Editorial

Microstructure and Mechanical Properties of Cast Iron

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1. Introduction

Cast iron is an important structural material of castings. Japan produced about 3 million tons of cast iron in 2020. Of the annual production, 63.7% was used for transportation machinery (including automobiles, railroads and ships), 23.7% for general or electric machinery (including industrial machinery and equipment, construction machinery, metal working tools & machine tools, and electric machinery), 7.8% for cast iron pipes, and the remaining 4.7% for other applications (including couplings, kitchen appliances and craftwork) [1].

Fig. 1 shows an example of hydraulic equipment for regular/compact excavators manufactured by Kayaba Industry Co., Ltd. [2] The compact hydraulic excavator has control valves whose body is made of cast iron.

Both cast iron and steel are classified into iron-carbon (Fe-C) alloys. They are differentiated from each other by carbon content. Steel has a carbon content of not more than approximately 2 mass% (hereinafter expressed in "%" only) while cast iron has a higher carbon content than the level. Practical cast iron is usually considered as Fe-C-Si alloys because of its carbon content as high as 3% to 4% and its silicon (Si) content of around 1% to 3%. With a higher percentage of carbon than 2%, carbide forms in iron (Fe) in the cast iron. In this sense, cast iron may be considered as a composite material consisting of steel and graphite in various forms.

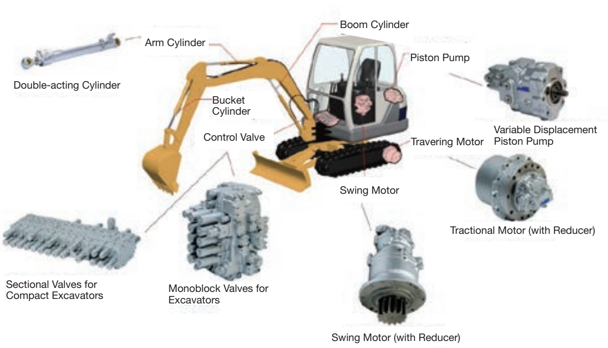

Fig. 1 Example of hydraulic equipment for regular/compact excavators

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The lower carbon content of cast iron compared to steel results in a substantially low solidifying (or melting) temperature and good fluidity. Cast iron also features good castability because of its low solidification shrinkage or less shrinkage cavities attributable to volume expansion taking place when the graphite is crystallized during solidification. In addition, the presence of graphite and the high silicone content give cast iron excellent industrial properties including vibration absorption, machineability, wear resistance, thermal conductivity, corrosion resistance and oxidization resistance.

This paper describes the microstructure and mechanical properties of cast iron that may affect its characteristics.

2. Microstructure of Cast Iron

The microstructure of cast iron greatly varies by the chemical composition of the molten iron, the solidification condition, and heat treatment given. What microstructure the solidified cast iron will have is a critical issue because cast iron is used in the as-cast condition in most cases; however, this does not matter a lot for steel because it is subjected to deformation processing, such as rolling, and heat treatment after solidification. The microstructure of cast iron can be roughly divided into graphite and matrix microstructures. The combination of these two microstructures greatly affects the mechanical, physical and chemical properties of the cast iron.

2.1 Graphite Microstructure

Fig. 2 shows how graphite can appear in iron castings. This classification was proposed by the technical committee in the World Foundry Congress held in 1962 in the U.S. [3]

Form I is flake graphite. Cast iron with graphite flakes is classified by the Japanese Industrial Standard (JIS) G5501 into gray cast iron. Form II is spheroidal graphite with pointed ends that is likely to appear when a spheroidizing agent such as magnesium (Mg) is added in an excessive amount during production of nodular graphite cast iron. Form III is quasi-flake graphite that may appear with a lack of graphite spheroidizing agent. This type of graphite forms in CV graphite cast iron. Form IV is massive graphite that may appear in malleable cast iron or graphite steel. Form V is quasi-spheroidal graphite. Form VI is com-

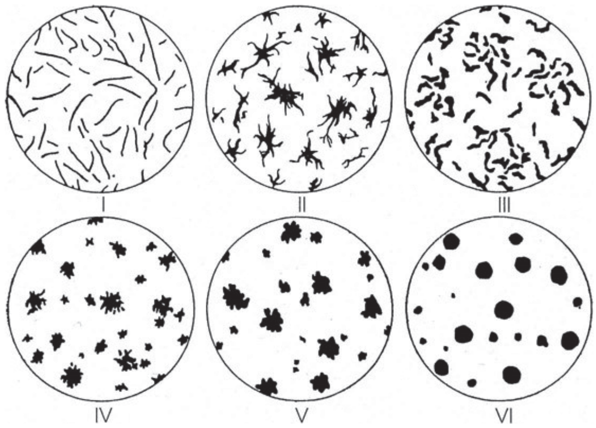

Fig. 2 Classification of graphite forms

pletely spheroidal graphite that often appears in nodular graphite cast iron. Among these, the forms II to VI are uniform graphite in a random distribution in most cases. However, form I, namely, flake graphite, changes in form and distribution depending on the chemical composition of the cast iron, its melting history and/or cooling rate during solidification. American Society for Testing Materials (ASTM) A247 classifies this category of graphite into Types A to E by distribution as shown in Fig. 3. Type A shows random flake graphite in a uniform distribution, which is the most optimally distributed flake graphite. Type B is called rosette flake graphite. Type C shows hypereutectic cast iron with coarse pro-eutectic graphite. Type D is called eutectic graphite that is likely to appear in titan (Ti)-added or undercooled molten iron. Type E is called interdendritic flake graphite.

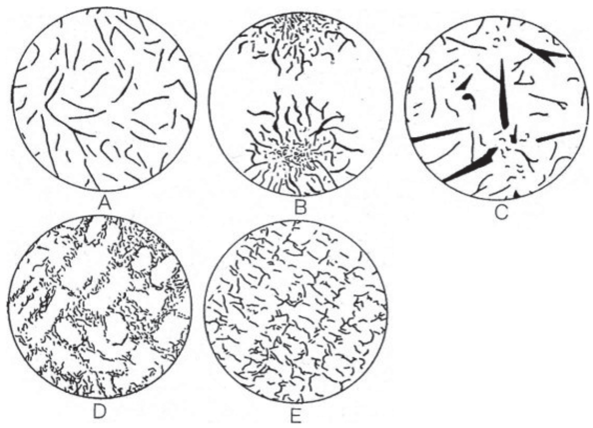

Fig. 3 Types of flake graphite by distribution [ASTM A247]

2.2 Matrix Microstructure

The matrix microstructure of cast iron varies by the cooling rate during solidification, the alloy element content, and/or heat treatment given. This section introduces three typical matrices:

(i) Ferrite

The ferrite matrix, which is also known as α-Fe or α solid solution, is soft iron with a trace quantity of carbon having a body-centered cubic crystal structure with a density of 7.9, a tensile strength of 200 MPa to 400 MPa, and a Brinell hardness of 90 HB to 150 HB. Ferrite in iron castings is called silico-ferrite because silicon (Si) incorporates into the ferrite to form a solid solution. The ferrite matrix with more silicon offers higher tensile strength and higher hardness.

(ii) Cementite

Cementite is a rhombic composition consisting of three Fe atoms and a C atom with a density of 7.7 and a Brinell hardness of 550 HB. This is the hardest and brittlest among all the cast iron microstructures.

(iii) Pearlite

Austenite breaks down (transforms) into ferrite and cementite during metastable eutectoid transformation. These two phases are generated in the form of a stack of sheets alternately overlayed with each other. They can be identified as a layered or banded structure under an optical microscope. It is a very tough microstructure with a density of 7.8, a tensile strength of 800 MPa to 900 MPa, and a Brinell hardness of 200 HB to 240 HB.

Nodular graphite cast iron normally has a so-called bull's-eye microstructure in which ferrite and pearlite coexist as shown in Fig. 4.

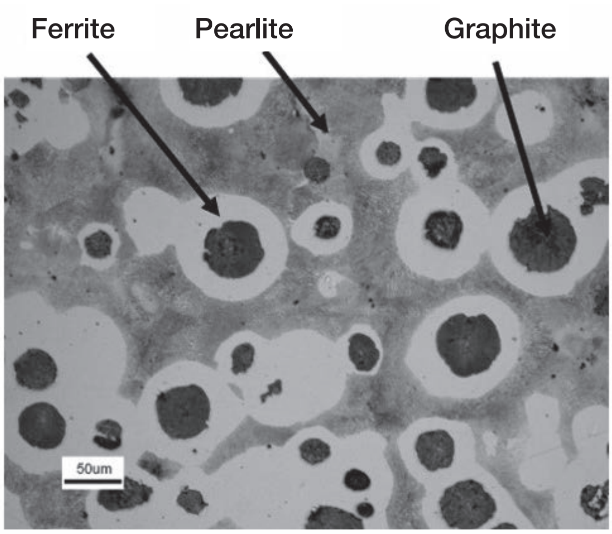

Fig. 4 Bull's eye microstructure of nodular graphite cast iron

3. Mechanical Properties of Cast Iron

Mechanical properties of material including tensile strength, hardness, elongation and fatigue strength are collectively called generalized strength. Any of these properties is a measure of resistance to deformation or fracture.

The strength of a metallic material is decided by its microstructure. In the case of cast iron, the strength is governed by the graphite, matrix and other microstructures.

3.1 Strength of Flake Graphite Cast Iron

As compared to the matrix, the graphite microstructure can easily fracture with a substantially lower force because of its tensile strength of around as low as 20 MPa. Therefore, the strength of cast iron is decided by the strength, form, and continuity of the matrix except graphite particles.

In other words, cast iron with fine graphite (Type A or E) may offer a high strength. Those with long-type graphite (Type A, B or C) usually have a low strength because of their low continuity of the matrix.

Fig. 5 illustrates how two types of flake graphite cast iron can fracture when they are applied with a tensile force: one has a ductile matrix (a) and the other a brittle matrix (b). [4] The former (a) with a ductile matrix will have a number of ductile cracks and partial ruptures. These will be connected with each other along the graphite flakes, thereby accelerating rupture.

The latter (b) with a brittle matrix in turn will accelerate rupture when brittle cracks occurring at the ends of the graphite flakes propagate.

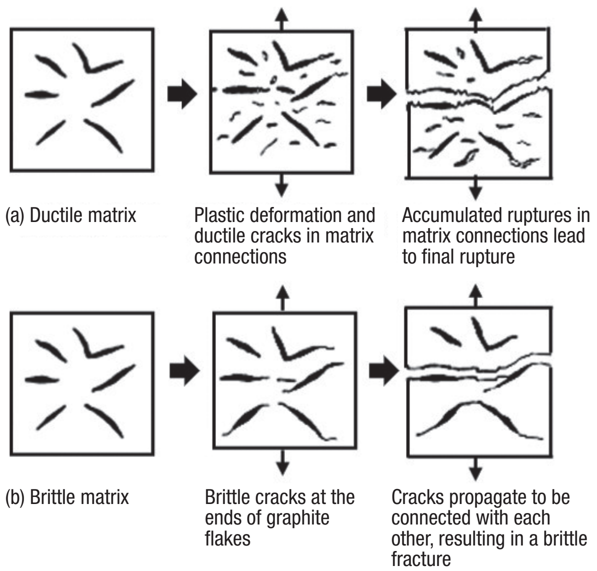

Fig. 5 How flake graphite cast iron fails with tensile fracture

Fig. 6 shows stress-strain curves of flake graphite cast iron. [5] The continuously warped curves include no obvious yield behavior. Determining the 0.2% yield point (or yield strength) will not make sense to flake graphite cast iron. Rather, it is necessary to define the yield strength against a small distortion as low as 0.05% or even smaller.

3.2 Strength of Nodular Graphite Cast Iron

Nodular graphite cast iron has a matrix with substantially higher continuity than that of the flake graphite type. The extent of continuity hardly varies by minor changes in form (the degree of spheroidization) or particle size of graphite as long as the degree of spheroidization is higher than a certain level (generally 0.7).

Fig. 7 illustrates how two types of nodular graphite cast iron can fracture when they are applied with a tensile force: one has a ductile matrix (a) and the other a brittle matrix (b). [6]

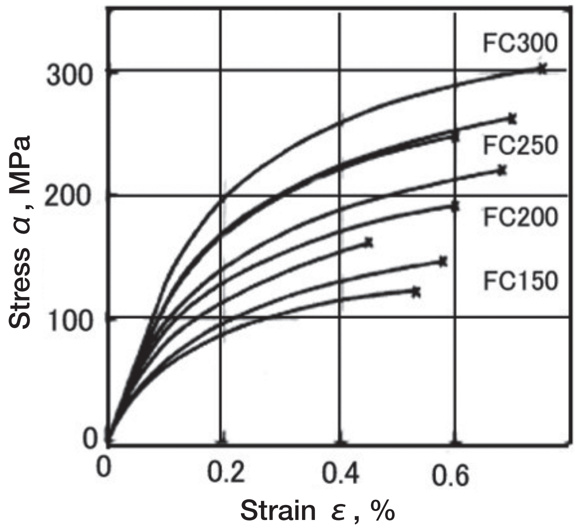

Fig. 6 Stress-strain curves of flake graphite cast iron

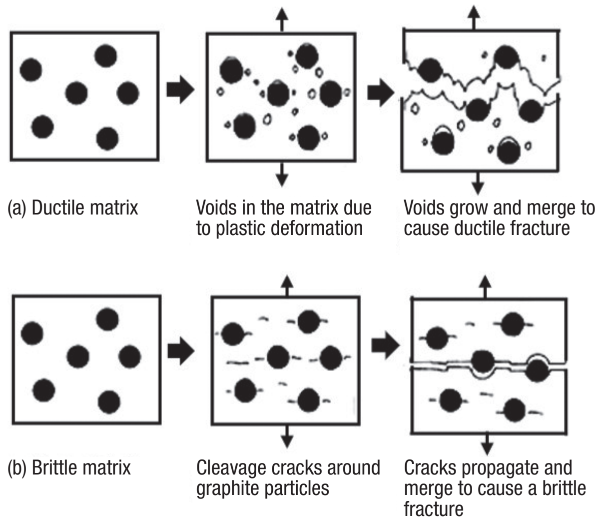

Fig. 7 How nodular graphite cast iron fails with tensile fracture

The former (a) with a ductile matrix involves sufficient plastic deformation. Many cracks occurring around the graphite particles merge into voids as deformation progresses. Voids also occur in the grain boundaries and inclusions within the matrix. These voids are connected with each other and merge into bigger voids, resulting in a rupture.

In this rupture development process, cracks tend to develop in a zigzag manner bridging the closest graphite particles or the weakest parts of the largest graphite particles.

For the latter (b) with a brittle matrix in turn, cleavage cracks occurring around the graphite particles will grow to cause rapid crack propagation, resulting in a rupture.

Fig. 8 shows the relationship between the tensile strength and the carbon equivalent (CE) value of nodular, compacted and flake graphite cast iron. [7] According to the figure, the strength of flake graphite cast iron greatly varies by the CE value while that of nodular graphite cast iron seldom depends on the CE value. The figure also implies that compacted graphite cast iron is almost midway between the two. This is because the strength of flake graphite cast iron heavily depends on the matrix continuity (i.e., to what extent the matrix among graphite flakes is sound with no break), in other words, the form and distribution of graphite flakes. For nodular graphite cast iron consisting of distributed independent spheroidal graphite particles (approximately 10 vol%) and a matrix (approximately 90 vol%) in turn, the matrix shows considerably higher continuity than for flake graphite cast iron. Naturally, the strength of nodular graphite cast iron heavily depends on the matrix microstructure and is seldom affected by the CE value.

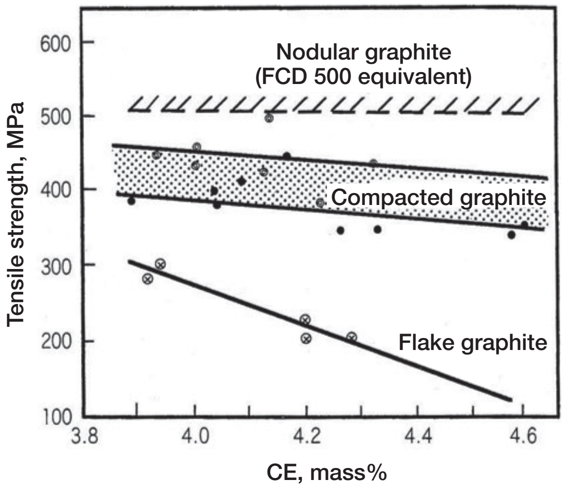

Fig. 8 Effect of CE value on the tensile strength of a variety of cast iron

Fig. 9 shows stress-strain curves of four types of nodular graphite cast iron with different matrix microstructures. [8] Specifically, these curves indicate the stress-strain relationship of austempered ductile irons (ADI) with ferrite matrix (curve 1), with ferrite and pearlite matrix (bull's eye microstructure) (curve 2), with pearlite matrix (curve 3), and with bainite matrix (curve 4). The curve 1 for ferrite matrix shows high elongation. As pearlite occupies a larger area of the matrix in order of the curves 2, 3, the stress-strain curve tends to show higher stress.

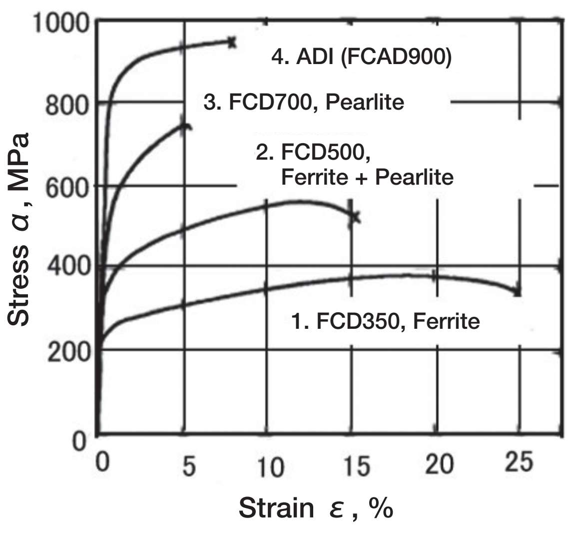

Fig. 9 Stress-strain curves of nodular graphite cast iron

Fig. 10 shows the correlation among pearlite area, tensile strength and elongation of nodular graphite cast iron. [9] As the pearlite area increases, the tensile strength goes up. By contrast, as the pearlite area slightly increases, elongation rapidly decreases and then tends to decrease gradually.

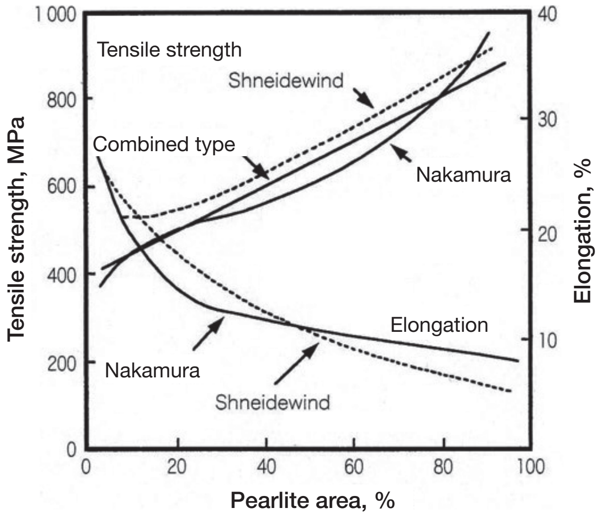

Fig. 10 Relationship among pearlite area, tensile strength and elongation of nodular graphite cast iron

4. In Closing

Cast iron can be considered as a composite material consisting of graphite and steel. Its strength is governed by the graphite, matrix and other microstructures.

The strength of flake graphite cast iron is primarily affected by the form of graphite flakes, namely, the matrix continuity between graphite flakes, and secondarily by the matrix microstructure.

In nodular graphite cast iron in turn, the matrix continuity is substantially higher than for flake graphite cast iron. This means that the strength of nodular graphite cast iron heavily depends on the matrix microstructure.

Iron castings can deliver excellent mechanical, physical and chemical properties when their graphite and matrix microstructures are properly controlled. High-strength, high-function cast iron whose microstructure has been suitably controlled can be expected to be applied to a variety of industrial applications. I hope this paper will help manufacturers achieve this.

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