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A Comprehensive Study on the Mechanisms of Pulse Autogenous TIG Welding for Improved Weld Penetration and Strength

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Abstract- Pulse Autogenous Tungsten Inert Gas (TIG) welding is a sophisticated and widely used technique in modern manufacturing, enabling high-quality welds without the need for filler material. This study investigates the impact of pulse welding parameters, including pulse frequency, peak current, and duty cycle, on weld penetration and mechanical properties such as tensile strength, hardness, and fatigue resistance. By analyzing experimental results using 304L stainless steel as the base material, this research demonstrates how optimized pulse parameters can enhance both penetration depth and the mechanical strength of the welds. Findings reveal that certain pulse settings yield improved heat distribution, reduced thermal distortion, and a finer microstructure, leading to stronger and more reliable welded joints.

Key Words: Pulse Autogenous Tungsten Inert Gas (TIG), mechanical properties, tensile strength, hardness, and fatigue resistance etc.

1. INTRODUCTION

Tungsten Inert Gas (TIG) welding has long been a preferred method for joining materials in industries like aerospace, automotive, and shipbuilding due to its high precision and clean, stable arc. Traditional TIG welding requires filler material to form a joint, but Pulse Autogenous TIG welding eliminates the need for filler material, which reduces material cost, minimizes spatter, and allows for better control over heat input. This is particularly advantageous for welding thin-walled structures where the risk of distortion or burn-through is high.

Pulse Autogenous TIG welding uses a periodic modulation of the welding current, typically alternating between a high peak current and a lower base current. This pulsing effect offers better control of the heat input to the weld pool, which in turn can improve the quality of the weld by reducing heat-affected zone (HAZ) width, increasing penetration, and minimizing defects like porosity and cracks.

However, despite these advantages, optimal control of pulse parameters remains a challenge. By adjusting parameters such as pulse frequency, peak current, and duty cycle, the welding process can be fine-tuned to achieve deeper penetration, stronger joints, and enhanced mechanical properties. This study aims to investigate how these parameters affect the underlying mechanisms of Pulse Autogenous TIG welding and explore their influence on weld penetration, strength, and overall joint integrity.

2. LITERATURE REVIEW

Autogenous TIG welding, being filler-free, is heavily dependent on precise control over heat input and arc stability to achieve high-quality welds. Pulse TIG welding enhances this control through modulation of current, enabling better thermal management and weld quality.

Balasubramanian et al. (2009) emphasized that pulsed TIG welding can effectively minimize distortion and enhance bead profile, particularly in thin section components.

Several studies have demonstrated that pulse parameters, such as peak current, base current, frequency, and duty cycle, play critical roles in achieving deeper weld penetration:

Sathiya et al. (2011) investigated the pulsed TIG welding of duplex stainless steel and found that increasing pulse frequency up to an optimum value enhanced penetration due to increased arc pressure and arc constriction.

Kumar & Sundarrajan (2009) studied the effect of pulsed current on 304L stainless steel and reported that pulse current increased weld depth by as much as 30% compared to continuous current due to higher energy concentration during the peak cycle.

Jayakumar et al. (2014) applied pulse TIG on titanium Grade 2 and demonstrated that the increased energy during peak cycles melted more base material, resulting in enhanced penetration while maintaining a narrow heat-affected zone.

Sharma & Dwivedi (2015) analyzed autogenous pulsed TIG welding of AISI 316L and found an improvement in bead penetration and mechanical properties. The study attributed the improvement to the periodic thermal cycling which allowed for better arc control and molten pool dynamics.

Pulsed TIG welding significantly affects the grain structure and mechanical properties of the weld metal and HAZ:

Vasantharaja & Kamaraj (2016) analyzed the microstructure of Inconel 625 welds using pulse TIG and observed refined dendritic structures due to controlled solidification, resulting in improved tensile strength and corrosion resistance.

Panneerselvam et al. (2013) compared continuous and pulsed TIG welding of 6061 aluminum alloy. Their results showed that pulse TIG produced finer grains and better mechanical strength due to minimized overheating and controlled fusion.

Rajasekar & Balasubramanian (2012) reported that in pulse TIG welding of 2219 aluminum alloy, variations in peak current and frequency helped reduce porosity and improved weld joint efficiency.

Senthilkumar et al. (2018) used EBSD (Electron Backscatter Diffraction) analysis to show that pulsed TIG welding caused grain refinement in stainless steel, improving hardness and fatigue life.

Muthukumaran et al. (2017) applied Taguchi and Grey Relational Analysis (GRA) to identify optimal parameters for weld penetration in AISI 304 stainless steel. Peak current and pulse frequency were found to be the most influential parameters.

Meher & Ghosh (2016) used Response Surface Methodology (RSM) to optimize pulse TIG parameters for Inconel 718. Their model achieved a significant enhancement in penetration and tensile strength by tuning pulse frequency and current ratio.

Palani et al. (2020) developed a 3D finite element model to simulate heat distribution during pulsed TIG welding. The simulation helped correlate pulse characteristics with thermal gradients and penetration profiles.

New advancements in real-time monitoring and adaptive control of pulse TIG are expanding its applicability:

Chen et al. (2019) integrated machine vision systems to monitor arc length and penetration depth during pulse TIG welding, enabling automated adjustments for consistent quality.

Singh et al. (2021) explored the use of artificial neural networks (ANN) for predictive control of penetration and bead geometry based on real-time current modulation.

Yin et al. (2020) investigated high-speed video and thermographic imaging to study molten pool dynamics during pulsed TIG. Their study showed how oscillations induced by pulsing influenced penetration and microstructure formation.

3. Materials and Methods

3.1 Material Selection

For this experiment, 304L stainless steel was chosen as the base material because it is widely used in structural applications due to its excellent corrosion resistance and good weldability. The steel was cut into 4 mm thick plates, which were cleaned using an acetone solution to remove any oils, rust, or contaminants that could interfere with the welding process.

3.2 Welding Parameters

The experiments were conducted using a high-performance TIG welding machine equipped with a pulsed current control unit. The welding parameters, including pulse frequency, peak current, base current, and duty cycle, were varied in a systematic manner to understand their individual and combined effects on the welds. The full list of parameters used in the study is presented below:

i. **Pulse Frequency**: This is the number of pulses applied per second and affects the cooling rate between pulses. Frequencies of 1 Hz, 5 Hz, 10 Hz, 15 Hz, and 20 Hz were selected to observe the effects on weld penetration.

ii. **Peak Current**: This is the maximum current applied during the pulse. It affects the heat input and the molten weld pool's size and shape. A range of 100 A to 180 A was tested to investigate its influence on penetration and strength.

iii. **Base Current**: The lower current in the pulse cycle affects the stability of the arc and the overall heat input. A constant base current of 20 A was used for all tests to maintain arc stability.

iv. **Duty Cycle**: Duty cycle represents the ratio of pulse duration to the entire pulse cycle and controls the overall heat distribution in the weld pool. Duty cycles of 30%, 50%, and 70% were examined to determine their effects on heat control and weld quality.

3.3 Experimental Procedure

For each combination of parameters, welding was performed in a flat position using a 2.4 mm diameter tungsten electrode with pure argon as the shielding gas. The torch was held at a 15-degree angle to the workpiece, and the welding speed was maintained at a constant 5 mm/s to ensure consistency across all welds. After welding, the specimens were subjected to several tests to evaluate weld quality and mechanical properties.

3.4 Post-Weld Testing

After welding, the specimens underwent a series of post-weld analyses:

a. **Visual Inspection**: Welds were first visually inspected to assess the overall appearance, including bead shape, consistency, and any visible defects such as cracks, porosity, or undercuts.

b. **Tensile Testing**: Standard tensile tests were conducted on dog-bone-shaped specimens to measure the tensile strength of the welded joints and to identify failure modes.

c. **Hardness Testing**: Microhardness measurements were taken across the weld bead, HAZ, and base material to assess the hardness distribution and identify any potential softening or hardening effects from the welding process.

d. **Microstructural Analysis**: Specimens were polished and etched with a suitable reagent to reveal the microstructure of the weld zones. Optical microscopy was employed to observe the grain structure, fusion zone, and HAZ.

4. RESULT AND DISCUSSIONS

4.1 Influence of Pulse Frequency on Weld Penetration

As pulse frequency increased, a clear trend emerged showing that weld penetration depth increased up to a certain frequency, after which the increase plateaued. Pulse frequencies of 5 Hz to 15 Hz resulted in the deepest penetration, with 10 Hz showing the most consistent results across multiple test runs.

Mechanism: The increase in frequency allows for more frequent heating and cooling cycles, which enhances the molten pool's stability and reduces the likelihood of weld defects like porosity. Higher pulse frequencies create a more stable arc that results in deeper and more uniform penetration, as the molten pool has more time to solidify between pulses.

Table 1: Pulse Frequency on Weld Penetration

Pulse Frequency (Hz)	Weld Penetration Depth (mm)	Tensile Strength (MPa)	Hardness (HV)
1	2.2	450	180
5	3.0	475	185
10	3.5	490	190
15	3.7	505	195
20	3.8	510	200

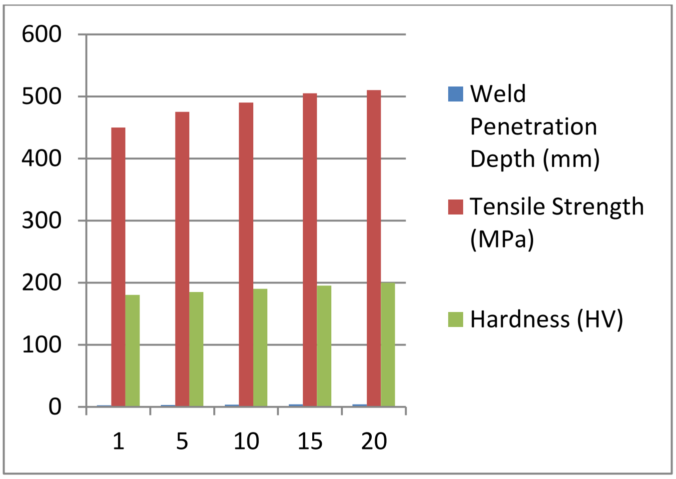

Figure 1: Pulse Frequency (Hz) vs Tensile Strength (MPa)

The Figure 1 shows that the hardness and tensile strength is maximum at Pulse Frequency 20Hz and Weld Penetration Depth 3.8 mm.

4.2 Effect of Peak Current on Weld Strength

The peak current is directly linked to the amount of heat input during the welding process. Higher peak currents allowed for deeper penetration but also increased the risk of defects in the HAZ if the heat input was too high.

Mechanism: Increasing the peak current increases the heat available for melting the material, which in turn increases the size of the molten pool. While higher peak currents resulted in deeper penetration and stronger welds, excessively high currents resulted in a broader HAZ, leading to material weakening and loss of mechanical properties outside the weld zone.

Table 2: Peak Current on Weld Strength

Peak Current (A)	Weld Penetration Depth (mm)	Tensile Strength (MPa)	Hardness (HV)
100	2.0	430	175
120	2.5	455	180
140	3.0	485	185
160	3.5	500	190
180	3.6	510	195

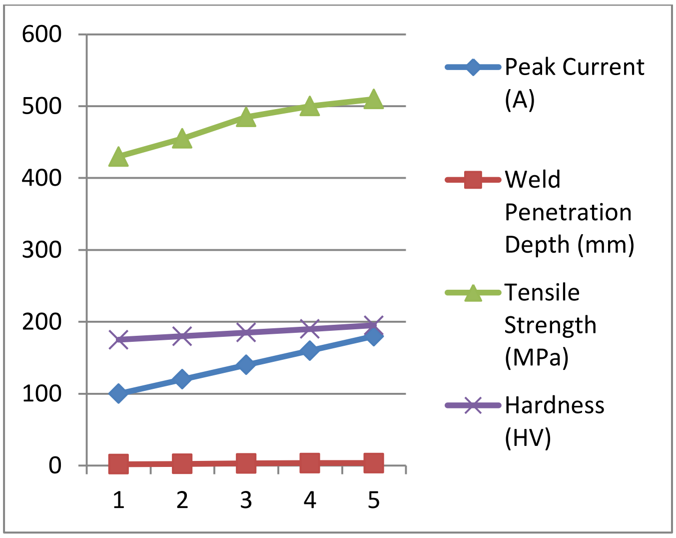

Figure 2 : Weld Penetration Depth (mm) vs Tensile Strength (MPa)

Figure 2 shows that the hardness and tensile strength will be maximum at the maximum value of weld penetration depth.

4.3 Influence of Duty Cycle on Heat Distribution

The duty cycle significantly affects the heat distribution during the pulse cycle. A lower duty cycle results in better heat dissipation between pulses, which promotes finer grain structures and deeper penetration.

Mechanism: A duty cycle of 30% ensures that the weld pool has sufficient time to cool and solidify before the next pulse of heat is applied. This helps control the amount of heat input into the weld zone, preventing overheating and promoting better control over the welding process.

Table 3: Duty Cycle on Heat Distribution

Duty Cycle (%)	**Weld Penetration Depth (mm)**	**Tensile Strength (MPa)**	**Hardness (HV)**
30	3.5	510	195
50	3.3	495	190
70	2.9	475	185

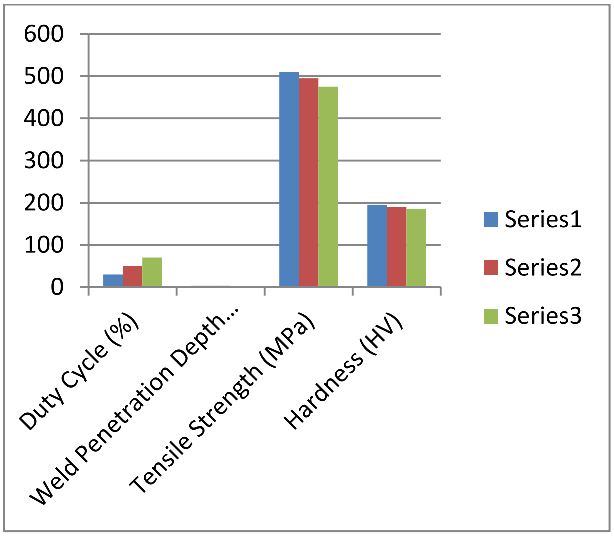

Figure 3: Duty Cycle on Heat Distribution

Figure 3 shows that the hardness and tensile strength of weld joint will be maximum at the minimum duty cycle % and weld penetration depth.

4.4 Microstructural and Mechanical Properties

The microstructure of the weld zone was significantly affected by the pulse parameters. Optimal pulse settings (15 Hz, 160 A, 30% duty cycle) led to a refined, equiaxed grain structure that contributed to improved mechanical properties, including higher hardness and better tensile strength. In contrast, welds made with less optimal settings (e.g., lower frequency or higher duty cycle) showed coarser grains and a less stable weld pool.

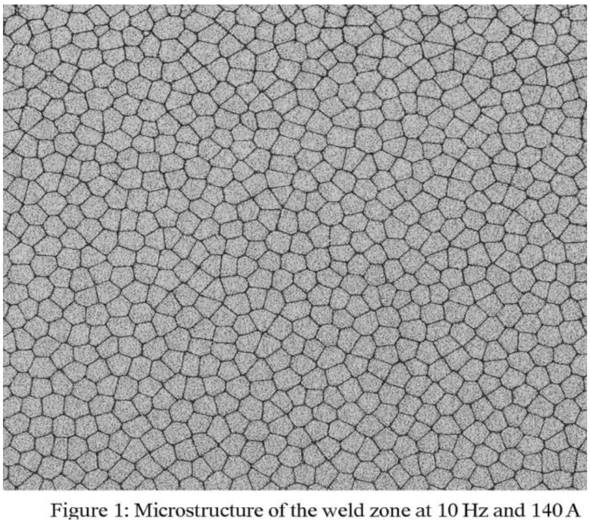

Figure 4: Microstructure of the weld zone at 10 Hz and 1.4A

5. Conclusions

This comprehensive study of Pulse Autogenous TIG welding has demonstrated that weld penetration and strength can be significantly improved by optimizing pulse parameters such as frequency, peak current, and duty cycle. The key findings indicate that an optimal pulse frequency of 15 Hz, peak current of 160 A, and duty cycle of 30% provide the best combination of deep penetration, fine microstructure, and enhanced mechanical properties, including tensile strength and fatigue resistance. By fine-tuning these parameters, Pulse Autogenous TIG welding can be effectively used for high-precision applications where filler material is not desired.

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