

Analysis of welding techniques for spheroidal graphite cast iron

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Abstract. Although Spheroidal Graphite Cast Iron (SGCI) has good machinability, high strength, and ductility, its high carbon content makes welding difficult because it forms martensite and carbides in the heat-affected areas. This study examines welding techniques used in SGCI, with an emphasis on process variables, filler metal selection, and the impact of thermal cycles. It has been demonstrated that nickel-based electrodes with Inconel 625 fillers are efficient in lowering carbide precipitation and encouraging graphite production, which enhances ductility and lowers the danger of cracking. Better mechanical strength and toughness are achieved by further reducing hardness gradients, residual stresses, and brittle microstructures with preheating and post-weld heat treatments. A comparative study of Tungsten Inert Gas (TIG) and Shielded Metal Arc Welding (SMAW) reveals that the most dependable method for creating strong, machinable joints in SGCI components is to combine nickel-based fillers with ideal thermal treatments.

1 Introduction

Spheroidal graphite cast iron (SGCI), or ductile cast iron, is a cast ferrous alloy in which carbon is mostly found as spheroidal graphite nodules in a ferritic–pearlitic matrix [1,4]. This morphology enhances ductility, toughness, and fatigue resistance compared to grey cast iron, making SGCI a preferred choice for components in the automotive, heavy equipment, and pressure-containing industries [1]. A variety of welding techniques, each with unique metallurgical and mechanical results, have been used on SGCI. Due to its adaptability and capacity to deposit electrodes made of stainless steel or nickel, shielded metal arc welding (SMAW) is frequently used to increase the ductility and decrease the brittleness of the weld metal [1]. Although less frequently employed in industrial settings, oxyacetylene welding (OAW) has proven useful for joining and repairs if grey cast iron filler rod is used, especially in situations where cost considerations take precedence over good mechanical performance [1]. When employing high-performance filler alloys like Inconel 625 to reduce carbide precipitation and enhance nodule shape, tungsten inert gas (TIG) welding offers better control over heat input and is beneficial for root passes [1].

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This study compares the effectiveness of various welding procedures or techniques in welding SGCI.

2 Literature review

The formation of brittle martensitic and carbide microstructures in the heat-affected zone (HAZ) and fusion zone (FZ), increases crack susceptibility and makes welding of spheroidal graphite (ductile) cast iron difficult. Pre-heating and post-weld heat treatment of nickel or nickel-iron electrodes reduces brittleness and improves ductility. On the other hand, spheroidal graphite cast iron maintains its natural brittle character even during heat cycles. Thus, this paper critically assesses both conventional and cutting-edge welding methods as well as various cast iron kinds to pinpoint successful tactics and identify areas that require more investigation.

2.1 Types of cast iron

Cast irons are a family of ferrous alloys containing 2.5–4.0% carbon and 1–3% silicon, with their properties determined by the form and distribution of carbon in the microstructure [4]. There are several primary varieties of cast irons as listed below, each having unique mechanical and physical properties, depending on composition, cooling rate, and manufacturing. These metallurgical factors lead to different mechanical properties that influence the particular areas of application as depicted in figure 1.

- Grey cast iron (GCI) contains carbon in the form of graphite flakes, which act as internal discontinuities and give the fracture surface a grey appearance [4,5]. This shape affects tensile strength and ductility because of the flake-induced stress concentration, but it also provides superior machinability, thermal conductivity, and excellent damping capability. [4]. This type of cast iron is normally used in engine blocks, machine bases, brake rotors, and cookware.
- White cast iron (WCI) is distinguished by the lack of free graphite and the presence of carbon in the form of cementite, or iron carbide, which makes the material brittle but robust and resistant to wear. [4,6]. Its continuous cementite network is reflected in its white fracture surface. White cast iron is frequently utilized in slurry pump housings, crusher parts, and mill liners because of its abrasion resistance.
- Malleable cast iron (MCI) is produced by heat-treating white cast iron to break down cementite into clusters of temper carbon clusters, improving ductility and toughness [4,7]. This type of cast iron is frequently used for fasteners, pipe fittings, and automobile parts that need to be moderately strong and machinable.
- Ductile cast iron (DCI) contains spherical graphite nodules. This shape makes ductile iron ideal for gears, crankshafts, heavy machinery parts, and structural applications by greatly increasing its tensile strength, impact resistance, and fatigue life, achieved by adding magnesium or cerium to molten iron before casting [4,8]. This morphology significantly enhances tensile strength, impact resistance, and fatigue life, making ductile iron suitable for gears, crankshafts, heavy machinery components, and structural applications.
- Compacted graphite iron (CGI) has linked worm-like (vermicular) graphite particles that have a graphite shape halfway between that of ductile and grey irons. [4,9]. CGI is appropriate for high-performance engine blocks, exhaust

manifolds, and brake discs because it combines strength, heat conductivity, and damping capacity.

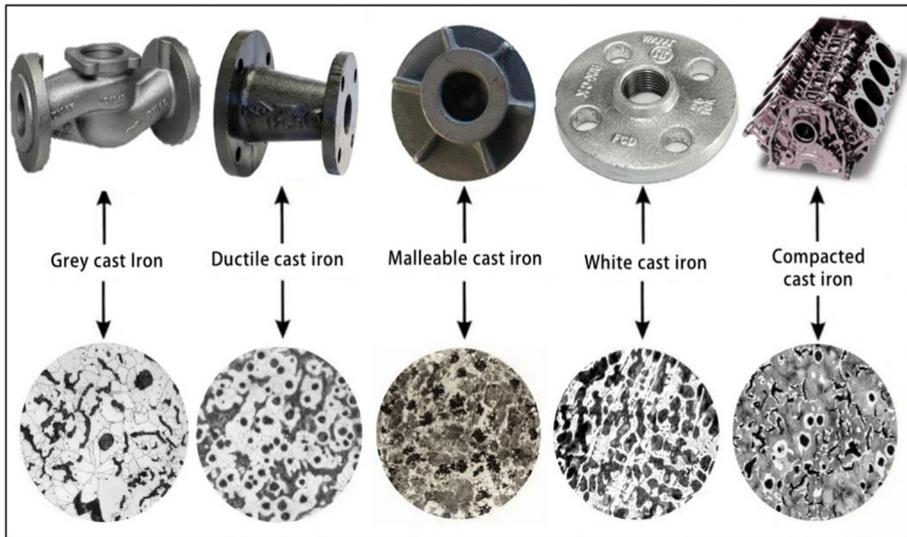


Fig. 1. Types of cast irons [26].

2.2 Weldability challenges

Despite its engineering benefits, SGCI poses significant weldability issues due to its complicated microstructure and high carbon content, usually ranging between 3.2 and 3.6 weight percent (wt.%). Fast cooling during welding encourages the precipitation of cementite and carbide in the heat-affected zone (HAZ) and fusion zone (FZ), increasing hardness and causing embrittlement [6]. Furthermore, residual stresses are created by the discrepancy in thermal expansion coefficients between graphite nodules and the metallic matrix, making them more prone to breaking [4,8].

Additionally, because nodules partially dissolve into the matrix at high temperatures, locally increasing the carbon concentration and encouraging martensitic transformation during cooling, the welding thermal cycle can impair graphite morphology [9]. Problems arise from both inadequate and excessive heat input. While excessive heat input can result in toughness loss and grain coarsening, low heat input speeds up cooling rates and martensite formation [10].

3 Welding methods overview

Welding is a fabrication technique that joins materials, typically metals, by heating the workpieces and melting the filler material to create a strong, permanent bond. This section gives a summary of the many welding techniques utilized for SGCI welding. Common methods such as gas and arc welding will be examined, along with their main features and uses.

3.1 Gas metal arc welding (GMAW)

GMAW, or MIG welding, as schematically presented in figure 2, is a popular welding method for welding SGCI because of its rapid deposition rates and ease of automation. However, if SGCI's high carbon content is not adequately controlled, it may result in the production of brittle phases like cementite and martensite. A study by Alizadeh et al. [11] looked into welding a high-Si DCI using the GMAW technique. A pure Ni filler encouraged graphite production in the fusion zone, leading to a softer weld and lower solidification stresses, whereas a Ni-Fe ($\approx 45\%$ Ni) filler created a cementite-rich fusion zone with high hardness and increased cracking risk. For this investigation, no heat treatments were used. In the heavy machinery and automotive industries, GMAW is frequently used for the manufacturing and maintenance of SGCI components, including suspension and engine blocks.

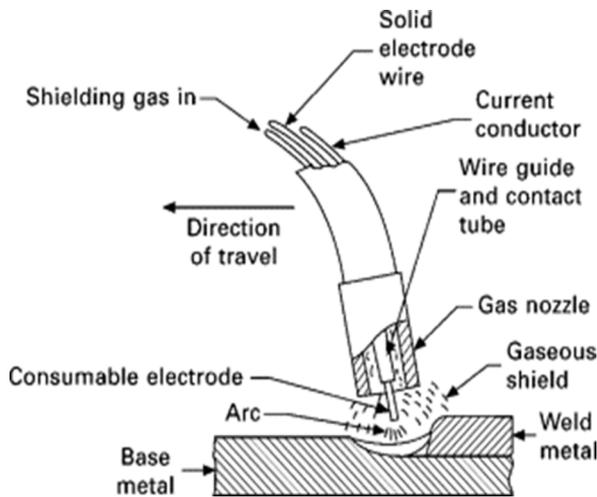


Fig. 2. GMAW process overview [24].

3.2 Shielded metal arc welding (SMAW)

Stick welding, or SMAW shown in figure 3, is a flexible technique appropriate for SGCI field repairs. To reduce the chance of cracking, proper electrode selection and preheating are necessary. According to Gouveia et al. [12], SMAW of ductile cast iron using electrodes based on copper was less successful and typically resulted in lower mechanical performance. Welds displayed localized brittle phases in the as-welded state, whereas annealing and stress relief treatments (about $600\text{ }^{\circ}\text{C}$) improved toughness, softer HAZ, reduced residual stresses, microstructure refinement, and improved characteristics. In industry, SMAW is often used to repair SGCI components, such as castings in pumps and valves, where mobility and ease of usage are crucial.

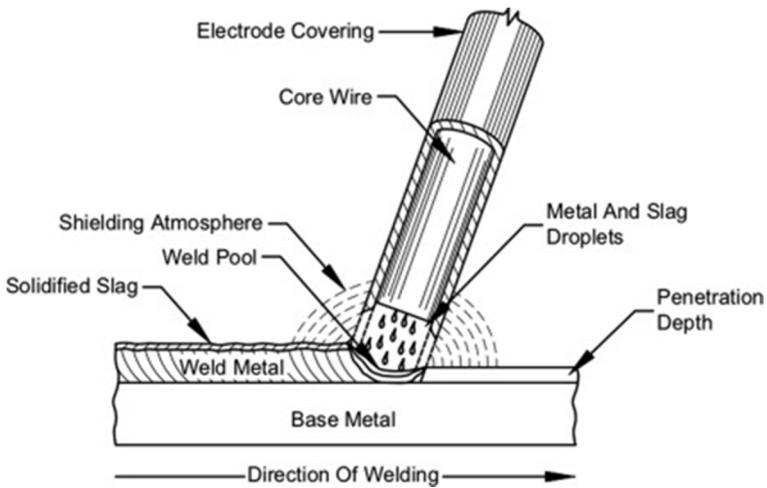


Fig. 3. SMAW process overview [23].

3.3 Gas tungsten arc welding (GTAW/TIG)

GTAW, schematically shown in figure 4, often known as TIG welding, provides accurate heat control and is perfect for SGCI thin-section welding. However, because of its low deposition rate, thicker areas may need more than one pass. According to a study by Suharto et al. [13], careful temperature management is necessary for GTAW of ductile cast iron to produce mechanically dependable welds. Brittle phases were substantially minimized, and residual stresses were reduced by preheating at 200–300 °C. Thin-walled SGCI components can be welded with GTAW in precision engineering and aerospace, two fields where excellent welds are crucial.

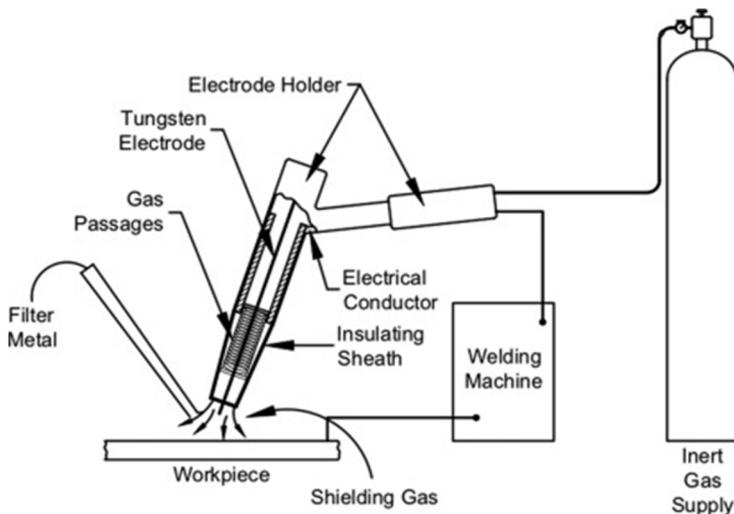


Fig. 4. GTAW process overview [23].

3.4 Laser beam welding (LBW)

As schematically depicted in figure 5, LBW is an advanced welding method that provides excellent accuracy with less heat input. To avoid the creation of unwanted microstructures, welding settings must be carefully controlled. Li et al. [14] examined the use of nickel-based filler materials in the laser welding of SGCI. According to the study, LBW decreased distortion and the heat-affected zone (HAZ), but because of its high cooling rates, it also made cracking more likely. To lessen these problems, it was crucial to employ the right filler materials and carefully monitor the welding settings. When producing high-precision SGCI parts, such as turbine blades and automobile components, where dimensional accuracy and low thermal distortion are essential, LBW is used.

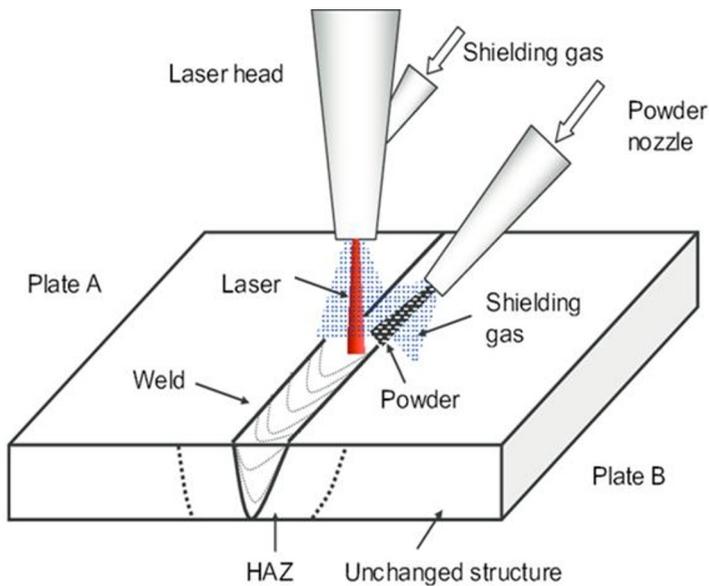


Fig. 5. Laser beam process overview [23].

3.5 Electron beam welding (EBW)

EBW is a high-precision welding technique that requires less heat and provides deep penetration, as illustrated in figure 6. But it needs a vacuum atmosphere, and it is usually only utilized for specific purposes. Sekiguchi et al. [15] examined how EBW affected SGCI joints. The study showed that although EBW generated deep penetration welds with little distortion, brittle phases might occur because of the fast-cooling rates. To enhance the mechanical qualities of the welds, the study suggested using insert metals like pure nickel or austenitic stainless steel. In the aerospace sector, EBW is used to weld SGCI components, including structural elements in aircraft engines, that need to be extremely precise and have little thermal distortion.

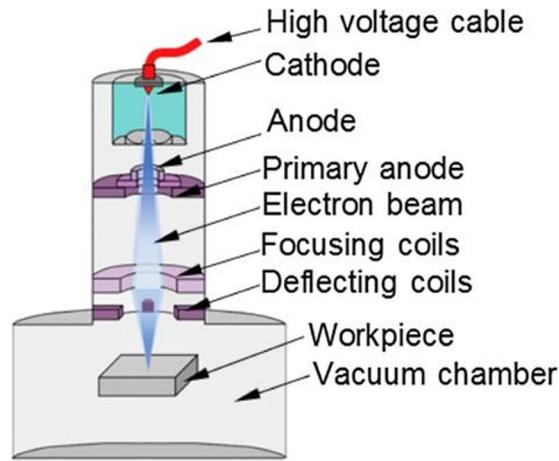


Fig. 5. Electron beam process overview [25].

A comprehensive summary of the all the above described SGCI welding techniques is presented in Table 1 below.

Table 1. Summary of SGCI Welding Techniques [11,12,13,14,15].

Welding Technique	Advantages	Limitations / Challenges	Typical Applications	Preheating / PWHT Recommendations
GMAW (Gas Metal Arc Welding)	High deposition rate; good heat input control; suitable for medium-to-thick sections	Susceptible to porosity; requires nickel-based fillers; HAZ cracking possible.	Fabrication and repair of SGCI components, medium-thickness plates	Preheat 200–300 °C; interpass \leq 350 °C; PWHT optional depending on service
SMAW (Shielded Metal Arc Welding)	Widely available; flexible for field repairs; low equipment cost	Slower deposition; high risk of HAZ cracking; requires low-hydrogen electrodes	On-site repairs, small to medium cast iron parts	Preheat 250–400 °C; controlled interpass; PWHT recommended to relieve residual stress
GTAW/TIG (Gas Tungsten Arc Welding)	Precise heat control; minimal dilution; suitable for thin sections	Low deposition rate; requires skilled operator; time-consuming	Thin sections, critical joints, precision repairs	Preheat 150–250 °C for thin sections; PWHT is optional but beneficial for ductility.
LBW (Laser Beam Welding)	Very low heat input; narrow HAZ;	High residual stresses; precise setup	High-precision components,	Preheat 150–200 °C; PWHT recommended for

	minimal distortion	needed; expensive	aerospace or automotive castings	thick sections or high-stress applications
EBW (Electron Beam Welding)	Deep penetration; excellent control; narrow HAZ	Vacuum requirement, high equipment cost, and potential cracking	Specialized industrial applications, high-value components	Preheat 150–250 °C; PWHT recommended for thick or critical joints

4 Filler metal selection

Selecting the right filler metal is essential for regulating weld quality and reducing flaws. Because of their superior compatibility with SGCI, which lowers the formation of hard phases and increases ductility, nickel-based fillers are the most employed. Additionally, Ni-Fe and Ni-Cu fillers are used to correct for thermal expansion mismatch and stop solidification cracking. [16]. The welding process, the planned service conditions, and the desired strength-to-toughness ratio all influence the filler selection.

5 Thermal management impact

To avoid cracking in SGCI welds, thermal management is essential. It is usually advised to preheat to 200–400 °C to decrease the production of martensitic structures in the heat-affected zone (HAZ), slow cooling rates, and lessen thermal gradients. [12]. Post-weld heat treatment (PWHT) and controlled interpass temperatures are also used to reduce residual stresses and enhance ductility. HAZ brittleness is minimised, and thermal distortion is further reduced by methods like low heat input welding (GTAW or pulsed GMAW). [11].

6 Microstructure and defect analysis

The welding parameters have a significant impact on the microstructure of SGCI welds. A mixture of pearlite, ferrite, and martensite is frequently seen in the fusion zone, although brittle phases may form in the HAZ if cooling occurs too quickly.[16]. Common defects include:

- Hot cracking: These start in the HAZ because of the carbon segregation and thermal stress.
- Porosity: Caused by trapped gases during solidification.
- Graphite flake degeneration: Reduces fatigue resistance and causes localized brittleness.

Scanning electron microscopy (SEM), optical microscopy (OM), and microhardness mapping are examples of advanced characterization techniques that are used to analyse weld microstructure and determine the causes underlying defect generation. [14]. These evaluations serve as a guide for choosing the best filler metal, welding conditions, and temperature control techniques.

7 Joining dissimilar metals

Welding SGCI to dissimilar metals, such as stainless steel or mild steel, presents unique challenges due to differences in thermal expansion, melting points, and microstructural characteristics. Several techniques have been explored to achieve sound joints:

- **Laser welding:** Research has indicated that laser welding between mild steel and SGCI is feasible. For example, a study by Katayama et al. [17] examined the laser welding of SGCI and low alloy steel, emphasizing the significance of regulating welding speed and laser power to reduce the production of brittle phases and guarantee joint integrity.
- **Electron beam welding (EBW):** Research shows that insert-type EBW can enhance joint performance by reducing the production of brittle phases, which is why it has been used to link SGCI to mild steel. Sekiguchi et al. [18] observed improvements in mechanical qualities when insert-type EBW was applied to mild steel and SGCI joints.
- **Friction stir welding:** To join SGCI to mild steel, friction welding methods like continuous drive friction welding (CDFW) have been used. Peak temperatures and effective stresses, two critical factors in welding parameter optimization, were predicted by experimental and simulation investigations by Winiczenko et al. [19] that replicated the CDFW method.

These methods require careful selection of welding parameters and filler materials to accommodate the differing properties of the base metals and achieve reliable joints.

8 Modeling approaches

For SGCI, welding process modeling is crucial for predicting microstructural evolution, stress distribution, and thermal cycles. Various approaches have been developed:

- **Finite element modelling (FEM)** is a widely used technique for simulating the mechanical and thermal characteristics of welding. Winiczenko et al. [19] Simulated the CDFW process using a linked thermal and mechanical 2.5D FEM model, predicting peak temperatures, effective stresses, and axial shortening, all of which are essential for understanding joint formation.
Microstructural Modeling: Models have been created that consider the pearlite nodule nucleation and growth in SGCI. A microstructural model that takes into consideration the metastable eutectoid transformation in SGCI was described in a study by Carazo et al. [20], which shed light on the microstructural changes that occur during welding.

These modeling techniques help to improve the quality and dependability of SGCI welds by predicting the results of welding processes and optimizing welding settings.

9 Conclusion

According to this study, nickel-based fillers that inhibit carbide formation, like pure Ni and Inconel 625, are the most successful at addressing the problems associated with SGCI welding. Hardness gradients are reduced, residual stresses are relieved, and toughness is further improved by thermal control using preheating and post-weld heat treatments. SMAW,

GMAW, and TIG welding consistently produce strong, ductile, and machinable joints when paired with nickel-rich fillers and precise temperature cycles. These results validate that the key to obtaining dependable weldability of SGCI components in industrial applications is the choice of filler metal and heat treatment techniques.

Practical Implications: By using nickel-based fillers in conjunction with carefully controlled preheating and post-weld heat treatments, the industry may increase the reliability of SGCI components in critical service settings, prolong component life, and reduce repair failure rates.

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