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Effect of nodularity on mechanical properties and fracture of ferritic spheroidal graphite iron

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Abstract: Ferritic spheroidal graphite irons with nodularity from 72% to 96% were prepared. The relationship between the nodularity and the mechanical properties of the ferritic spheroidal graphite iron was investigated. The effect of nodularity on the mechanical properties and tensile fracture of the cast iron were studied. Results showed that the tensile strength R_m, yield strength $R_{p0.2}$, elongation to failure A_5, and impact energy KV_2 of the cast iron had a good linear relationship with its nodularity. Nodularity and annealing treatment would obviously affect the fracture characteristics of ferritic spheroidal graphite iron. The annealed ferritic spheroidal graphite iron with 93% nodularity showed a completely ductile rupture. With the decrease of nodularity from 93% to 72%, the cleavage fracture area ratio increased gradually from 0% to 8.3%. Compared with as-cast ferritic spheroidal graphite iron, annealing treatment reduced the cleavage fracture area of the ferritic spheroidal graphite iron.

Key words: ductile iron; nodularity; mechanical property; fracture

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As an important engineering material, spheroidal graphite cast iron has been widely applied in industry, with a global production in 2017 of more than 2,643 million tons [1]. The spheroidal graphite particles in the spheroidal graphite cast iron are characteristics of its microstructure. Nodularity, as a parameter representing the shape of the graphite particles in group, is one of the most important quality indications of spheroidal graphite cast irons [2]. The influence of nodularity on the tensile property, impact property and fatigue strength of spheroidal graphite cast irons have been extensively studied [3-6]. The results indicated that the shape of graphite particles has obvious effect on the mechanical properties of spheroidal graphite cast irons [7-8]. Generally, with the decrease of nodularity, the mechanical properties decline [9-13]. However, the exact relations between the graphite particles's shape and mechanical properties are not declared up to now. The main reason is that the mechanical properties of spheroidal graphite cast irons are not only related to the shape of graphite particles, but also to its matrix, including its microstructure and the chemical composition. The reported research studies were based on samples taken from different melts or different locations within a casting with different thicknesses and different solidification rates [14-15]. In these cases, it is too difficult to tell the effect of the graphite particles or of the matrix.

In order to control the influence of nodularity and the matrix on mechanical properties of spheroidal graphite cast iron, samples having different nodularity were prepared. The effect of nodularity on the mechanical properties was investigated and the tensile fracture mechanism of a ferritic spheroidal graphite cast iron was analyzed.

1 Experimental

1.1 Material preparation

The chemical composition of a spheroidal graphite cast iron is shown in Table 1. Q10 pig iron, steel scrap and foundry returns, as raw materials, were melted in a medium-frequency induction furnace. The sandwich method of spheroidizing process was employed to treat the liquid metal. Samples with different nodularity were obtained by regulating the addition amount of nodulizer during the spheroidizing treatment process. The nodulizer contains 5.5wt.%–6.6wt.% Mg and less than 1.0% RE. The particle sizes were in the range of 5–15 mm. Silicon-barium inoculants and post-inoculation were used in this work. The pouring temperature was controlled in the range of 1,400–1,360 °C. Type-Y

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Table 1: Chemical composition of the test pieces (wt.%)

C	Si	Mn	P	S	Re	Mg	Fe
3.65	2.56	0.18	0.03	<0.02	≤0.01	0.021–0.036	Bal.

blocks were cast in sand molds and the test pieces were cut from the bottom of the block, as shown in Fig. 1.

In order to get a uniform ferritic matrix, an annealing process, as shown in Fig. 2, was applied to the samples to eliminate the pearlite and cementite. The annealing treatment was carried out in an electrical furnace.

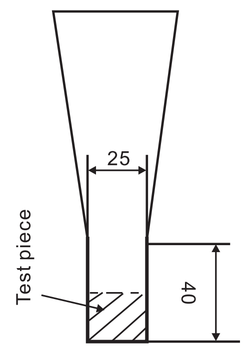


Fig. 1: Type-Y block and location of test piece

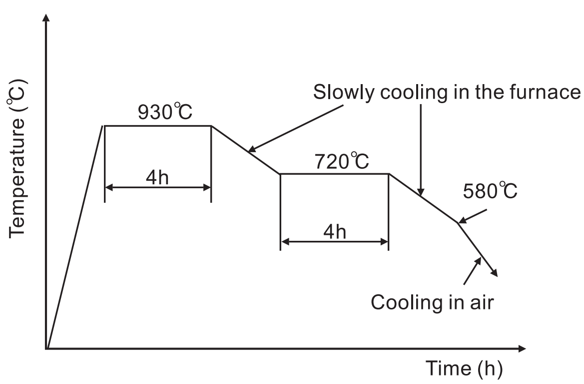


Fig. 2: Annealing process for test samples

1.2 Microstructure and mechanical property analysis

1.2.1 Nodularity evaluation

The microstructure and the graphite shape were observed under a LEICA DM4000 M optical microscopy. The nodularity was evaluated using the LAMOS master V18.3 software and the average value was obtained from 10 fields of views randomly selected in each sample.

1.2.2 Mechanical property test

(1) Tensile property test

The tensile property test was performed according to GB/T228-2002 at a strain rate of 0.25×10^{-3} using a CMT5205 tensile testing machine. The diameter of the sample was 10 mm and the gauge length was 50 mm. The surface roughness of the sample was 0.8–1.6 μm.

(2) Impact test

The size of the V-notched sample was 10 mm×10 mm×55 mm. The V-notch of all samples was checked using a profile projector. Impact energy was the average value of three samples.

1.2.3 Fracture morphology analysis

The tensile fracture morphology was analyzed under a HITACHI S-3600 scanning electron microscope. Image analysis software Pro Plus was used to measure the area of the cleavage plane in the fracture. The average area ratio of the cleavage plane was obtained from 10 fields of views in a sample. The field was 420 μm × 300 μm, which is selected at random on the tensile fracture of the sample.

2 Results and discussion

2.1 Effect of nodularity on mechanical properties

Figure 3 shows the relationship between the mechanical properties and nodularity of a ferritic spheroidal graphite iron. Figure 3 demonstrates that with the increase of nodularity, the tensile strength, yield strength, elongation to failure and impacting energy generally increased. However, the properties of the samples having the same nodularity fluctuated a lot. For example, among 6 samples having nodularity of 92 %, the tensile strength changed in the range from 415 MPa to 424 MPa, and the elongation to failure from 18 % to 20 %.

The fitted equations of nodularity p_{nod} vs tensile strength R_m, yield strength $R_{p0.2}$, elongation to failure A_5, and impact energy KV_2, were as follows:

$$R_m = 99.1\, p_{nod} + 326.7 \qquad R^2=0.77 \tag{1}$$

$$R_{p0.2} = 35.9\, p_{nod} + 247.0 \qquad R^2=0.32 \tag{2}$$

$$A_5 = 19.6\, p_{nod} + 0.86 \qquad R^2=0.50 \tag{3}$$

$$KV_2 = 9.49\, p_{nod} + 6.44 \qquad R^2=0.54 \tag{4}$$

The correlation coefficients R^2 of the fitted equations were 0.77, 0.32, 0.50 and 0.54, respectively. It seems that the mechanical properties of a ferritic spheroidal graphite iron had a low correlation with nodularity. As is known, the measured value of the mechanical properties of a ferritic spheroidal graphite iron is not only affected by nodularity, but also by many other factors, such as, chemical composition, matrix, machining quality of the sample, manual operation, etc. In this work, in order to reduce the distraction from other factors, the raw materials, liquid metal, pouring process, location of the test pieces, surface roughness of the test samples and the notch shape of impact sample were kept as similar as possible. A precise annealing treatment was applied to the samples and all of samples were heat-treated together to obtain an identical matrix structure. However, there are always some unavoidable factors which would result in the disturbance of the mechanical property.

These random interference factors can obviously affect the test results of a single sample. According to statistical theory, increasing the number of samples would reduce the effects of interference. The greater the number of samples, the more stable the obtained statistical data would be. An average tensile

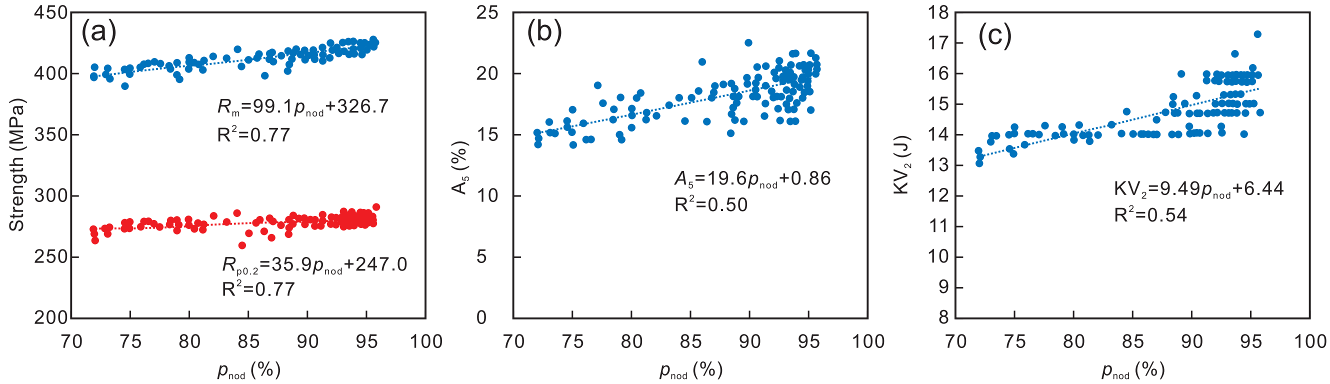


Fig. 3: Relationship between mechanical properties and nodularity of ferritic spheroidal graphite iron: (a) tensile strength; (b) elongation; (c) impact energy

strength R_m, average yield strength $R_{p0.2}$, elongation to failure A_5 and average impact energy KV_2 were obtained from the test results of Fig. 3 for the samples which had the same nodularity and the number of the samples was equal to and more than 3. The relationships between nodularity and the average mechanical properties were as shown in Fig. 4. The fitting equation of nodularity p_{nod} and R_m, $R_{p0.2}$, A_5, and KV_2 could be expressed as follows:

$$R_m = 104.1\ p_{nod} + 321.9 \qquad R^2=0.95 \qquad (5)$$

$$R_{p0.2} = 42.3\ p_{nod} + 241.3 \qquad R^2=0.84 \qquad (6)$$

$$A_5 = 20.5\ p_{nod} + 0.17 \qquad R^2=0.89 \qquad (7)$$

$$KV_2 = 8.75\ p_{nod} + 7.04 \qquad R^2=0.80 \qquad (8)$$

Obviously, the fitting equation of nodularity p_{nod} and average mechanical properties increased the correlation coefficient R^2. The correlation coefficient R^2 of the fitting equation of nodularity p_{nod} and average tensile strength increased from 0.77 to 0.95, average yield strength increased from 0.32 to 0.84, average elongation to failure increased from 0.50 to 0.89 and average impact energy increased from 0.54 to 0.80. Therefore, it could be concluded that the tensile strength, yield strength, elongation to failure and impact energy of ferritic spheroidal graphite iron had a good linear relationship with its nodularity, when the nodularity is in the range of 72% to 96%. With the decrease of the nodularity, the tensile strength, yield strength, elongation to failure and impact energy of ferritic spheroidal graphite cast iron gradually decreased. It is easy to understand that the lower nodularity means the more irregular graphite particles, which will result in stress concentration, destroying the continuity of the matrix and decrease the mechanical properties of the metal.

From Fig. 3(a) and Fig. 4(a), it can be found that with the decrease of the nodularity, the decline of the tensile strength of ferritic spheroidal graphite iron was quicker than its yield strength. The decline rate of the average tensile strength was 2.46 times that of its average yield strength. As is known, ferrite has very good ductility compared to pearlite. Stress concentration caused by the existence of small graphite particles, especially irregular graphite particles, would promote micro-zone plastic deformation. Its notch effect increased the strength of ferritic matrix locally and offset the negative effect of irregular graphite particles on yield strength to some extent.

The graphite particles in spheroidal graphite iron can be considered as the cavity or inclusions in the matrix. This is because the strength of the graphite is far lower than that of the matrix and the bonding strength between graphite particles and the matrix is poor, the graphite particles can easily break away from the matrix. If the graphite particles in spheroidal graphite iron were treated as cavities or inclusions in the metal, it can be supposed that total mechanical load was on the spheroidal

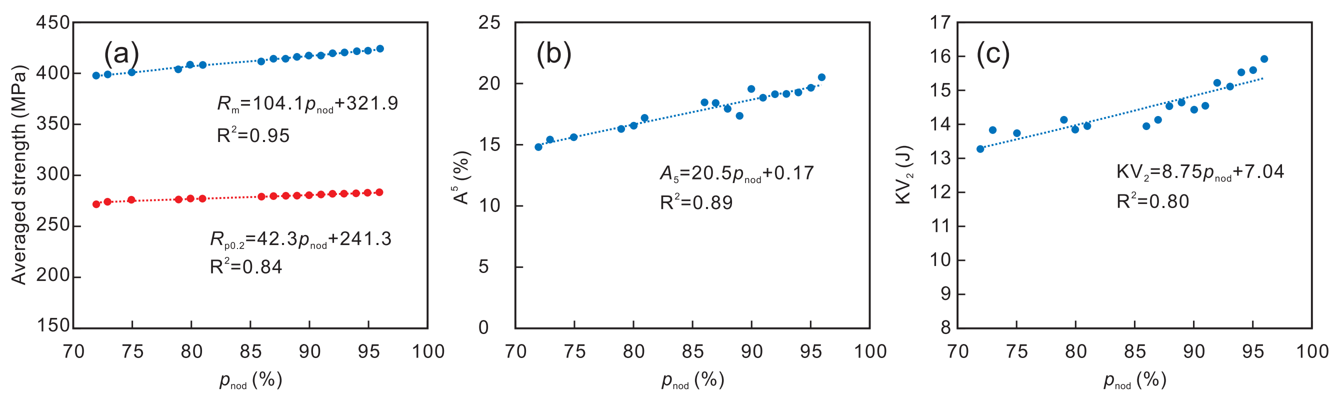


Fig. 4: Relationship between the average value of (a) $\overline{R_m}$, $\overline{R_{p0.2}}$, (b) $\overline{A_5}$, (c) $\overline{KV_2}$ and nodularity of ferritic spheroidal graphite iron

graphite iron. The effect of graphite particles on the mechanical property of the ferritic spheroidal graphite iron can be treated as the effect of a cavity or inclusion in the property of the metals.

Cavities in metals cause stress concentrations in the principal stress direction [16-18]. As shown in Fig. 5, the stress concentration factor is closely related to the shape of the cavity. An elliptical hole would produce a greater stress concentration factor than a round hole. The bigger the a/b value is, the greater the stress concentration factor k_0 is [19]. So, graphite particles in spheroidal graphite iron would cause stress concentration and decrease the strength of the metals. The lower nodularity means more irregular graphite particles and/or worse roundness of the graphite particles in spheroidal graphite iron, which would result in more high-stress areas and/or increase the stress in the matrix around the graphite particles. This will reduce the strength of the metal.

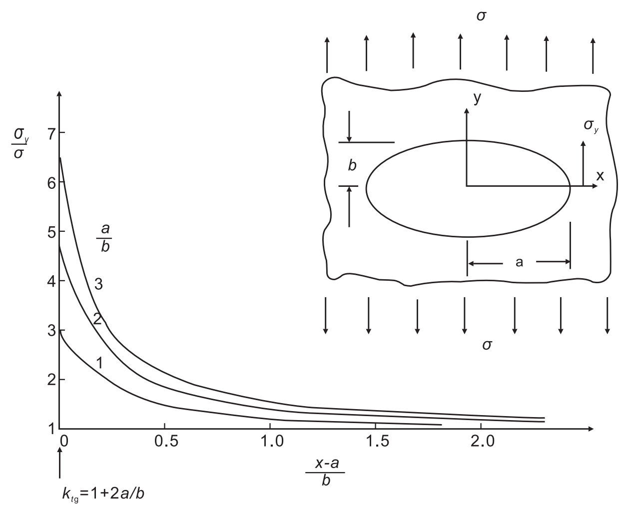


Fig. 5: σ_y stress with distance (x-a) away from an elliptical hole in uniaxial tension [18]

Research has discovered that the stress concentration was not only related to the shape of the hole or inclusion particle, but also closely related to its distribution [20]. When the ratio of the distance between two particles l and the radius of the particles a is close to 2, the stress concentration obviously increases [20]. When the l/a value is close to 6, the stress concentration is equal to the stress concentration caused by a single particle [17-18]. This means that the greater the distance between graphite particles, the less the stress concentration in the matrix. High stress concentration would change the stress distribution. The tensile stress would be changed into a complex stress, especially when the area is near irregular graphite particles, which would increase the brittleness and reduce the plasticity of the metal. For spheroidal graphite iron, the carbon content is usually controlled near the eutectic composition, the volume ratio of the graphite particles is about 10%–12%. As the content of graphite is nearly fixed, it can be concluded that the more uniform the distribution of graphite particles, the greater the distance between the graphite particles, therefore the lower the stress concentration would be within the material. As a result, the uniform distribution of graphite particles is beneficial to the mechanical properties of spheroidal graphite irons.

2.2 Effect of nodularity on fracture mechanism

Figure 6 shows the tensile fractures and microstructure of as-cast and annealed ferritic spheroidal graphite iron with 93% nodularity. The annealed iron showed a typical ductile fracture, full of dimples around the graphite particles, as shown in Fig. 6(a). Figure 6(b) shows that the annealed iron was 100% ferritic matrix. Some cleavage planes with large numbers of dimples could be found in the tensile fracture of the as-cast

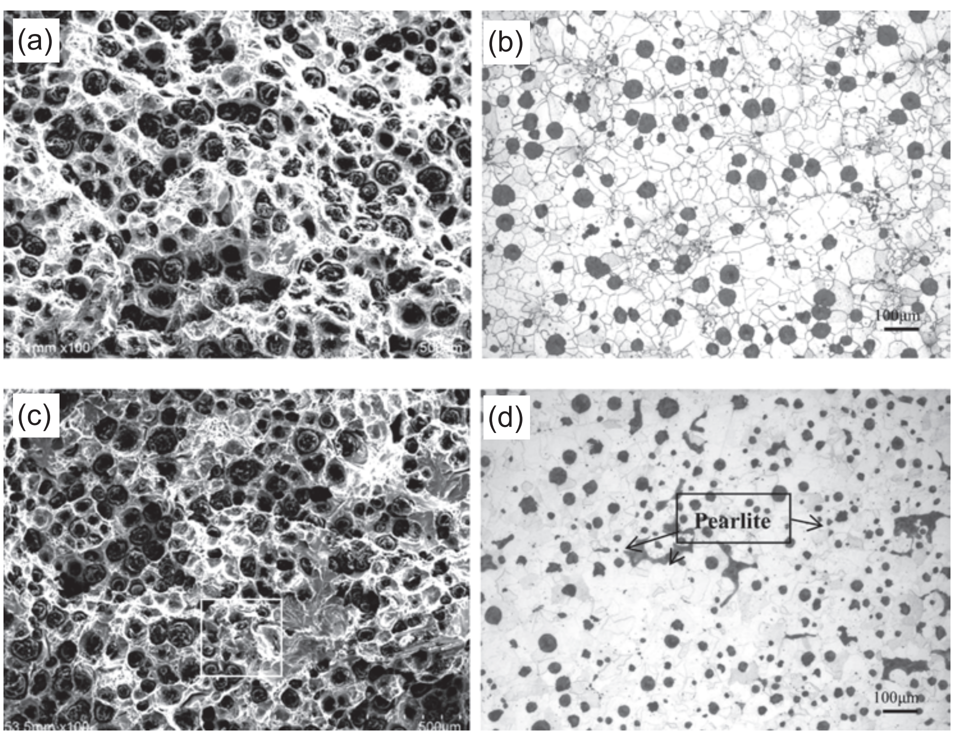
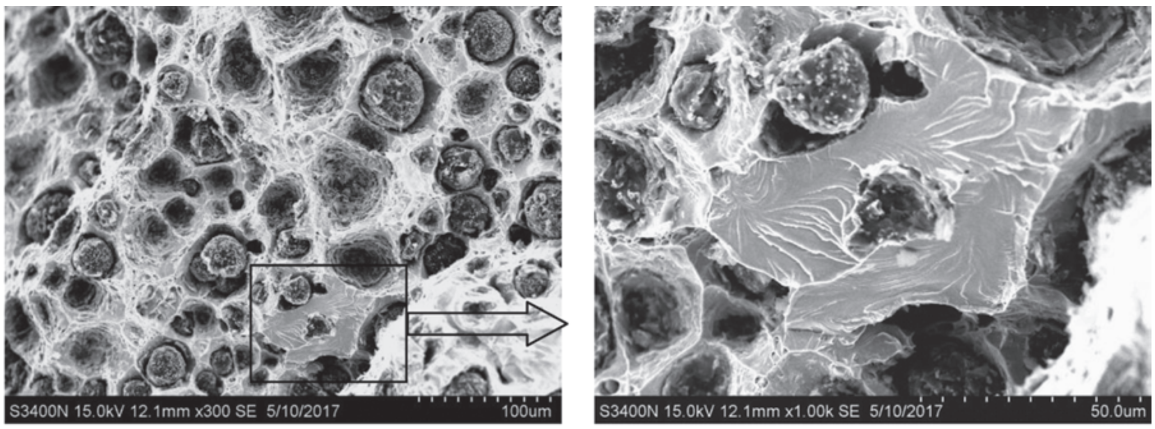


Fig. 6: Fractures and microstructures of ferritic spheroidal graphite cast iron (93% nodularity): (a) Fracture of annealed sample; (b) Microstructure of annealed sample; (c) Fracture of as-cast sample; (d) Microstructure of as-cast sample

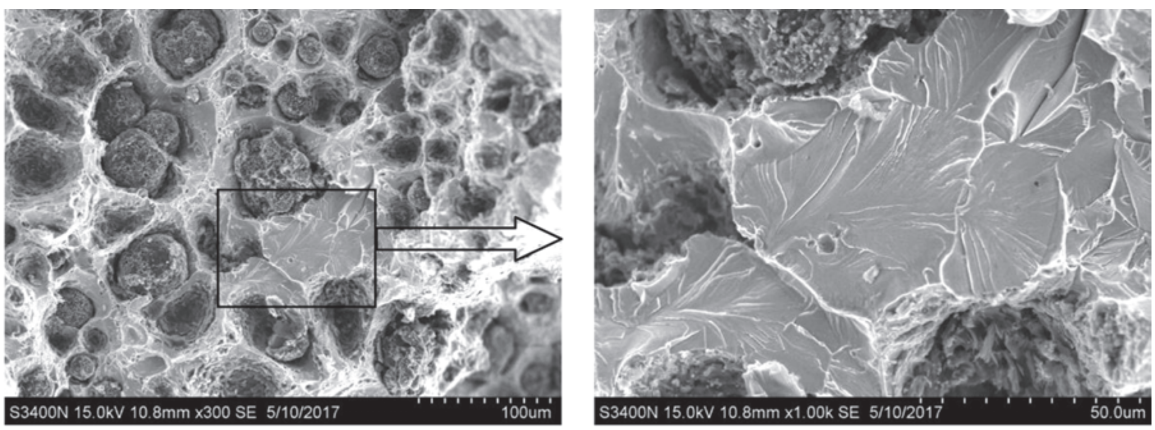
iron, as seen in Fig. 6(c). Small amounts of pearlite can be found in the as-cast iron as shown in Fig. 6(d). This is due to the existence of pearlite in the matrix. Pearlite has a lower plasticity than ferrite, and promotes the formation of cleavage fractures. Annealing treatment not only eliminated the pearlite in the matrix, but also could remove supersaturated carbon atoms from ferrite, reducing its lattice distortion and increasing the plasticity of the ferrite. So, high temperature annealing treatment would change the tensile fracture mechanism of ferritic spheroidal graphite iron.

Figure 7 shows the tensile fractures of annealed ferritic spheroidal graphite iron with different nodularity from 91% to 75%. The images on the right show the locally enlarged images taken from the images on the left. In Fig. 7 (a), the sample had 91% nodularity. A large number of dimples and some cleavage plane areas could be found in the fracture. With the decrease of nodularity from 91% to 75%, the cleavage fracture area increased gradually, as shown in Fig. 7 (a) to (d). Many cleavage fracture areas appeared in the fracture of annealed ferritic spheroidal graphite iron with 75% nodularity, as shown in Fig. 7 (d).

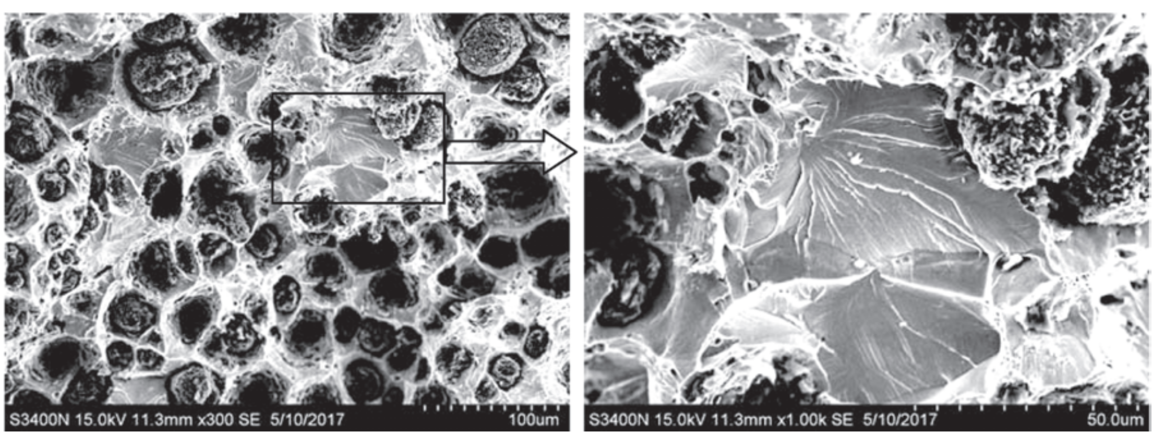
Figure 8 shows the cleavage fracture area ratio of annealed ferritic spheroidal graphite iron having different levels of nodularity. No cleavage fracture was found in annealed ferritic spheroidal graphite iron with 93% nodularity, as stated before. The cleavage fracture area ratios of annealed ferritic spheroidal graphite iron with 91%, 89%, 87%, 85%, 79% and 75% nodularity were 3.0%, 3.5%, 4.5%, 4.6%, 6.3% and 8.3%, respectively.



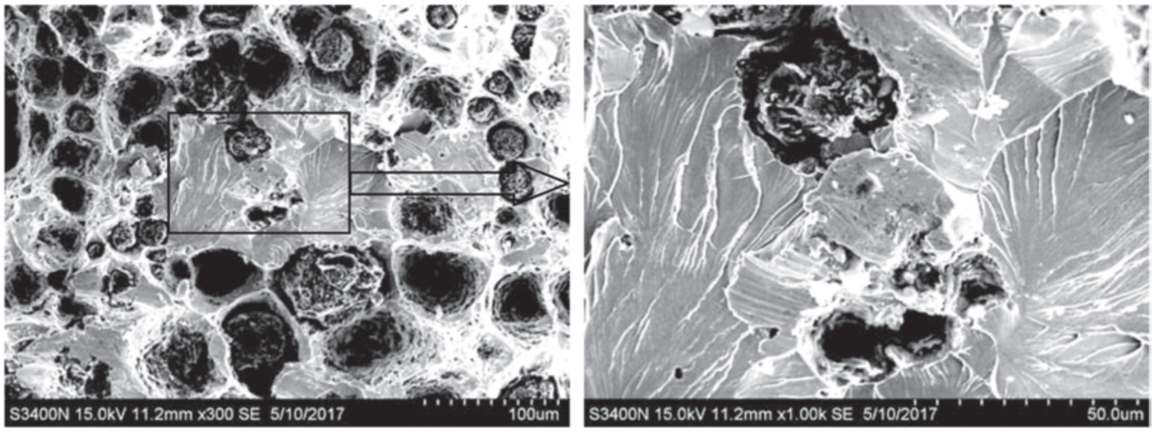
(a) 91% nodularity



(b) 87% nodularity



(c) 79% nodularity



(d) 75% nodularity

Fig. 7: Tensile fractures of annealed ferritic spheroidal graphite iron: (a) 91% nodularity; (b) 87% nodularity; (c) 79% nodularity; (d) 75% nodularity

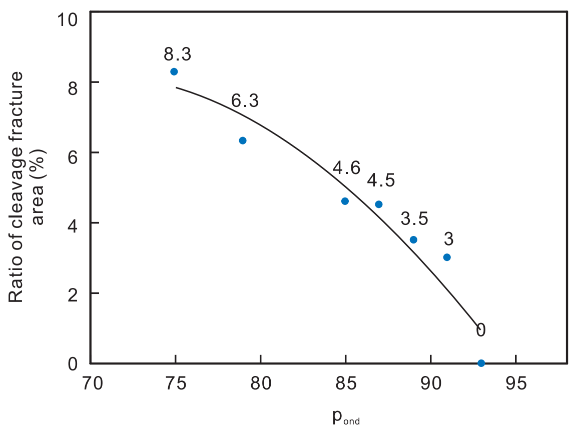


Fig. 8: Cleavage fracture area ratio and nodularity of annealed ferritic spheroidal graphite iron

With the decrease of nodularity, the cleavage fracture area ratio increased gradually. This was caused by the notch effects of irregular graphite particles [21]. The irregular angle of graphite particles could change the stress distribution of the matrix from a single tensile stress into a two- or three-dimensional stress, which makes the crystal-plane slipping of ferrite difficult. In turn, more cleavage fracture would appear. As is known, the lower the nodularity, the more the irregular angles exist, the greater the notch effect. So it can be concluded that the lower the nodularity, the more the cleavage fracture area appears, and the worse the toughness.

3 Conclusions

The effect of nodularity on the mechanical properties and tensile fracture of ferritic spheroidal graphite iron was studied. The following conclusions can be obtained:

(1) The tensile strength R_m, yield strength $R_{p0.2}$, elongation to failure A_5 and impact energy KV_2 of ferritic spheroidal graphite iron all had a good linear relationship with nodularity p_{nod}. The fitting equations of the average R_m, $R_{p0.2}$, A_5 and KV_2 were $R_m = 104.1\, p_{nod} + 321.9$, $R_{p0.2} = 42.3\, p_{nod} + 241.3$, $A_5 = 20.5\, p_{nod} + 0.17$ and $KV_2 = 8.75\, p_{nod} + 7.04$, respectively, and their correlation coefficients R^2 were 0.95, 0.84, 0.89 and 0.80, respectively.

(2) Nodularity would clearly affect the fracture characteristics of annealed ferritic spheroidal graphite iron. With decrease of nodularity from 93% to 72%, the cleavage fracture area ratio increased gradually from 0% to 8.3%.

(3) Annealing treatment could reduce the cleavage fracture of ferritic spheroidal graphite iron. Annealed ferritic spheroidal graphite iron with 93% nodularity shows a wholly ductile rupture.

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