EJENS
European Journal of Engineering and Natural Sciences
e-ISSN : 2458-8156

Microstructural Evaluation and Mechanical Properties of 0.75% Vanadium-Alloyed Spheroidal Graphite Cast Iron

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Abstract

Spheroidal graphite cast irons (SGCIs) have been widely used in automotive and energy industries owing to their unique microstructures consisting of graphite nodules in ferritic, pearlitic, or ferritic/pearlitic matrices. Alloying elements can be added to improve the mechanical strength of the SGCIs by changing the amount, size, volume, and distribution of the microstructural components. In this study, GGG40, also known as EN-GJS-400-15, grade spheroidal graphite cast iron was alloyed with 0.75% vanadium in an induction furnace, and its microstructural evolution and mechanical properties were investigated compared to the unalloyed commercial alloy. Both unalloyed and 0.75% V-alloyed ductile iron specimens fabricated by sand mold casting were examined by a light optical microscope equipped with image analysis software, a universal tensile test machine, and a Brinell hardness tester. The alteration in the volume, nodularity, count, size, and distribution of graphite, and the alteration in the ferrite/pearlite ratio, hardness, and tensile test results were discussed as a function of V content.

Keywords

Spheroidal graphite cast iron, alloying, vanadium, microstructural evolution

1. INTRODUCTION

Spheroidal graphite cast irons, which emerged at the end of the first half of the 20th century, are today referred to as the first generation in various sources. When looking at the microstructure of these first-generation cast irons containing approximately 2-3% silicon, it is seen that the matrix is composed of ferrite, perlite, or a mixture of both. While pearlite creates an effect that strengthens the material but reduces its ductility, ferrite allows obtaining a more ductile material. Therefore, by changing the pearlite and ferrite ratios in the structure, the desired hardness, strength, and elongation of the produced part values can be obtained [1]. The ratio of ferrite and pearlite is important to optimize mechanical properties in first-generation spheroidal graphite cast irons. The common problem in this type of cast iron is the formation of varying amounts of pearlite in sections of different thicknesses since the amount of pearlite in the structure changes not only depending on the chemical composition but also depending on the cooling rate. For this reason, while the ferrite ratio, which gives ductility to the structure, increases in slowly cooling thick sections of a cast piece with different section thicknesses, pearlite formation, which reduces ductility but strengthens the structure, is observed at a higher rate in fast cooling thin sections [2].

There has been an extensive research effort to develop micro-alloyed ductile iron in which small additions of elements such as niobium and vanadium provide significant increases in strength through grain size control and precipitation hardening. Since vanadium is a carbide stabilizer, it modifies the solidification of the metastable austenite/cementite system and therefore tends to promote the formation of eutectic carbide. Vanadium slightly encourages the formation of ferrite. When vanadium is added to cast iron, white inclusions with more or less random distribution are also observed in the microstructure. It was stated that the wear and hardness values increased, and the elongation values decreased with increasing vanadium values [3,4,5].

In this study, microstructural evolution and the alteration in mechanical properties were investigated with the addition of 0.75% vanadium and the difference between thick and thin sections.

2. MATERIALS AND METHODS

2.1. Fabrication

Charge materials composed of pig iron, steel scrap, and electrolytic copper were prepared and melted using a 100 kg capacity induction furnace. The melt was overheated at 1540 °C, and the determined amount of vanadium was added to the melt during furnace charging.

Following the treatment at 1540 °C, 1.4 wt.% FeSiMg5 as a modifier and 0.3 wt.% FeSi75 as an inoculant were added to the melt at 1400 °C.

Two ingots were fabricated with 0% and 0.75% vanadium. Following the production, the specimens for tensile and hardness tests and microscopic examinations were sectioned along the vertical central axis and machined to obtain the appropriate dimensions required from the tests.

Table 1. Chemical compositions of V-alloyed nodular cast irons (wt%).

C	Si	Mn	Cr	S	Cu	P	Mg	V
3.72	2.55	0.10	0.02	0.0014	0.15	0.042	0.06	0
3.8	2.5806	0.0926	0.0395	0.0177	0.0408	0.0375	0.0611	0.76

2.2. Characterization

Image analyzer software via optical microscopy was used to determine phase ratios, nodule counts, and graphite sizes.

Rectangular dog-bone-shaped samples with a gauge length of 50 mm and a width of 12.5 mm were subjected to tensile strength measurements using a universal tensile tester equipped with an axial extensometer. Two specimens were analyzed for each ductile iron alloyed with various amounts of vanadium, and the results were reported as an average of these tests.

A Brinell tester was used to measure the hardness of the samples after production. A load of 1839 N was applied by an indenter with a diameter of 2.5 mm during 10 s. Three random measurements were taken from each sample surface, and the average hardness values of these calculations were given.

3. RESULTS AND DISCUSSION

3.1. Formed Phases

Fig. 1 shows the as-polished microstructures of the spheroidal graphite iron specimens. The cast iron demonstrated in Fig. 1a does not contain vanadium, whereas the samples in Fig. 1b and Fig. 1c are alloyed with 0.75% vanadium. The thickness values are 10mm for the thin section and 60 mm for the thick section. The ferritic/pearlitic matrix in white color is surrounded by the graphite particles in black color for all samples. When the micrographs were examined, it was observed that the nodularity decreased with increasing vanadium.

Vanadium, like many other elements, restricts the formation of austenite, causing the contraction in austenite in the Fe-C equilibrium diagram. It means that vanadium slightly encourages the ferrite formation by increasing the transformation temperature [6]. Fig. 2 demonstrates the optical microscope images of the samples etched with %2 Nital to reveal the ferrite/pearlite boundaries. The amounts of ferrite increased with increasing vanadium, while the graphite nodule counts increased, as given in Fig. 3.

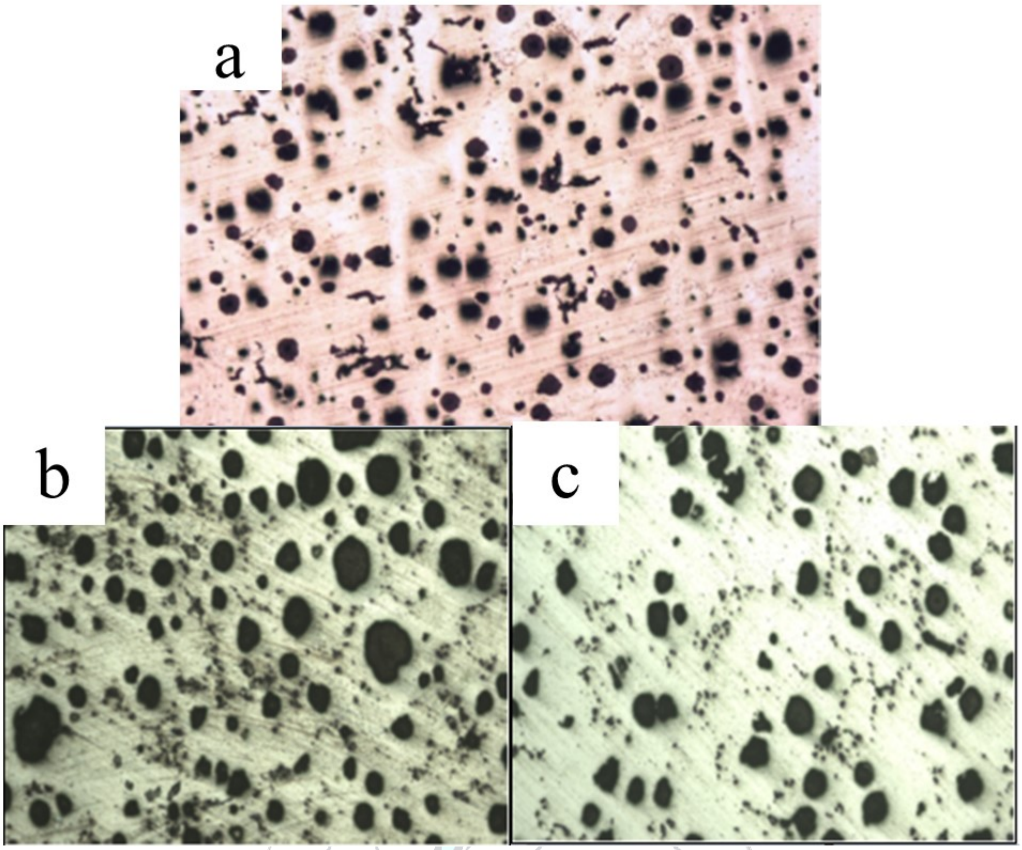

Figure 2. As-polished microstructures of nodular cast irons alloyed with a) 0% V, b) 0.75% V thin section, and c) 0.75% V thick section

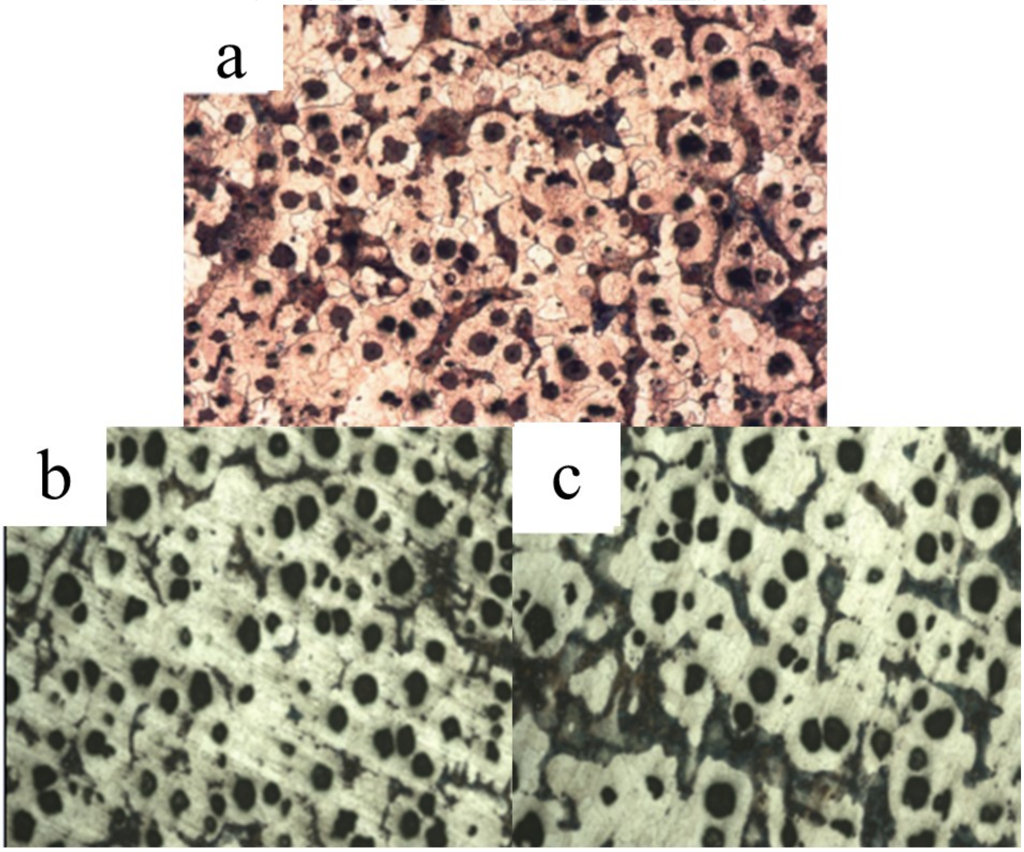

Figure 2. Etched microstructures of nodular cast irons alloyed with a) 0% V, b) 0.75% V thin section, and c) 0.75% V thick section (etched with 2% Nital)

Apart from the tendency of vanadium to promote eutectic iron carbide formation during solidification and its mild tendency to promote pearlite formation during eutectoid transformation, its addition to ductile iron caused the formation of an additional phase in the microstructure.

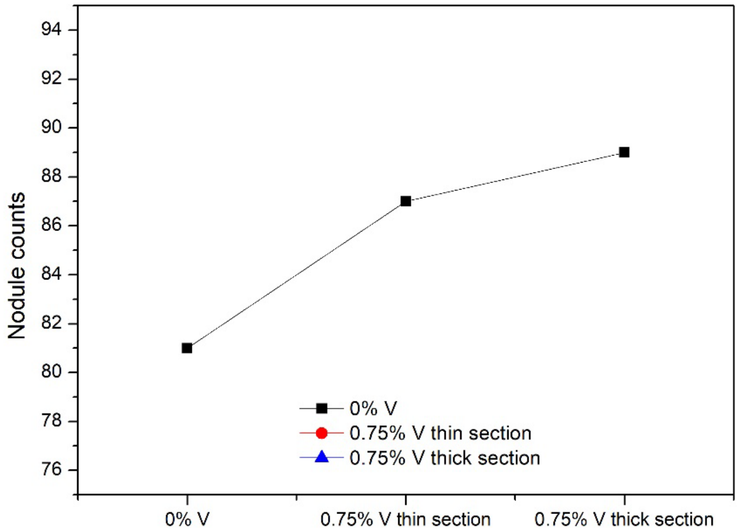

Figure 3. Influence of amount of vanadium on the formed phases and nodules count

3.2. Mechanical Test Results

Figs. 4 and 5 show the average results of the ultimate tensile strength (UTS) and elongation. While the UTS of the samples with vanadium addition are close to each other, the difference between the elongation values is significant, as expected. This can be attributed to a reduction in the volume fraction of graphite and the presence of vanadium carbide particles.

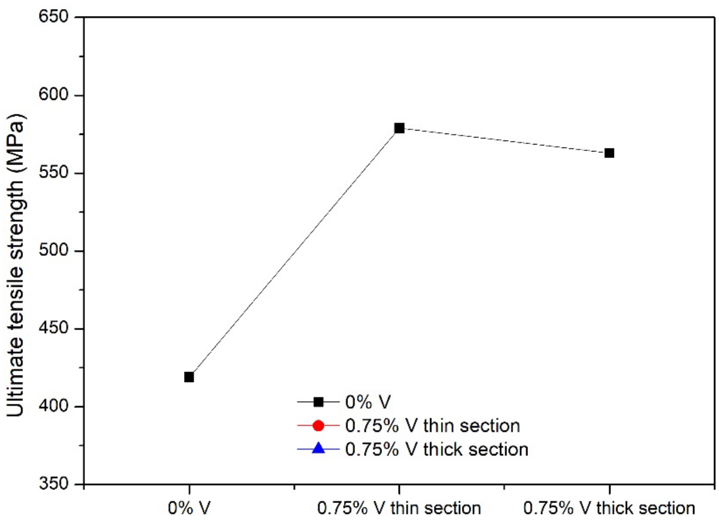

Figure 4. Influence of vanadium on ultimate tensile strength

The yield strength of ferrite was controlled by the grain size and solid solution strengthening, whereas the yield strength of pearlite was a function of the interlamellar spacing, colony size, cementite plate thickness, and solid solution strengthening of the ferrite.

Hence apart from the effect of vanadium carbide particles on decreasing the ferrite grain size, vanadium also improves the yield strength by increasing the volume fraction of pearlite. The reduction in total elongation of ductile iron as increased vanadium content (Fig. 5) can be attributed to the increased volume fractions of second phase particles (vanadium carbide) and pearlite.

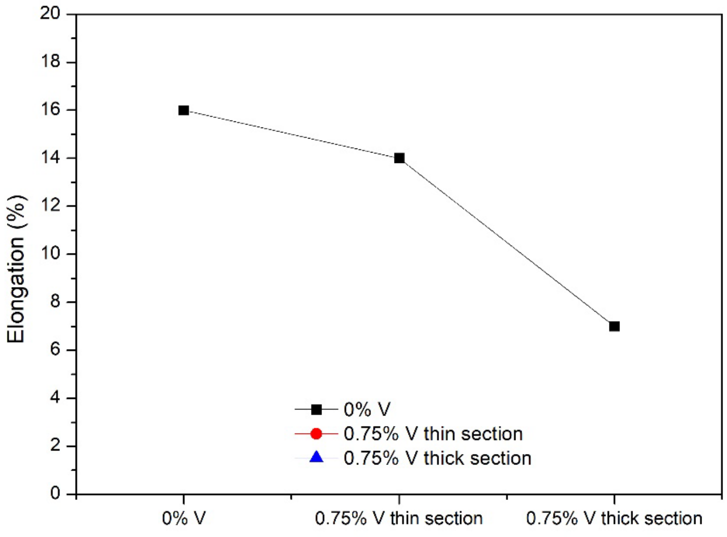

Figure 5. Influence of vanadium on ultimate tensile strength

The hardness results are given in Fig 6. The results are associated with the tensile strength values. The hardness values were higher in the thin section than the thick section, although vanadium addition provided better hardness for both specimens compared to the unalloyed sample.

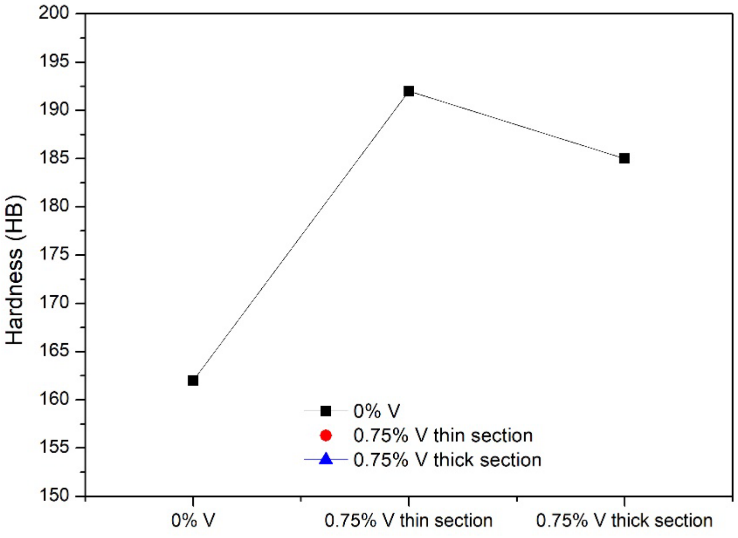

Figure 6. Influence of vanadium on hardness results

4. CONCLUSIONS

The following conclusions were found from the microstructural and mechanical characterization.

- As the vanadium content in iron increased, the ultimate tensile strength increased while the elongation decreased.
- Hardness values increased due to the carbide-forming effect of vanadium. Due to the cooling difference, thick-sectioned parts had lower hardness than the thin sections.
- Vanadium had a strong tendency to promote the formation of eutectic carbide in ductile iron. The ferrite content increased by the addition of 0.75% vanadium.
- The amount of nodularity has increased since vanadium acted as a spheroidizer in the cast irons.

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

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