

A Novel Approach to Pulse Laser Welding of Nodular Cast Iron Without Pre- and Post-Weld Heat Treatment

Nodular cast iron is widely used in industry for its excellent mechanical properties, but its poor weldability mainly due to brittle martensite formation. Conventional Shielded Metal Arc Welding (SMAW) typically requires preheating and post-weld heat treatment (PWHT). This study, conducted between August 2024 and May 2025, investigates the use of Pulsed Laser Welding (PLW) as a novel repair method without preheating or post-weld heat treatment (PWHT). Microstructural and hardness analyses showed that multi-layer PLW significantly reduces martensite formation and promotes a pearlitic structure in Heat Affected Zone (HAZ) PLW joints exhibited more uniform and lower hardness than SMAW, reducing brittleness and crack susceptibility

Pulse Laser Welding Technology

Pulse Laser Welding (PLW) is an advanced joining technology that utilizes high-intensity laser pulses, rather than a continuous arc, to create precise and localized welds. Unlike conventional arc welding methods, which rely on

electric arcs and plasma as the heat source. PLW employs focused light energy in the form of short, controlled pulses. Each pulse delivers a concentrated energy burst within milliseconds, enabling fusion of the base and filler materials with minimal thermal distortion. This makes PLW particularly well-suited for applications requiring high precision, low heat input, and minimal impact on the surrounding material.

Unique Advantages of Pulsed Laser Welding

The pulsed nature of PLW offers several unique metallurgical and operational advantages that are difficult to achieve with conventional arc welding or cladding technologies.

First, the extremely short welding duration occurring within a fraction of a second, minimizes heat-affected zones and residual stress. This reduces the likelihood of distortion, cracking, or undesirable microstructural transformations. Second, the process provides full metallurgical bonding between the base material and filler metal. Lastly, the low overall energy input

enables welding of heat-sensitive or Crack-susceptible material, such as cast iron, without requiring thermal treatments pre and post-welding. These features make PLW a highly efficient and reliable method, especially in applications where precision and structural performance are critical.

Introduction

Nodular cast iron, also known as ductile iron, is extensively used in industrial applications that require high strength, good wear resistance, and excellent fatigue performance. Typical components manufactured from nodular cast iron include worm gear housings, gland seal guides, and impellers, which are widely employed in power transmission systems, rotating machinery, and fluid-handling equipment. These components are frequently subjected to cyclic loading, thermal variation, and severe service conditions, making repair and refurbishment unavoidable during their service life. Representative examples of such industrial cast-iron components are illustrated in Figure 1.



Fig 1: Representative nodular cast iron components commonly used in industrial applications:

(a) housing of a worm gear, (b) guide of a gland seal, and (c) impeller.

These components typically require repair welding during service due to wear, fatigue, or localized damage

Traditional arc welding methods, such as Shielded Metal Arc Welding (SMAW), typically necessitate preheating, post-weld heat treatment (PWHT), and tempering to prevent cracking and to stabilize the weld and HAZ microstructures. These additional thermal steps are labor-intensive, energy-consuming, and often impractical for large workpieces or in-field refurbishments.

Pulsed Laser Welding (PLW) has gained increasing attention due to its ability to deliver high-energy pulses of very short duration, typically in the millisecond range,

This process offers high energy density, narrow fusion zones, and low heat input, which help to minimize thermal distortion and preserve the mechanical properties of the surrounding material. Several studies have demonstrated the effectiveness of PLW in joining thin-section steels and high-strength alloys, highlighting its advantages in minimizing metallurgical defects, controlling phase transformations, and improving weld bead geometry. However, relatively few studies have examined the application of PLW to cast irons—materials inherently prone to solidification cracking,

porosity, and brittle microstructures due to their high carbon and silicon content.

The use of PLW presents a novel and promising approach to addressing the weldability challenges of cast iron, particularly through the development of a temper bead mechanism. By leveraging the precise thermal control of PLW, it is possible to promote beneficial microstructural evolution in the HAZ without the need for conventional preheating or PWHT. The temper bead effect

Table 1 The summary of welding parameters of PLW

Welding conditions	Welding process	Weld layer	Filler metal	Pulse frequency	Travel speed	Beam diameter	Pulse duration	Welding heat input
1	PLW	1 st	DSI Inconel 625 ϕ 1.2 mm	45 Hz	3 mm/s	5.5 mm	3.2 ms	0.4 kJ/mm
2	PLW	1 st	DSI Inconel 625 ϕ 1.2 mm	45 Hz	3 mm/s	5.5 mm	3.2 ms	0.4 kJ/mm (maximum)
	PLW	2 nd	DSI M 90 ϕ 1.6 mm	45 Hz	3 mm/s	5.5 mm	3.2 ms	

Table 2 The summary of welding parameters of SMAW

Welding conditions	Welding process	Weld layer	Filler metal	Electrode diameter	Welding current	Welding voltage	Welding heat input
1	SMAW	1 st	ENi-CI	3.2 mm	110 A	25 V	0.96 kJ/mm
2	SMAW	1 st	ENi-CI	3.2 mm	110 A	25 V	0.96 kJ/mm (maximum)
	SMAW	2 nd	E7016	3.2 mm	90 A	23 V	

Materials used in the study

Base material

The primary material used in this study was nodular cast iron grade EN-GJS-500, also known as FCD500 under JIS standards. This material is a type of ductile iron characterized by its spheroidal graphite microstructure, which imparts a unique combination of high strength, good ductility, and excellent fatigue resistance. FCD500 is widely used in the manufacturing of machine bases, engine blocks, pumps, gearbox casings, and various structural parts in heavy industries. Its ability to absorb impact energy while maintaining dimensional stability under cyclic loading.

Filler metals for PLW and SMAW

Proper filler metal selection is essential for achieving metallurgical compatibility and minimizing cracking in cast iron welding. In this study, different filler metals were applied for PLW and SMAW.

For PLW:

- 1) EN ISO 18274 (DSI Inconel 625) was used as the buttering layer. Its high nickel content improves compatibility with cast iron and reduces crack risk by accommodating thermal expansion and limiting hard phase formation.
- 2) EN ISO 21952-A (DSI M 90) was used in the second layer to enhance mechanical

performance. This nickel-iron alloy offers good strength and ductility for structural repairs.

For SMAW:

- 1) EN ISO 1071: E C Ni-CI 3 A specialized nickel electrode for cast iron, applied as the buttering layer. It provides excellent weldability and reduces the risk of cracking by allowing for a softer transition between the weld metal and the base material.
- 2) EN ISO 2560-A (E7016): A low-hydrogen, iron-based covered electrode. This filler metal provides strong mechanical performance, good resistance to hydrogen-induced cracking.

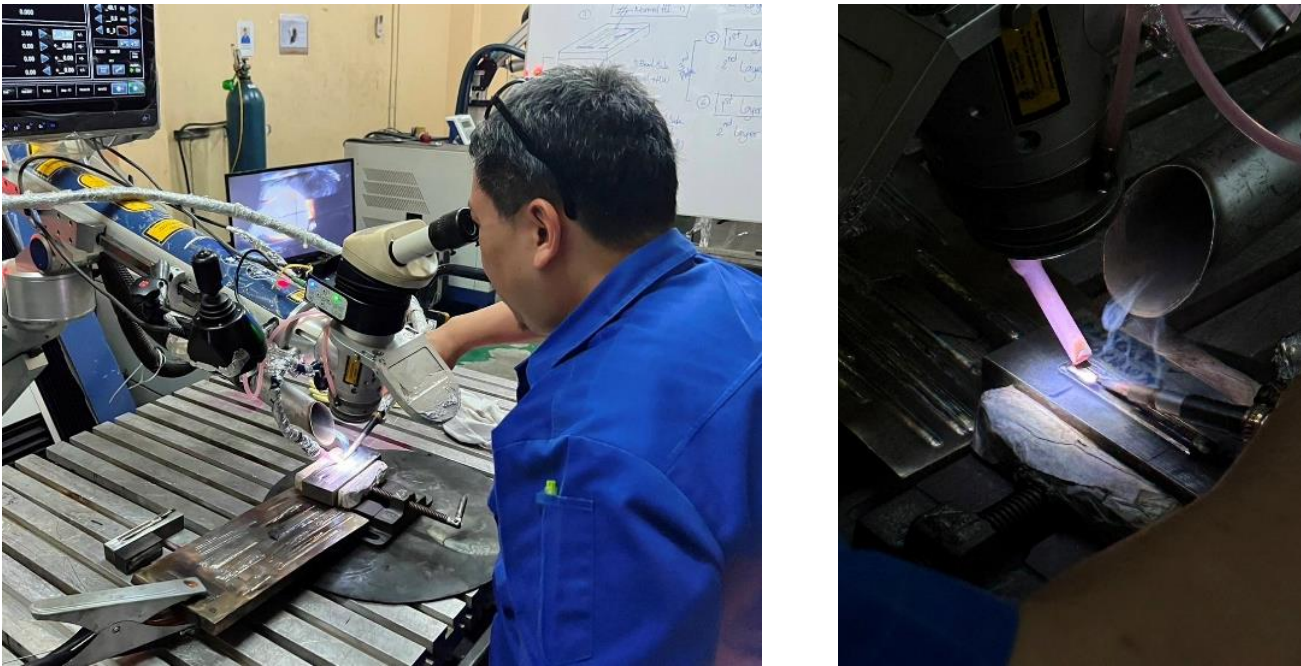


Fig 2: The experimental set-up (left) Operator performing welding using a PLW (right) Weld bead appearance and weld pool formation (© DSI Laser Service Thailand)

Pulsed Laser Welding (PLW) parameters

PLW was carried out using a pulsed laser welding system operated at 1200 W, with a pulse duration of 3.2 ms, a frequency range of 45 Hz, and a beam diameter of 5.5 mm. A welding speed of 3 mm/s was applied, and argon shielding gas (99.9% purity) was used to prevent oxidation. The experimental set-up and weld bead appearance are shown in Figure 2.

Shielded Metal Arc Welding (SMAW) parameters

SMAW specimens were prepared using E C Ni-CI 3 electrodes (Ø3.2 mm) for the first layer and E7016 electrodes (Ø3.2 mm) for the second layer. Two welding conditions were tested. The first condition involved single-layer welding without preheating or post-weld heat treatment (PWHT). The second condition

used two-layer welding, also performed without any thermal treatment.

These welding parameters were selected based on manufacturer recommendations and preliminary trials to achieve complete fusion while minimizing the risk of cracking.

Results and discussions Macrostructure and Heat Affected Zone (HAZ) formation

The macrostructure results for PLW under all conditions showed complete joint penetration without welding discontinuities. One of the notable advantages of PLW in welding nodular cast iron is its ability to produce a remarkably narrow HAZ. In this study, the HAZ width generated by PLW was consistently measured in the range of approximately 0.4 to 0.5 mm, significantly smaller than that observed in conventional Shielded Metal Arc Welding

(SMAW), where the HAZ typically exceeds 2.0 mm. This narrow HAZ is a direct result of the precise heat input control achievable with the pulsed laser beam, which delivers short, high-intensity energy bursts localized within a small region of the material. As a result, the HAZ produced by PLW is approximately 70% to 80% narrower than that formed by SMAW under comparable conditions. The macrostructures of PLW and SMAW are shown in Figure 3.

The ability to tightly confine the thermal cycle is particularly valuable when welding high-carbon materials such as FCD500, which are prone to cracking when exposed to large thermal gradients. Overall, the narrow HAZ produced by PLW offers significant metallurgical and mechanical advantages for cast iron welding applications.

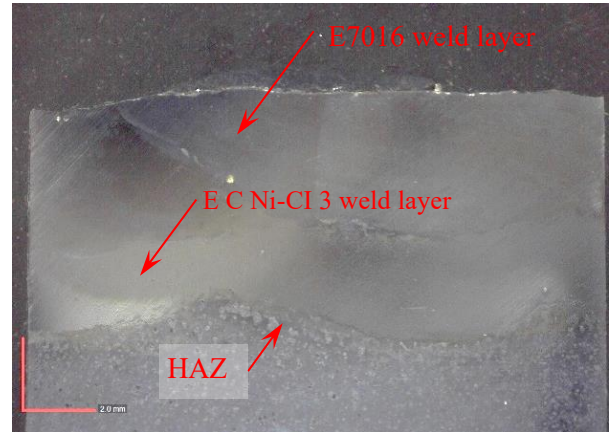
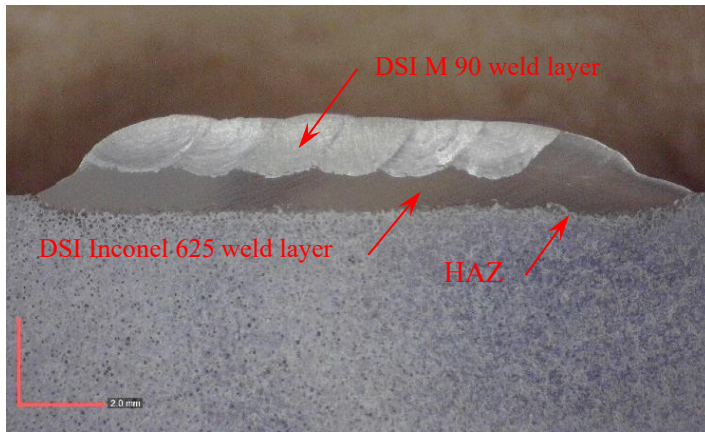


Fig 3: Macrostructure of (Left) PLW with first layer of Inconel 625 and second layer of DSI M90; (Right) SMAW with first layer of E C Ni-CI 3 and second layer of E7016. (© KMUTT)

Microstructural Evolution and Temper Bead Effect in Pulse Laser Welding

The microstructure of the HAZ in PLW under single-layer conditions showed a large amount of martensitic structure near the weld metal interface. This is due to the high cooling rates inherent to the PLW process, which transform the austenitized region of nodular cast iron into hard and brittle martensite. The presence of martensite in the HAZ increases hardness but also raises the risk of cracking. The microstructure of

PLW with a single layer is shown in Figure 4.

After Pulse Laser Welding under multi-layer conditions, the microstructure of the HAZ showed a clear reduction in martensite and a corresponding increase in pearlite. The application of a second weld layer provided additional heat that altered the microstructure of the first layer's HAZ. The martensitic structure formed during the first pass underwent a tempering-like transformation due to reheating. This microstructural evolution is

characteristic of the well-known temper bead effect. In the HAZ, re-austenitization occurred, followed by slow cooling, which promoted pearlite formation. As a result, the final HAZ contained a mixture of martensite and pearlite, with a reduced amount of martensite. This reduction lowers crack susceptibility and enhances mechanical properties compared to conventional arc welding methods such as SMAW. The microstructure of PLW under multi-layer conditions is shown in Figure 5.

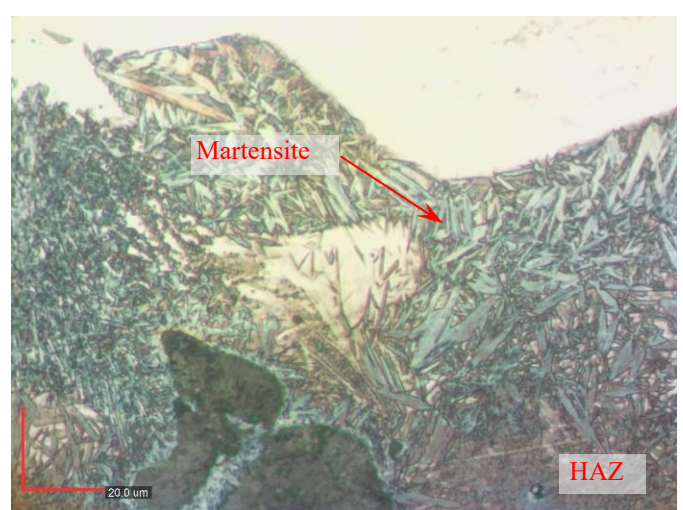
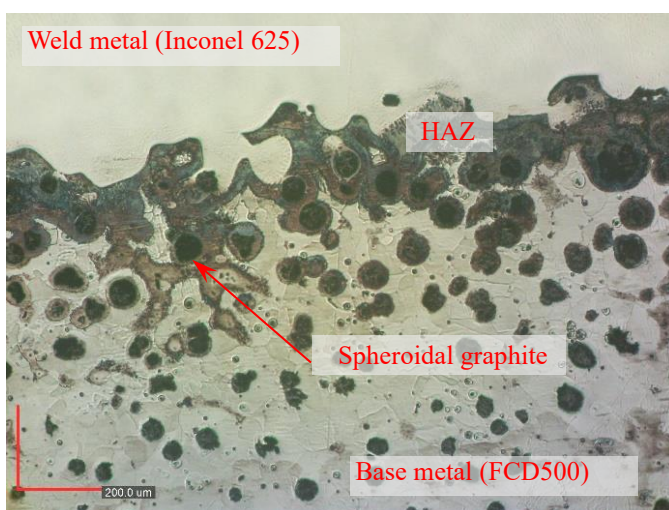


Fig 4: Microstructure of the HAZ in FCD500 base material welded by PLW with a single layer: (Left) 50× magnification; (Right) 500× magnification. (© KMUTT)

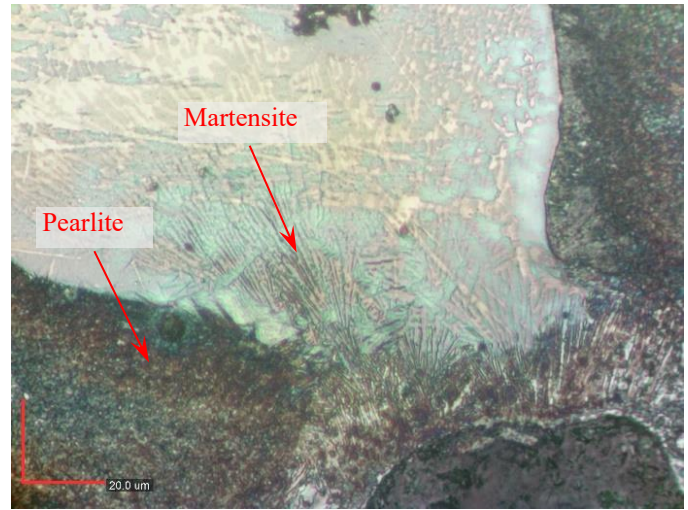
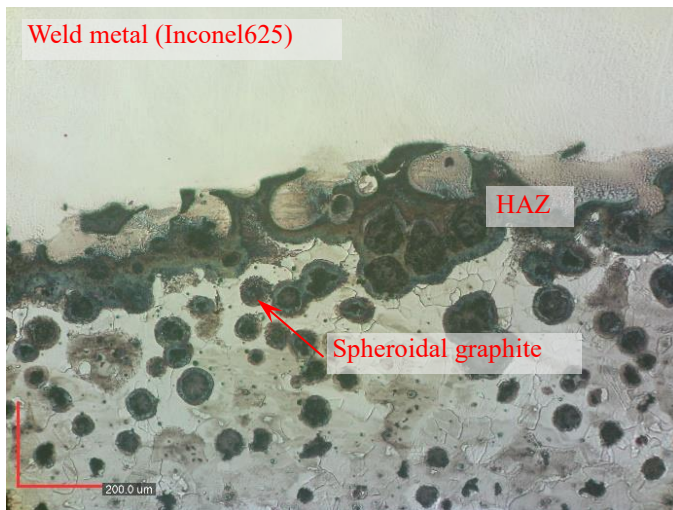


Fig 5: Microstructure of the HAZ in FCD500 base material welded by PLW with multiple layers: (Left) 50× magnification; (Right) 500× magnification. (© KMUTT)

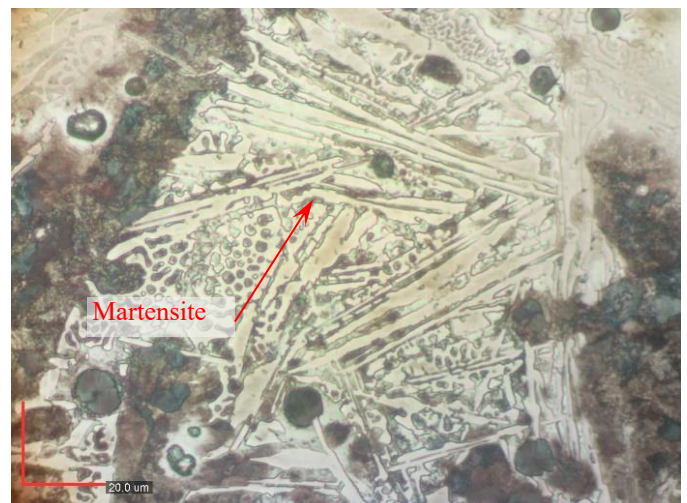
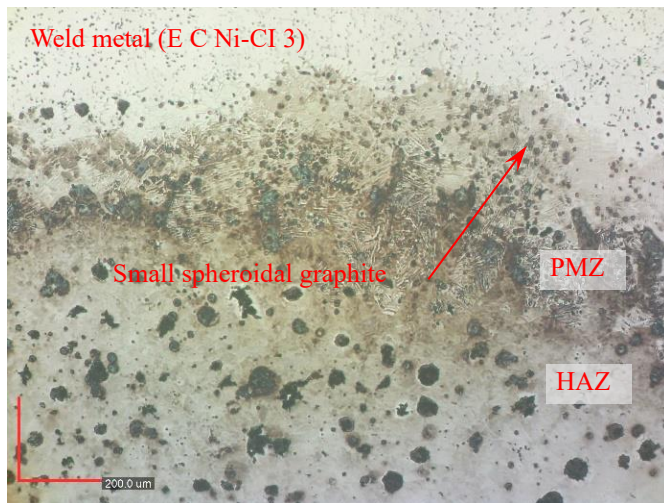


Fig 6: Microstructure of the HAZ in FCD500 base material welded by SMAW with a multiple layer: (Left) 50× magnification; (Right) 500× magnification (© KMUTT)

Compared to the microstructure of the HAZ in SMAW with both single-layer and multi-layer conditions, the results showed a large amount of martensitic structure remaining in the HAZ in both cases. Additionally, the presence of a Partially Melted Zone (PMZ) near the fusion boundary was clearly observed, along with small spheroidal graphite. This indicates that the high heat input of SMAW leads to the formation of a PMZ, where the original spheroidal graphite becomes remelted.

After rapid cooling, the graphite re-solidifies in a smaller, rounded shape. The retention of martensite in the HAZ and PMZ contributes to increased hardness and brittleness, which in turn raises the risk of cracking and reduces overall toughness and weldability, especially under service conditions. These characteristics contrast with the modified microstructure observed in the PLW multi-layer condition, where temper bead effects help to mitigate such risks. The microstructure of SMAW under multi-layer conditions is shown in Figure 6.

Due to the retention of martensite in the HAZ and PMZ, the recommended welding procedure for cast iron using SMAW or other arc welding processes should include preheating to a minimum temperature of 400°C and post-weld heat treatment (PWHT) at a minimum of 800°C. However, in many practical cases, applying preheating and PWHT can be very challenging especially when dealing with large components, restricted working environments, or limited access to the weld area.

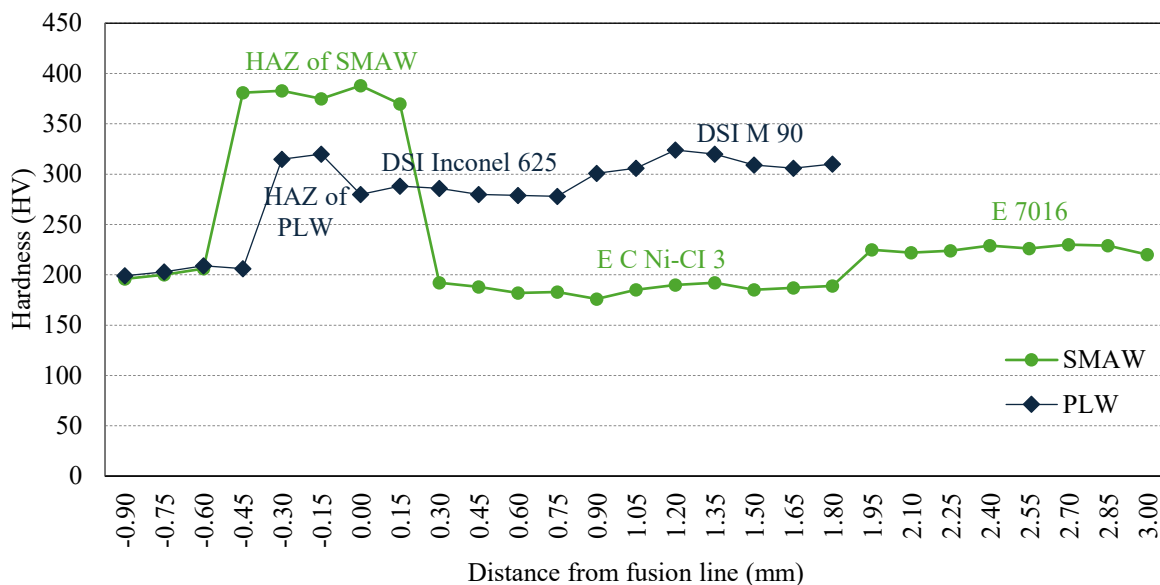


Fig 7: Hardness distribution across the weld zones of FCD500 welded by PLW and SMAW (© KMUTT)

Comparison of Hardness Profiles

The hardness profiles across the weld zones for both PLW and SMAW are shown in Figure 7. In the case of SMAW, the HAZ exhibited a significant hardness increase, reaching values of approximately 400 HV, due to the formation of large amounts of untempered martensite. This high-hardness zone extends over a wider region of the HAZ, increasing susceptibility to cracking. In contrast, the PLW process produced a much narrower HAZ with a moderate hardness peak of approximately 300–320 HV. The reduced hardness in the PLW HAZ reflects the influence of the temper bead effect, where the second layer tempered the initial martensitic structure, promoting partial transformation to pearlite. In the fusion zones, the hardness of the weld metal with Inconel 625 and DSI M90 remained stable and lower than the HAZ peak observed in SMAW. Conversely, the SMAW weld metal (E C Ni-CI 3 and E7016 layers) exhibited lower and more uniform hardness compared to its HAZ. Overall, the PLW process demonstrated superior control over hardness distribution, resulting in a

smoother transition from weld metal to base metal and significantly reducing the likelihood of crack initiation in the HAZ.

Conclusion: A Novel Approach to PLW of Nodular Cast Iron FCD500

This study demonstrated the novel application of Pulsed Laser Welding (PLW) for repairing FCD500 nodular cast iron without the need for preheating or post-weld heat treatment. The results confirmed that the temper bead mechanism, achieved through multi-layer PLW, effectively reduced martensite content in the heat-affected zone (HAZ) by promoting pearlite formation, thereby improving mechanical properties and lowering crack susceptibility. Compared to conventional SMAW, which typically produces a HAZ width of approximately 2.0–2.5 mm, the PLW process generated a significantly narrower HAZ of only 0.4 – 0.5 mm. This reduction up to 80%, demonstrates the precision and low thermal impact of PLW, contributing to better weld integrity and reduced cracking risk. Additionally, the "healthy supporting effect" of the narrow hardness peak, stabilized by

the surrounding softer weld and base material enhances impact resistance and overall service durability. These findings highlight the potential of this novel PLW technique as an efficient, low-heat-input, and reliable method for the practical refurbishment of nodular cast iron components.

Acknowledgement

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AUTHORS



Dr. Titinan Methong
Lecturer, Department of
Production Engineering, King
Mongkut's University of
Technology Thonburi
(KMUTT), Thailand
titinan.met@mail.kmutt.ac.th



Stephan Thiemonds (IWS)
Principal, DSI Thailand
Laser Welding Academy,
Deputy General Manager, DSI
Laser Service (Thailand) Co., Ltd.,
Chonburi/Thailand,
thiemonds@dsilaser.com



Rangsimma Russell
Undergraduate Students,
Department of Production
Engineering, King Mongkut's
University of Technology
Thonburi (KMUTT), Thailand



Sarina Hautekiet
Undergraduate Students,
Department of Production
Engineering, King Mongkut's
University of Technology
Thonburi (KMUTT), Thailand



Ratchuwan Tantiwong
Undergraduate Students,
Department of Production
Engineering, King Mongkut's
University of Technology
Thonburi (KMUTT), Thailand

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Pulse Laser Welding Note [22]



The classic **Jedi Knights** fight in the **STAR WARS** universe,
created in 1977 by US producer George Lukas.

The modern Jedi Knights fight in the **ALPHA LASER** industrial world,
founded in 1994 by the German physicist Josef Höllbauer.

The once use **Lightsabers**.

The other **Pulse Laser Welding** Machines.

The one is a Space Opera played on cinema screen.

The other is a **Welding Revolution** in professional work-life.

Both are united by their positive fight to prevent the **Good Force**.

More inspiration at DSI Thailand Laser-Welding-Academy