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STUDY OF THE MICROSTRUCTURAL FEATURES OF HIGH-STRENGTH CAST IRON

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Abstract: This study focuses on the structural and microstructural characteristics of high-strength spheroidal graphite cast iron and their relationship with the mechanical performance of the material. Particular attention is paid to the morphology, size, distribution, and degree of spheroidization of graphite nodules, as well as to the phase composition of the metallic matrix. The applicability of metallographic examination, optical microscopy, and digital image analysis for evaluating the microstructure of spheroidal graphite cast iron is discussed. The analysis demonstrates that the mechanical behavior of the material is strongly influenced by graphite morphology and nodularity, the spatial distribution of graphite particles, and the relative proportions of ferrite and pearlite in the matrix. A more uniform and highly spheroidized graphite structure contributes to a reduction in local stress concentration and promotes improved strength and plasticity. At the same time, an increase in pearlite content generally results in higher hardness and tensile strength, while a predominantly ferritic matrix provides greater ductility and impact resistance. The presence of compacted, irregular, vermicular, or other degenerated graphite forms may lead to deterioration of the mechanical characteristics. The obtained results emphasize the importance of controlling microstructural parameters during the production of high-strength spheroidal graphite cast iron.

Keywords: High-strength cast iron, spheroidal graphite iron, microstructural characterization, graphite morphology, graphite nodules, nodularity, ferritic matrix, pearlitic matrix, metallographic analysis, mechanical properties, GGG-45, EN-GJS-450-10.

Аннотация: В работе исследованы структурные и микроструктурные особенности высокопрочного чугуна с шаровидным графитом и их взаимосвязь с механическими характеристиками материала. Основное внимание уделено морфологии, размерам, распределению и степени сфероидизации графитовых включений, а также фазовому составу металлической матрицы. Рассмотрены возможности применения металлографического исследования, оптической микроскопии и цифрового анализа изображений для количественной и качественной оценки микроструктуры чугуна с шаровидным графитом. Установлено, что механические характеристики материала в значительной степени определяются формой и степенью сфероидизации графита, характером распределения графитовых включений, а также соотношением ферритной и перлитной составляющих металлической матрицы. Равномерное распределение высокосфероидизированного графита способствует снижению локальной концентрации напряжений и повышению прочности и пластичности чугуна. Повышение содержания перлита, как правило, сопровождается увеличением твёрдости и прочности при растяжении, тогда как преобладание ферритной составляющей обеспечивает повышение пластичности и сопротивления ударному воздействию. Наличие уплотнённых, неправильных, вермикулярных и других вырожденных форм графита может приводить к ухудшению механических характеристик. Полученные результаты подтверждают важность управления параметрами микроструктуры на различных этапах производства высокопрочного чугуна с шаровидным графитом.

Ключевые слова: высокопрочный чугун, чугун с шаровидным графитом, микроструктурный анализ, морфология графита, графитовые включения, степень сфероидизации, ферритная матрица, перлитная матрица, металлографическое исследование, механические свойства, GGG-45, EN-GJS-450-10.

Annotatsiya: Mazkur tadqiqotda mustahkamligi yuqori sferografitli cho‘yanning strukturaviy va mikrostrukturaviy xususiyatlari hamda ularning materialning mexanik koʻrsatkichlari bilan oʻzaro bogʻliqligi oʻrganilgan. Tadqiqotda grafit nodullarining morfologiyasi, oʻlchami, taqsimlanishi va sferoidlanish darajasi, shuningdek, metall matritsaning fazaviy tarkibiga alohida e'tibor qaratilgan. Sferografitli choʻyan mikrostrukturasini sifat va miqdor jihatdan baholashda metallografik tadqiqot, optik mikroskopiya hamda tasvirlarni raqamli tahlil qilish usullarining imkoniyatlari koʻrib chiqilgan. Tahlil natijalari materialning mexanik xususiyatlari grafitning shakli va sferoidlanish darajasi, grafit zarrachalarining matritsadagi taqsimlanish xususiyati hamda ferrit va perlit fazalarining nisbatiga sezilarli darajada bogʻliqligini koʻrsatadi. Grafitning yuqori darajada sferoidlangan va bir tekis taqsimlangan strukturasi mahalliy kuchlanish konsentratsiyasini kamaytirib, choʻyanning mustahkamligi va plastiklik xususiyatlarini yaxshilashga yordam beradi. Perlit miqdorining ortishi odatda qattiqlik va choʻzilishdagi mustahkamlikning oshishiga olib keladi, ferrit fazasining ustunligi esa plastiklik va zarbiy qovushqoqlikning yuqori boʻlishini ta'minlaydi. Zichlashgan, notekis, vermikulyar va boshqa degeneratsiyalangan grafit shakllarining mavjudligi materialning mexanik xususiyatlarini yomonlashtirishi mumkin. Olingan natijalar mustahkamligi yuqori sferografitli choʻyan ishlab chiqarish jarayonida mikrostrukturaviy parametrlarni boshqarish muhimligini koʻrsatadi.

Kalit soʻzlar: mustahkamligi yuqori choʻyan, sferografitli choʻyan, mikrostrukturaviy tahlil, grafit morfologiyasi, grafit nodullari, sferoidlanish darajasi, ferrit matritsa, perlit matritsa, metallografik tadqiqot, mexanik xossalar, 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.

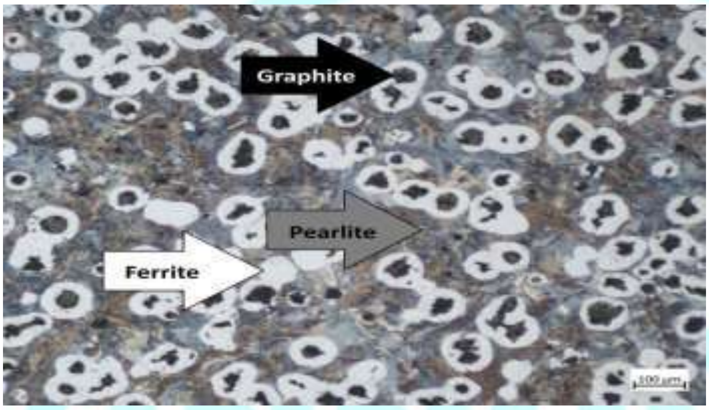
MATERIALS AND METHODS: The research object was high-strength spheroidal graphite cast iron, particularly a cast iron of the GGG-45/EN-GJS-450-10 type. Such cast irons can be used in mechanical engineering, automotive applications, and components subjected to various mechanical loads. For metallographic 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

The conducted study demonstrates that the mechanical performance of high-strength spheroidal graphite cast iron is strongly governed by the characteristics of its microstructure. The obtained findings allow the following conclusions to be drawn:

The principal structural factors affecting the mechanical behavior of spheroidal graphite cast iron include graphite morphology, nodularity level, graphite nodule size and spatial distribution, as well as the relative proportion of ferrite and pearlite in the metallic matrix.

A well-developed spherical graphite morphology contributes to a more uniform distribution of stresses within the matrix and, consequently, supports improved strength and ductility. In contrast, irregular, vermicular, and degenerated graphite forms can act as potential sites for stress concentration and microcrack initiation, adversely affecting the mechanical performance of the material.

The metallic matrix also plays a significant role in determining the final properties of the cast iron. A ferritic structure is generally associated with increased ductility and toughness, while a higher pearlite content promotes greater hardness and strength. Therefore, the ferrite–pearlite balance should be selected with consideration of the operating conditions and functional requirements of the cast component.

The formation and refinement of the required microstructure can be influenced by several technological parameters, including inoculation and modification treatment, cooling conditions, solidification rate, and subsequent heat treatment. Appropriate control of these parameters is essential for obtaining a stable and desirable structural state.

Metallographic examination provides an effective approach for assessing the structural quality of high-strength spheroidal graphite cast iron. The combination of optical microscopy with digital image analysis enables the quantitative determination of graphite nodule morphology, nodularity, particle distribution, and the ferritic–pearlitic composition of the metallic matrix.

Overall, the production of high-strength spheroidal graphite cast iron cannot be achieved solely through adjustment of the chemical composition. The required combination of mechanical properties depends on the formation of highly nodular and uniformly distributed graphite together with a properly balanced ferritic–pearlitic matrix. Consequently, comprehensive control of both metallurgical and technological parameters is essential for producing cast iron with stable mechanical characteristics and reliable performance in service.

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