

# Coarse grain formation within Heat Affected Zone (HAZ) comparison between classical arc-welding methods with pulse laser welding technology

Pulsed Laser Welding (PLW) has emerged as an advanced joining and repair technology, offering precise energy control, low heat input, and minimal thermal distortion compared to conventional arc welding processes. Unlike Gas Tungsten Arc Welding (GTAW), which involves continuous heat input and high peak temperatures, PLW utilizes short, high-energy pulses that significantly reduce the thermal impact on the base material. As reported in this study, the heat input of PLW (1.44 kJ/cm) is substantially lower than that of GTAW (5.88 kJ/cm), resulting in reduced peak temperatures and faster cooling rates during welding. These characteristics enable PLW to produce a narrower Heat Affected Zone (HAZ) and finer microstructures, which are critical factors in maintaining the integrity and performance of engineering components.

In many industrial applications, large and high-value components such as large spur gears, rubber-covered rollers, and integrally bladed rotors (shown in Figure 1-3) are frequently subjected to wear, fatigue, or localized damage during service. The repair of such components is technically challenging due to their size, complex geometry, and stringent performance requirements. Conventional arc welding processes, such as GTAW, often introduce excessive heat input, leading to wide HAZ regions, coarse grain structures, and increased hardness gradients. These metallurgical changes can result in residual stresses, distortion, and a higher susceptibility to cracking, particularly in medium-carbon low-alloy steels such as 42CrMo4 used in this study. Consequently, achieving reliable repair without compromising the mechanical properties of the component remains a significant challenge.

To address these limitations, Pulsed Laser Welding offers a promising alternative for repair applications due to its localized heat input and controlled thermal cycle. The present investigation focuses on comparing PLW and GTAW processes in terms of thermal behavior, macrostructure, microstructure, and mechanical properties. The results demonstrate that PLW significantly reduces HAZ width and promotes finer microstructures with improved mechanical stability. These advantages highlight the potential of PLW as an effective repair technique for critical industrial components, where minimizing thermal damage and ensuring structural reliability are of paramount importance.



Figure 1 : Large spur gears



Figure 2 : Rubber covered rollers



Figure 3 : Integrally bladed rotors

Table 1 The summary of Pulse Laser Welding parameters

| Condition | Filler metal | Pulse laser welding parameter |                     |                |                    |       |                   |                          |            |                            |                    |
|-----------|--------------|-------------------------------|---------------------|----------------|--------------------|-------|-------------------|--------------------------|------------|----------------------------|--------------------|
|           |              | Peak power (W)                | Pulse duration (ms) | Frequency (Hz) | Beam diameter (mm) | Shape | Average power (W) | Traveling speed (cm/min) | Shield gas | Shielding gas flow (l/min) | Heat input (kJ/cm) |
| 1&2       | ø1.2         | 9800                          | 3.4                 | 40             | 3.9                | 2     | 1200              | 15.0                     | Ar 99%     | 15                         | 1.44               |

Table 2 The summary of Gas Tungsten Arc welding parameters

| Condition | Filler metal | Gas tungsten arc welding parameter |             |                          |            |                            |                    |
|-----------|--------------|------------------------------------|-------------|--------------------------|------------|----------------------------|--------------------|
|           |              | Voltage (V)                        | Current (A) | Traveling speed (cm/min) | Shield gas | Shielding gas flow (l/min) | Heat input (kJ/cm) |
| 3&4       | ø1.2         | 14.0                               | 119         | 10.2                     | Ar 99%     | 20                         | 5.88               |

### Material and Filler materials

The base material used in this study was 42CrMo4 steel (EN 1.7225), equivalent to AISI/SAE 4140, JIS SCM440, and ASTM B7. This medium-carbon low-alloy steel, alloyed with chromium (Cr) and molybdenum (Mo), Which is widely applied in high-strength components such as shafts and gears due to excellent hardenability and mechanical performance.

The filler material employed was DSI M90, a molybdenum-containing low-alloy martensitic laser welding wire. This filler metal is specifically designed for pulsed laser welding, ensuring good metallurgical compatibility and it's supporting formation of control microstructure rapid thermal cycles.

### Experimental set up

The experimental program was designed to compare the performance of Pulsed Laser Welding (PLW) and Gas Tungsten Arc Welding (GTAW) processes under controlled conditions. Both processes were selected due to their relevance in industrial repair applications, particularly for high-value components requiring precision and reliability.

A total of four experimental conditions were established to

evaluate the influence of welding process and layer configuration on thermal behavior, microstructure, and mechanical properties. These conditions include:

- (1) Pulsed Laser Welding with a single layer (PLW1L),
- (2) Pulsed Laser Welding with multiple layers (PLW3L),
- (3) Gas Tungsten Arc Welding with a single layer (GTAW1L), and
- (4) Gas Tungsten Arc Welding with multiple layers (GTAW3L).

This comparative approach allows for a systematic investigation of the effects of heat input and thermal cycling associated with each welding technique, as well as the influence of repeated thermal exposure in multi-layer welding.

### Pulsed Laser Welding (PLW) Parameters

As summarized in Table 1, the Pulsed Laser Welding (PLW) process was carried out using a 1.2 mm diameter filler metal. The welding parameters were selected to achieve controlled heat input and stable weld formation, with an average power of 1200 W, a pulse duration of 3.4 ms, and a pulse frequency of 40 Hz. The laser beam diameter was set to 3.9 mm, and a constant travel speed of 15 cm/min was maintained throughout the process. High-purity argon gas (99.996 %) was employed as shielding gas. These parameters were carefully chosen to promote localized heating and minimize

thermal distortion, which are key advantages of the PLW process. The weld bead configuration and the experimental setup for PLW are shown in Figure 4.

### Gas Tungsten Arc Welding (GTAW) Parameters

For comparison, the Gas Tungsten Arc Welding (GTAW) process was conducted using the same filler metal diameter of 1.2 mm, as detailed in Table 2. The welding parameters were set at a voltage of 14 V and a current of 119 A, with a travel speed of 10.2 cm/min. Argon gas (99.996% purity) was also used as shielding gas to protect the weld pool from atmospheric contamination. In contrast to PLW, the GTAW process involves a continuous heat input, leading to higher overall thermal energy during welding. This difference in heat input is expected to significantly influence the thermal cycle, heat-affected zone (HAZ), and resulting microstructure. The weld bead geometry and GTAW experimental setup are also presented Figure 4.

### Weld bead appearance and NDT Result

The weld bead appearance results indicate that all welding conditions are free from unacceptable discontinuities (Figure 5-8), and No relevant indications were detected by Penetrant Testing.

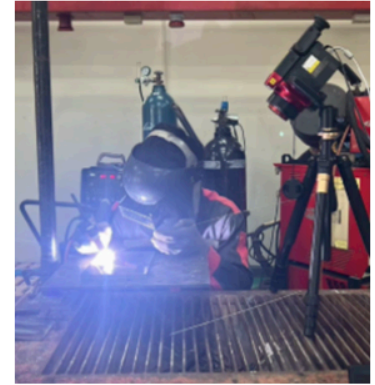
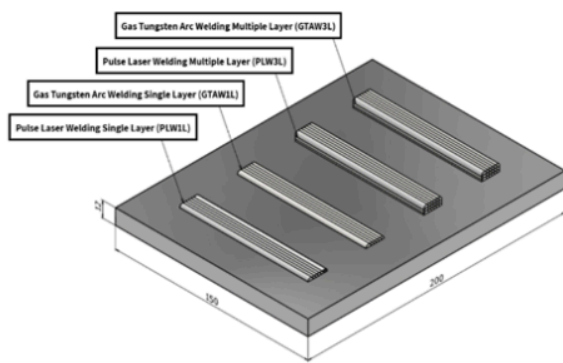


Figure 4 : The layout of weld bead (left) Operator performing Pulse Laser Welding (mid) Gas tungsten arc welding (right)

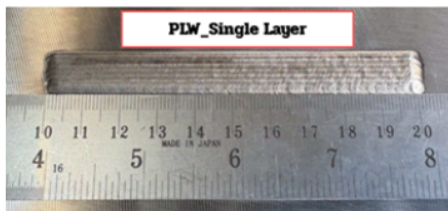


Figure 5 : PLW Single Layer (PLW1L) Weld Bead



Figure 6 : PLW Multiple layer (PLW3L) Weld Bead



Figure 7 : GTAW Single Layer (GTAW1L) Weld Bead



Figure 8 : GTAW Multiple layer (GTAW3L) Weld Bead

contrast, the PLW1L sample cooled from 447°C to 150°C in only 4 seconds, yielding a faster cooling rate of 74.3°C/s.

**Multiple layer condition :**  
Based on the thermal cycle analysis presented in Figure [14], Before welding the temperature of the workpiece was approximately 80°C for PLW3L process and 140°C for GTAW3L. The maximum temperature at center of weld pool for PLW3L reached only 362°C with a heating rate of 50°C/s, whereas the GTAW3L reached an extreme peak of 1,710°C at 151°C/s.

In terms of the cooling phase, the GTAW3L specimen cooled from 1,710°C down to 175°C in 23.5 seconds, equivalent to a cooling rate of 65.3°C/s. By comparison, the PLW3L specimen dropped from 362°C to 175°C in just 3 seconds, resulting in a cooling rate of 62.3°C/s.

## Results and discussions - Macrostructure and Heat Affected Zone (HAZ) characteristics

As shown in Figure [9-12], the macrostructures indicate that the weld metal in all conditions is sound and free from unacceptable discontinuities.

It can be concluded that the HAZ width of the single-layer PLW1L (Figure 9) was approximately 60% narrower than that of the single-layer GTAW1L (Figure 11). Similarly, for the multi-layer conditions, the PLW3L (Figure 10) resulted in a 50% reduction in HAZ size compared to the GTAW3L (Figure 12). This significant difference is primarily attributed to the heat input; the PLW process shows utilization of a much lower heat input of 1.44 kJ/cm, whereas

the GTAW process required 5.88 kJ/cm.

## Temperature Distribution Characteristics during Welding via Thermal Camera

**Single layer condition :**  
According to the thermal cycle analysis in Figure [13], the initial temperature of the workpiece before welding was approximately 50°C for PLW1L and 70°C for GTAW1L. At the center of weld pool, where the peak temperature of PLW1L reached only 447°C with a heating rate of 53°C/s but GTAW1L reached a higher temperature of 1,717°C at 110°C/s.

Regarding the cooling stage, the temperature of the GTAW1L sample decreased from 1,717°C to 150°C within 23.5 seconds, resulting in a cooling rate of 66.7°C/s. In

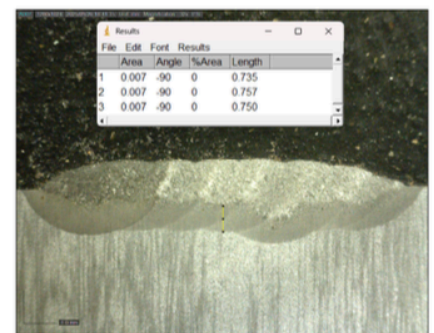


Figure 9 : PLW1L HAZ 0.747 mm

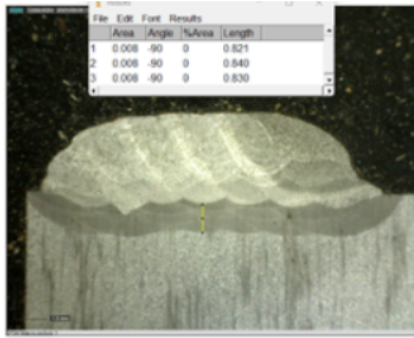


Figure 10 : PLW3L HAZ 0.830 mm

### Microstructural Examination and Grain Characteristic in the Heat Affected Zone

**Single layer condition :** The microstructure of the weld metal (WM) in the PLW1L (Figure 15) specimen consists of bainite, martensite, and clearly columnar dendritic from the relatively lower - peak temperature ( $447^{\circ}\text{C}$ ) at the center of weld pool. In contrast, the WM in the GTAW1L (Figure 17) shows lath martensite from higher peak temperature ( $1,717^{\circ}\text{C}$ ) during welding.

The Heat Affected Zone PLW1L (Figure 15) produced a fine martensitic structure, whereas the - GTAW1L (Figure 17) resulted in coarse martensite. This structural difference is a direct result of the cooling rates, the PLW1L (Figure 15) process has a significantly higher cooling rate ( $74.3^{\circ}\text{C/s}$ ) compared to GTAW1L ( $66.7^{\circ}\text{C/s}$ ).

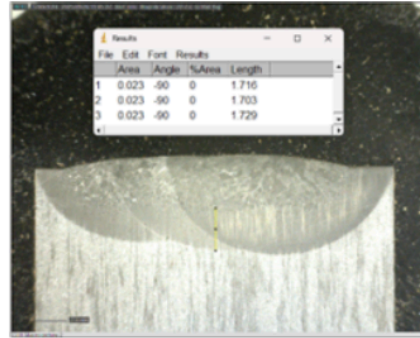


Figure 11 :GTAW1L HAZ 1.716mm

Rapid cooling in PLW1L (Figure 15) limits grain growth, preventing the coarsening seen in the GTAW1L (Figure 17).

**Multiple layer condition :** Both PLW3L (Figure 16) and GTAW3L (Figure 18) exhibit fine martensite in the weld metal (WM). This similarity is attributed to the temper bead effect, where the heat from subsequent passes refines the microstructure of the previous layers. In the HAZ, PLW3L (Figure 16) retains fine martensite while GTAW3L (Figure 18) shows coarse martensite, proving PLW's effective suppression of grain growth in multi-pass welding.

### Mechanical Properties - Vickers Hardness Analysis

**Single layer condition :** According to the hardness profiles presented in Figure [19], both the PLW1L and GTAW1L conditions exhibit comparable hardness values

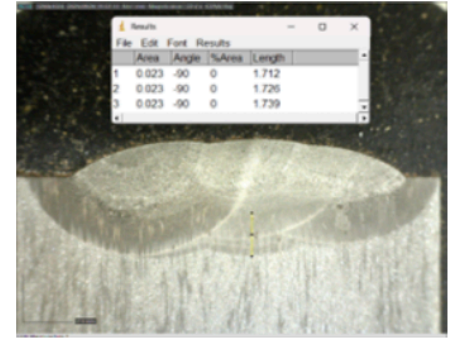


Figure 12:GTAW3L HAZ 1.726mm

In the Weld Metal (WM) region, ranging between 300 and 400 HV0.1.

In the HAZ, PLW1L exhibits lower hardness ( $\sim 420$  HV) compared to GTAW1L ( $\sim 450$  HV), indicating superior impact resistance and reduced cracking risk. Additionally, the significantly narrower HAZ width in PLW1L aligns perfectly with macrostructural results.

**Multiple layer condition :** Based on Figure [20], PLW3L exhibits lower WM hardness ( $\sim 290$  HV) than GTAW3L ( $\sim 350$  HV), suggesting improved ductility and reduced fracture susceptibility.

In the HAZ, both processes - reach similar peak hardness, yet PLW3L displays a much narrower hardened zone. This restricted distribution supports previous macrostructural findings, demonstrating that PLW effectively controls microstructural evolution in multi-layer welds.

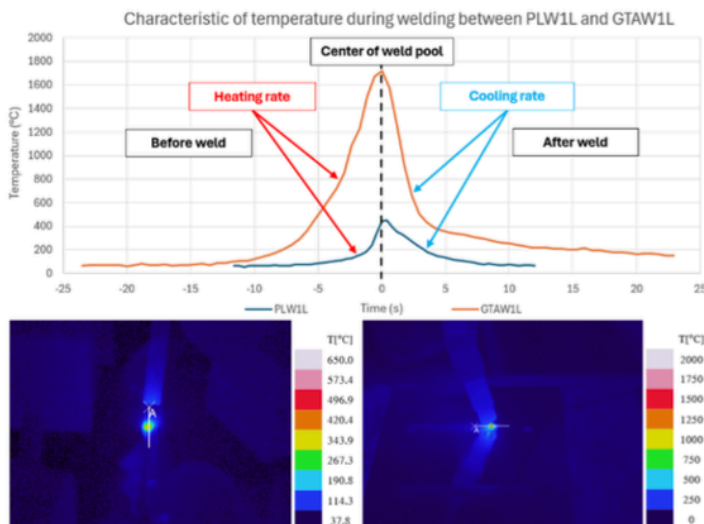


Figure 13 : Temperature Chart in Single layer

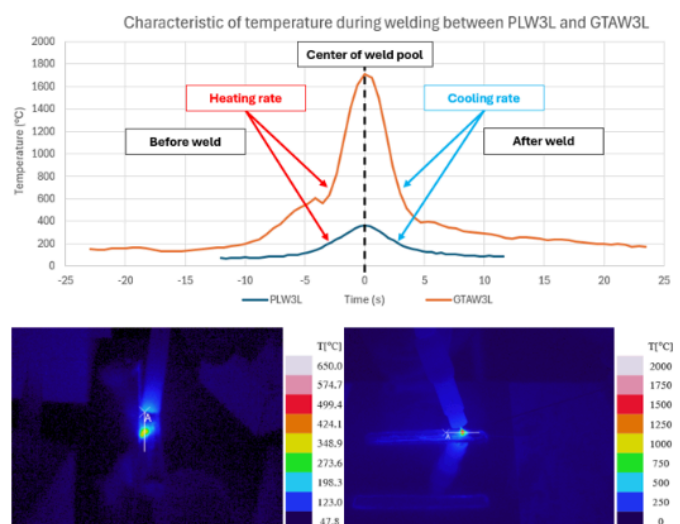


Figure 14 : Temperature Chart in Multiple layer

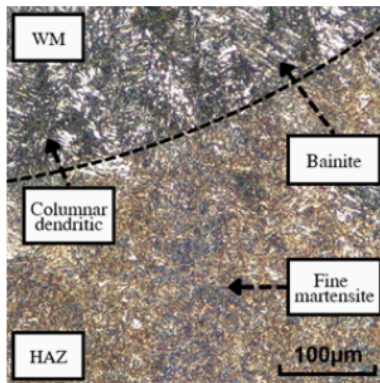


Figure 15 : Microstructure PLW1L

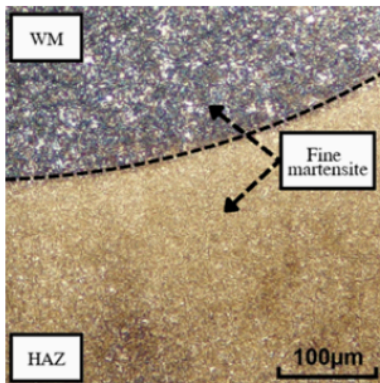


Figure 16 : Microstructure PLW3L

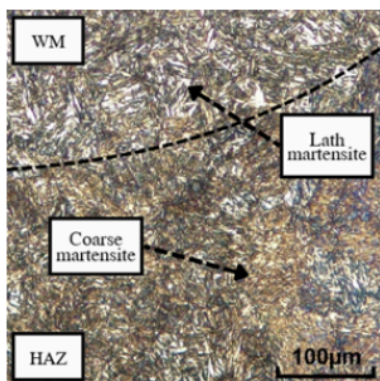


Figure 17:Microstructure GTAW1L

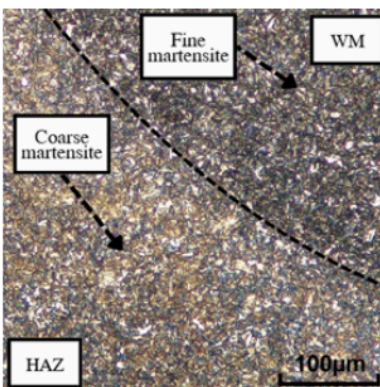


Figure 18:Microstructure GTAW3L

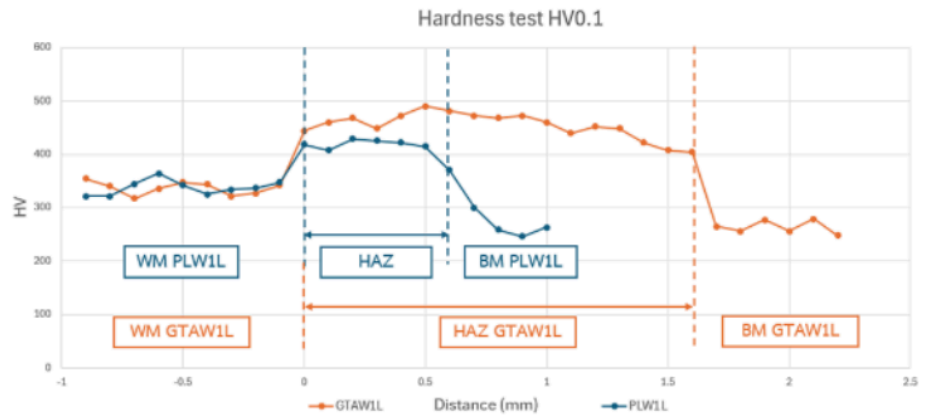


Figure 19 : Hardness testing result chart in single layer

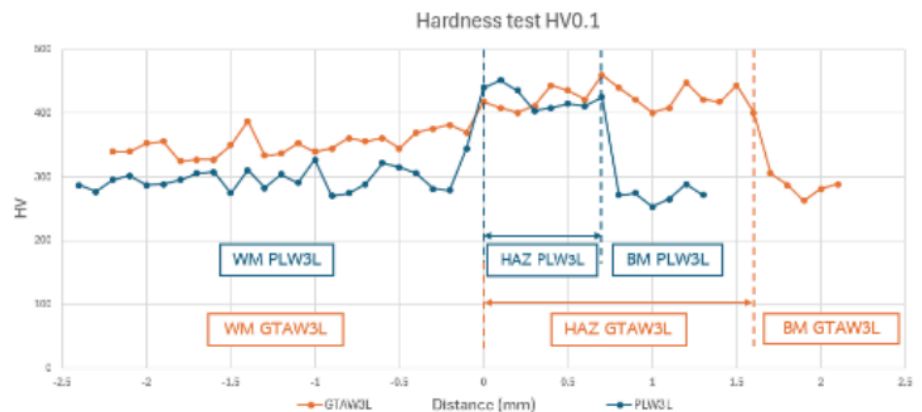


Figure 20 : Hardness testing result chart in multiple layer

## Conclusion

All welding conditions produced sound, defect-free joints. However, Pulsed Laser Welding (PLW) demonstrated significant advantages over Gas Tungsten Arc Welding (GTAW), reducing the Heat Affected Zone (HAZ) width by 60% in single-layer and 50% in multi-layer welds. This reduction is attributed to PLW's lower heat input and peak temperatures. Furthermore, the rapid cooling inherent in PLW fostered a refined, fine-grained microstructure. While GTAW exhibited higher hardness over a broader HAZ—increasing cracking susceptibility—PLW provided superior mechanical stability through a restricted hardness distribution and refined grains.

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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 Thiemoonds (IWS)**  
Principal, DSI Thailand  
Laser Welding Academy,  
Deputy General Manager,  
DSI Laser Service (Thailand)  
Co., Ltd., Chonburi/Thailand,  
thiemoonds@dsilaser.com



**Apiwit Lengvilas**  
Undergraduate Students,  
Department of Production  
Engineering, King Mongkut's  
University of Technology  
Thonburi (KMUTT), Thailand