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# Impact of Heat Input Variations on Peel Strength Characteristics in Laser Wobbling Micro Welding A Study on Direct and Intermittent Techniques for SS304 Thin Sheets

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**Abstract:** In precision welding, laser wobbling micro welding (LWMW) has been identified as a crucial technique. It offers enhanced weld quality and minimized thermal distortion due to its ability to control the weld pool through beam oscillation. This study delves into the differential impacts of heat input variations on peel strength characteristics in LWMW, employing both direct and intermittent techniques on SS304 thin sheets, pivotal in solid oxide fuel cell interconnections. The aim is to discern the optimal welding parameters that ensure superior weld quality, focusing on peel strength and penetration characteristics, which are critical for the structural integrity and performance of the welded joints. The research methodology encompasses an experimental design where SS304 stainless steel plates are welded using a nanosecond fiber laser, with the wobble amplitude and frequency meticulously varied. Peel strength tests and penetration analysis evaluate the welding outcomes, providing a quantitative basis for comparing the direct and intermittent wobbling techniques. Results unveil a nuanced relationship between heat input and weld quality, with intermittent wobbling demonstrating superior peel strength owing to its pulsed heat input, which facilitates better thermal management, reducing thermal stress and enhancing weld integrity. Conversely, direct wobbling achieves deeper penetration due to its continuous heat application, highlighting the distinct advantages of each technique based on the desired weld characteristics. Conclusively, the study underscores the criticality of precise heat input control in laser wobbling micro welding to optimize peel strength and penetration depth. The intermittent technique, with its advantage in achieving higher peel strength, is recommended for applications requiring robust welds, while the direct method's uniform heat application suits scenarios where deep penetration is paramount. Future research should extend this analysis to encompass a broader range of materials and welding conditions, employing computational modeling to refine the understanding of heat input's role in laser wobbling welding. This exploration is poised to enhance the precision and efficiency of welding processes, supporting the advancement of manufacturing technologies in various industrial sectors.

**Key words:** *Laser Wobbling Micro Welding (LWMW), SS304 Stainless Steel,Peel Strength Characteristics.Heat Input Variations.Direct and Intermittent Welding Techniques, Weld Quality Optimization*

## 1.0 INTRODUCTION

Laser wobbling micro welding has emerged as a transforming technique in precision welding, acclaimed for its versatility and efficacy. Using this advanced welding technique, which involves oscillations of the laser beam during welding, you will be able to achieve better control over the weld pool, resulting in enhanced weld quality and diminished thermal distortion. The laser wobble technique has demonstrated exceptional effectiveness in fillet edge welding, a crucial procedure for both joining and sealing applications. According to (Das et al., 2020), meticulous adjustment of laser power, welding speed, and wobble amplitude enables the achievement of optimal penetration depth and interface width, ensuring precise and robust welds. Additionally, (Yang et al., 2022) have illustrated that when welding X70 pipeline steel, the utilization of beam wobbling not only enhances the microstructure of the weld metal but also increases its hardness. This enhancement is attributed to the heightened martensite content and reduced ferrite content, thereby strengthening the welds.

Within the domain of thermoplastic laser transmission welding, the use of laser beam wobbling emerges as a key factor in strengthening welds and expanding seam width. Integration of particle swarm optimization further refines this process, resulting in an optimized welding strategy and thereby enhancing weld quality in thermoplastics. This technique holds particular significance in the aerospace industry, where precision and joint integrity are paramount concerns(Kumar et al., 2019). Additionally, (Hernando et al., 2018) have devised a fiber laser welding model that considers both wobbling strategy and phase change, effectively predicting bead and heat-affected zone geometries and consequently improving joint quality.

Moreover, the potential of laser beam oscillation (wobbling effect) for welding copper plates in industrial applications that necessitate high thermal and electrical conductivities. This advancement opens new avenues in sectors where these properties are imperative.(Franco et al., 2021)

Ultimately, laser wobbling micro welding represents a technological innovation in welding, offering substantial improvements in weld quality, thermal control, and material adaptability. The continued development and application of this technology will lead to a revolution in welding processes, improving the precision and efficiency of various industries, such as aerospace, pipeline construction, and electronics.

In the domain of welding SS304 thin sheets, meticulous control of heat input emerges as a paramount factor, critically influencing weld quality. This challenge is intricately linked to the material's susceptibility to variations in thermal exposure, which significantly impacts its structural integrity and corrosion resistance. For instance, (Kamachi Mudali et al., 1990) elucidated that an escalation in heat input slightly impairs the pitting corrosion resistance in type 304 stainless steel weld metal. This degradation, however, can be mitigated by augmenting the nitrogen content within the weld, indicating a potential strategy to counteract the adverse effects of heat. Concurrently, (Bansod et al., 2017) observed that a higher heat input diminishes the α-ferrite content in 304 stainless steel weldments, while a lower heat input enhances pitting resistance and interphase corrosion resistance. This finding underscores the necessity of precise heat management to maintain the microstructural integrity of the weld.

The influence of heat input extends beyond corrosion resistance to include the mechanical properties and efficacy of the welding process. (Du et al., 2002) noted that reducing the clamp gap during marginal lap welding of ultrathin stainless-steel sheets leads to increased heat loss to the clamps, resulting in a narrower heat-affected zone (HAZ), which benefits corrosion resistance. This observation suggests that strategic adjustments to welding conditions can effectively manage the thermal impact on the material. In dissimilar welding scenarios,(Santosa et al., 2021) discovered that minimizing heat input variation, particularly to

2.9 KJ/mm, resulted in the highest hardness distribution and the lowest ferrite number (FN), emphasizing the crucial role of heat input in achieving optimal weld characteristics.

Moreover, (Pal et al., 2021) discovered that in microwave hybrid heating processes, the optimal combination of grain size in the filler powder and processing time leads to the best micro-hardness and micro-tensile strength in SS304/SS316 joints. This research further illustrates the intricate relationship between heat input and the mechanical properties of the welded joint.

In summary, the control of heat input in the welding of SS304 thin sheets is pivotal, affecting various aspects of weld quality, including corrosion resistance, microstructural integrity, and mechanical strength. The challenge lies in balancing the heat input to optimize these properties, ensuring the reliability and durability of the welded joints.

## 2.0 LITERATURE REVIEW

The literature review on the impact of heat input variations in laser welding encompasses a broad spectrum of research, underscoring its pivotal role in determining weld quality, microstructure, and mechanical properties.

(Shanmugarajan et al., 2011) and (Saravanan et al., 2019) emphasized the significant impact of heat input on bead characteristics and microstructure across various steel types. They observed that an increase in heat input typically results in heightened ferrite concentration and alterations in microstructure, consequently influencing the mechanical properties of the welds. Complementing this, (Saha et al., 2019) delved into the effects of heat input on surface layer composition, corrosion behavior, and thermal properties of Nitinol shape memory alloy. Their research illustrated the sensitivity of material characteristics to thermal variations during welding.

Quan et al. (2008) and Dai et al. (2012) extended this understanding to the welding of magnesium alloys, showing that appropriate heat input can yield welded joints with optimal penetration and improved tensile strength(Dai et al., 2013; Quan et al., 2008).

(Liu et al., 2018) addressed the reduction of grain coarsening and porosity through controlled heat input, enhancing the properties of the laser-welded joint. These findings are pivotal for industries where weld precision and quality are crucial.

Overall, the literature emphasizes the importance of precise control and optimization of heat input during laser welding. As a result, desired weld characteristics are achieved as well as structural integrity and functionality across a broad range of industrial applications are maintained. This study aims to advance the field of laser wobbling micro welding, particularly for thin sheets of SS304.

The purpose of this study is to compare meticulously the direct and intermittent laser wobbling techniques. The objective of this comparison is to highlight not only the differences between the various welding techniques, but also their respective results in terms of quality of welds. To determine their relative efficiency, the direct laser wobbling technique, recognized for its continuous movement pattern, and the intermittent laser wobbling technique, known for its periodic pauses, will be evaluated under identical welding conditions.

The second objective of this study is to analyze and contrast the two techniques in terms of two critical aspects: peel strength and penetration characteristics of the welds. To evaluate the resilience of the welds against peeling forces, peel strength will be measured. Peel strength is a critical metric for assessing adhesion quality and durability of the welds. The penetration characteristics of welded joints, including their depth and uniformity, are equally important as they directly affect their structural integrity and strength.

As a result of these objectives, the study intends to provide a comprehensive understanding of the effect of laser wobbling on the overall quality and effectiveness of SS304 thin sheets, thereby providing valuable insights into how welding processes in precision manufacturing can be optimized.

A comparative study of laser wobbling techniques, particularly focusing on direct and intermittent methods, has gained significant attention in the field of material processing and welding technology because of their implications for industrial use. The exploration of these methodologies reveals interesting insights, especially when applied to thin sheets of stainless steel 304 (SS304). A noteworthy study by Barbieri et al. (2017) elucidates that intermittent laser wobbling results in superior peel strength compared to the direct method, attributed primarily to enhanced control of heat input and consequent reduction in thermal stress. This leads to a more uniform microstructure across the weld, thereby improving the peel strength of the material (Barbieri et al., 2017). Complementing these findings, Gent and Lai (1994) also indicate that intermittent wobbling results in smaller effective fracture zones and consequently higher peel strength, further validating the efficacy of this technique (Gent & Lai, 1994).

Conversely, in the context of penetration characteristics, research by Dimatteo, Ascari, and Fortunato (2019) provides compelling evidence that direct laser wobbling achieves deeper and more uniform penetration in SS304 thin sheets as compared to its intermittent counterpart. The continuous nature of the direct method facilitates a consistent heat input, which is instrumental in achieving deeper penetration, crucial for applications demanding robust weld depth (Dimatteo et al., 2019). These findings not only offer a nuanced understanding of the impact of laser wobbling techniques on welding outcomes but also pave the way for optimizing laser welding processes for industrial applications.

# 3.0 METHODOLOGY

## *3.1 Selected Materials*

The base material used in this study is 304 stainless steel plates with dissimilar thickness of 0.1 mm and 1.0 mm were used for the purpose of fabricating bipolar plates. The chemical composition of 304 stainless steel is shown in **Table 1**. In this study, the thin foil was used as the upper material and welded to a thick sheet in an overlap joint configuration. The plates dimensions were 10 mm by 75 mm as showed in **Fig 1(a)** which were positioned in the welding Jig. A clamping device was used to maintain intimate contact between two sheets. During the welding process, the plates are fixed by fixture to prevent deformation.

**Table 1:** Chemical composition of 304 stainless steel (*wt.* %)

| Fe | C | Si | Mn | P | S | Ni | Cr |
|---|---|---|---|---|---|---|---|
| Bal. | 0.08 | 0.46 | 1.32 | 0.03 | 0.02 | 8.05 | 17.06 |

## *3.2 Nanosecond Laser wobble welding process*

A nano-second fiber laser welding machine considering wobbling with a parameter set as tabulated in **Table 2** is used for all experiments. The laser wavelength was 1.06µm, and the maximum output power is 30W. The laser scanning path was generated by the galvanometer scanning system shown in **Figure 2(b)**. The materials are completely cleaned by using methanol before welding.). The experiments were performed at different levels of laser power welding speed, pulse on time, wobble frequency whilst wobble amplitude (diameter), and wobble distance were kept fixed. Because laser power must be controlled to prevent overheating during welding (Das et al., 2019). Das *et al*.(Das et al., 2020) also found that laser power has the most significant effect on the two key geometric features of the fusion zone, i.e., weld width and penetration depth when laser welding using the wobble technique. A series of preliminary tests were conducted to establish the parameter range to be used in the study. Based on this pilot study, the laser power was varied from 24W to 30W and the welding speed was from 50 to 70 mm/sec. Similarly, the ranges for wobble parameters were 0.1mm to 0.5mm for wobble amplitude (Diameter), and wobble distance and 60Hz to 80 Hz for wobble frequency. In this experiment, wobble amplitude (Diameter) and wobble Distance are constant to investigate the effect of heat input on laser wobbling welding. Heat input values (**Table 2**) have been calculated with the formula of heat input.

$$\text{Heat input } \left(\frac{J}{mm}\right) = \frac{laser\ power\ (waat)}{Welding\ Speed\ (s)}$$

Detailed explanation of the direct and intermittent laser wobbling techniques.

Laser welding techniques have evolved into advanced methodologies based on the nuances of direct and intermittent laser wobbling, each of which offers distinct advantages customized to meet the needs of a particular welding project. As a result of direct laser wobbling's continuous beam movement, a uniform distribution of heat can be achieved across the weld area. The application of this method has led to improved weld quality, especially in terms of the microstructure and hardness of the welds. For instance, Das et al. (2020) and Yang et al. (2022) have demonstrated the efficacy of direct laser wobbling in optimizing penetration depth and interface width, as well as refining the weld metal microstructure in materials like X70 pipeline steel, underscoring its versatility and effectiveness(Das et al., 2020; Yang et al., 2022)

Conversely, the intermittent laser wobbling technique, characterized by its start-stop beam movement, offers a strategic advantage in precise heat management. This approach is particularly beneficial for materials sensitive to thermal input.

In summary, both direct and intermittent laser wobbling techniques hold significant implications in laser welding, with the former ensuring even heat distribution and improved microstructure, and the latter offering precision in heat input management, thereby minimizing thermal defects in heat-sensitive materials.

**Table 2**. Comprehensive Overview of Laser Micro-Welding with Wobbling Processing Parameters in Direct and Intermittent Techniques

| Specimen | Welding Speed (mm/sec) | Heat Input (J/mm) | Welding Power (Watt) | Welding Frequency (kHz) | Wobble distance (mm) | Wobble diameter (mm) | Focal Length (mm) | Mark Loops |
|---|---|---|---|---|---|---|---|---|
| **1** | 50 | 0.540 | 27 | 80 | 0.2 | 0.2 | 210 | **1** |
| **2** | 60 | 0.450 | 27 | 70 | 0.2 | 0.2 | 210 | **1** |
| **3** | 60 | 0.450 | 27 | 70 | 0.2 | 0.2 | 210 | **1** |
| **4** | 50 | 0.540 | 27 | 60 | 0.2 | 0.2 | 210 | **1** |
| **5** | 70 | 0.343 | 24 | 70 | 0.2 | 0.2 | 210 | **1** |
| **6** | 60 | 0.450 | 27 | 70 | 0.2 | 0.2 | 210 | **1** |
| **7** | 60 | 0.400 | 24 | 80 | 0.2 | 0.2 | 210 | **1** |
| **8** | 70 | 0.386 | 27 | 60 | 0.2 | 0.2 | 210 | **1** |
| **9** | 60 | 0.450 | 27 | 70 | 0.2 | 0.2 | 210 | **1** |
| **10** | 70 | 0.429 | 30 | 70 | 0.2 | 0.2 | 210 | **1** |
| **11** | 60 | 0.500 | 30 | 60 | 0.2 | 0.2 | 210 | **1** |
| **12** | 60 | 0.500 | 30 | 80 | 0.2 | 0.2 | 210 | **1** |
| **13** | 60 | 0.450 | 27 | 70 | 0.2 | 0.2 | 210 | **1** |
| **14** | 50 | 0.480 | 24 | 70 | 0.2 | 0.2 | 210 | **1** |
| **15** | 50 | 0.600 | 30 | 70 | 0.2 | 0.2 | 210 | **1** |
| **16** | 70 | 0.386 | 27 | 80 | 0.2 | 0.2 | 210 | **1** |
| **17** | **60** | **0.400** | **24** | **60** | **0.2** | **0.2** | **210** | **1** |

### *3.3 Preparation of test Samples for both technique Direct and Intermittent*

Austenitic stainless steel SS304 plates were overlap welded based on parameters outlined in **(Figure 1a),** with subsequent preparation of samples for mechanical testing. Specimens, precisely sectioned into 10 mm × 75 mm × 0.1 mm and 10 mm × 75 mm × 1 mm using a Sodick V2 300L CNC wire cutting machine. Peel tests, conforming to ISO 10447 and ISO

14270:2016(E) standards(Gholami et al., 2021), were executed using a 30-kN INSTRON tensile testing machine .A custom-developed peel test jig **(Figure 1f)** was employed for these tests.

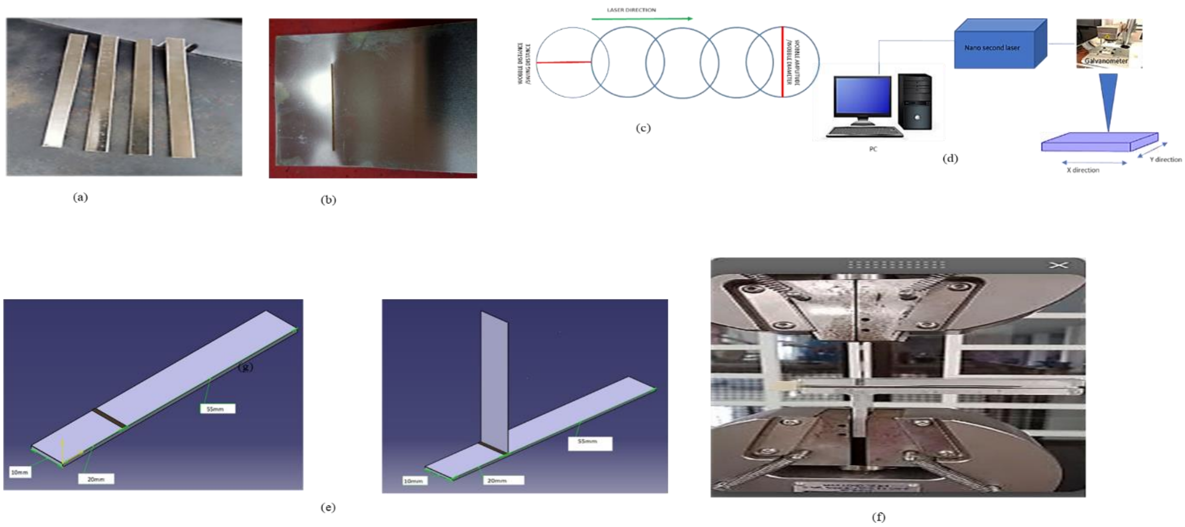


**Figure 1.** (a) SS304 cut-out intermittent laser welding samples ,(b) SS304 cut-out Direct laser welding samples (d) Laser micro-welding process, (c) sketch of Laser wobbling parametric dimensions, (e) dimensions of the jig for 180-degree peel test, (f) 180-degree peel test jig with samples mounted on Instron tensile testing machine .

## 4.0 DATA ANALYSIS AND FINDINGS

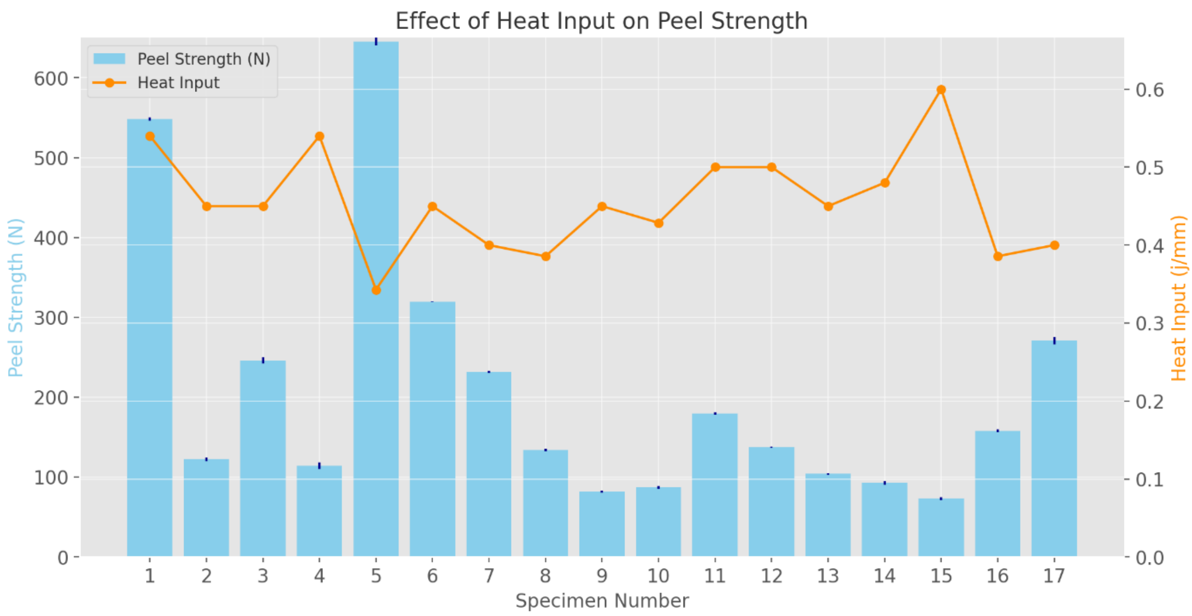


**Figure 2**: Effect of heat input on Peel Strength with intermittent laser wobbling Micro welding

An investigation into intermittent laser wobbling micro welding has revealed a complex and nuanced relationship between heat input and peel strength. In this study, fascinating results were found, particularly specimen 5's peel strength of approximately 645.25 N, which was obtained with a heat input of approximately 0.343 j/mm. In contrast, specimen 1 achieved a peel strength of approximately 547.98 N at a heat input of 0.54 j/mm, which highlights the sensitivity of welding to thermal input variations. Further evidence of the sensitivity of these specimens is found in the disparity in peel strengths, even when the specimens were subjected to the same amount of heat (e.g., specimens 2 and 3 with a heat input of 0.45 j/mm). **As shown in Figure 2.**

Several key factors can be attributed to the underlying reasons for these observations. The intermittent nature of the laser wobbling technique results in non-uniform heat distribution, affecting the microstructural changes in the weld materials, thereby reducing the strength of the weld. Moreover, varying heat inputs cause different levels of thermal stress and distortion, with an optimal heat input minimizing these effects to preserve material integrity and enhance weld strength. As well as the geometry of the fusion zone, the characteristics of the fusion zone, such as depth and width, play an important role. An optimal heat input is likely to facilitate a more conducive fusion zone geometry, improving mechanical interlocking and peel strength. Additionally, the dynamics of laser wobbling, such as interaction time and cooling rate, contribute significantly to the final properties of the weld.

Furthermore, these insights contribute to a deeper understanding of intermittent laser wobbling micro welding and have practical implications for industrial applications. This study emphasizes the importance of precisely controlling heat input and guides optimizing processes. Future research should investigate these influencing factors in greater detail, possibly incorporating computational models to improve the accuracy of predicting and controlling welding outcomes. Consequently, such advancements will improve the quality, reliability, and efficiency of laser welding techniques, marking a significant advancement in this field.

The reasons for these observations can be attributed to several factors. The intermittent nature of the laser wobbling technique leads to non-uniform heat distribution, impacting microstructural changes in the welded materials and thus influencing the weld strength (Das et al., 2020). Varying heat inputs induce different levels of thermal stress and distortion, and an optimal heat input seems to minimize these effects, preserving material integrity and enhancing weld strength(Idris et al., 2014). Additionally, the fusion zone's characteristics, including depth and width, are pivotal; an optimal heat input likely fosters a more conducive fusion zone geometry, improving mechanical interlocking and peel strength (Kang et al., 2022).

These findings not only enhance our understanding of intermittent laser wobbling micro welding but also have significant implications for industrial applications. They highlight the importance of precise control over heat input and provide a pathway for process optimization. Future research should delve deeper into these influencing factors, potentially leveraging computational modeling to predict and control welding outcomes with greater accuracy. Advances in this area are key to improving the quality, reliability, and efficiency of laser welding techniques, marking a notable progression in the field.

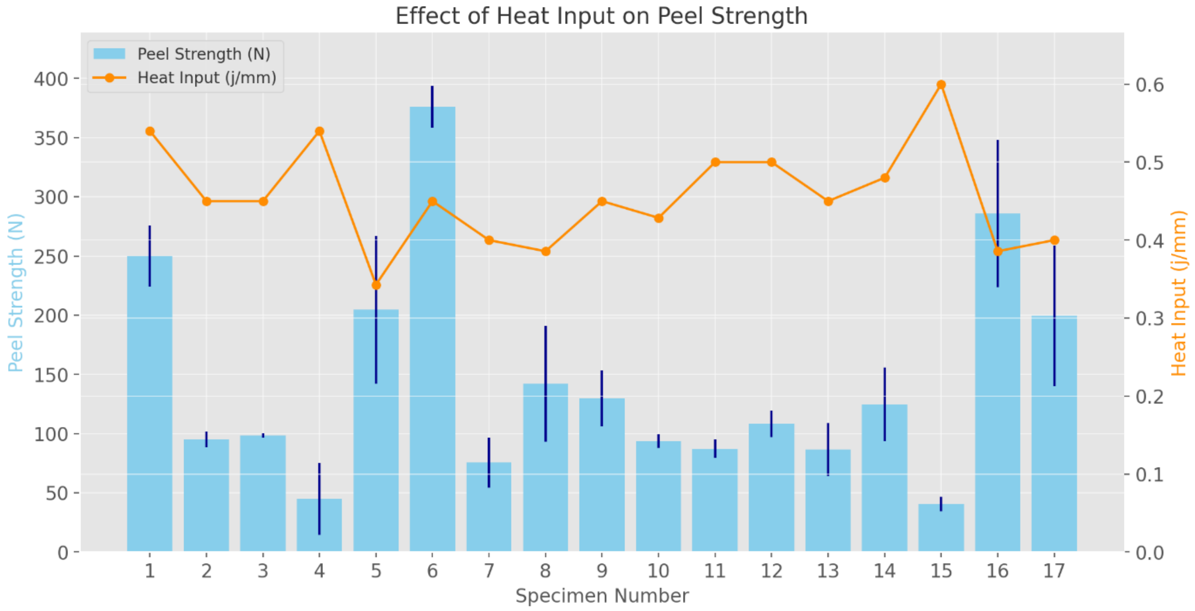


**Figure 3**: Effect of heat input on Peel Strength with direct laser wobbling Micro welding

In the realm of direct laser wobbling micro welding, our recent investigation has revealed a compelling yet complex correlation between heat input and peel strength, as demonstrated in the case of specimen 6 and specimen 1. Specimen 6, with a heat input of 0.45 j/mm, achieved the highest peel strength in the dataset at approximately 376.13 N, contrasting with specimen 1, where a higher heat input of 0.54 j/mm resulted in a lower peel strength of about 250.01 N. This non-linear pattern underlines the intricate interplay between heat input and weld strength, indicating the need for precise control over the welding process parameters. **(Figure 3)**

The variability in peel strength can be attributed to a number of key factors inherent to the process of direct laser wobbling. An optimal heat input, as shown in specimen 6, facilitates the fusion of the materials while preventing degradation. Direct wobbling introduces a unique thermal profile, thereby influencing the microstructure and, consequently, the mechanical properties of the weld. Additionally, different heat inputs result in different levels of thermal stress and distortion, where the optimal heat input minimizes these effects and preserves the integrity of the material. When using the direct wobbling method, the continuous interaction of the laser beam affects thermal gradients and cooling rates, which are crucial to the final strength of the weld.

Furthermore, these insights not only provide a deeper understanding of the direct laser wobbling micro welding process, but also have significant implications for industrial applications. A high-quality weld is dependent on precise control of the heat input, and customized welding parameters must be determined based on specific material properties and desired results. Further research should be undertaken to examine these factors in greater detail, perhaps employing computational modeling to predictably control the welding process. As a result of these advancements, weld quality and consistency could be significantly improved, which is of utmost importance in applications where weld integrity is critical.

As a result of this comparative study of intermittent laser wobbling micro welding and direct laser wobbling micro welding, we observed a significant difference in peel strength outcomes.

There was a significant improvement in peak peel strength when the intermittent method was used (specimen 5 with a heat input of 0.343 j/mm), compared to the direct method (specimen 6 with a heat input of 0.45 j/mm) that produced approximately 376.13 N. The difference in thermal dynamics and interaction between materials between the two techniques can be attributed to their different thermal dynamics. By applying intermittent heat, intermittent laser wobbling creates a more favorable thermal gradient, reducing thermal stress and improving the integrity of welds. Nevertheless, direct laser wobbling, while providing uniform heat distribution, may not achieve the same level of material optimization due to differences in the thermal stress profile.

These findings are pivotal for the welding industry, highlighting the need to carefully select the welding technique based on specific task requirements, such as desired strength, heat tolerance of materials, and precision of heat application. The intermittent technique, with its higher peak strength, may be preferable for applications requiring robust welds, while the direct method could be chosen for scenarios where uniform heat application is crucial.

The results underscore the importance of ongoing research into the interplay of thermal dynamics, material properties, and welding techniques. Future studies should aim to deepen the understanding of these factors, potentially employing advanced simulation and modeling to predict outcomes under varying conditions. As the welding industry continues to evolve, such insights will be invaluable in guiding the development of more sophisticated, precise, and efficient welding methods, catering to a wide range of industrial applications.

Relevant references include studies on laser beam micro welding with high brilliant fiber lasers (Schmitt et al., 2010), continuous laser welding with spatial beam oscillation(Dimatteo et al., 2019), and the effects of beam wobbling on the microstructure and hardness during laser welding of X70 pipeline steel(Yang et al., 2022). These studies provide valuable insights into the effects of process parameters and the resultant weld characteristics in laser wobbling welding processes.

## 5.0 DISCUSSION AND CONCLUSIONS

Ultimately, our study reveals the intricate dynamics of direct laser wobbling micro welding, emphasizing the critical role of heat input in determining the peel strength of welds. The results indicate a non-linear relationship between heat input and peel strength, as demonstrated by specimens 6 and 1 (where a lower heat input led to a higher peel strength). A balance between thermal input and weld integrity is demonstrated by this dichotomy, which challenges conventional notions of a linear relationship between heat input and strength.

This comprehensive study explores the complex dynamics of direct laser wobbling micro welding, emphasizing that heat input is crucial to the peel strength of welds. Heat input and peel strength are not linearly related, as demonstrated by specimens 6 (with lower heat input yielding higher strength) and 1 (with higher heat input yielding lower strength). It challenges conventional notions of linear heat input-strength correlation by emphasizing the nuanced and complex interplay between thermal input and weld integrity.

Key factors contributing to this complexity include the balance between material fusion and degradation, the unique thermal profiles introduced by direct wobbling techniques, and the influence of varying heat inputs on thermal stress and material distortion. These elements collectively dictate the mechanical properties and final quality of the weld, highlighting the need for precise and tailored control over the welding process.

In addition, our study highlights the importance of selecting appropriate welding strategies according to the specific application requirements based on a comparative analysis of intermittent versus direct laser wobbling micro welding techniques

Welds produced with the intermittent method generally exhibit a stronger peak peel strength, making it particularly suitable for applications requiring robust welds. In contrast, the direct method, which emphasizes uniform heat distribution, may be more appropriate when scenarios require a consistent distribution of heat.

This study significantly contributes to the field of laser welding by providing critical insights into optimizing welding processes for increased quality and efficiency. Furthermore, these findings suggest that parameter selection should be customized based on material properties and desired results, not only enhancing our understanding of the laser wobbling micro welding process, but also offering valuable guidance for industrial applications.

Future research directions should focus on a more granular analysis of the influencing factors in laser welding, potentially integrating computational modeling for predictive control of welding processes. Such advancements hold the promise of significantly enhancing the quality, reliability, and efficiency of laser welding techniques, marking a notable progression in the field and supporting the evolving needs of industrial applications.

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