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MICROSTRUCTURAL ANALYSIS OF HIGH-STRENGTH CAST IRON

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Abstract: This paper analyzes the microstructural characteristics of high-strength spheroidal graphite cast irons, including the morphology of graphite nodules, the phase composition of the metallic matrix, and their influence on mechanical properties. The scientific and methodological aspects of using metallographic analysis, optical microscopy, and digital image processing techniques for microstructural characterization are considered. It is shown that the strength of spheroidal graphite cast iron largely depends on the spherical shape of graphite, the degree of nodularity, the size and distribution of graphite nodules, and the ferrite-to-pearlite ratio. The results indicate that a high degree of graphite spheroidization reduces stress concentration in the metallic matrix and consequently improves the strength and ductility of the material. An increase in the pearlite fraction enhances hardness and tensile strength, whereas an increase in the ferrite fraction improves ductility and impact toughness. In addition, irregular, vermicular, or otherwise degenerated graphite morphologies can adversely affect the mechanical properties of the material.

Keywords: High-strength cast iron, spheroidal graphite cast iron, microstructure, graphite nodules, nodularity, ferrite, pearlite, metallography, mechanical properties, GGG-45, EN-GJS-450-10.

Annotatsiya: Ushbu maqolada mustahkamligi yuqori sferografitli cho‘yanlarning mikrostrukturaviy xususiyatlari, grafit zarrachalarining morfologiyasi, metall matritsaning fazaviy tarkibi hamda ularning mexanik xossalarga ta‘siri tahlil qilingan. Tadqiqotda metallografik tahlil, optik mikroskopiya va tasvirlarni raqamli qayta ishlash usullaridan foydalanishning ilmiy-metodik jihatlari ko‘rib chiqildi. Sferografitli cho‘yanning mustahkamligi asosan grafitning sferik shakli, nodulyarlik darajasi, grafit zarrachalarining o‘lchami va taqsimlanishi hamda ferrit-perlit nisbatiga bog‘liqligi ko‘rsatildi. Tadqiqot natijalari shuni ko‘rsatadiki, grafitning yuqori darajadagi sferikligi matritsada kuchlanish konsentratsiyasini kamaytirib, materialning mustahkamligi va plastiklik xususiyatlarini yaxshilaydi. Perlit miqdorining ortishi qattqlik va mustahkamlikni oshirsa, ferrit miqdorining ko‘payishi plastiklik va zarbiy qovushqoqlikni yaxshilaydi. Shuningdek, grafit zarrachalarining notekis, vermikulyar yoki boshqa degeneratsiyalangan shakllari materialning mexanik xususiyatlarini pasaytirishi mumkinligi aniqlangan.



Kalit so‘zlar: Yuqori mustahkam cho‘yan, sferografitli cho‘yan, mikrostruktura, grafit nodullari, nodulyarlik, ferrit, perlit, metallografiya, mexanik xossa, GGG-45, EN-GJS-450-10.

Аннотация: В статье проведён анализ микроструктурных характеристик высокопрочных чугунов с шаровидным графитом, включая морфологию графитовых включений, фазовый состав металлической матрицы и их влияние на механические свойства. Рассмотрены научно-методические аспекты применения металлографического анализа, оптической микроскопии и методов цифровой обработки изображений для исследования микроструктуры. Показано, что прочность чугуна с шаровидным графитом в значительной степени зависит от сферической формы графита, степени его сфероидизации, размера и распределения графитовых включений, а также соотношения феррита и перлита. Результаты показывают, что высокая степень сфероидизации графита снижает концентрацию напряжений в металлической матрице и, как следствие, способствует повышению прочности и пластичности материала. Увеличение доли перлита повышает твёрдость и прочность, тогда как увеличение содержания феррита способствует повышению пластичности и ударной вязкости. Кроме того, наличие неравномерных, вермикулярных и других вырожденных форм графита может отрицательно влиять на механические свойства материала.

Ключевые слова: Высокопрочный чугун, чугун с шаровидным графитом, микроструктура, графитовые включения, степень сфероидизации, феррит, перлит, metallografiya, mexanicheskiye svoystva, GGG-45, EN-GJS-450-10.

INTRODUCTION

The increasing requirements for structural materials in modern mechanical engineering have created a growing demand for materials capable of simultaneously providing high strength, wear resistance, impact toughness, and sufficient ductility. Among such materials, spheroidal graphite cast irons occupy an important position. Unlike conventional gray cast iron, spheroidal graphite cast iron is characterized by carbon being present predominantly in the form of spherical graphite nodules rather than flake graphite. The spherical morphology of graphite reduces stress concentration within the metallic matrix and, as a result, significantly improves the mechanical properties of cast iron [1]. The microstructure of spheroidal graphite cast iron generally consists of graphite nodules distributed within a metallic matrix. The matrix may be ferritic, pearlitic, or ferritic-pearlitic. Therefore, cast irons with the same chemical composition may exhibit significantly different mechanical properties depending on their microstructure and solidification conditions. Previous studies have demonstrated that the ferrite-to-pearlite ratio in the metallic matrix, as well as the number, size, and distribution of graphite nodules and the degree of nodularity, have a considerable influence on mechanical properties [1,2]. During the production of spheroidal graphite cast iron, magnesium, rare-earth metals, calcium, and other modifying elements are commonly used to promote the formation of spherical graphite. Melt treatment and inoculation processes affect the number of graphite nucleation sites and consequently influence the size and distribution of graphite nodules. The cooling rate also has a



significant effect on the resulting microstructure. In general, a higher cooling rate promotes the formation of finer graphite nodules and a more homogeneous microstructure [3]. Microstructural analysis is particularly important for evaluating the quality of high-strength cast iron because it provides a physical explanation for mechanical properties such as tensile strength, hardness, and elongation. For example, highly spheroidized graphite reduces stress concentration, while an increased pearlite fraction generally improves strength and hardness. In contrast, vermicular or irregular graphite morphologies may provide favorable sites for crack initiation and propagation [3,4]. The objective of this study is to analyze the microstructure of high-strength spheroidal graphite cast iron using metallographic methods, to evaluate the morphology and distribution of graphite nodules, and to determine the influence of microstructural parameters on the mechanical properties of the material.

MATERIALS AND METHODS

The research object was high-strength spheroidal graphite cast iron, particularly a cast iron of the GGG-45/EN-GJS-450-10 type. Such cast irons can be used in mechanical engineering, automotive applications, and components subjected to various mechanical loads. For metallographic examination, specimens were cut from different regions of the cast material. During sampling, the central region, areas close to the surface, and transition zones were considered separately. This approach is important because differences in cooling conditions can result in variations in the size, morphology, and distribution of graphite nodules within different regions of the same casting. The surfaces of the specimens were initially leveled by mechanical machining. The samples were subsequently ground using abrasive papers with progressively finer grades. Final polishing was performed to obtain a sufficiently smooth surface suitable for microscopic examination. The prepared specimens were then etched using appropriate metallographic reagents. Optical metallography was used to investigate the microstructure. Microscopic observations were performed at low and medium magnifications. First, the overall distribution of graphite nodules was examined. Subsequently, their morphology, size, and spatial relationship with the metallic matrix were evaluated. The degree of graphite nodularity is one of the important parameters used to characterize spheroidal graphite cast iron. According to ISO 945-4, graphite morphology can be classified into different categories ranging from highly spheroidal graphite to vermicular and flake graphite. Highly spheroidal graphite is desirable in high-quality ductile iron because it minimizes stress concentration in the metallic matrix [5,6].

The following principal microstructural parameters were evaluated:

- morphology of graphite nodules;
- degree of graphite nodularity;
- average diameter of graphite nodules;
- number of graphite nodules per unit area;
- uniformity of graphite distribution;
- ferrite fraction;
- pearlite fraction;



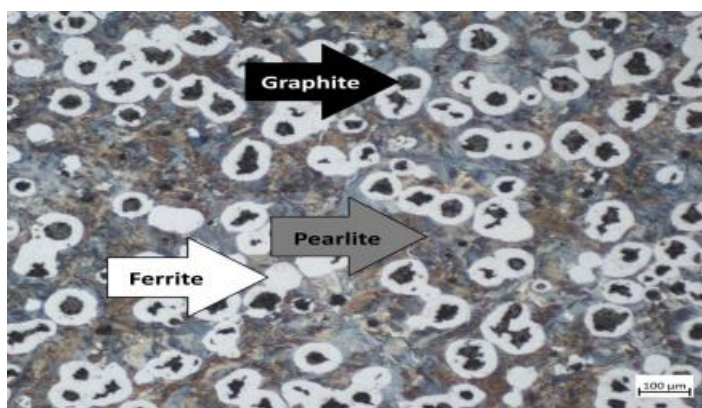
- presence of carbides and other undesirable phases.

The number of graphite nodules can be determined by counting the particles within a defined microscopic field and expressing the result per unit area. Modern metallographic analysis also allows digital image processing to be used for quantitative characterization of graphite particles, including their area, perimeter, equivalent diameter, and shape factors. The metallic matrix was evaluated according to the relative fractions of ferrite and pearlite. Ferrite generally appears as relatively bright regions, while pearlite appears darker after etching and exhibits a lamellar structure. The formation of a ferritic halo around graphite nodules may occur in spheroidal graphite cast irons and is associated with the characteristic so-called “bull's-eye” microstructure [7].

RESULTS:

Metallographic analysis showed that the microstructure of high-strength spheroidal graphite cast iron predominantly consists of spherical graphite nodules embedded in a ferritic-pearlitic metallic matrix. Relatively uniform distribution of graphite particles was identified as an important positive microstructural characteristic. The spherical morphology of graphite has a direct influence on the mechanical properties of cast iron. Compared with flake or sharp-edged graphite morphologies, spherical graphite particles produce lower local stress concentrations. Therefore, increasing the degree of graphite spheroidization can improve the strength and ductility of the material [7,8]. Previous studies have demonstrated that high nodularity values are generally associated with high-quality spheroidal graphite cast iron. In some studies, nodularity values above approximately 80% have been considered favorable for achieving good mechanical performance [9]. The presence of ferrite and pearlite in the microstructure also has a significant effect on material properties. Ferrite is a relatively soft and ductile phase that contributes to increased elongation and toughness. Pearlite, in comparison with ferrite, possesses higher hardness and strength. Therefore, increasing the pearlite fraction generally increases the tensile strength and hardness of the cast iron, although it may reduce its ductility. The optimum microstructure of high-strength cast iron cannot be determined solely by increasing the pearlite fraction. The number and size of graphite nodules are also important. Studies have shown that increasing the number of graphite nodules can improve structural homogeneity and, under certain conditions, reduce the probability of carbide formation. The cooling rate also has a considerable influence on the resulting microstructure. Under faster cooling conditions, graphite nodules generally become finer and their number increases, while the metallic matrix may also become finer. In contrast, slower cooling can lead to coarser graphite particles and, under certain conditions, the formation of degenerated graphite morphologies. High-silicon spheroidal graphite cast irons also demonstrate the importance of controlling graphite morphology. Although silicon can contribute to strengthening of ferrite, excessive silicon content under certain processing conditions may promote graphite degeneration, including the formation of chunky graphite [9,10].





1-Pic: Microstructure of High-Strength Cast Iron

DISCUSSION

The obtained results demonstrate that the mechanical properties of high-strength cast iron are closely related not only to its chemical composition but also to its microstructural condition. Spheroidal graphite cast iron can be considered a natural composite material in which graphite nodules act as a dispersed phase embedded in a continuous ferritic-pearlitic metallic matrix [5]. The morphology of graphite is one of the primary factors determining the behavior of this composite material under mechanical loading. An ideal spherical graphite nodule produces a relatively uniform distribution of stresses. However, when graphite particles have elongated, irregular, or sharp-edged morphologies, stress concentration occurs at their edges and tips. These regions may subsequently become sites for the initiation of microcracks. Consequently, controlling graphite morphology is one of the most important technological objectives in the production of high-strength cast iron. In addition to nodularity, the size of graphite nodules is also important. Very large graphite nodules may increase local stress concentrations. Fine and uniformly distributed graphite nodules, on the other hand, contribute to a more homogeneous microstructure. Therefore, under optimized processing conditions, it is desirable to achieve a high nodule count combined with a sufficiently high degree of spheroidization. From the perspective of the metallic matrix, controlling the ferrite-to-pearlite ratio is another important factor. If high ductility and impact toughness are required, increasing the ferrite fraction is generally beneficial. If a component is subjected to high static loads or severe wear conditions, increasing the pearlite fraction can improve strength and hardness. Heat treatment can also be used to modify the initial ferritic-pearlitic microstructure. In particular, austempering can produce an ausferritic structure capable of combining high strength with relatively high ductility. In ADI-type ductile irons, spherical graphite nodules are embedded in an ausferritic matrix, and this microstructure provides high mechanical performance. Therefore, the microstructure of high-strength cast iron can be characterized by three principal groups of parameters: graphite morphology, graphite distribution, and phase composition of the metallic matrix. The interaction and balance among these three factors determine the final mechanical and service properties of the material.



CONCLUSION

Based on the conducted analysis, it was established that the mechanical properties of high-strength spheroidal graphite cast iron are directly associated with its microstructural characteristics.

- The most important microstructural parameters determining the strength of spheroidal graphite cast iron are the morphology of graphite nodules, degree of nodularity, nodule size and distribution, and the ferrite-to-pearlite ratio.
- The spherical morphology of graphite reduces stress concentration and improves the mechanical properties of cast iron. Irregular, vermicular, and other degenerated graphite morphologies facilitate microcrack initiation and may consequently reduce mechanical performance.
- Ferrite contributes primarily to ductility and toughness, whereas pearlite increases strength and hardness. Therefore, the ferrite-to-pearlite ratio should be controlled according to the specific service requirements of the component.
- Inoculation, modification, cooling rate, and heat treatment are among the main technological factors that can be used to control the microstructure of high-strength cast iron.
- Metallographic analysis is an effective method for evaluating the quality of high-strength cast iron. Optical microscopy combined with digital image processing makes it possible to quantitatively evaluate graphite morphology, nodularity, graphite distribution, and the phase composition of the metallic matrix.

In general, obtaining high-strength cast iron requires more than simply optimizing its chemical composition. High graphite nodularity, uniform graphite distribution, and an optimized ferritic-pearlitic matrix are key conditions for achieving high strength and satisfactory service performance.

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