747, and the cooling rates of different parts are 43.48, 33.70, and 29.48 °C·s⁻¹, respectively.

(3) The mechanical properties of the point with 20 mm away from the surface and 1/2R of HCCDIBs with 145 mm in diameter are better than that of the center. The tensile strength of the point with 20 mm away from the surface, 1/2R and center is 551.6, 607.0 and 485.7 MPa, and the elongation is 12.5%, 10.5% and 5.8%; the torsional strength is 557.7, 551.2 and 470.5 MPa, and the corresponding torsion angle is 417.5, 383.8 and 144.2 degrees, respectively.

(4) There are similar size dimples on the surface of tensile and torsion fractures at different parts. These dimples are all made of graphite nodules as the core and show ductile

fracture. The cleavage fracture occurs under tensile stress due to the absence of holes in the graphite nodules in the matrix. This indicates that the tensile and torsional specimen fracture belongs to the ductile-brittle hybrid fracture.

(5) There are two kinds of crack propagation in ductile iron profiles: one is the crack propagation along the boundary between graphite nodules and substrate when tensile normal fracture occurs; another is torsional shear fracture in which transverse graphite nodules expansion is dominant.

References

- [1] Wu Huaichao, He Yongyong, Wang Zhangjun, et al. Study on hydraulic system for performance test of the slipper pair in high pressure axial piston pump. *Chinese Hydraulics & Pneumatics*, 2015, 15(1): 8–10. (In Chinese)
- [2] Shin J H, Kim K W. Effect of surface non-flatness on the lubrication characteristics in the valve part of a swash-plate type axial piston pump. *Meccanica*, 2014, 49(5): 1275–1295.
- [3] Li Juan, Yang Hongzhi, Han Mei, et al. Application and design of plunger pump lifting viscoelastic fluid. *Advanced Materials Research*, 2011, 291–294: 2507–2511.
- [4] Xu Chunjie, Xu Xinfeng, Zhao Zhen, et al. Horizontal continuous casting technology of cast iron and application of dense bars. *Foundry Technology*. 2017, 38(11): 2559–2564. (In Chinese)
- [5] Xu Chunjie, Guo Quanfen, Zhang Ting, et al. Effect on the microstructure and properties of HCC gray iron bars with normalizing treatment. *Transactions of Materials and Heat Treatment*. 2017, 38(4): 146–151. (In Chinese)
- [6] Xu Chunjie, Dai Pan, Zhang Zhengyang, et al. Effect of austempering parameters on microstructure and mechanical properties of HCC ductile iron dense bars. *China Foundry*, 2015, 12(2): 104–110.
- [7] Meng Lingnan, Xu Chunjie, Zhang Zhongming. Flow behavior of liquid iron in horizontal continuous mould and its effects on mechanical properties of cast iron. *Special Casting & Nonferrous Alloys*. 2010, 30(10): 932–934. (In Chinese)
- [8] Xu Chunjie, Zhang Zhengyang, Meng Lingnan, et al. Effects of Cu and Mo on microstructure and mechanical properties of horizontal continuous cast ductile iron profiles. *Special Casting & Nonferrous Alloys*. 2011, 31(6): 407–409. (In Chinese)
- [9] Wang Jincheng, Li Weiming, Zhang Zhongming, et al. Effect of austempering processing parameters on microstructure and hardness of nodular cast iron dense bar. *Transactions of Materials and Heat Treatment*. 2013, 33(1): 70–75. (In Chinese)
- [10] Xu Chunjie, Feng Gangwen, Zhang Ting, et al. Microstructure and properties of high strength hcc gray iron bars with large diameter 220 mm. *Foundry Technology*. 2016, 37(11): 2309–2317. (In Chinese)
- [11] Pongsak C, Panya S. Continuously cast ductile iron: Processing, structures, and properties. *Journal of Materials Processing Technology*, 2011, 211(8): 1372–1378.
- [12] Zheng Liang. Effect of Solidification Cooling Rate on Microstructure of Cast Nickel Base Superalloy K417G[J]. *Journal of Aeronautical Materials*, 2006, 26(3): 7–11. (In Chinese)
- [13] Chen Xiaofeng, Guo Dazhan, Lu Wenhua, et al. The fracture toughness of shaped ferritic ductile iron by horizontal continuous cast. *Foundry*, 1991, 39(5): 9–13. (In Chinese)
- [14] Ghahremaninezhad A, Ravi-Chandar K. Deformation and failure in nodular cast iron. *Acta Materialia*, 2012, 60(5): 2359–2368.
- [15] Marino B, Mudry F, Pineau A. Experimental study of cavity growth in ductile rupture. *Engineering Fracture Mechanics*, 1985, 22(6): 989–996.
- [16] Shi Junping, Han Dong, Tang Anmin. The Fracture Analysis of Ductile Iron Fracture Test under Complex Stress Condition. *Journal of Xi'an University of Technology*, 2009, 25(3): 288–291. (In Chinese)
- [17] Hao Shijin, Song Xuding. *Ductile Cast Iron*. Beijing: Chemical Industry Press, 2015: 47–50. (In Chinese)
- [18] Hütter G, Zybell L, Kuna M. Micromechanisms of fracture in nodular cast iron: From experimental findings towards modeling strategies – A review[J]. *Engineering Fracture Mechanics*, 2015, 144(12): 118–141.

This work was financially supported by the Shaanxi Provincial Science and Technology Achievement Transfer and Promotion Plan-absorb Achievement Transformation Project (No. 2017CGZH-XNGJ-03), Shaanxi Provincial Education Department Scientific Research Program Project—service Local Special Industrialization Cultivation Project (No. 17JF018), Xi'an Science and Technology Planning Project Science and Technology Innovation Guide Projects (No. 201805037YD15CG21(19)) and Xi'an University of Technology Scientific and Technological Achievement Transformation Project-technical Requirement Solving Project of Enterprises (No. 2018-1).