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Effects of vermiculariser, inoculant and copper addition on microstructure and corrosion properties of vermicular graphite cast iron

Vermikülerleştirici, aşılayıcı ve bakır ilavesinin vermiküler grafitli dökme demirin mikroyapı ve korozyon özelliklerine

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Effects of Vermiculariser, Inoculant and Copper Addition on Microstructure and Corrosion Properties of Vermicular Graphite Cast Iron

Highlights

- *Effects of vermiculariser, inoculant and Cu addition on the vermicularisation*
- *Effects of vermiculariser, inoculant and Cu addition on the microstructural properties*
- *Effects of vermiculariser, inoculant and Cu addition on the corrosion properties*
- *Effects of vermiculariser, inoculant and Cu addition on the graphite shape, matrix structure and grain size*

Graphical Abstract

In this study, the microstructure and corrosion properties of Vermicular Graphite Cast Iron (VGCI) produced via different methods and parameters were investigated. VGCI was produced from a base ductile iron material using different proportions of vermiculariser and inoculant. The microstructures and corrosion properties of samples were investigated in saltwater media. In electrochemical corrosion studies, VGCI was superior in corrosion resistance compared to SGCI and addition of vermiculariser, inoculants and copper was found effective in improving the corrosion resistance of the VGCI material (Figure 1)

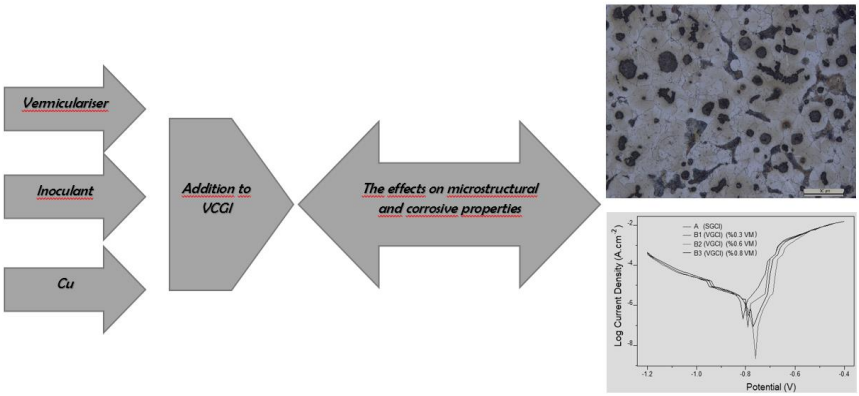


Figure 1. *Effects of vermiculariser, inoculant and Cu addition on the vermicularisation, microstructural and corrosion properties of VCGI*

Aim

This study aimed to determine the effects of vermicularization, inoculation and Cu addition to VCGI on microstructural and corrosive properties.

Design & Methodology

The effects of vermicularization, inoculation and Cu addition to VCGI on microstructural and corrosive properties has been evaluated experimentally.

Originality

There is no study in which the effects of vermicularization, grafting and Cu addition on microstructural and corrosive properties were evaluated together.

Findings

In electrochemical corrosion studies, VGCI was superior in corrosion resistance compared to SGCI and addition of vermiculariser, inoculants and copper was found effective in improving the corrosion resistance of the VGCI material.

Conclusion

Corrosion rate of VGCI material was decreased, and corrosion resistance was increased by increased rate of the inoculant. Microstructure grain size change was thought to be effective in increasing corrosion resistance.

Declaration of Ethical Standards

The author of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Effects of Vermiculariser, Inoculant and Copper Addition on Microstructure and Corrosion Properties of Vermicular Graphite Cast Iron

Research Article

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ABSTRACT

In this study, the microstructure and corrosion properties of Vermicular Graphite Cast Iron (VGCI) produced via different methods and parameters were investigated. VGCI was produced from a base ductile iron material using different proportions of vermiculariser and inoculant. Copper was added to a group of samples as an alloying element. The microstructures and corrosion properties of samples were investigated in saltwater media. The effects of production parameters on the microstructure and corrosion behavior were determined. It was observed that as the ratio of vermiculariser applied was increased, the vermicular graphite ratio and vermicularity was also increased. The matrix grain size decreased while the inoculant and pearlite phase ratio increased due to the addition of copper. In electrochemical corrosion studies, VGCI was superior in corrosion resistance compared to SGCI and addition of vermiculariser, inoculants and copper was found effective in improving the corrosion resistance of the VGCI material.

Keywords: Vermicular, compact, cast iron, microstructure, corrosion.

1. INTRODUCTION

Due to its superior fluidity and casting properties, high wear resistance and other mechanical properties, good machining capability and low production costs, cast iron materials are used in many industrial fields which are automotive, machinery, pipes and nuclear waste containers [1, 2]. Cast iron with excellent mechanical properties and desirable castability is extensively used as the engineering material [3]. Alloying, vermiculation, inoculation and heat treatment applications are used to develop suitable structures in various types of cast iron [1,2,4–7]. Matched to different applications, cast irons could be further improved in their properties. These are different types of cast irons such as; white cast iron (WCI), lamellar graphite cast iron (LGCI), spheroidal graphite cast iron (SGCI), temper cast iron (TCI) and vermicular graphite cast iron (VGCI) [1,2,4–7]. VGCI, a type of cast irons, discovered as a result of insufficient Mg and Ce inoculation during the production of SGCI exhibited superiority in certain properties. Among the lamellar, spheroidal, and vermicular types, VGCIs have its very unique microstructure with a complicated graphite formation. The vermicular graphite is thicker than the lamellar graphite's and ends of its coverslips are roundish. [7, 8]. VGCIs are superior in properties such as strength, plasticity, toughness, impact damping and heat conduction when compared to LGCIs. VGCIs are superior in casting performance, thermal fatigue, and thermal conductivity compared to SGCIs.

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Hence, VGCIs are widely used in the production of brake discs, exhaust manifolds, blocks and engine heads, and other fields of the automotive industry [8-14, 15]. Vermicular cast irons are produced in a similar way as nodular cast irons, but with smaller amounts of inoculants which can be magnesium and/or cerium. Elements to modify graphite morphology are added during pouring, such as spheroidizers (magnesium, calcium or rare earth metals) and anti-spheroidizers (titanium, aluminum). The additions of these elements must be well controlled, in order to obtain a microstructure containing graphite in the forms of compacted veins and nodules. When compared to gray cast irons, vermicular cast irons present graphite in the form of shorter and thicker veins, in addition to having rounded contours. The obtained graphite has vermicular morphology, hence the name vermicular cast iron. The irregular surface causes the veins to show strong adhesion with the matrix [16]. The parameters such as matrix phase, microhardness, graphite content and graphite shape may influence the properties of cast iron. For instance, the elastic modulus of wide variations of cast iron grades is strongly associated with the shape of the graphite inclusions, whereas yield and tensile strength are affected by both graphite morphology and matrix characteristics [17]. Although numerous studies were conducted on the mechanical properties of cast iron, the corrosion studies are considered insufficient. In particular, the number of studies on the corrosion properties of VGCI is negligible. Watson et al. [14] in their study of the corrosion behavior of WCIs produced via powder metallurgy, reported that while in general materials

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degradation was less, the degradation in the abrasion corrosion effect was more and much faster. Melchers [18] examined the corrosion properties of LGCI in marine and atmospheric environments. They found that, the protective corrosion products formed by the graphitized layer are effective in barrier formation, that the corrosion loss on the treated surface was twice as high as compared to the untreated surface. Neville et al. [19] examined the erosion corrosion behavior of LGCI and stated that temperature and solution salt ratio increased corrosion losses. Akinribide et al. [1] reported that austempering heat treatment applied to SGCI improved the corrosion resistance of the material. Hsu and Chen [2] examined the effects of Ni alloying and austempering on corrosion behavior of SGCIs, and found that Ni addition which increased the grain size also improved corrosion resistance. It was reported that the fraction of residual austenite increases and corrosion resistance improves with the addition of nickel and austempering. Medynski and Jonus [20] investigated the effects of heat treatment on the wear and corrosion properties of austenitic SGCI. Moreover, the heat treatment was reported to be beneficial in terms of corrosion resistance. It was seen that the form of corrosion changes from the local corrosion to the uniform corrosion. Al-Hashem et al. [21,22] investigated the effects of microstructure on cavitation corrosion in seawater of SGCI and reported that the onset of the cavitation erosion was at the graphite/ferrite interface due to micro-galvanic effect and mechanical factors and those micro-cracks were formed alongside corrosion pits. Jeong and Kim [23] examined the effects of plasma nitrating and oxidation surface treatments on corrosion of SGCI. Graphite corrosion was observed in the untreated sample while corrosion resistance was improved with plasma nitrating. Guo et al. [8] investigated the effects of vermicular graphite ratio on oxidation resistance and mechanical properties in VGCI, and reported that as the rate of vermicular graphite decreases, oxidation mass gain rapidly decreases and graphite are the main diffusion channels for oxygen. Liu et al. [24] studied the effects of oxidation on wear resistance in VGCI that indicated that graphite morphology and matrix structure had a significant role where surface oxidation increased wear rate. In studies on corrosion of high chromium cast irons, it has been reported that as the chromium content in the structure increases, the passive range increases and the corrosion current decreases. The volume fraction, shape, and size of carbides in the structure are also affected by the corrosion behavior. Due to the increase in carbon content, total volume ratios of carbides increase and corrosion resistance decreases. Inclusions in the structure are also found effective, preferentially dissolving these inclusions by acting anodically relative to the matrix [25–28].

The studies on cast irons are generally conducted to investigate their mechanical properties. There are few studies on the corrosion behavior of cast irons. In this study, the microstructure of VGCIs produced with different parameters and corrosion behaviors were investigated.

2. EXPERIMENTAL PROCEDURES

In this study, the microstructure and corrosion behavior of SGCI and VGCI samples produced with different parameters were investigated. FeSi-Mg material was used in SGCI production (A). In the experimental studies, first spheroidal graphite cast iron was produced and then vermicular graphite cast iron samples were obtained from this SGCI material by vermicularization process (B). Some samples were obtained by additional inoculation (FeSi) to form a different microstructure (C). In addition to the vermiculariser and inoculant, Cu was added to the last group sample (D). The chemical compositions of samples were given in Table 1. Table 2 presented the ratios of added vermiculariser (VM) to convert spheroidal graphite into vermicular graphite together with the ratios of inoculant (IM) and copper (Cu). The chemical compositions of vermiculariser and inoculant materials were given in Table 3–4.

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Table 1. Chemical composition of the cast iron samples (wt.%)

Samples	C	Si	Mn	P	S	Cu	Fe
A, B1, B2, B3, C1, C2, C3	3.5	2.6	0.164	0.026	0.007	-	Balance
D1, D2, D3	3.5	2.6	0.164	0.026	0.007	0.6	Balance

Table 2. Addition rates of the samples (wt.%)

Samples	Type of cast iron	Vermiculariser ratio	Inoculant ratio	Cu ratio
A	SGCI	-	0.3	-
B1	VGCI	0.3	0.3	-
B2	VGCI	0.6	0.3	-
B3	VGCI	0.8	0.3	-
C1	VGCI	0.5	0.3	-
C2	VGCI	0.5	0.5	-
C3	VGCI	0.5	0.8	-
D1	VGCI	0.5	0.3	0.6
D2	VGCI	0.5	0.5	0.6
D3	VGCI	0.5	0.8	0.6

Metallographic studies were carried out for microstructural characterization of the samples obtained by casting process. In metallographic studies, sanding, polishing and etching in 2 % nital solution were applied to the samples, respectively. LEICA DM 4000 M model optical metal microscope used to obtain microstructure images. Electrochemical corrosion tests were carried out by using potentiodynamic method in 3.5 % NaCl solution to determine the corrosion behavior of the samples. The corrosion studies of cast iron samples were conducted cold-molded with epoxy resin, and the other surface was exposed to 1 cm^2 surface area where cast iron working electrodes were obtained. In the corrosion tests, Ivium potentiostat/galvanostat, corrosion cell with three electrode, cast iron working electrodes, platinum counter electrode and standard calomel reference electrode (SCE) were used. In the two-stage potentiodynamic corrosion studies, first of all, polarization curves were obtained by applying the potential between –1500 mV and –300 mV from the cathodic direction to the anodic direction and back to the cathodic direction. From these curves, the general corrosion behavior of the materials was determined. In the second stage, Tafel polarization curves were obtained by applying potential to the samples which were initialized by sanding with a scan rate of 2 mV s^{-1} from cathodic direction to anodic direction between –1200 mV and –400 mV. Corrosion potentials (E_{cor}), corrosion current densities (I_{cor}) and corrosion rates of all samples were determined from the Tafel polarization curves.

Table 3. Chemical composition of the vermiculariser material

Element	Al	Mg	Si	B	Ti	Ca
wt.%	45	25	15	5	5	5

Table 4. Chemical composition of the inoculant material

Element	Si	Ba	Al	Ca	Fe
wt.%	75	2.1	1.1	1.2	Balance

3. RESULTS AND DISCUSSION

3.1. Microstructure

The microstructure image of the SGCI material, the first sample that produced during the production stage, was used as the base material of VGCI production, given in Fig. 1. As shown in the figure, the microstructure generally consists of light colored ferritic matrix phase and black spheroidal graphite. The spheroidal graphite appeared in different sizes, and distributed homogeneously in the matrix.

The particle size of the ferritic matrix phase is approximately 30 µm. Microstructure images of VGCI materials produced via different amounts of vermiculariser, inoculant and 0.6 % Cu applied, were given in Fig. 2. While the vermicular graphite ratio in SGCI sample (A) was 2 %, it was determined as 20 %, 35 % and 65 % respectively in VGCI samples (B1–B3). The vermicular graphite ratio was approximately 45 % in other VGCI samples (C1–C3 and D1–D3). Since the vermiculariser ratio was the same in these samples, the vermicular graphite ratios were same. Increased inoculant ratio did not affect vermicularity.

VGCIs are cast iron types that contain both low levels of spheroidal graphite and higher levels of vermicular graphite in the structure.

In the samples of B group (B1, B2, B3) that were produced with three different rates of vermiculariser as 0.3 %, 0.6 % and 0.8 %; the rate of vermicular graphite in the structure increased as the rate of vermiculariser increased, more vermicularity occurred in the vermicular graphite shapes, and the ferritic matrix grain size did not change and reached to 30 µm level. There has been some increase in the ratio of pearlite phase in the structure.

It is believed that the pearlite phase ratio increase was influenced by the substances which promote pearlite formation in the vermiculariser added during production. In the samples produced with three different inoculants (C1, C2, C3), 0.3 %, 0.5 % and 0.8 % by keeping the vermiculariser ratio constant, while the pearlite ratio in the structure did not change, the ferritic matrix grain size decreased from 30 µm to approximately 20 µm. By the addition of the inoculant and with an increase in its proportion, the solidification was started at more points during casting, hence, resulted in more grain and refined grain sizes. 0.6 % Cu addition (D1, D2, D3), the most notable difference in the increase of pearlite phase observed, was associated with the decrease in graphite ratio. Cu added to the structure was an alloying element that promoted the formation of pearlite.

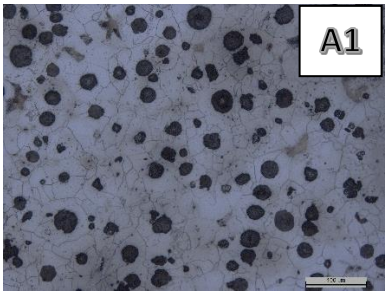


Figure 1. Microstructure image of SGCI

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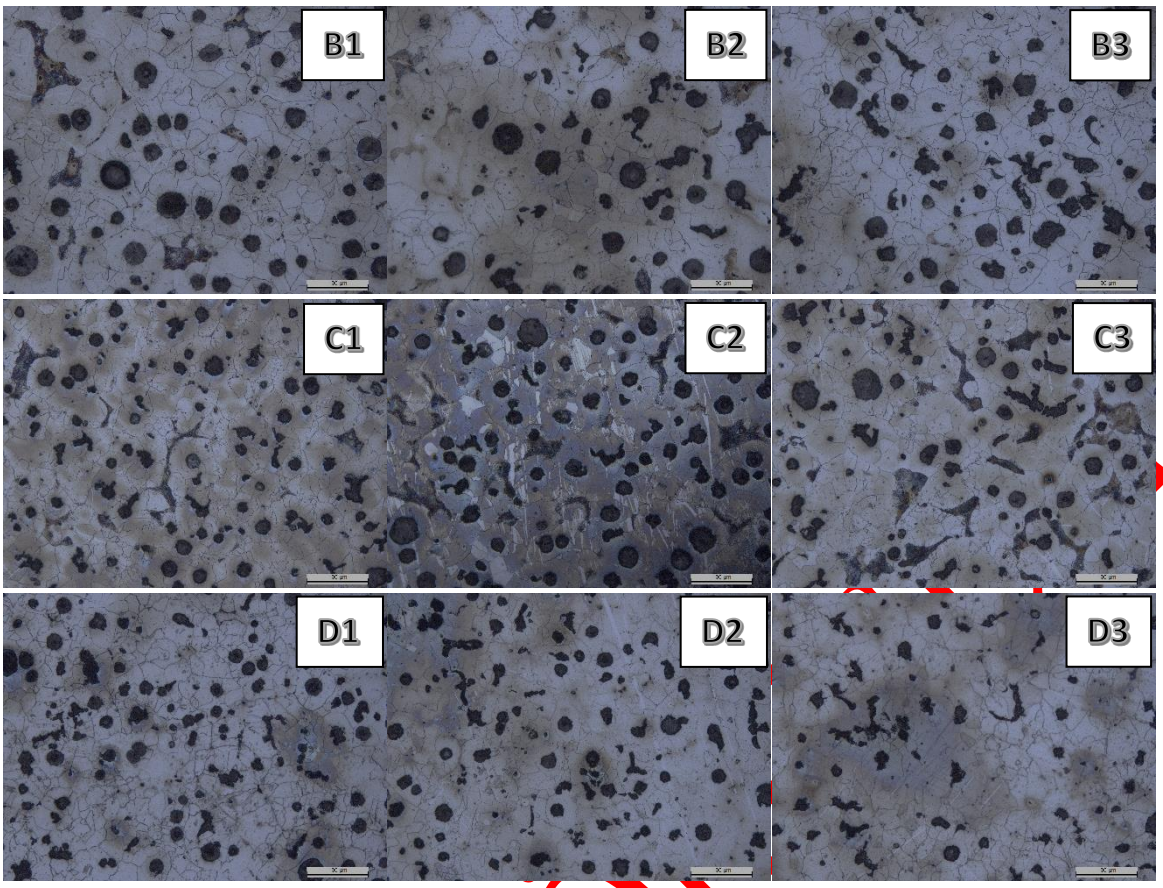


Figure 2. Microstructure images of VGCI produced with different parameters

3.2. Corrosion behavior

Polarization curves obtained as a result of potential screening between –1500 mV and –300 mV in 3.5 % NaCl solution of SGCI produced as an initial material. Modification applied VGCI samples via vermiculariser, inoculant and Cu are also given in Fig. 3.

Potential application to SGCI and VGCI materials was applied from a cathodic region such as –1500 mV to an anodic region such as –300 mV, and from there it was returned to the initial potential. In the polarization curves represented, the bottom curves are the anodic travel curve where the upper curves are the cathodic return curve. The purpose of this process was to determine the passivation potential ranges, deterioration, and dissolution potential range of the materials. As it is known, despite the potential increase, there was no change in the current, the passivation occurred in the material as a result of the barrier effect of iron oxide film formed on the surface of the material. The dissolution of the material was prevented and no corrosion occurred in the material.

When the potential was raised in the positive direction which is anodic direction in this case, a sudden increase in the current flowing through the material initiates where a certain potential value is reached. In this situation where the current suddenly increases, the passivation deteriorates, the transition to the ion state as a result of oxidation in the cast iron material, the loss of metal as a result of corrosion begins. Due to the polarization curves of similar materials, the information about the differences between their corrosion behaviors is hard to be detected.

However, the corrosion behavior in general is possible to be acquired. When the general corrosion behavior of the samples were examined through the polarization curves, it appeared that the passivation in the negative potential value of –650 mV was deteriorated in SGCI material compared to other VGCI materials. Moreover, the current passing through the material, had increased rapidly, in other words, the dissolution in the metal was started.

In the case of VGCI materials, the potential in which the passivation deteriorates and the current starts to increase, i.e. the metallic dissolution begins at –550 mV values. The more positive the passivation potential is, the better the corrosion resistance of the material. In other words, the passive film retains its strength up to the higher potentials forcing the corrosion. Passivation resistance of 100 mV is observed in positive direction in VGCI materials. The differences between the corrosion behaviors of materials could be determined more efficiently by examination of the Tafel polarization curves.

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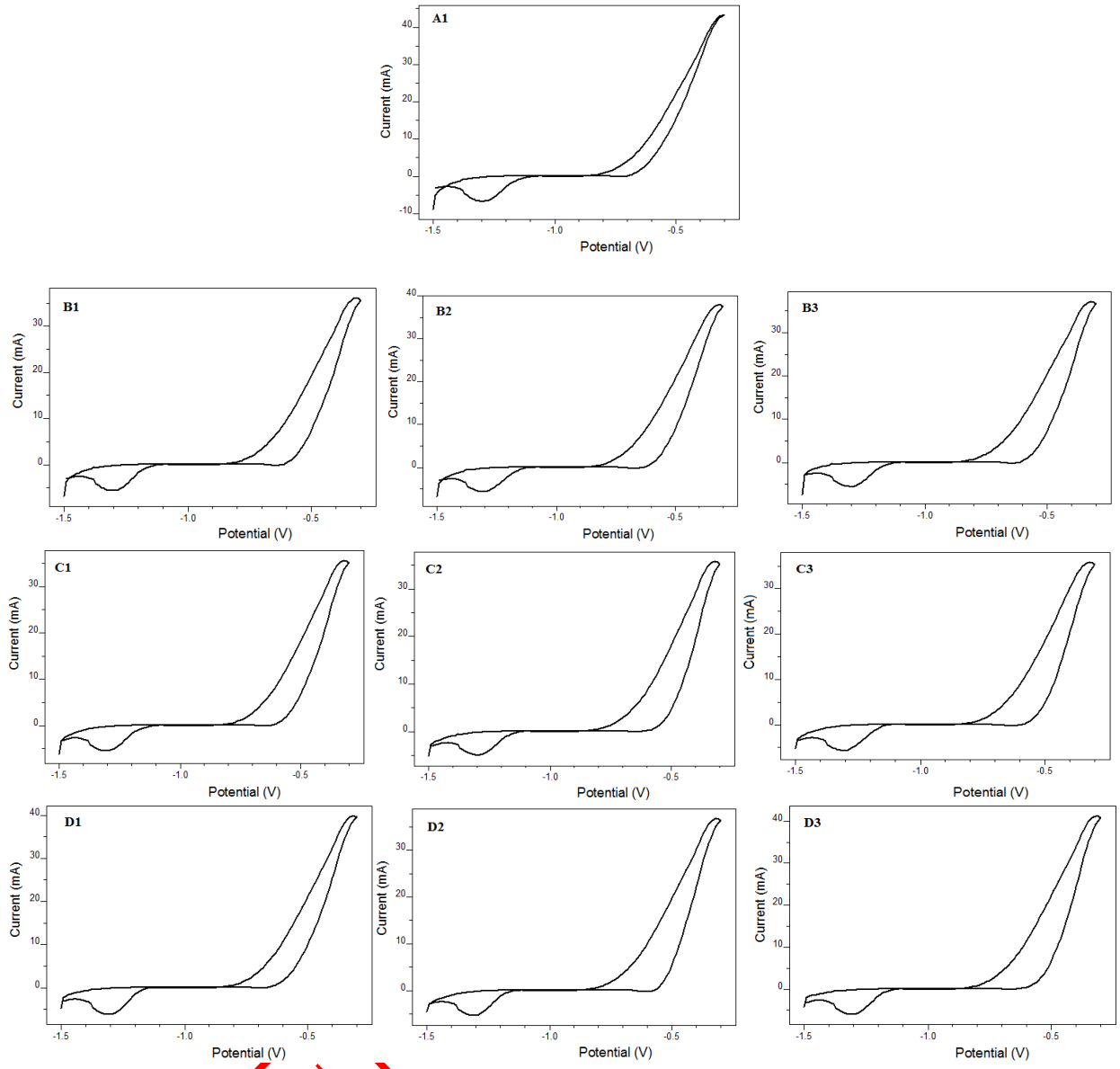


Figure 3. Polarization curves of SGCI materials (A) and VGCI materials (B1, C1 and D1) produced with different parameters

Tafel polarization curves of SGCI and VGCIs with different proportions of vermiculariser material (VM) in Fig. 4, Tafel polarization curves of SGCI and VGCIs with different ratios of inoculant (IM) in Fig. 5, Tafel polarization curves of SGCI and VGCIs with Cu applied were presented in Fig. 6. Corrosion potentials (E_{cor}), corrosion current densities (I_{cor}) and corrosion rates obtained from the Tafel polarization curves of the samples were given in Table 5–7, respectively.

SGCI and VGCI materials contain iron based matrix (ferritic, pearlitic) and graphite phases in their structures. Various additions can be made according to the type of cast iron. In this type of cast iron, the iron-based phase which forms the main material, is more electrochemically active and dissolves into an ion by oxidation reaction by acting anodically in the event of corrosion. Graphite in the structure is steadier than iron, hence, it acts cathodically during the event of corrosion [4, 29, 30]. When Tafel polarization curves given in Fig. 4 and corrosion values given in Table 5 are considered, it appeared that there were significant changes in corrosion properties of SGCI and VGCI material containing different proportions of vermiculariser. While SGCI material a corrosion potential of –811 mV was acquired, the corrosion potentials of VGCI materials containing different amounts of vermiculariser changed in the positive direction, i.e. the Tafel polarization curves was shifted to the right. The corrosion potential of VGCI materials was reached to levels of approximately –770 mV. In terms of corrosion resistance, the positive change in the corrosion potential of the material was a positive indicator. Due to the corrosion currents and corrosion rates, within the increase in the ratio of vermiculariser, lower corrosion current density and lower corrosion rates were obtained in VGCI material.

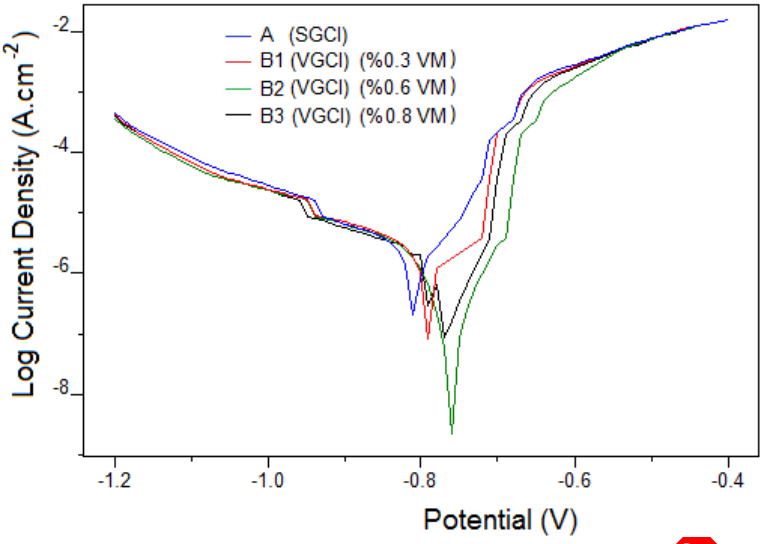


Figure 4. Tafel polarization curves of SGCI and VGCI containing vermiculariser material (VM) in different ratios

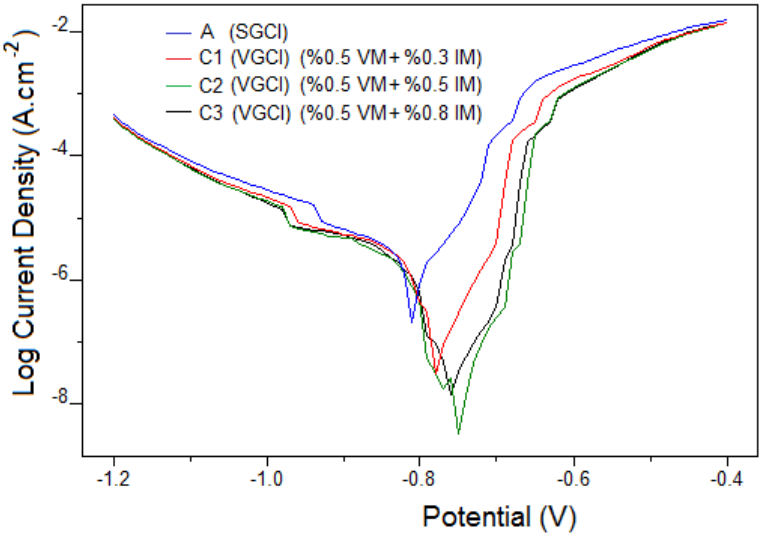


Figure 5. Tafel polarization curves of SGCI and VGCI containing inoculant material (IM) in different ratios

Tafel polarization curves of VGCI materials were aimed downwards due to the decrease in the corrosion current density. The amount of current flowing through the material in corrosion is a measure of the corrosion rate of the material. According to the Faraday's law, the amount of current flowing through the material is directly proportional to the amount of dissolved materials [31]. As the current increases during corrosion, the amount of dissolved material increases and corrosion resistance decreases. On the contrary, the amount of dissolved material decreases and the corrosion resistance of the material increases where the amount of current flowing through the material decreases. Corrosion current density value which was $2.45.10^{-6}$ A cm^{-2} in SGCI material decreased to $1.22.10^{-6}$ A cm^{-2} and corrosion rate decreased from 0.0288 mm y^{-1} to 0.0144 mm y^{-1} in VGCI material in which the highest rate (0.8 %) of vermiculariser applied. In other words, the corrosion rate of VGCI material was quite low compared to SGCI material where the corrosion resistance was considerably high.

When VGCI was produced from SGCI material, it was converted from spheroidal graphite to vermicular graphite with the addition of vermiculariser, while the total graphite ratio (vermicular, spheroidal) in the matrix decreased slightly and cementite phase formation increased. It was thought that the decrease in the rate of graphite phase, which indicates cathodic behavior, was effective in decreasing the corrosion rate of VGCI material. Vermicular cast irons present graphite in the form of shorter and thicker veins, in addition to having rounded contours. The irregular surface causes the veins to show strong adhesion with the matrix [16]. The parameters such as matrix phase, graphite content and graphite morphology may influence the properties of cast iron [17]. Two different studies on the corrosion of SGCI material [2, 3] supported that the corrosion resistance of the SGCI material was improved by decreasing the spheroidal graphite ratio in the structure. The same effect was also valid for the VGCI material examined in this study.

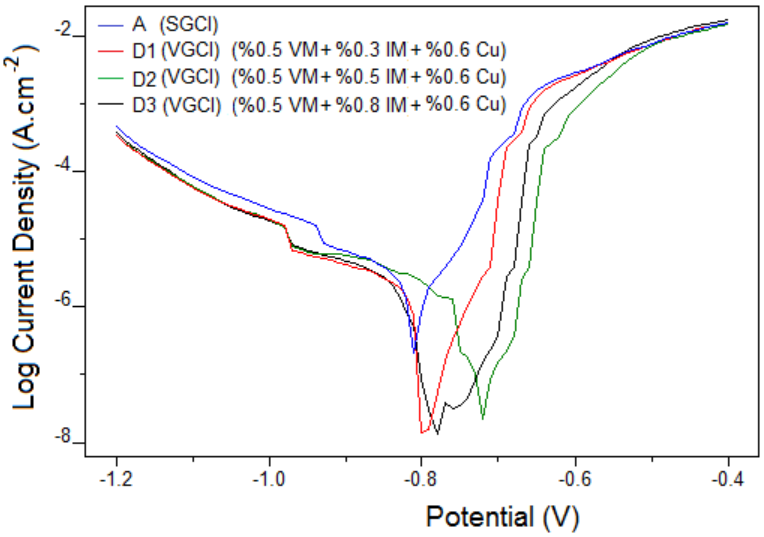


Figure 6. Tafel polarization curves of SGCI and VGCI containing inoculant material (IM) in different ratios, 0.5 % VM and 0.6 % Cu

Table 5. Corrosion values of SGCI and VGCI containing vermiculariser materials in different ratios

Samples	Type of cast iron	Vermiculariser ratio (wt.%)	Inoculant ratio (wt.%)	Corrosion potential (mV)	Corrosion current density (A cm^{-2})	Corrosion rate (mm y^{-1})
A	SGCI	-	0.3	–811	2.45×10^{-6}	0.0288
B1	VGCI	0.3	0.3	–794	2.31×10^{-6}	0.0271
B2	VGCI	0.6	0.3	–767	1.46×10^{-6}	0.0171
B3	VGCI	0.8	0.3	–773	1.22×10^{-6}	0.0144

Table 6. Corrosion values of SGCI and VGCI containing inoculant material (IM) in different ratios

Samples	Type of cast iron	Vermiculariser ratio (wt.%)	Inoculant ratio (wt.%)	Corrosion potential (mV)	Corrosion current density (A cm^{-2})	Corrosion rate (mm y^{-1})
A	SGCI	-	0.3	–811	2.45×10^{-6}	0.0288
C1	VGCI	0.5	0.3	–782	1.17×10^{-6}	0.0137
C2	VGCI	0.5	0.5	–774	0.83×10^{-6}	0.0098
C3	VGCI	0.5	0.8	–770	0.78×10^{-6}	0.0092

Table 7. Corrosion values of SGCI and VGCI materials containing inoculant material (IM) in different ratios, 0.5 % VM, 0.6 % Cu

Samples	Type of cast iron	Vermiculariser ratio (wt.%)	Inoculant ratio (wt.%)	Cu ratio (wt.%)	Corrosion potential (mV)	Corrosion current density (A cm^{-2})	Corrosion rate (mm y^{-1})
A	SGCI	-	0.3	-	–811	2.45×10^{-6}	0.0288
D1	VGCI	0.5	0.3	0.6	–800	0.99×10^{-6}	0.0117
D2	VGCI	0.5	0.5	0.6	–746	1.06×10^{-6}	0.0125
D3	VGCI	0.5	0.8	0.6	–803	1.13×10^{-6}	0.0133

Fig. 5 and Table 6 presents the Tafel polarization curves of the SGCI and VGCI materials with 0.5 % vermiculariser and different amounts of inoculant, and the corrosion values obtained from these curves. Structurally, with the inoculant applied, solidification from the liquid state has started on more points which resulted in more grain formation where grain size of VGCI was reduced. Due to the microstructures of the materials given in Fig. 2, it was determined that the phase ratios did not change much while the grain size decreased from 30 µm to 20 µm. In other words, the grain size reduction occurred together with the increased rate of inoculant. Materials with small grain size exhibit superior mechanical properties such as higher hardness, strength, fatigue strength and abrasion resistance. Since VGCI materials should have high strength, hardness and abrasion resistance properties in working conditions, inoculant applied becomes a useful modification, in terms of strength improvement. When the corrosion behavior of this group of samples (C1, C2, C3) was considered, there was a positive change in the corrosion potential compared to SGCI materials. This change in corrosion potentials of approximately 40 mV was positive, in terms of corrosion resistance. Corrosion current densities and corrosion rates

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of VGCI materials decreased due to increased rate of inoculant. Compared to SGCI materials, the corrosion rate was decreased considerably. However, the corrosion rates of the samples with inoculant ratios of 0.5 % and 0.8 % were very close to each other. While the corrosion rate of SGCI material was 0.0288 mm y^{-1}, corrosion rates of VGCI materials with 0.5 % and 0.8 % inoculants applied was decreased to 0.0090 mm y^{-1}. Thus, a significant increase in corrosion resistance was observed. In this type of VGCI samples, the ratio of the current phase (ferritic matrix, pearlite, graphite) did not change with the increased amount of inoculant while its grain size was reduced. Particularly in VGCI samples containing 0.5 % and 0.8 % inoculant, the grain size was reduced by 30 %. It was thought that grain size would be the only determinant parameter that could be effective in decreasing the corrosion rate and increasing the corrosion resistance by increasing ratio of inoculant in such VGCI materials.

Due to Tafel polarization curves and corrosion rates of group D materials which were obtained by adding 0.6 % Cu to Group C containing 0.5 % vermiculariser material together with different amounts of inoculant; it appeared that the corrosion rate was much lower than the SGCI materials, i.e. the corrosion resistance was superior. However, with the absence of Cu (C1, C2, C3), corrosion currents and corrosion rates increased slightly, compared to VGCI materials. Corrosion current density values of $0.78.10^{-6}$ A cm^{-2} in VGCI materials containing high rates of inoculant increased to $1.13.10^{-6}$ A cm^{-2} with 0.6 % Cu addition, and corrosion rate values of 0.0092 mm y^{-1} levels increased to 0.0133 mm y^{-1} levels with Cu addition. As a structural evaluation; ferrite phase ratio decreases and pearlite phase ratio increased by the Cu applied, in cast irons. In other words, Cu is an alloying element that promotes pearlite formation. The pearlite phase, formed by the aligning of ferrite and cementite (Fe_3C) lamellas side by side, is not superior in resistance against corrosion. The addition of alloying elements such as copper, nickel and molybdenum delays the end of the transformation of the ausferrite [16]. Furthermore, if the alloying elements added to the structure do not have an ability to form a passive film to cover the surface, they generally have no effect on material's corrosion resistance. However, Cu, added in minor proportions, is not an element with a passivation effect. VGCI had no positive effect when evaluated in terms of corrosion resistance of Cu, where it had an effect on improving the other necessary properties of the material, such as mechanical and conductivity. In the case of VGCIs, it was more appropriate to choose other elements, which will provide pearlite formation for increasing the mechanical properties such as strength and hardness, but will not increase the corrosion rate.

The most effective factor on the corrosion properties of VGCI is addition of vermiculariser. The corrosion rate of 288 mm y^{-1} of SGCI material consisted not vermiculariser decreased to 144 mm y^{-1} levels with the addition of vermiculariser. The second effective factor on the corrosion properties of VGCI is addition of inoculant. Corrosion rate of 170 mm y^{-1} decreased to 92 mm y^{-1} levels by increasing the ratio of inoculant in VGCI material. Contrary to these two factors, the addition of copper generally had an effect on increasing the corrosion rate of VGCI materials. For example, corrosion rate of 98 mm y^{-1} increased to 125 mm y^{-1} levels by copper addition in VGCI material. The effect mechanisms of these factors were explained in the paragraph above.

4. CONCLUSIONS

The following results were obtained in this study, the effects of different amounts of vermiculariser, inoculant and Cu addition on microstructure was investigated. The corrosion properties of VGCIs preferred to be used in some applications due to superior properties were aimed to be found. In this study, which investigated the corrosion properties of VGDD with its own superior mechanical properties, the following results were found.

- Vermicular graphite ratio and vermicularity of graphite shapes in VGCI microstructure increased with increasing amount of vermiculariser.
- Increasing the amount of inoculant decreased the grain size.
- The addition of Cu increased the perlite amount.
- It was also observed that corrosion resistance of VGCI materials obtained by addition of vermiculariser was improved according to corrosion resistance of SGCI materials, and increased vermiculariser ratio was increased corrosion resistance by decreasing corrosion rate. This increase in corrosion resistance was thought to be due to the decrease in the total graphite content which indicated cathodic behavior.
- Corrosion rate of VGCI material was decreased, and corrosion resistance was increased by increased rate of the inoculant. Microstructure grain size change was thought to be effective in increasing corrosion resistance.
- Although, a slight increase in corrosion rate was observed due to Cu applied to VGCI material together with inoculant modification, the corrosion resistance was decreased slightly, but, a superior corrosion resistance was obtained when compared to SGCI. It was thought that the increased pearlite ratio due to Cu applied, affected its corrosion resistance, negatively.

DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods they use in their studies do not require ethics committee permission and / or legal-specific permission.

AUTHORS' CONTRIBUTIONS

Kubilay KARACIF: He made corrosion tests and took part in publication.

Berkay KARATAY: Literature reviews and casting processes

Hasan HASIRCI: He did casting, microstructure analysis and took part in publication. Submitting the

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article, editing it, preparing it for the format and contacting author..

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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