

Research Paper

Effect of Preheating Temperature on Microstructure and Tribological Properties of Welded High Silicon Gray Cast Iron

Naser Talebi, Mahdi Omid^{*}, Mahdi Rafiei, Mohsen Abbasi-Baharanchi

Department of Materials Engineering, Na.C., Islamic Azad University, Najafabad, Iran

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ABSTRACT

In this study, the microstructure and tribological properties of high silicon gray cast iron samples welded by the shielded metal arc welding (SMAW) process and the effect of preheating temperature during welding were investigated. Cast gray iron samples containing 14–15 wt.% silicon were used for the welding process. Preheating temperatures of 300 °C and 600 °C were selected prior to welding. For microstructural evaluation, the cross sections of the welded samples were prepared using standard metallographic procedures and examined. In addition, hardness measurements were carried out using the Vickers method under a load of 30 kg (HV30), and hardness profiles were obtained for both welded samples. The results showed that increasing the preheating temperature led to an expansion of the weld zone and a higher degree of dilution between the base metal and the weld metal. Furthermore, the hardness in the heat affected zone (HAZ) and the weld region decreased by approximately 20 Vickers. The wear behavior of the as cast sample and the welded samples was evaluated using a reciprocating sliding wear test under dry conditions by analyzing weight loss curves, friction coefficient variations, worn surfaces, and wear debris using scanning electron microscopy (SEM). The wear test results indicated that increasing the preheating temperature in welded samples resulted in higher weight loss and an increased coefficient of friction. After a sliding distance of 1000 m, the as-cast sample showed a weight loss of approximately 45 mg, while the welded samples exhibited lower values of about 15 mg and 25 mg for preheating temperatures of 300 °C and 600 °C, respectively. The dominant wear mechanisms in the welded samples were adhesive wear and oxidation; however, these mechanisms occurred with lower intensity in the sample preheated at 300 °C.

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*** Corresponding Author:**

E-Mail: MahdiOmidⁱ@iau.ac.ir

Introduction

Cast irons represent a broad family of ferrous alloys primarily containing more than 2% carbon and 1% silicon. Various factors, such as the low cost of raw materials, ease of production, and economic efficiency in manufacturing these alloys, have led to their utilization in numerous engineering applications. The most prominent feature of cast irons is their high castability. Due to favorable casting properties such as fluidity, relatively suitable melting points, low shrinkage, and high yield, they can be easily used to manufacture complex components [1]. In general, alloying elements are added to increase the resistance of cast irons to wear, abrasion, and corrosion. By modifying certain characteristics, production processes, and adding various alloying elements, it is possible to achieve a wide range of properties such as strength, hardness, machinability, wear resistance, and corrosion resistance [2-5].

Silicon is one of the most important alloying elements added to cast irons and is considered the strongest graphitizer among other alloying elements. As the silicon content in cast iron increases, corrosion resistance improves, especially when the amount of this element exceeds 14%. Typically, cast irons containing 14% to 17% silicon are referred to as high-silicon cast irons. These cast irons are almost resistant to sulfuric acid and nitric acid at all concentrations and temperatures. Due to their high corrosion resistance, high-silicon cast irons are commonly used for transporting corrosive acids and environments exposed to mineral acids, except for hydrofluoric acid. Applications of this alloy include the manufacturing of equipment for sulfuric and nitric acid production, chemical fertilizer industries, explosives (military industries), petroleum refineries, and pickling processes [2].

As mentioned, high-silicon cast irons are used to produce components subjected to critical conditions, high temperatures, and corrosive environments. Therefore, the welding of these alloys must also meet such conditions so as not to be considered a weak point for the component [6, 7]. However, since the casting of these cast irons faces difficulties due to the tendency to form hot cracks, and considering the brittleness of these alloys, they exhibit low weldability [8]. Based on conducted studies, limited information is available regarding the welding of high-silicon gray cast irons and their mechanical properties, some of which are presented below.

In a study by Sadeghi et al., who welded gray cast iron using the SMAW method, higher wear resistance was observed for carbon electrodes compared to nickel-based electrodes [9]. Pascual et al. investigated the effect of electrode type on the microstructure and

hardness in the welding of high-silicon gray cast iron. The results showed that nickel-iron electrodes result in lower hardness in the weld zone compared to nickel electrodes [10]. Generally, as a solution, preheating and post-heating processes have been used to improve the weld properties of gray cast iron. Results have shown that inducing heat into the base metal and the heat-affected zone (HAZ) leads to the decomposition of cementite and the formation of a mixture of cementite and pearlite. With increasing post-heating temperature, the pearlite fraction decreases and cementite is eliminated. Finally, the remaining pearlite dissolves into the matrix, and the hardness of the base metal decreases [10].

According to the conducted research, there is still a significant information gap in the field of welding high-silicon gray cast irons. Furthermore, the effect of various welding parameters on weld quality for assessing hardness and wear resistance has not yet been investigated. Therefore, the present research focuses on investigating the effect of preheating temperature on the microstructural evolution, hardness distribution, and tribological behavior of welded high-silicon gray cast iron.

Materials and Methods

To produce the gray cast iron used in this research, low-carbon scrap, ferrosilicon, and carbon were utilized. These materials were melted in a medium-frequency induction furnace, and finally, up to 17% ferrosilicon was used to achieve high-silicon cast iron. To prepare the plates, the molten iron was poured into sand molds with CO₂-hardened sodium silicate binder. The pouring temperature was set between 1420 and 1440 °C. To ensure the production of high-silicon gray cast iron with the target silicon percentage, a spectrometer was used for chemical analysis. The results of this analysis are presented in Table 1. Figure 1 shows the prepared and cut specimens with dimensions of 15 × 3 × 1 cm³ from the produced high-silicon gray cast iron. These parts were joined using E1094 nickel electrodes and the SMAW welding method. High-purity argon gas was used in this method to protect the resulting weld. Direct current electrode negative (DCEN) was employed.

Experimental Equipment

Sample Preparation and Joining

After the cast iron parts were cut to the desired dimensions using the wire-cut method, cleaning was performed with acetone solution to remove surface grease and contamination. Subsequently, sample preparation was conducted based on the metallographic standard for cast irons. Cross-sectional cuts of all samples were flattened and polished using abrasive papers ranging from coarse to fine grades. The joint design for the samples was

considered a butt joint without any beveling or angle. The samples were preheated at two different temperatures, 300 and 600 °C, for a specific duration. In this study, the SMAW welding method under argon shielding gas was used. Figure 2 shows a view of the welding process. Table 2 and Figure 3 show the specifications and images of the joints obtained from welding the cast irons, respectively. Subsequently, two samples were cut from the cross-section and metallographically prepared and etched in a 5% Nital solution for microstructural investigations.

Optical Microscopy Analysis

An optical microscope was used to investigate the graphite, pearlite, ferrite, and carbide phases, as well as the width of the HAZ.

Scanning Electron Microscopy Analysis

To investigate the morphology of the wear surfaces of the samples, a Philips XL30 scanning electron microscope was used using backscattered and secondary electron signals under a voltage of 20 kV. Backscattered electron signals produce suitable images due to the difference in atomic number between the matrix, hard phase, and other constituents in the microstructure. Additionally, an AIS2300C series scanning electron microscope was used to ensure the correspondence of the percentage of elements in the products with the desired chemical composition and to investigate the level of contamination.

Table 1. Chemical analysis of the high-silicon cast iron obtained by spectrometer (wt.%)

Element	Fe	Si	C	Mn	P	S	Ni	Cr	Mo	Cu
Weight percentage	Balance	14.99	0.82	0.23	0.023	0.038	0.51	0.25	0.01	0.10

Carbon Equivalent: 5.878



Fig. 1. A view of the produced high-silicon gray cast iron specimens.



Fig. 2. A view of the welding process of the specimens.

Table 2. Specifications of the samples prepared from the weld cross-sections

Weld Samples	Welding Method	Electrode Material	Preheating Temperature (°C)
Sample No. 1	SMAW	Nickel E1094	300
Sample No. 2	SMAW	Nickel E1094	600

X-ray Diffraction (XRD) Phase Analysis

Phase analysis of the as-cast samples was performed using an XRD diffractometer operating at 40 kV and 30 mA. The diffraction patterns were recorded in the 2θ range of 10°–90° with a step size of 0.05°. A copper target (Cu-Kα radiation, $\lambda = 1.5406 \text{ \AA}$) and an aluminum sample holder were utilized. After obtaining the diffraction patterns, the constituent

phases were identified by comparing the diffraction peak angles and intensities with standard reference cards using X'Pert HighScore software.

Hardness Testing

Vickers hardness testing was conducted under an applied load of 30 kg (HV30) and a dwell time of 10 seconds according to ASTM E92[11].

Wear Testing

In this study, a reciprocating sliding wear test under dry conditions was employed to investigate and

compare the tribological behavior of the welded joints and the base metal (cast iron). The apparatus is capable of measuring the frictional force between the contacting surfaces.



Fig. 3. Photographs of the plates welded by the SMAW method with preheating temperatures of (a) 300 °C and (b) 600 °C.

Non-Destructive Liquid Penetrant Testing

To investigate common welding defects such as porosity and surface cracks, liquid penetrant testing (PT) was conducted in compliance with the requirements of the DIN 1371 standard. The penetrant was sprayed onto the samples and allowed a dwell time of ten minutes. After cleaning, the developer was applied to the specimens.

Research Procedure

The research procedure included the preparation of raw materials and samples, welding, sampling for wear and hardness tests, optical microscopy imaging, and finally, evaluating the hardness and tribological behavior of the welded joints.

Results and Discussion

In this study, the shielded metal arc welding (SMAW) process using E1094 coated electrodes was utilized at two preheating temperatures to join the

specimens. Subsequently, the microstructure and mechanical properties, including hardness and tribological behavior, were evaluated.

Microstructure of High-Silicon Gray Cast Iron

To investigate the microstructure of the as-cast gray iron specimens in this research, the samples were examined via optical microscopy following standard preparation. Figure 4 presents the optical micrograph of the as-cast specimen. As observed, the microstructure consists of flake graphite morphology uniformly distributed within the matrix. The produced gray cast iron was classified according to the ISO 945-1 standard. Based on the specifications of this standard, gray cast irons are categorized and designated according to their graphite type, size, and distribution pattern.



Fig. 4. Microstructure of the as-cast high-silicon gray cast iron.

Relationship 1 illustrates this classification through an example:

Relationship 1: I A 4

This relationship indicates that the microstructure of the produced gray cast iron comprises Type I graphite morphology with Distribution A and Size 4. Figure 5 summarizes these comparative reference images. Based on the micrographs of the as-cast sample and the requirements of the ISO 945-1 standard, the

produced cast iron is classified as type IC4. To determine the volume fraction of the phases and graphite in the structure, images captured from various regions of the sample were analyzed using ImageJ software. Table 3 presents the results of this evaluation. According to this table, the average graphite content in the structure is 19.75%, while the matrix phase constitutes 80.25%.



Fig. 5. (a) Type and (b) distribution pattern of graphite in the produced cast iron [12].

Table 3. Determination of phase and graphite fractions in the gray cast iron microstructure (Area fraction %)

	Image 1	Image 2	Image 3	Image 4	Average
Graphite percentage	18.39	20.51	20.21	19.89	19.75
Matrix phase percentage	81.61	79.49	79.79	80.11	80.25

The final properties of cast irons are highly dependent on their microstructure. The morphology and distribution of graphite, along with the matrix phase, are the primary determinants of the properties of this alloy. One of the key parameters for achieving desirable properties in gray cast irons is the absence of carbides within the microstructure. As observed in the micrographs of the as-cast sample, no traces of carbide presence are detectable. The matrix phase in these cast irons consists of silicoferrite (a ferritic matrix containing a high concentration of dissolved silicon in solid solution). According to the Fe-Si

binary phase diagram, increasing the silicon content in the iron matrix leads to the formation of a silicoferrite solid solution. The formation of this ferritic matrix, in conjunction with flake graphites, not only enhances corrosion resistance in acidic environments but also increases the hardness to approximately 500 Brinell, as well as improving the strength of the gray cast iron [12].

To further investigate the phases formed in the as-cast gray iron, X-ray diffraction (XRD) phase analysis was conducted. Figure 6 illustrates the XRD pattern of this specimen.

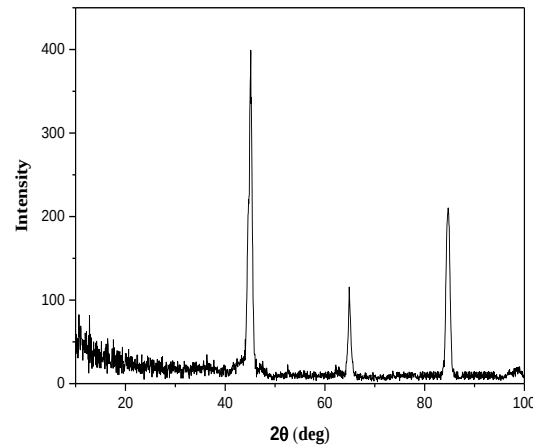


Fig. 6. X-ray diffraction (XRD) pattern of the as-cast high-silicon gray cast iron sample.

As can be seen, the dominant phase in this specimen is Fe_3Si . By matching the obtained diffraction pattern with the standard reference pattern (Card No. 00-035-0519), it is confirmed that the patterns are fully consistent, verifying the presence of the predominant silicoferrite phase [13].

Microstructure of the Welded Samples

Macroscopic Examination

The as-cast samples were joined using the shielded metal arc welding (SMAW) process with coated electrodes. To study the effect of preheating temperature on the microstructure and properties of the welds, two preheating temperatures—300 °C and 600 °C—were selected. The specimens were welded under these two conditions using the E1094 electrode and subsequently evaluated. The chemical composition and mechanical properties of the

selected electrode play a crucial role in cast iron welding. In cast iron welding, the electrode must be chosen such that dilution (changes in chemical composition between the base metal and filler metal in the weld zone) is minimized [14]. Therefore, based on previous studies and practical experience, the E1094 electrode was selected as the filler metal for joining the high-silicon gray cast iron. The nickel-based weld metal is chemically different from the high-silicon gray cast iron base metal; therefore, dilution control is important to limit excessive compositional mixing and to reduce the formation of undesirable brittle regions near the fusion interface. To examine the macroscopic structure of the welded specimens at the two different preheating temperatures, the weld cross-sections were analyzed. Figure 7 shows the macroscopic images of the weld cross-sections for the two welded samples.

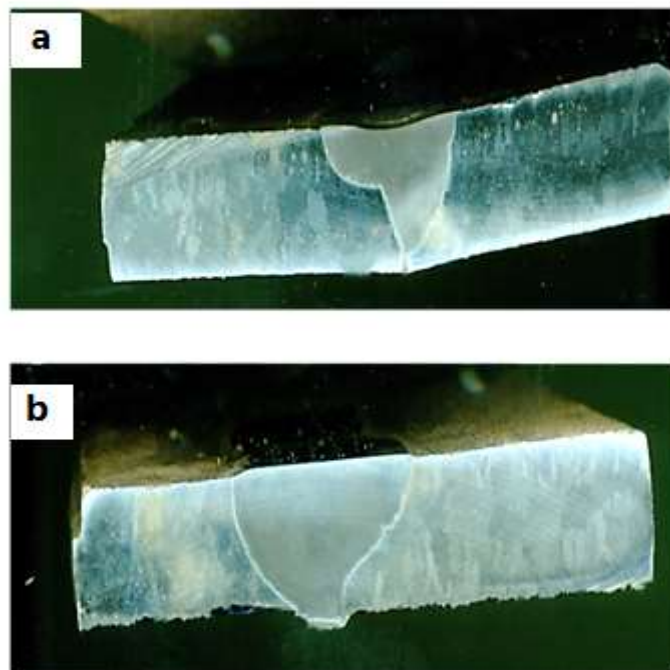


Fig. 7. Macroscopic cross-sectional images of the welded specimens at preheating temperatures of (a) 300 °C and (b) 600 °C.

As observed, a sound joint was formed in both specimens. Despite the differences in chemical composition between the base metal and the weld metal, common welding defects such as porosity, voids, incomplete fusion, and undercut were not

detected. Figure 8 shows the results of the liquid penetrant testing (PT) for both welded specimens. The absence of welding defects is further confirmed in these images.

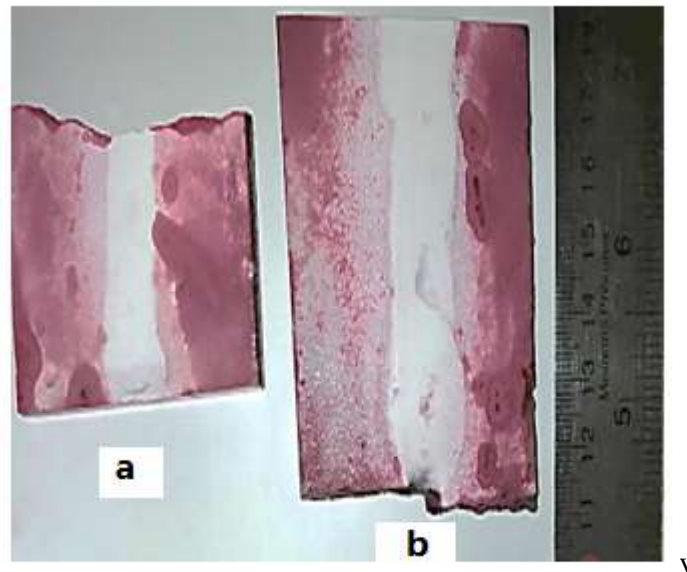


Fig. 8. Results of liquid penetrant testing (PT) on the surface of the welded specimens: (a) preheating temperature of 600 °C and (b) preheating temperature of 300 °C.

In order to investigate the effect of preheating temperature on the microstructure of the formed joint, all geometrical dimensions of the welded

specimens were measured according to the schematic shown in Figure 9. The results of these measurements are presented in Table 4.

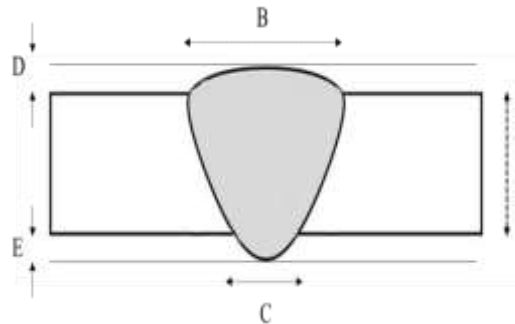


Fig. 9. Schematic cross-section of the welded specimens.

Table 4. Measurement of the dimensions of various weld zones (mm).

Specimen	A	B	C	D	E
Preheating temperature 600 °C	10	19	6	1.5	0
Preheating temperature 300 °C	10	14	1	0.5	0

Based on Figure 11 and the data presented in Table 4, it is evident that the weld toe angle in the specimen preheated to 600 °C is significantly larger than that of the specimen preheated to 300 °C. Furthermore, an increase in the dilution of the base metal into the weld metal is observed at the higher preheating temperature. The increase in weld zone width and dilution at higher preheating temperature can be explained by the fundamental thermodynamics of the welding process: increasing the preheating temperature extends the time required for the weld metal to

solidify. Simultaneously, as the temperature of the base metal increases, its thermal conductivity decreases. This reduction in thermal conductivity hinders the rate of heat dissipation from the weld pool into the surrounding material. Consequently, the molten metal remains in a liquid state for a more extended period, facilitating greater interaction and mixing between the filler and base metals, which ultimately results in a higher percentage of dilution [15, 16].

Microstructure of the Weld Metal

The microstructural evolution of the weld metal (WZ) was meticulously analyzed using optical microscopy. Figures 10 and 11 illustrate the microstructures across various regions of the welded joints at different magnifications. As shown in these micrographs, the joint architecture in both specimens consists of three distinct regions: the Weld Zone (WZ), the Base Metal (BM), and the Fusion Interface. In the center of the weld metal, the microstructure is entirely austenitic with an equiaxed dendritic morphology, which is characteristic of the nickel-based filler metal used. Interestingly, as we traverse from the weld center toward the fusion interface, the morphology transitions from equiaxed to columnar. The final morphology and scale of the microstructure are governed by two critical solidification parameters: the solidification rate R and the thermal gradient (G). At the center of the weld pool, where the G/R ratio is lower, the formation of equiaxed dendrites is favored. Conversely, moving toward the interface, the cooling rate and heat transfer dynamics shift, causing the G/R ratio to decrease in a manner that promotes the transition from equiaxed to columnar structures near the base metal boundary [15].

Graphite Evolution in the Heat-Affected Zone (HAZ)

A detailed examination of the HAZ reveals significant alterations in the size and distribution of the graphite flakes compared to the original as-cast structure. Since the specimens underwent preheating, the thermal cycles experienced by the base metal and HAZ have modified the graphite morphology. As depicted in Figure 13, the length and thickness of the graphite flakes increased following the application of preheating, with the effect being more pronounced at 600 °C. This growth can be attributed to the solid-state diffusion of carbon from the matrix to the existing graphite flakes. During welding, as the HAZ temperature rises, the solubility of carbon in the matrix phase increases. Because the re-diffusion of carbon back into the graphite is a time-dependent kinetic process, the reduced cooling rate associated with higher preheating temperatures provides the necessary “dwell time” for carbon atoms to migrate from the matrix to the graphite flakes. Thus, the slower cooling cycle facilitates this diffusion-controlled growth, leading to the observed coarsening of the graphite [17, 18].

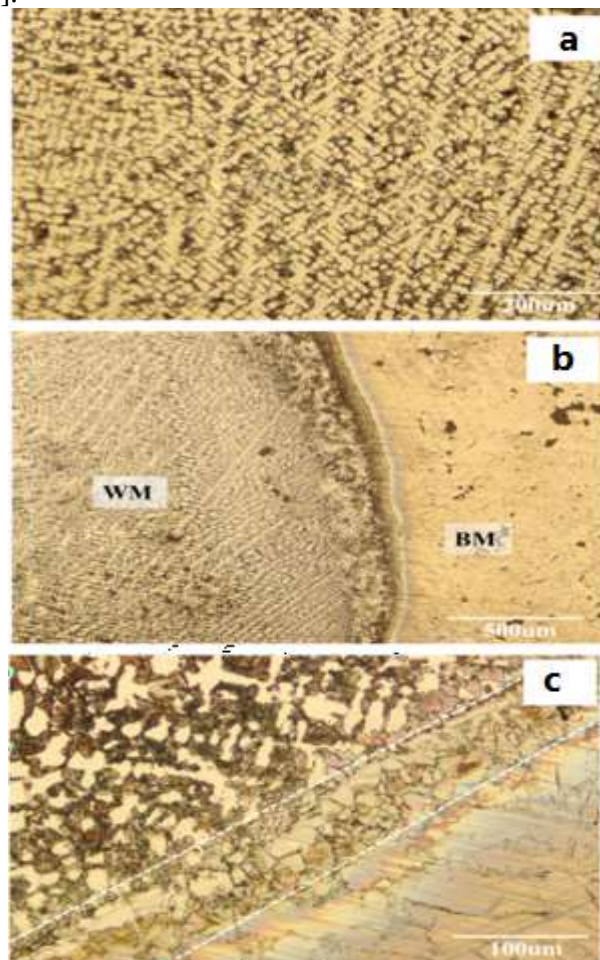


Fig. 10. Microstructure of the specimen welded at a preheating temperature of 300 °C: (a) weld metal, (b) boundary between the weld metal and base metal, and (c) weld metal/base metal interface.

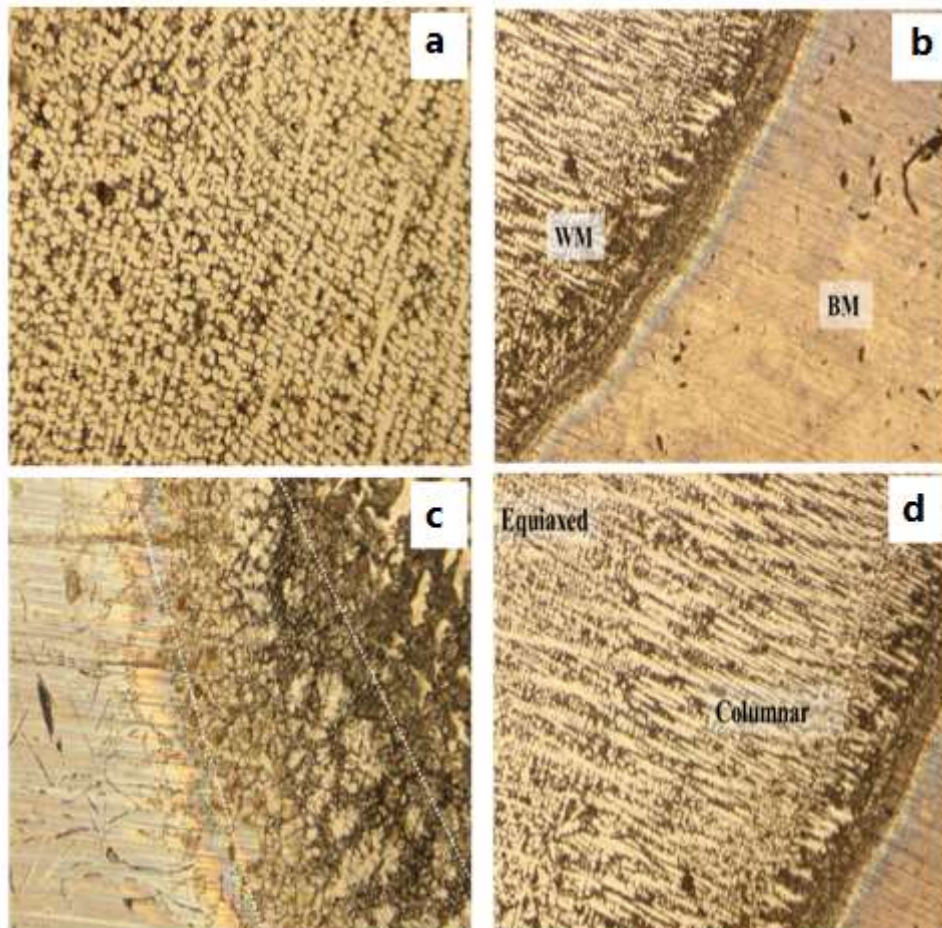


Fig. 11. Microstructure of the specimen welded at a preheating temperature of 600 °C: (a) weld metal, (b) weld metal/base metal boundary, (c) weld metal/base metal interface (higher magnification), and (d) higher magnification of image (b).

As previously established, in the specimen subjected to a higher preheating temperature, the cooling rate is significantly lower, and the solidification duration is extended compared to the specimen preheated at a lower temperature. Under these conditions, the dilution—the intermixing of the base metal and filler metal—is enhanced. This is clearly evidenced in the micrographs, where the width of the mixing zone at the interface of the weld and base metal is broader in the 600 °C preheated sample than in the 300 °C sample. Beyond the fusion zone, the Heat-Affected Zone (HAZ) also undergoes significant morphological expansion with the increase in preheating temperature. Elevated preheating reduces the cooling rate within the HAZ, providing a longer “thermal window” for microstructural transformations to occur. Consequently, the HAZ width in the specimen preheated at 600 °C is substantially larger than that in the specimen preheated at 300 °C [16, 19].

Microhardness Evaluation of the Welded Specimens

To investigate the hardness fluctuations across the various regions of the welded joints relative to each other and the base metal, as well as to determine the impact of preheating temperature on these profiles,

Vickers hardness testing was conducted. Hardness profiling was performed with a 30 kg load (HV30) on the cross-section of the specimens, strictly adhering to the ASTM E92 standard. Figure 12 illustrates the hardness profiles for both welded specimens. As seen in the profiles, hardness values fluctuate across the different zones. In both specimens, moving from the base metal toward the weld center initially results in a marginal hardness increase followed by a more significant rise. The data indicates that this localized hardness increment occurs specifically within the HAZ. This phenomenon is a direct consequence of the thermal cycle, which alters the local matrix properties [14].

Furthermore, it is observed that as the preheating temperature increases, this hardness peak in the HAZ occurs at a lower rate (i.e., the hardness is lower). This shift is attributed to the microstructural kinetics driven by the preheating temperature; as previously noted, higher preheating provides more time for carbon atoms to re-diffuse from the matrix into the graphite flakes. This depletion of carbon from the matrix effectively lowers the overall hardness of the region compared to specimens subjected to more rapid cooling [16, 20].

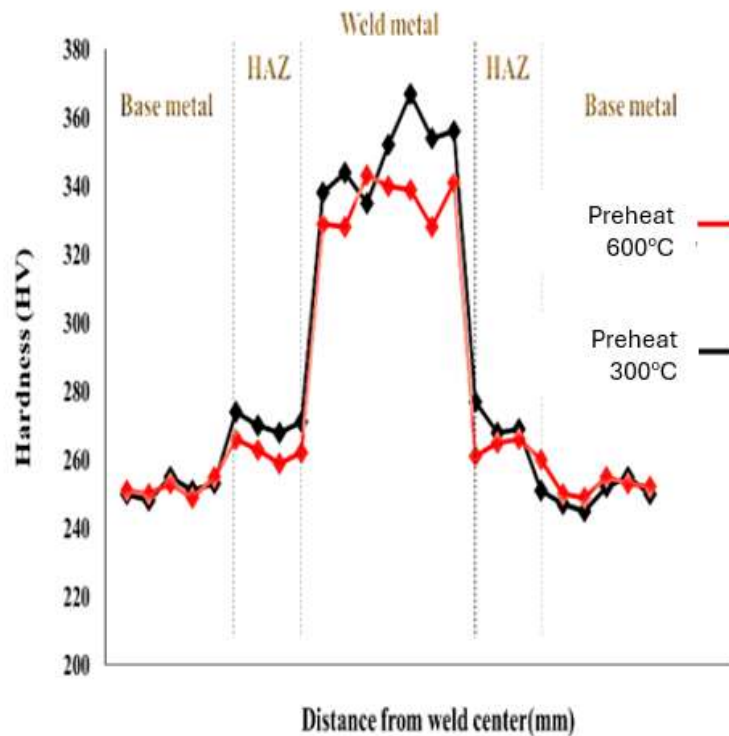


Fig. 12. Hardness profile of the welded specimens.

Analyzing the hardness profiles, it is immediately apparent that both welded specimens exhibit a profound surge in hardness within the weld metal relative to the base metal. This hardening effect is likely a manifestation of the equiaxed dendritic architecture formed during solidification, coupled with the probable precipitation of intermetallic complexes and the formation of highly concentrated solid solutions in this region. When comparing the hardness of the weld metal across the two different preheating temperatures, the discrepancy is governed by two critical factors: the scale of the equiaxed dendrites and the distribution of intermetallics within the fusion zone. The specimen preheated to 300 °C demonstrates slightly higher hardness values compared to the 600 °C specimen. From a kinetic perspective, the higher preheating temperature (600 °C) prolongs the solidification interval, thereby intensifying diffusion-driven processes. This extended thermal window facilitates grain coarsening and dendritic growth within the weld metal, which, according to the Hall-Petch relationship, inherently leads to a reduction in hardness [10, 21].

Evaluation of Tribological Behavior: As-Cast vs. Welded Specimens

To rigorously assess and compare the wear characteristics of the pristine as-cast material and the

welded specimens, a reciprocating sliding wear test under dry conditions was conducted. Our analysis focuses on weight loss trajectories, friction coefficient fluctuations, and the detailed morphology of the worn surfaces via Scanning Electron Microscopy (SEM). Figure 13 delineates the cumulative weight loss of the as-cast and welded samples as a function of the total sliding distance. As illustrated in Figure 13, all three specimens exhibit an expected upward trajectory in weight loss as the sliding distance increases. However, the as-cast specimen follows a much sharper gradient, signifying a significantly higher wear rate compared to the welded counterparts. Quantitatively, the as-cast material experienced a loss of approximately 8 mg after the initial 100 meters, which escalated to nearly 45 mg by the conclusion of the 1000-meter test. Remarkably, both welded specimens demonstrate superior wear resistance compared to the as-cast baseline. The most optimized performance is observed in the specimen preheated to 300 °C, which recorded a maximum weight loss of only ~15 mg after 1000 meters. In contrast, the 600 °C preheated specimen exhibited a weight loss of approximately 25 mg over the same distance, indicating that while welding improves wear characteristics, the specific preheating temperature is a decisive variable in optimizing the surface durability.

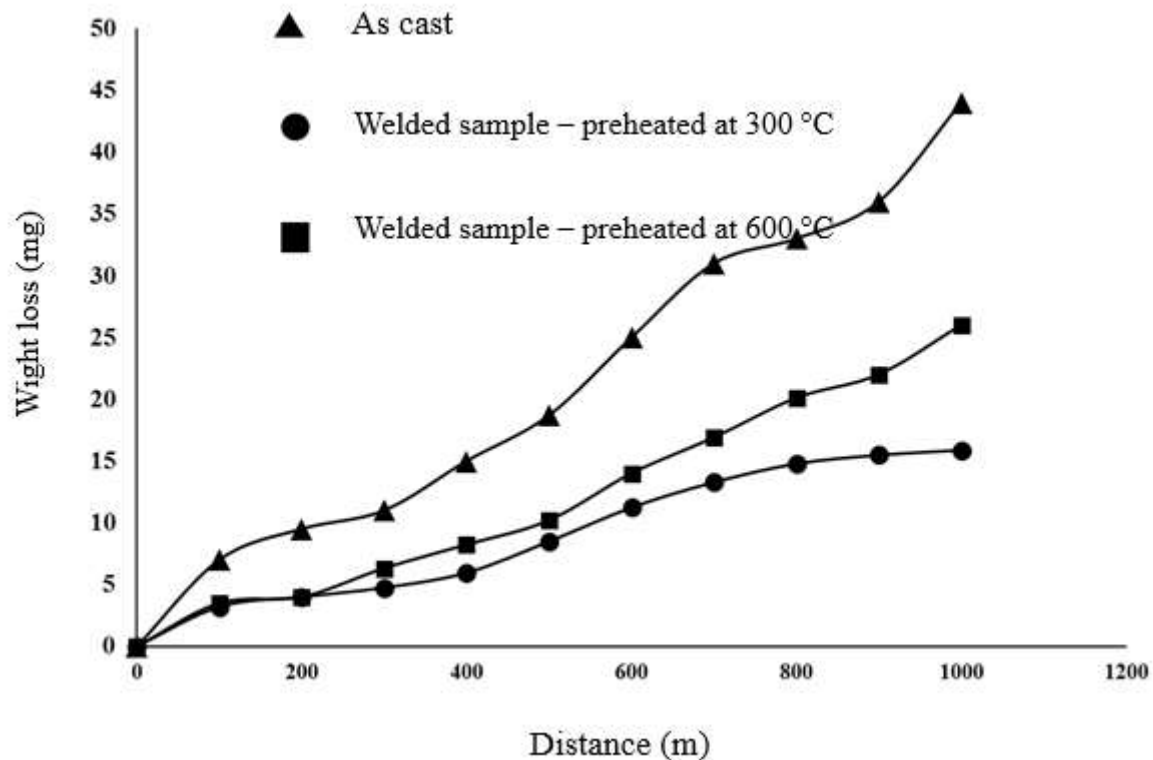


Fig. 13. Weight loss of specimens during the wear test.

The superior wear resistance of the welded specimens compared to the as-cast material is fundamentally rooted in the solidification-induced dendritic architecture and the resulting higher hardness within the fusion zone. However, the intra-welded comparison reveals a clear trend: as the preheating temperature increases, the wear rate follows suit. From a microstructural standpoint, elevating the preheating temperature to 600 °C extends the solidification interval. This prolonged exposure to high temperatures provides an ample “kinetic window” for diffusion-driven grain coarsening. Larger grains typically correlate with reduced hardness (consistent with the Hall-Petch phenomenon), which ultimately diminishes the surface’s resistance against the abrasive action of the counter-body pin. Consequently, the 600 °C specimen exhibits a significantly higher cumulative weight loss compared to the 300 °C specimen [22].

Analysis of the Friction Coefficient

Figure 14 illustrates the evolution of the friction coefficient (μ) for the three specimens. All samples exhibit a characteristic “run-in” phase during the initial 20 meters of sliding, where μ climbs sharply before reaching a steady-state regime. This initial instability is dictated by surface phenomenology specifically micro-topographical heterogeneities such as porosity, oxide scales, and surface impurities, alongside the geometric adaptation of the pin to the specimen’s surface. Remarkably, the mean friction coefficient for the 300 °C preheated specimen

remains the lowest, staying below 0.15, whereas the 600 °C and as-cast specimens demonstrate higher values. This disparity becomes particularly pronounced in the 800–1000 meter interval, a trend that corroborates the mass-loss data.

The higher cooling rate in the 300 °C preheated sample produces a refined micro-dendritic structure, particularly in the weld center. This structural refinement not only bolsters hardness but also serves as a primary driver for the observed reduction in μ and enhanced wear resistance.

Thermodynamic Considerations and Wear Mechanisms

The fluctuation of the friction coefficient can be further analyzed through the lens of interfacial temperature. Since the tests were performed at ambient temperature, the surface temperature is governed by the heat generated through friction, which can be quantified using the following relationship [23]:

$$Q = \mu W V \quad (1)$$

Where:

Q is the frictional heat.

μ is the friction coefficient.

W is the applied normal load (Newtons).

V is the sliding velocity (m/s).

Given that W and V were held constant for all welded specimens, the heat flux entering the tribological system is directly proportional to μ . Thus, the 600 °C preheated specimen experienced a significantly higher frictional heat input.

This temperature rise at the sliding interface triggers two competing effects:

1- Thermal Softening: Elevated temperatures reduce the material's yield strength, leading to increased plastic deformation, higher μ , and greater material loss.

2- Oxide Glaze Formation: High temperatures promote the growth of oxide layers. If stable, these layers can act as a solid lubricant, preventing metal-to-metal contact and potentially reducing friction.

To resolve which mechanism dominates, we utilized Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDS). Figures 15 and 16 display the worn surface morphologies for the 300 °C and 600 °C specimens, respectively.

Micro-Morphological Findings

In the 300 °C preheated specimen (Figure 15), the wear surface shows evidence of adhesive wear and localized oxidation. However, compared to the 600 °C sample, the delamination of material layers is markedly less severe. The EDS analysis further confirms a relatively lower oxygen concentration on

this surface. The lower μ in this specimen resulted in less frictional heating, thereby suppressing intense oxidation and the subsequent spalling of brittle oxide flakes.

Conversely, the 600 °C specimen (Figure 16) exhibits extensive layer delamination and “plate-like” debris on the verge of detachment. Point 2 on the EDS spectrum reveals a substantial oxygen percentage, indicating a dominant oxidative wear mechanism. In this case, the higher frictional heat promoted the formation of thick, brittle oxide scales which, under the reciprocating stress of the pin, fractured and detached, accelerating the wear rate. To conclude the analysis, the wear debris was examined (Figure 17). The debris from the 300 °C specimen is notably smaller in dimension and contains less oxygen than that of the 600 °C specimen. This confirms that at higher preheating temperatures, the combination of grain growth and increased frictional heat shifts the wear regime toward more aggressive adhesion and macro-oxidation, leading to the detachment of larger, more oxidized metallic sheets from the surface.

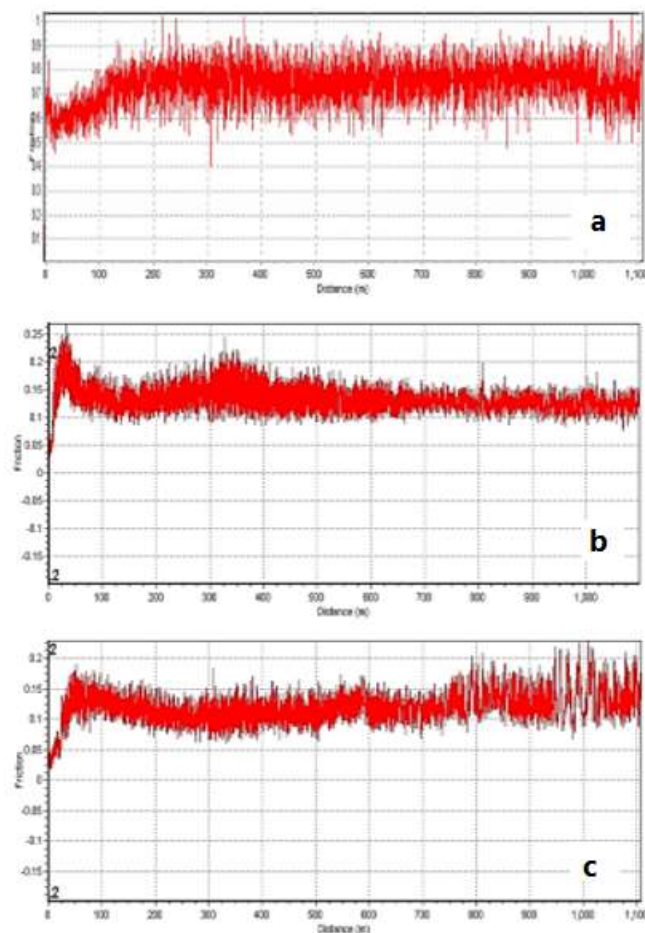


Fig. 14. Friction coefficient profiles for: (a) the high-silicon gray cast iron specimen, (b) the specimen welded at a preheating temperature of 300 °C, and (c) the specimen welded at a preheating temperature of 600 °C.

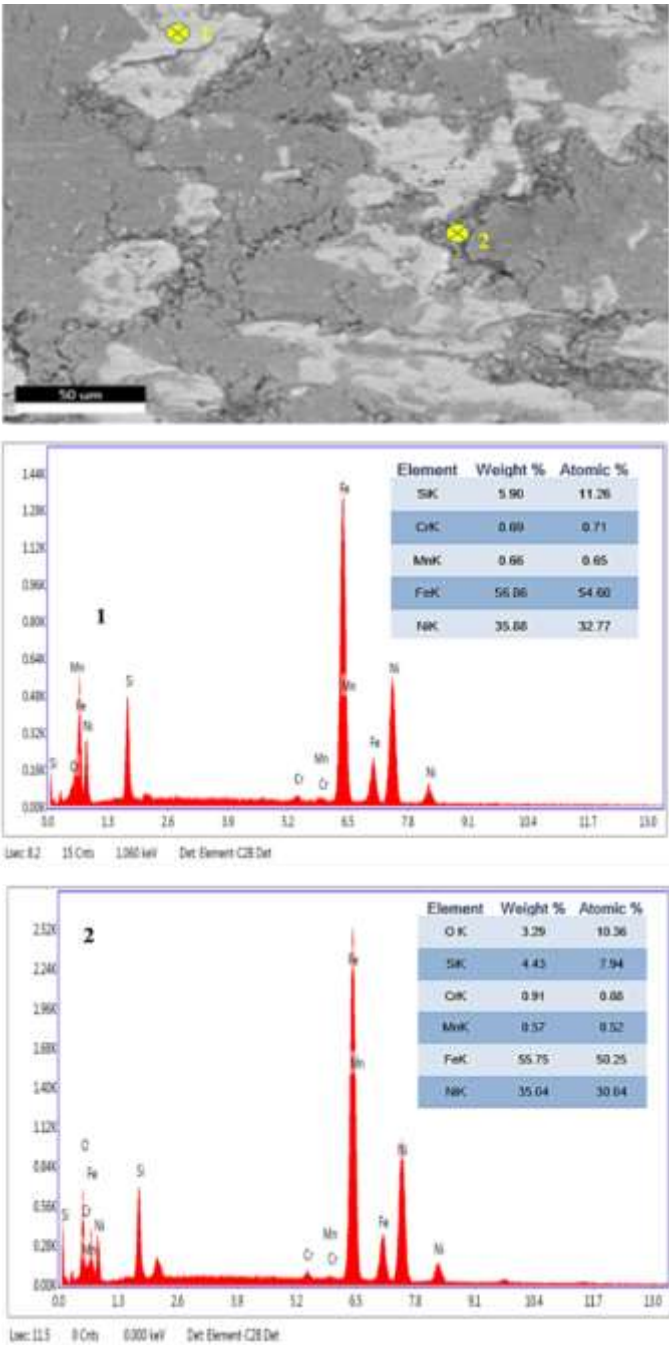


Fig. 15. Worn surface morphology and corresponding EDS analysis of the specimen welded at a preheating temperature of 300 °C.

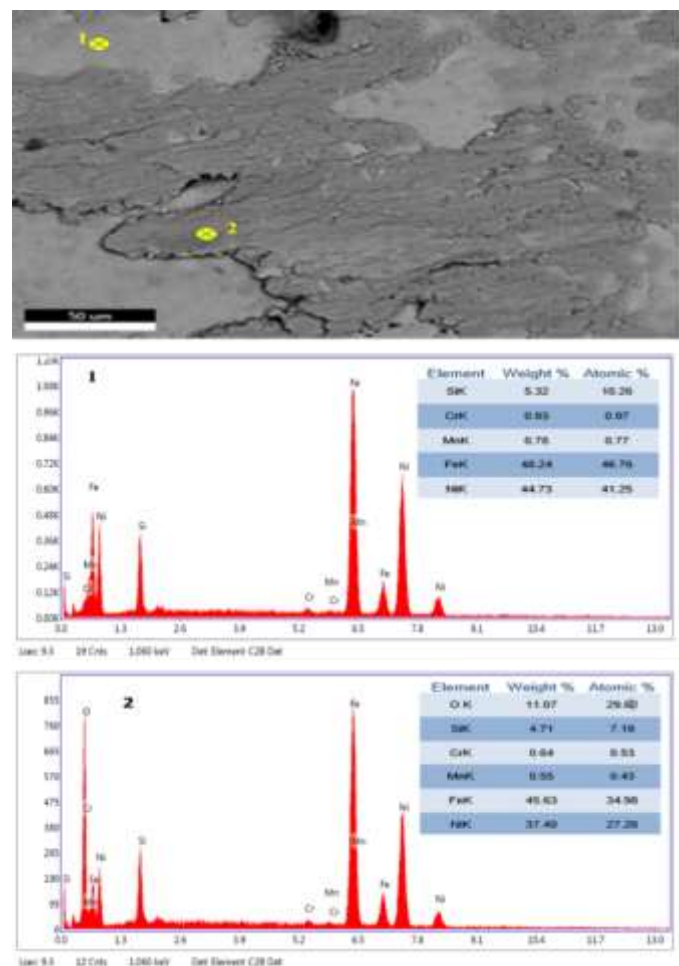


Fig. 16. Worn surface morphology and Energy-Dispersive X-ray Spectroscopy (EDS) analysis for the specimen welded with a preheating temperature of 600 °C.

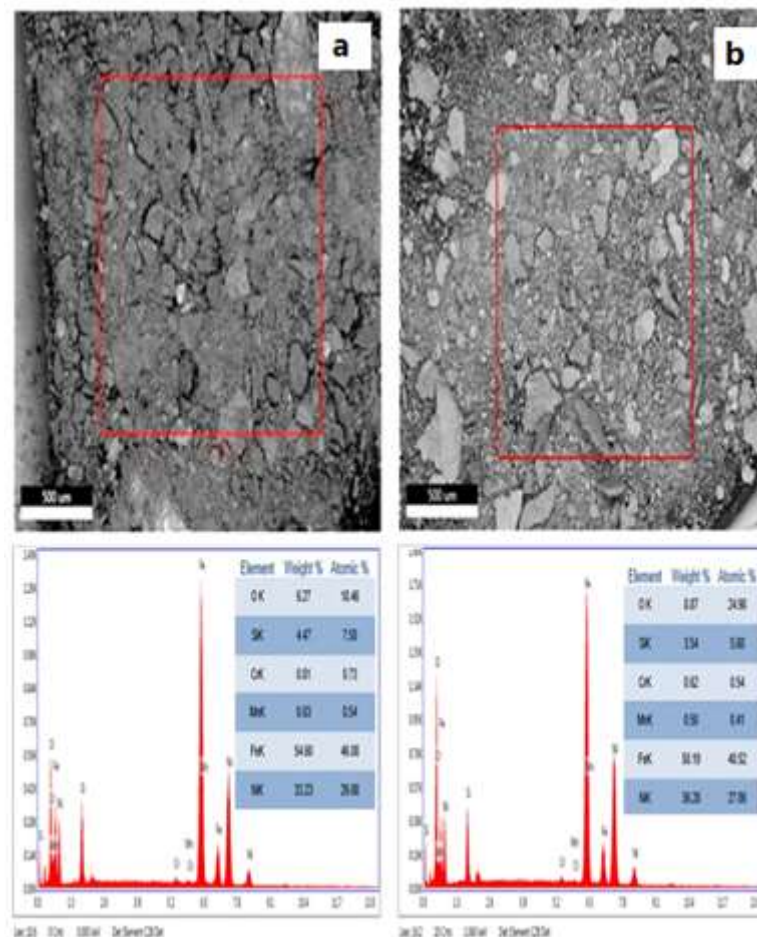


Fig. 17. Wear debris morphology: (a) specimen welded at 300 °C preheating temperature, and (b) specimen welded at 600 °C preheating temperature.

Conclusions

In this comprehensive investigation, high-silicon gray cast iron was successfully synthesized via casting and subsequently joined using the Shielded Metal Arc Welding (SMAW) process with coated electrodes. To elucidate the influence of thermal management on the resulting joint integrity, two distinct preheating temperatures—300 °C and 600 °C—were employed. The microstructural evolution and mechanical properties were rigorously evaluated using advanced microscopy (OM and SEM), Vickers microhardness profiling, and reciprocating wear analysis. The salient findings of this research are summarized as follows:

- **Joint Integrity:** Sound, defect-free welds were achieved at both preheating temperatures (300 °C and 600 °C). Macroscopic and liquid penetrant testing (PT) confirmed the total absence of common welding defects, including porosity, lack of fusion, or solidification cracking.
- **Microstructural Architecture:** The weld metal (WZ) exhibited a spatially heterogeneous morphology in both specimens. The central region of the fusion zone was characterized by equiaxed dendritic structures, whereas the regions adjacent to

the fusion boundary transitioned into columnar dendrites—a phenomenon dictated by the local solidification rate and thermal gradient (G).

- **Thermal Kinetics at 600 °C:** Elevating the preheating temperature to 600 °C significantly extended the solidification interval. This prolonged thermal exposure facilitated a broader weld zone and a marked coarsening of the microstructure compared to the lower preheat condition.
- **Hardness Variations:** The specimen preheated to 300 °C exhibited consistently higher hardness in both the weld metal and the heat-affected zone (HAZ) relative to the 600 °C specimen. This is attributed to the more rapid cooling rate which restricted grain growth and limited the diffusion-controlled growth of graphite flakes in the HAZ.
- **Tribological Performance:** The dominant wear mechanisms for the welded specimens were identified as adhesion and oxidation. The as-cast specimen exhibited more severe wear behavior compared with the welded specimens. Notably, the specimen preheated at 300 °C demonstrated superior wear resistance, as the refined microstructure and higher hardness suppressed the intensity of adhesive pull-out and the subsequent spalling of brittle oxide

layers. Therefore, under the investigated laboratory conditions, a preheating temperature of 300 °C is recommended for improving hardness and tribological performance.

- Although the present study clarified the effect of preheating temperature on the microstructure, hardness, and wear behavior of welded high-silicon gray cast iron, the investigation was limited to two preheating temperatures and one nickel-based electrode. Future studies may investigate the effect of post-weld heat treatment, different electrode materials, and corrosion behavior of the welded joints.

References

- [1] D. Stefanescu, "Casting, ASM Handbook, Vol. 15," ASM International Publisher, 1998.
- [2] M. Stawarz, W. Kajzer, A. Kajzer, and M. Dojka, "Physicochemical properties of silicon cast iron," *Archives of Foundry Engineering*, vol. 17, pp. 101–106, 2017.
- [3] H. Abbasi, M. Bazdar, and A. Halvae, "Effect of phosphorus as an alloying element on microstructure and mechanical properties of pearlitic gray cast iron," *Materials Science and Engineering: A*, vol. 444, pp. 314–317, 2007.
- [4] J. Hitchings and J. Klein, "Titanium in Cast Iron—Its Reactions and Effects," in *93rd AFS Casting Congress*, 1989.
- [5] T. Nylén, "Niobium in cast iron," in *International Symposium on Niobium*, 2001, pp. 1–25.
- [6] J. Dodd, "Microstructures and Notes on Acid Resisting High Silicon Iron Casting," *Foundry*, 1961, pp. 58–63.
- [7] G. Safronov, N. Safronov, and L. Kharisov, "Corrosion resistant high silicon cast iron for chemical engineering components," *Chemical and Petroleum Engineering*, vol. 51, pp. 142–144, 2015.
- [8] R. K. Bhatnagar and G. Gupta, "A review on weldability of cast iron," *International Journal of Scientific & Engineering Research*, vol. 7, 2016.
- [9] A. Sadeghi, A. Moloodi, M. Golestanipour, and M. M. Shahri, "An investigation of abrasive wear and corrosion behavior of surface repair of gray cast iron by SMAW," *Journal of Materials Research and Technology*, vol. 6, pp. 90–95, 2017.
- [10] M. Pascual Guillamón, C. Ferrer Giménez, and E. Rayón Encinas, "Weldability of spheroidal graphite ductile cast iron using Ni/Ni Fe electrodes," *Revista de Metalurgia*, vol. 45, pp. 334–338, 2009.
- [11] ASTM E92, *Standard Test Methods for Vickers Hardness and Knoop Hardness of Metallic Materials*. ASTM International.
- [12] H. T. Angus, *Cast Iron: Physical and Engineering Properties*. Elsevier, 2013.
- [13] J. R. Davis, *ASM Specialty Handbook: Cast Irons*. ASM International, 1996.
- [14] A. Suharto, D. D. Risanti, and Sekartedjo, "On welding gray cast iron using SMAW and GTAW process," in *AIP Conference Proceedings*, 2019, p. 060002.
- [15] S. Kou, *Welding Metallurgy*. New Jersey, USA, pp. 431–446, 2003.
- [16] E. El Banna, "Effect of preheat on welding of ductile cast iron," *Materials Letters*, vol. 41, pp. 20–26, 1999.
- [17] F. Unkic, S. Tounec, and M. Mikulic, "Microstructural and mechanical properties of the modified high silicon cast iron," *Strojarstvo*, vol. 36, pp. 241–245, 1994.
- [18] M. Pouranvari, "On the weldability of grey cast iron using nickel based filler metal," *Materials & Design*, vol. 31, pp. 3253–3258, 2010.
- [19] B. K. Srivastava, S. Tewari, and J. Prakash, "A review on effect of preheating and/or post weld heat treatment (PWHT) on mechanical behavior of ferrous metals," *International Journal of Engineering Science and Technology*, vol. 2, pp. 625–631, 2010.
- [20] R. Bushey, "Welding of cast irons," *ASM Handbook*, vol. 6, pp. 708–721, 1993.
- [21] G. E. Dieter and D. J. Bacon, *Mechanical Metallurgy*, vol. 3. McGraw Hill, New York, 1986.
- [22] R. Thornton, T. Slatter, A. H. Jones, and R. Lewis, "The effects of cryogenic processing on the wear resistance of grey cast iron brake discs," *Wear*, vol. 271, pp. 2386–2395, 2011.
- [23] I. Hutchings and P. Shipway, *Tribology: Friction and Wear of Engineering Materials*. Butterworth Heinemann, 2017.